Doctoral Thesis

Droplet production over a boiling pool during a slow depressurization

Author(s): Cosandey, Jérôme

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DROPLET PRODUCTION
OVER A BOILING POOL
DURING A SLOW DEPRESSURIZATION

A dissertation submitted to the

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presented by

JÉRÔME COSANDEY

Dipl.-Ing. ETH
born 18th September 1970
citizen of Sassel (Switzerland)

Accepted on the recommendation of

Prof. Dr. Ph. Rudolf von Rohr, examiner
Prof. Dr. B. R. Sehgal, co-examiner

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Summary

In this work, the entrainment of droplets which are produced by the burst of steam bubbles at the surface of a boiling pool is determined experimentally in a pilot scale facility. The experiments are carried out under conditions comparable to those prevailing during a severe core melt accident in a nuclear power plant. The measurements are made far above the air-liquid interface in the so called deposition controlled region.

The boiling pool has a variable volume of 137 to 367 litre, contains soluble (KI, CsI) or non-soluble fission product simulants (Al₂O₃). The bulk concentration in the pool is varied between 3.8 and 11.7 g/l for the soluble and 0.2 and 4.9 g/l for the non-soluble tracer substances. The entrainment factor is determined in different containment atmospheres (air-steam ratio: 0.0 to 0.47 kg/kg) and different pressures (2 to 6 bar). The vertical temperature gradient in the containment atmosphere is also varied in order to enhance the free convection above the boiling pool.

The entrainment factors measured with soluble tracer substances range from $E = 3.14 \cdot 10^{-6}$ to $E = 7.10 \cdot 10^{-5}$, whereas neither the pool volume, nor the type (KI vs. CsI) and the concentration of the tracer substance have any influence. However, the entrainment factor increases with the containment pressure for experiments with a pure steam atmosphere and decreases for experiments with an air-steam atmosphere. Furthermore, even if the pool water is totally evaporated, the entrainment factor is only slightly affected by the stronger boiling occurring shortly before the molten core is uncovered.

The entrainment factors measured with solid tracer substances range from $E = 5.22 \cdot 10^{-6}$ to $E = 5.11 \cdot 10^{-4}$. In contrast to the experiments with soluble substances, the entrainment factor does not depend on the pressure. Furthermore, the tracer concentration in the containment atmosphere remains constant, independently from the concentration in the boiling pool.

Using the present results, a new correlation based on the dimensionless Froude, Weber and Rayleigh numbers is obtained, which enables the prediction of the entrainment in pure steam as well as in air-steam atmospheres with one single correlation. The correlation uses different sets of constants for the prediction of the entrainment of solid or soluble tracer substances.

Summary
The results obtained in this work for soluble and solid fission product simulants are in good agreement with literature data on the entrainment factors measured in both, smaller and larger boiling pools. Therefore, the data presented in this work are particularly suitable for the validation of thermal-hydraulic codes and constitute a useful database for scale-up considerations.

**Zusammenfassung**

In dieser Arbeit wird der Mitriss von Tropfen, die beim Zerplatzen von Dampfblasen an der Oberfläche einer siedenden Flüssigkeit entstehen, experimentell in einer Pilotanlage untersucht. Die Experimente werden unter Bedingungen durchgeführt, wie sie in ähnlicher Form während eines schweren Kernschmelzeunfalls in einem Kernkraftwerk herrschen. Der Tropfenmitriss wird weit oberhalb der Sprudelschicht gemessen, in der sogenannten depositionskontrollierten Zone.

Der siedende Sumpf hat ein variables Volumen von 137 bis 367 Liter und enthält im Wasser lösliche (KI, CsI) oder nicht-lösliche (Al$_2$O$_3$) Modellsubstanzen. Die Sumpfkonzentration wird zwischen 3.8 und 11.7 g/l für die löslichen und zwischen 0.2 und 4.9 g/l für die nicht-löslichen Substanzen variiert. Der Entrainment-Faktor wird für unterschiedliche Luftanteile der Versuchsbehälteratmosphäre (Verhältnis Luft-Dampf: 0.0 bis 0.47 kg/kg) und für verschiedene Betriebsdrücke (2 bis 6 bar) bestimmt. Der vertikale Temperaturgradient kann in der Containment-atmosphäre eingestellt werden, um die freie Konvektion in der Gasphase oberhalb des Sumpfs zu verstärken.

Der Entrainment-Faktor von löslichen Substanzen variiert zwischen $E = 3.14 \cdot 10^{-6}$ und $E = 7.10 \cdot 10^{-5}$, wobei weder das Sumpfvolumen noch die Art der Substanz (KI vs. CsI) und die Konzentrationen der Modellsubstanzen im Sumpf einen Einfluss ausüben. Hingegen nimmt der Entrainment-Faktor mit steigendem Betriebsdruck bei Experimenten mit Luft-Dampfatmosphären zu, bei Experimenten mit reiner Dampfatmosphäre hingegen ab. Schliesslich, selbst wenn das Sumpfwasser oberhalb der Heizplatte ausdampft, ist der Entrainment-Faktor bis kurz vor der Freilegung der Heizplatte vom stärkeren Siedeverhalten nur leicht beeinflusst.

Der Entrainment-Faktor für Versuche mit nicht-löslichen Substanzen variiert zwischen $E = 5.22 \cdot 10^{-6}$ und $E = 5.11 \cdot 10^{-4}$. Im Gegensatz zu den
Experimenten mit löslichen Substanzen, ist der Entrainment-Faktor für unlösliche Substanzen vom Druck unabhängig. Zudem bleibt die Konzentration der Modellsubstanz in der Containmentsatmosphäre konstant, und zwar unabhängig davon, wie groß deren Sumpfkonzentration ist.


Die Korrelation verwendet zwei Sätze von Konstanten, um die verschiedenen Tropfenmitriss-Mechanismen von löslichen und nicht-löslichen Substanzen zu berücksichtigen.


Résumé

Ce travail a pour but d'étudier expérimentalement, dans une installation pilote, l'entraînement de gouttelettes produites lors de l'éclatement de bulles de vapeur à la surface d'un liquide. Les expériences sont conduites dans des conditions similaires à celle qui régneraient lors de la fonte accidentelle du cœur du réacteur dans une centrale nucléaire. Les mesures sont effectuées à une distance élevée au dessus de l’interface air-liquide dans la région dite: zone contrôlée par les effets de déposition.

Le puisard bouillonnant a un volume pouvant varier entre 137 et 367 litres et contient des traceurs solubles (KI, CsI) et non-solubles (Al₂O₃). Leur concentration dans le puisard varie entre 3.8 and 11.7 g/l pour les substances solubles et entre 0.2 et 4.9 g/l pour les substances non-solubles. Le facteur d'entraînement est déterminé pour différents types d’atmosphère dans l’enceinte de confinement (rapport air-vapeur: de 0.0 à 0.47 kg/kg) et pour différentes pressions (de 2 à 6 bar). Le gradient vertical de température peut être varié pour amplifier la convection naturelle au dessus du puisard.
Les facteurs d’entraînement mesurés avec des traceurs solubles varient entre $E = 3.14 \cdot 10^{-6}$ et $E = 7.10 \cdot 10^{-5}$, quand bien même ni le volume du puisard, ni le type (KI ou CsI) et la concentration des traceurs ne semblent avoir d’influence. Cependant, le facteur d’entraînement augmente avec la pression lors d’expériences conduites dans des atmosphères de vapeur pure et diminue dans des atmosphères d’air et de vapeur. D’autre part, lorsque l’eau du puisard est totalement évaporée, le facteur d’entraînement n’est que peu affecté par le bouillonnement plus intense qui apparaît peu de temps avant que la plaque chauffante ne soit plus recouverte d’eau.

Les facteurs d’entraînement mesurés avec des traceurs non-solubles varient entre $E = 5.22 \cdot 10^{-6}$ et $E = 5.11 \cdot 10^{-4}$, mais contrairement aux expériences conduites avec des traceurs solubles, ne dépendent pas de la pression. De plus, la concentration des traceurs dans l’atmosphère du caisson reste constante, quelque soit leur concentration dans l’eau du puisard.

Les résultats obtenus dans ce travail ont été utilisés pour développer une nouvelle corrélation se basant sur les nombres caractéristiques de Froude, de Weber et de Rayleigh. Cette corrélation permet de prédire le facteur d’entraînement avec une seule corrélation, aussi bien dans une atmosphère de vapeur pure que dans une atmosphère d’air et de vapeur. Le modèle fait appel à différents jeux de constantes pour la prédiction de l’entraînement de substances solubles ou non-solubles.

Les résultats obtenus dans le cadre de ce travail avec les traceurs solubles et non-solubles sont en bon accord avec les valeurs trouvées dans la littérature; ceci aussi bien pour des puisards bouillonnants plus grands ou plus petits que celui utilisé dans ce projet. Par conséquent, les données présentées dans ce travail sont particulièrement adaptées pour valider des codes thermo-hydrauliques et constituent une base de données importante pour le transfert de ces résultats sur des installations réelles.

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## Nomenclature

### Latin letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>([m^2])</td>
<td>surface</td>
</tr>
<tr>
<td>C</td>
<td>([g/l])</td>
<td>concentration</td>
</tr>
<tr>
<td>C</td>
<td>[-]</td>
<td>transformation matrix</td>
</tr>
<tr>
<td>Cp</td>
<td>([J/kg \ K])</td>
<td>heat capacity</td>
</tr>
<tr>
<td>d</td>
<td>([m])</td>
<td>diameter</td>
</tr>
<tr>
<td>D</td>
<td>([m])</td>
<td>containment diameter</td>
</tr>
<tr>
<td>D</td>
<td>([m^2/s])</td>
<td>diffusion coefficient</td>
</tr>
<tr>
<td>df</td>
<td>[-]</td>
<td>degree of freedom</td>
</tr>
<tr>
<td>E</td>
<td>[-]</td>
<td>entrainment factor</td>
</tr>
<tr>
<td>E</td>
<td>([J])</td>
<td>energy</td>
</tr>
<tr>
<td>F</td>
<td>([\text{N}])</td>
<td>force</td>
</tr>
<tr>
<td>g</td>
<td>([m/s^2])</td>
<td>gravitational acceleration</td>
</tr>
<tr>
<td>G</td>
<td>([J/kg])</td>
<td>free formation enthalpy</td>
</tr>
<tr>
<td>h</td>
<td>([J/kg])</td>
<td>specific enthalpy</td>
</tr>
<tr>
<td>H</td>
<td>([m])</td>
<td>containment height</td>
</tr>
<tr>
<td>H</td>
<td>([J])</td>
<td>enthalpy</td>
</tr>
<tr>
<td>j</td>
<td>([m/s])</td>
<td>superficial velocity</td>
</tr>
<tr>
<td>J</td>
<td>([1/\text{sec}])</td>
<td>nucleation rate, aerosol flux</td>
</tr>
<tr>
<td>k</td>
<td>[-]</td>
<td>correction coefficient, constant</td>
</tr>
<tr>
<td>L</td>
<td>([m])</td>
<td>length, characteristic length</td>
</tr>
<tr>
<td>m</td>
<td>[-]</td>
<td>counter</td>
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<tr>
<td>M</td>
<td>([\text{kg}])</td>
<td>mass</td>
</tr>
<tr>
<td>(m)</td>
<td>([\text{kg/s}])</td>
<td>mass flow</td>
</tr>
<tr>
<td>n</td>
<td>[-]</td>
<td>counter</td>
</tr>
<tr>
<td>N</td>
<td>[-]</td>
<td>amount of particles</td>
</tr>
<tr>
<td>(n)</td>
<td>([l/s])</td>
<td>production rate</td>
</tr>
<tr>
<td>p</td>
<td>([\text{Pa}])</td>
<td>pressure</td>
</tr>
<tr>
<td>Q</td>
<td>([\text{W}])</td>
<td>heat power</td>
</tr>
<tr>
<td>r</td>
<td>([m])</td>
<td>radius</td>
</tr>
<tr>
<td>R</td>
<td>([J/kg \ K])</td>
<td>gas constant</td>
</tr>
<tr>
<td>s</td>
<td>[%]</td>
<td>standard deviation</td>
</tr>
<tr>
<td>t</td>
<td>[-]</td>
<td>test statistic</td>
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<td>T</td>
<td>([\text{K}])</td>
<td>temperature</td>
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<tr>
<td>V</td>
<td>([m^3])</td>
<td>volume</td>
</tr>
<tr>
<td>w</td>
<td>([m/s])</td>
<td>velocity</td>
</tr>
<tr>
<td>W</td>
<td>[-]</td>
<td>probability</td>
</tr>
<tr>
<td>x</td>
<td>([\text{kg/kg}])</td>
<td>mass ratio</td>
</tr>
</tbody>
</table>
Greek letters

- \( \alpha \) \quad [W/m^2 K] \quad heat transfer coefficient
- \( \beta \) \quad [1/K] \quad thermal coeff. of volumetric expansion
- \( \delta \) \quad [m] \quad liquid film thickness
- \( \varepsilon \) \quad [m^3/m^3] \quad void fraction
- \( \Phi \) \quad [1/m] \quad size distribution
- \( \eta \) \quad [-] \quad scaling factor
- \( \lambda \) \quad [W/m K] \quad thermal conductivity
- \( \Lambda \) \quad [m] \quad mean free path
- \( \mu \) \quad [kg/m/s] \quad viscosity
- \( \nu \) \quad [m^2/s] \quad kinematic viscosity
- \( \rho \) \quad [kg/m^3] \quad density
- \( \sigma \) \quad [N/m] \quad surface tension
- \( \tau \) \quad [s] \quad residence time
- \( \xi \) \quad [-] \quad drag coefficient

Subscripts

- air \quad air
- as \quad air/steam
- b \quad bubble
- BP \quad boiling pool
- burst \quad at the time when the bubble bursts
- conc \quad concave
- cond \quad condensate
- cont \quad containment
- cool \quad cooling coil
- crit \quad critical
- dr \quad droplet
- dcr \quad deposition controlled region
- dyn \quad dynamic
- el \quad electrical
- g \quad gas
- hl \quad heat loss
- HP \quad heat plate
- hom \quad homogenous
- i \quad counter
- is \quad isenthalpic
- j \quad counter

Nomenclature
XIII

kin kinetic
l liquid
lam laminar
m homogenous
mcr momentum controlled region
n cg non-condensable gas
nsr near surface region
p particle
pot potential
§ shield
stat static
surf surface
t student
tot total	

Superscripts
^ dimensionless
~ matrix
\cdot time derivation
° total
- vector

Mathematic
<> average
Δ Laplace-operator

Acronyms
2D, 3D two resp. three Dimensional
AC Alternative Current
AAS Atomic Absorption Spectroscopy
AES Atomic Emission Spectroscopy
ALPHA Assessment of Loads and Performance of Containment
in a Hypothetical Accident
BFE Swiss Federal Office of Energy
DSA Droplet Shape Analysis

Nomenclature
Dimensionless numbers

\[ E = \frac{\dot{m}l}{m_g} \]  
Entrainment factor

\[ Fr = \frac{w^2}{g \cdot d_r} \]  
Froude-number

\[ Gr = \frac{H^3 \cdot g \cdot \beta \cdot \Delta T \cdot \rho^2}{\mu^2} \]  
Grasshof-number

\[ Kn = \frac{2 \cdot \Lambda}{d_p} \]  
Knudsen-number

\[ M = \frac{g \cdot \mu_j \cdot (\rho_j - \rho_g)}{\rho_j^2 \cdot \sigma^3} \]  
Morton-number

\[ Nu = \frac{\alpha \cdot L}{\lambda} \]  
Nusselt-number

\[ Ra = Gr \cdot Pr \]  
Rayleigh-number

\[ Re = \frac{\rho \cdot d \cdot w}{\mu} \]  
Reynolds-number

\[ Pr = \frac{C_p \cdot \mu}{\lambda} \]  
Prandtl-number

\[ We = \frac{\rho_j \cdot w^2 \cdot d}{\sigma} \]  
Weber-number
1 Introduction

The protection of the public from the potential consequences of accidents in nuclear power plants has always been a major goal of the nuclear industry. Early investigations of these consequences concluded that they could be prevented by ensuring that the nuclear fuel does not melt. Accordingly, Western-type reactors are equipped with redundant emergency core cooling systems to reduce the probability of fuel melt. Further, these systems are housed in containment buildings designed to retain the radioactivity in the unlikely event that they failed. However, even though severe core melt accidents might be extremely unlikely, they cannot be excluded. Therefore, investigations have been continuously made to ensure that the risks to the public from nuclear power plants are reduced to a minimum.

The risks from nuclear power plants may be decreased either by reducing the likelihood of the accidents or by reducing their consequences. The reduction of the frequency of the accidents may be possible in plants which have weaknesses in their design or operation. However, the extent to which this can further reduce the risk is nowadays limited. Further risk reduction, therefore, must be obtained by reducing the consequences of the accidents by accident mitigation.

Accident mitigation has to be understood as a part of the defence in depth concept. First, the operators have to be trained in order to enable them to analyse the situation under stress conditions and discern which actions have to be undertaken in order to re-establish the cooling of the reactor or at least to reduce the release of radioactive products to the environment. In addition, technical measures must be implemented to support the operators in their tasks and prevent the loss of integrity of the containment (see [111]). If this cannot be granted, for instance in the case of accidents involving failure of the containment caused by overpressurization (see Section 1.1), additional devices limiting the damages to the containment and simultaneously reducing the contamination outside of the facility have to be installed.

Eventually, if radioactive material is released to the environment, emergency plans must exist and be exercised in order to limit the exposure to radiation of the population in the short (radiation by inhalation
during the release phase) as well as in the long term (radiation from the ground and by ingestion in the post-release phase) [81].

1.1 Reference scenario

There are many different scenarios leading to a severe core melt accident. In this work a scenario called station black out is considered as reference scenario [63].

In case of loss of off-site power, the reactor is automatically shut down and the power for the active safety systems is supplied by the emergency power systems (diesel engines). If those engines also fail to start, the power plant has no AC power any more (station black-out) and the feed of the secondary loop of the steam generator can no more be delivered. At first, the decay heat produced by the reactor is removed from the primary loop by the steam generator, which boils its secondary water. After ca. 45 min., all the secondary water has been evaporated and no heat can be removed any more. Hence, the temperature and the pressure in the primary loop increase until the pressure relief valve of the reactor vessel opens. The produced steam is then released in the containment where it condenses in contact with the colder containment walls. The condensed steam is gathered in the lower part of the containment and builds a water sump.

After ca. 2 hours, the upper part of the core is no more covered by water and the decay heat cannot be fully removed by the steam flow. The uncovered part of the reactor heats up. As the temperature reaches ca. 1000 °C, the zircaloy cladding material of the fuel rods starts to react with the produced steam. This reaction is strongly exothermic and releases hydrogen gas [39], [103]. Consequently, the heating of the reactor is accelerated and as its temperature reaches ca. 1200 °C, the fuel material starts to melt. Part of the reactor melt relocates then to the lower plenum of the pressure reactor vessel [69]. After about 4 hours, the molten core melts through the pressure vessel and falls into the sump on the containment floor. Due to the decay heat, large amounts of the sump water are evaporated and the pressure in the containment increases. Additionally, the molten core debris react thermally and chemically with the concrete of the containment cavity (Molten Core/Concrete Interaction, MCCI). During this reaction, combustible gases
as hydrogen and carbon monoxide are released [104]. Depending on
the reactor type and on the thermal power of the NPP, the total release
of hydrogen can reach several hundreds of kilos. If the resulting con-
centrations of hydrogen and oxygen exceed 4.5% resp. 6.5%, a defla-
gration might occur and pressure peaks up to 4 times the prevailing
pressure can be reached [35].

The gas produced by the MCCI and the steam produced in the sump
water increase the pressure in the containment and the failure pressure
of the containment is reached after ca. 20 hours [35] resp. 4 to 5 days
[4], depending on the type of reactors considered. If the pressure
exceeds the failure pressure, fissures might be expected and the con-
tainment loses its integrity.

The chronology of this reference scenario is summarized in Tab. 1-1.

<table>
<thead>
<tr>
<th>Time [hr.]</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Station black-out.</td>
</tr>
<tr>
<td>0-0.75</td>
<td>Water in secondary loop is boiled out.</td>
</tr>
<tr>
<td>0.75-2.3</td>
<td>Primary water blows out through pressure relief valve.</td>
</tr>
<tr>
<td>2.3-2.5</td>
<td>Zirconium-steam reaction.</td>
</tr>
<tr>
<td>2.5-4.3</td>
<td>Fuel start melting, relocation to the lower plenum of the Pressure Reactor Vessel (PRV).</td>
</tr>
<tr>
<td>4.3</td>
<td>Core melts through the PRV and falls on the ground of the containment.</td>
</tr>
<tr>
<td>4.5-24.0</td>
<td>Molten core/concrete reaction, release of H₂ and CO.</td>
</tr>
<tr>
<td>20-120</td>
<td>Containment failure pressure is reached.</td>
</tr>
</tbody>
</table>

TABLE 1-1: Chronology of the reference scenario [35].

Beside the production of steam, hydrogen and carbon oxides, light vol-
atile fission products (iodine elements, radioactive inert gases) are
released in the containment atmosphere during the melting of the reac-
tor core. The concentration of these aerosols in the containment is
strongly dependent on time. Due to impaction, coagulation and sedi-
mentation effects (see Section 2.5.2), the concentration of aerosols in
the containment is reduced by 5 orders of magnitude in the first 5 days
[64]. It is therefore important to maintain the containment intact as
long as possible, in order to keep an eventual release of fission prod-
ucts in the environment as low as possible. This means that pressure peaks, e.g. caused by hydrogen or steam explosion, have to be prevented and efforts have to be made to avoid that the pressure in the containment excesses the failure pressure in the long term.

1.2 Filtered venting containment systems

Among the many systems to avoid overpressurization in the containment (see [2], [35] and [111]), Filtered Venting Containment Systems (FVCC) will be presented in this section.

The main idea of a venting system is to remove part of the containment atmosphere through a pipe located in the upper part of the containment. The removed gas containing air, steam and fission products is led through filters where a large part of the radioactive aerosols is retained. The venting system can be operated either automatically using a rupture disk or manually by the plant operators.

This system have several advantages:

- It reduces the pressure in the containment, ensuring its integrity.
- The effluents are filtered limiting the release of radioactivity to the environment (compared to a release due to containment leakage).
- During the venting, large amounts of oxygen are removed from the containment atmosphere and are replaced by steam. This makes the containment inert and prevents hydrogen explosions [28].
- As soon as the integrity of the containment is no more threaten by overpressurization, the venting system can be closed stopping immediately the release of radioactivity (which were not possible if the containment were fissured).
- Venting systems are especially attractive as they can be retrofitted to operating plants. The filter system can be housed in a separate building outside the containment and be connected to it through a venting pipe [118].

On the other hand, venting strategies are inconsistent with the initial aim of the containment building: retaining the fission products. If the threat of the containment integrity is not acute, a closed and tight containment is still better for the environment.
Therefore, in order to estimate the overall benefit of venting systems, numerous Probabilistic Safety Analyses (PSA) were carried out ([26], [76], [79], [118], [120]). The analyses show that the resulting benefit of containment venting depend on the accident path, on the type of reactor and on the location of the nuclear power plant. Therefore, the decision to vent the containment must consider the following elements: the situation in the containment (pressure, hydrogen resp. oxygen concentration), the grade of protection of the population close to the NPP, the weather category and the wind direction [105].

As in Switzerland the overall benefits of a FCVS prevail in many accident scenarios, the Swiss Federal Nuclear Safety Inspectorate (HSK) constrained all Swiss NPPs to install such a venting system. The imposed specifications for the filter systems are to retain by a factor of 1000 the aerosols (especially cesium compounds) to prevent or limit a long term ground contamination and by a factor of 100 the elementary iodine to prevent or limit thyroid doses and avoid short term evacuation [61]. However, the NPPs were free to chose the type and the suppliers of the filter systems (for more details about the chosen systems, see [45] and [115]).

Another problem by using a venting system has not yet been mentioned. As the venting valve opens, the pressure in the containment decreases and severe changes in the containment atmosphere occur. Containment venting may cause flashing of the water pool at the bottom of the containment or, at least, will cause a stronger boiling of the pool. Tiny droplets are produced by the sparkling pool and thus, previously deposited aerosols in the sump will be re-entrained into the containment atmosphere. If the droplet’s terminal velocity is smaller than the gas superficial velocity above the pool, the droplets will be carried out into the open venting system. Releases, which were otherwise small, may largely increase due to this effect.
1.3 State of the art

1.3.1 Areas of application

Aerosol release and aerosol behaviour over a sparkling pool were investigated in a large number of separate effect studies and integral experiments. The reason for this broad interest is the numerous fields of applications:

- efficiency of evaporators and bubble columns in the chemical industry,
- nuclei source term for the clouds formation over oceans,
- air contamination above whirling pools (waste water treatment, leisure centre)
- emergency depressurization of pressure vessels

In the following paragraphs, the mentioned fields of application are considered in more details.

Efficiency of evaporators and bubble columns

Evaporation has been used for centuries in order to separate a liquid from solid particles. For instance, salt was obtained by evaporating sea water with sun radiation. Nowadays, distillation resp. rectification columns are used for this task as well as for the separation of two liquid with different boiling points. In so called bubble columns or plate columns, a gas resp. a steam flow rise through a liquid phase. As the gas bubbles reach the upper part of the column, they burst at the surface of the liquid and small droplets are produced which are partly entrained in the distillate. The quality of the obtained essences depends mostly on this amount of “impure” droplets which are carried out in the distillate.

Therefore, experiments were carried out in the 1930’s in order to determine the efficiency of rectification resp. absorption plate columns [5], [27], [70], [83], [126], [128]. It was shown that the amount of entrained droplets is mainly a function of the superficial velocity, of the plate geometry (cap or sieve plate) and of the distance separating two plates. As the distance between the plates determines the height of the column, this means the investment costs, and as the quality of the distillate determines the cost of production, a trade-off has to be found in
order to reduce the overall expenses. Depending on the costs of the product, the superficial velocity resp. the dimensions of the column are adapted.

Similarly, in the middle of this century, many experiments were carried out in order to investigate the entrainment of water in evaporators. This evaporators are used for the production of dry steam in the energy production, [41], [49], [97], (in order to avoid damages in the steam turbines), for the production of desalinated drink water [54], [113], and for the treatment of water spoiled with radioactive material [92]. Here too, a compromise has to be found between the costs of complicated evaporator geometry and the benefits of an absolute pure steam.

*Nuclei source term for the clouds formation over oceans*

When the whitecap of sea waves burst, small droplets containing sea-salt are produced. The water of these droplets evaporates but the salt crystals remain as airborne. These airbornes provide the most important part of the nuclei for the cloud formation over the oceans. Hence, the weather in costal regions is mainly determined by the entrainment phenomena over the sea.

Consequently, a large amount of experiments were carried out in order to describe the production of droplets (source term of nuclei) over the oceans (e.g. [12], [15], [31], [108], [129], [131]). These experiments were mainly focused on the influence of the salt concentration, of the water temperature and of the size of the bursting bubbles. It was shown that the bubble diameter plays a major role in the determination of the size and the amount of the ejected droplets. The results of these experiments will be further described in Section 2.3.1.

*Whirling pools*

Communal waste water are often decomposed biologically. Therefore, the water is put in a pool where air is supplied in order to aerate the water so that bio-organisms can growth and survive. Due to the burst of these air bubbles however, droplets containing microorganisms are transported as airborne far away from the waste water treatment plant. Experiments in order to determine the enrichment of these organisms above such a whirling pool ([116], [137]) are therefore important in order to determine the threat to the health of the people living or working close to such a treatment plant.
Emergency depressurization of pressure vessels

Due to a sudden pressure drop, a liquid close to its boiling temperature tends to reach a new equilibrium state. This forces part of the liquid to evaporate (flash-boiling) and a strong bubbling is expected. This sudden pressure drop might occur during the emergency depressurization of a chemical stirred reactor or by the operation of the venting system in a NPP. In this case, radioactive material contained in the liquid droplets will be carried into the containment atmosphere. This special application will be discussed in the following section.

1.3.2 Entrainment of nuclear aerosols: a research survey

Although all of the experiments described in the above section deal with the entrainment of droplets, most of them cannot directly be used for the prediction of the aerosol entrainment in a venting system. As a matter of fact, the measurements were mostly made just above the gas-liquid interface. At this distance above the pool, droplets with settling velocities higher than the rising gas velocity were also measured. These droplets might be important for the dimensioning of a plate column but are not relevant in the case of severe core melt accident. As the location of the venting pipe is far above the boiling water surface, those heavy droplets will have fallen back to the pool before they have reached the venting system.

Furthermore, most of the experiments described in the former section were not carried out under conditions (pressure, temperature, specific gas flow) typical for a severe core melt accident.

Consequently, the nuclear community has undertaken several programs in order to investigate the entrainment of droplets far above the boiling pool and under prototypical conditions of a nuclear accident. Comprehensive reviews of these projects are given by Covelli [34] and Schöck et al. [121].

In the following paragraphs, the experimental set-ups and the main results of the programs relevant for this work are summarized.
Garner's experiments

These experiments were carried out by F. H. Garner in a pilot plant evaporator [49]. The diameter of the evaporator was 0.305 m and the pool had a volume of 45 litres (pool depth: 0.610 m). The experiments were carried out in a pure steam atmosphere at a pressure of 1 bar.

The entrainment was determined by integral measurements (see Section 3.2.1) using potassium nitrate as tracer substance and by local measurements using microscope slides coated with magnesium oxide. In the latter method, droplets striking the slide penetrate the surface giving a well defined circular impression. The ratio of the diameter of the original droplet to that of the impression is a constant which can be determined by calibration.

The size and the amount of the entrained particles were determined as a function of the tracer concentration ($0 \text{ g/l} < C_{\text{BP}} < 165 \text{ g/l}$) and of the superficial velocity in the evaporator ($46 \text{ cm/s} < j_g < 130 \text{ cm/s}$). The latter parameter was found to have the greatest effect upon the amount of entrainment.

The LACE experiments

The LWR Aerosol Containment Experiments (LACE) program investigated the aerosol behaviour in the containment during a severe nuclear accident [106]. This program was sponsored by an international consortium and organised by the Electric Power Research Institute (EPRI). The LACE program consisted of six tests focusing on four postulated accident situations:

- containment bypass (LA-1, LA-3)
- failure to isolate the containment (LA-2)
- delayed containment failure (LA-4)
- rapid depressurization of the containment (LA-5, LA-6).

The objectives of LA-5 and LA-6 was to study the entrainment from a flashing pool which may occur during a containment failure accident. Therefore, these two experiments benefit of particular interest in this work and only those two will be described here (for the LA-1 to LA-4 experiments, see Schöck et al. [121]). The facility consisted of a steel container with a volume of 852 m$^3$. The vessel had an inner diameter
of 7 m and was 20.3 m high. A sump unit with a diameter of 1.5 m and a pool volume of 5300 litres was placed inside the containment. The experiments were carried out in a nitrogen-steam atmosphere and the containment was pressurized up to 4.4 bar and vented in 1 minute down to 1 bar [17].

In both test, the pool was spiked with solutions of soluble lithium sulphate (80 g/l) and suspensions of zinc oxide (5 g/l). In LA-6, a two-components aerosol was additionally released into the containment atmosphere at the beginning of the test (soluble cesium hydroxide and insoluble manganese (II) oxide). The deposition of the produced aerosols was determined at several location in the vessel, at the walls and in the venting pipes using glass-fibre filters.

The elemental content of the aerosols was determined by atomic absorption resp. by atomic emission spectroscopy (AAS resp. AES). The chemical species were identified by means of x-ray diffractometers and IR-spectroscopy. The shape of the particles was analysed with a scanning electron microscope (SEM). It was shown that a plug of material was ejected when the containment is rapidly depressurised and that there is a preferential deposition of the water-soluble components.

The REST experiments

These experiments were performed by Bunz et al. in the framework of the shared-cost action program 1985-1987 [20]. The experiments were carried out in the REST facility (REsuspension Source Term) at the Kernforschungszentrum Karlsruhe (nowadays Forschungszentrum Karlsruhe FzK). The facility consisted of a stainless steel container with a volume of 3.7 m$^3$. The vessel had an inner diameter of 1.5 m and its height was 1.5 m. A sump unit with a diameter of 0.108 m and a pool volume of 12 litres was placed inside. The experiments were carried out in an air-steam atmosphere and the grade of humidity was varied.

In the sump both, solutions of fluorescine or suspensions of barium sulphate, were brought to boiling. The entrainment was determined by leading part of the atmosphere through filters. The particles deposited on the filters were then washed and their concentration was measured.
The amount of the entrained particles (solutions and suspensions) as well as the size distribution (suspensions) were determined as a function of the tracer concentration ($3 \text{ g/l} < C_{BP} < 30 \text{ g/l}$), of the heat power in the boiling pool (250-1'000 W) and of the pool depth. Only the heating power was found to have a significant effect upon the amount of entrainment. Furthermore, by experiments with solid model substances (suspensions), the entrained mass of particles was not dependent on the sump concentration.

The ALPHA experiments

The ALPHA program (Assessment of Loads and Performance of Containment in a Hypothetical Accident) was carried out at the Japan Atomic Energy Research Institute, JAERI, by Kudo et al. [82]. The facility consisted of a model containment with an inner diameter of 3.9 m, a height of 5.7 m and an inner volume of 50 m$^3$. Inside of it, a 1 m diameter and 2 m deep pool was installed. The experiments consisted in the rapid depressurisation of an atmosphere of nitrogen and steam from a pressure of 13 resp. 15 bar down to ambient pressure in ca. one hour.

The boiling/flashing pool contained solutions of sodium sulphate. The entrainment was determined by leading part of the atmosphere through cascade impactors. After the experiments, the dishes of the impactors were washed with pure water and the concentration of the sodium ion was measured with an ion chromatograph.

The amount and the size distribution of the entrained particles were determined as a function of the pool volume (800 resp. 400 litres) and of the time of sampling. Only two experiments were carried out and the results showed large scattering. However, the order of magnitude of the entrainment could be determined.

The REVENT experiments

The REVENT experiments (REentraiment by VENTing) were carried out at the Swiss Federal Institute of Technology, ETH, by Müller [96]. The facility consisted of a model containment with an inner diameter
of 1.5 m, a height of 3 m and an inner volume of 5 m$^3$. At the lower part, a pool with a variable volume (140 to 370 litres) exists. A more detailed description of the REVENT facility is given in Section 3.1. The experiments were carried out under steady state conditions (constant pressure) or during slow (containment venting) or fast depressurization (containment leakage).

The boiling/flashing pool contained tracer substances (soluble and solid particles). The entrainment was determined by measuring their concentration in the boiling pool and in the steam removed from the containment atmosphere. The ratio of the two concentrations equals the entrainment factor (see Section 3.2). The concentration in the solutions was measured with ion selective probe and with ion chromatography and those in the suspensions by gravimetry and SEM.

The amount of the entrained particles (experiments with solutions and suspensions) as well as the size distribution (experiments with suspensions) were determined as a function of the tracer substance, of the tracer concentration ($0.8 \text{ g/l} < C_{BP} < 12 \text{ g/l}$), and of the depressurization rate. The tracer materials used were sodium sulphate, potassium iodide and cesium iodide for the soluble model substances and silicium carbide with different size distributions for the solid model substances.

It was shown that, at the beginning of the depressurization, the entrainment has a peak but decreases very rapidly below the level of the entrainment rate observed under steady state conditions. Therefore, the results obtained under steady state conditions in the REVENT facility are on the safe side.

Furthermore, Müller developed a deterministic model describing his own results quite accurately. The model underlines the importance of the velocity field above the water surface and the major effect of the bubble size in the boiling pool.

A quantitative comparison of the results presented in this section will be given in Chapter 6.
1.4 **Scope and project objectives**

The aim of this project is to provide experimental data about the entrainment of aerosols from a boiling pool under conditions which are prototypical for a severe core melt accident. Especially, the interaction between the aerosol source term in the pool and the transport of the produced aerosols in the containment atmosphere shall be investigated.

In this work, as suggested by Müller [96], special attention shall be paid to the bubble size distribution in the pool and to the flow pattern in the containment atmosphere. The investigations should be carried out in a large scale facility in order to reduce the boundary effects but, in the same time, the dimensions of the set-up should be chosen such that extensive parameter studies and easily reproducible experiments remain feasible.

Therefore, the REVENT facility shall be modified and operated in order to reach the following goals:

- to determine the bubble size distribution in the boiling pool as it is a main factor in the determination of the aerosol source term,
- to determine the influence of the free convection in the containment atmosphere on the entrainment of droplets from the boiling pool by varying the atmosphere composition and the vertical temperature gradient prevailing in the containment,
- to determine the entrainment at pressures and temperatures occurring during an hypothetical venting of the containment.

During these investigations, the influence of the pool volume, as well as the effects of the type (soluble or non-soluble) and the amount (concentration) of impurities in the pool shall also be considered.

The final objective of this work is to provide valuable information for the validation of thermal-hydraulical models and for the optimization of the venting strategy. Hence, the data have to be presented in such a form that a scaling-up of the obtained results on existing or planned nuclear power plants is possible.
2 On bubbles, droplets and entrainment

In this chapter, the entrainment of droplets from a boiling pool in the containment of a nuclear power plant is illustrated. After a short description of the phenomena occurring in and above the boiling pool, the entrainment factor is defined. In the following sections, the entrainment process is split into successive steps and the basics for each step are described in details. At the end of the chapter, the technical possibilities to quantify the entrainment factor are presented.

2.1 Definition of the entrainment factor

Consider the closed vessel shown in Fig. 2-1. Through the sump water in the lower part of the vessel, a gas flow, \( m_g \), rises as a bubble swarm. It consists of a steam flow, \( m_v \), which is produced for instance by the decay heat of the molten core and of a flow of non-condensable gas, \( m_{ncg} \), which could be resulting from the molten core/concrete interaction.

\[
\dot{m}_g = \dot{m}_v + \dot{m}_{ncg}
\]  

(2-1)

Part of the steam flow, \( \dot{m}_{v,w} \), condenses at the containment wall and the rest, \( \dot{m}_{v,cond} \), leaves the vessel through the venting pipe and condenses in a heat exchanger.

\[
\dot{m}_v = \dot{m}_{v,cond} + \dot{m}_{v,w}
\]  

(2-2)

Due to the break-up of the gas bubbles, droplets are projected in the atmosphere above the pool. Droplets with a terminal velocity higher than the gas superficial velocity, \( j_g \), fall back to the pool. The rest, \( \dot{m}_l \), is carried out by the gas flow. Due to Brownian motions, impaction forces and thermophoresis, part of the droplet flow, \( \dot{m}_{l,w} \), hits the wall and flows back to the pool. The rest, \( \dot{m}_{l,cond} \), is carried out in the venting pipe.

\[
\dot{m}_l = \dot{m}_{l,cond} + \dot{m}_{l,w}
\]  

(2-3)

In order to describe the amount of liquid entrained by the gas flow, one defines the entrainment factor as the ratio of the mass flow of entrained liquid divided by the mass flow of the carrier gas.
Fig. 2-1: Burst of bubbles and entrainment of droplets.

\[ E = \frac{\dot{m}_l}{\dot{m}_g} = \frac{j_l \cdot \rho_l}{j_g \cdot \rho_g} = \frac{\dot{m}_{l,\text{cond}} + \dot{m}_{l,w}}{\dot{m}_{v,\text{cond}} + \dot{m}_{v,w} + \dot{m}_{\text{nog}}} \]  

(2-4)

In order to determine the variables mentioned in Eq. 2-4, the different steps in the entrainment process, namely the rise of the bubbles to the pool surface, the break-up of the bubbles, the production of droplets and their transport in the containment atmosphere, will be presented in the following sections.

### 2.2 Bubble behaviour in a pool

The energy released by the burst of a bubble is mainly provided by the pressure inside the bubbles. Because of the surface tension, this pressure is greater than the pressure in the surrounding liquid. For a gas bubble, this difference is called capillary pressure and equals:
Furthermore, if the bubble consists of steam, its pressure could at the most equal the saturation pressure, $p_s$, at the temperature of the surrounding liquid. In fact, it is somewhat lower as the surface of the liquid surrounding the bubble is concave [56]. Thus, its vapour pressure is reduced compared with a flat surface by the amount:

$$\Delta p_{\text{conc}} = \frac{4 \cdot \sigma}{d_b} \cdot \frac{\rho_v}{\rho_l - \rho_v}$$ \hspace{1cm} (2-6)

The total pressure in the steam bubble is then given by Eq. 2-7:

$$p_s - \Delta p_{\text{conc}} = p_\infty - \rho_l \cdot g \cdot z + \Delta p_{\sigma}$$ \hspace{1cm} (2-7)

Rearranging this equation, one obtains for the pressure difference between the bubble and its surrounding:

$$\Delta p_b = p_s - p_\infty = \frac{4 \cdot \sigma}{d_b} \cdot \frac{\rho_l}{\rho_l - \rho_v} - \rho_l \cdot g \cdot z$$ \hspace{1cm} (2-8)

Note that the pressure in bubbles close to the surface is mainly influenced by the bubble diameter and that small bubbles contain more energy per unit of volume than larger one. Experiments over large pressure ranges (1- to 200 bar) were carried out in order to determine the effect of pressure on the mean bubble diameter ([42], [74], [77], [86], [140]). It is shown that the bubble distribution gets narrower and shifts to smaller mean diameter as the pressure in the system increases. However, no significant influence is observed for pressure variation between 1 and 16 bar.

Another energy source for the burst of a rising bubble is its kinetic energy. Several correlations are given in the literature for determining the terminal velocity of a gas bubbles (see e.g. [42], [55],[94] and [110]). For a given fluid, the drag coefficient of a rising bubble is mainly a function of the bubble shape (spherical, ellipsoidal, etc.), which can be determined using the dimensionless Eotvös- and Reynolds numbers [33]. The Eotvös-number, $Eo$, is only a function of the fluid properties. The Reynolds number however depends on the bubble
velocity which is a function of the flow regime in the pool. According to Wallis [136], three flow regimes which correspond to different superficial velocities can be distinguished.

*Bubbly flow or quiescent bubbling*

This regime occurs at low superficial velocities. This regime is characterized by almost uniformly sized bubbles with equal radial distribution. The burst of one bubble is not influenced by the burst of the following one.

*Churn turbulent flow or heterogeneous regime*

At higher gas velocities the homogenous gas dispersion cannot be maintained and an unsteady flow pattern with channelling occurs. This heterogeneous flow regime is characterized by large bubbles moving with high rise velocities in the presence of small bubbles [125].

*Slug flow*

In small diameter columns, at high gas flow rates, large bubbles are stabilized by the column wall leading to the formation of bubble slugs.

In this work, bubbly flow is considered (for transition criteria from the bubbly to the churn turbulent regime, see [78],[136]) and terminal velocity in the range of 0.2 m/s are expected [125]. Thus, the kinetic energy is about three orders of magnitude lower than the energy provided by the pressure in the bubble and can be therefore almost neglected.

### 2.3 Droplet production at liquid gas interface

#### 2.3.1 Bubble burst

As a bubble rises to a liquid surface and penetrates the surface film, a dome-shaped lamina of liquid is formed. Due to the gravity force, liquid drains from the dome until the upper part is so weakened that the cap disintegrates. With pure liquids, drainage from the dome is very rapid, so that the bubble ruptures almost immediately as it reaches the surface. However, the presence of impurities, dissolved salts or mono-molecular films, stabilises the bubble and its floating time at the
surface may be sufficient to form a foam [49]. Even in reasonably pure water, the time-lag before collapse is of the order of 1/100 sec.

The mechanism of the collapse of the bubble was already suggested by Stuhlman in 1932, [133], but it was Newitt in 1954, [97], who first photographed it. The disintegration of the bubbles is illustrated in Fig. 2-3.

The thin liquid film at the apex of the bubble breaks up by the initial formation of a number of perforations which subsequently expands to give a lace-like structure (see Fig. 2-2). The liquid ligaments so formed are unstable and break into small droplets of a few microns in diameter. Those droplets are known as film droplets and are carried away by the rush of gas issuing from the perforated dome with the velocity, \( w_{g, burst} \). This gas forms a vortex ring which entrains the film droplets and lifts them above the water surface [73]. These vortex rings decay exponentially with time, and linearly with the distance to the pool. The results of these events is to set up a system of standing waves and to leave a well defined crater (e) in Fig. 2-3 in the interface. Liquid streams back into the remaining cavity, forming a jet originated by the momentum of the liquid, which moves at high velocity perpendicular to the surface towards the atmosphere. With increasing length, liquid jet disturbances may occur leading to instabilities within the jet and causing the detachment of one or more droplets from the apex. These comparatively large droplets are called jet droplets, (g), (h) in Fig. 2-3.

Fig. 2-2: Possible lacelike structure of the film cap immediately before break-up [108].

The characteristics of the two families of produced droplets can be briefly summarized as follows [108]:

Chapter 2 On bubbles, droplets and entrainment
**Film droplets:**

Film droplets are produced as early as ~100 μs after the film cap ruptures. Their diameter usually ranges between 1 μm and 100 μm. Their number is an increasing unknown function of the bubble diameter and is highly dependent upon the nature of the surfactants present in the pool. The ejection height is of the order of 1 cm.

**Jet droplets:**

Jet droplets are produced later than the film droplets (~10 ms after the cap ruptures). The diameter ranges between 0.1 and 0.15 times the generating bubble diameter [109]. Their number never exceeds 10 and is a decreasing known function of the bubble diameter. As a rule of thumb, the first drop produced from the bubble jet is approximately one-tenth of the bubble diameter [12]. Their ejection height is approximately 100 times the diameter for bubble diameters smaller than 2 mm and decreases when the bubble is larger than 2 mm [109].

Both film and jet droplets, however, have an ejection speed of the same order of magnitude, up to 40 m/s [12].

*Fig. 2-3: Mechanism of the burst of an air bubble on the surface of water [97].*
As already mentioned, the number and the distribution of the droplets is mainly influenced by the size of the bubble bursting at the liquid interface. Several experiments focusing on the production of film droplets ([15], [31], [49], [108], [109] and [131]) were carried out. The bubble diameters considered in those experiments range from 0.1 mm to 14.6 mm.

Surprisingly, even for the same experiment under well defined initial conditions and identical measuring techniques, the number of produced droplets varies considerably. As shown in Fig. 2-4, [57], the amount of droplets for one single bubble diameter scatters up to two orders of magnitude! This shows that not only the bubble diameter but also the break-up mechanism itself (location of the cap rupture, oscillations in the thin liquid film, etc.) govern the droplet production.

Fig. 2-4: Comparison of the amount of droplet produced for a single bubble size based on experimental data ([12], [15], [108], [109] and [131]) summarized by Günther et al. [57].
Nevertheless, considering the average production rate for a given bubble size, one notes that the measured amount of film droplets increases exponentially with the bubble diameter [143]:

\[ n_d = 1.07 \cdot d_b^{2.15} \]  

(2-9)

This is mainly explained by the fact that the surface of the dome increases quadratically with the diameter of the bubble.

However, Blanchard and Syzdek discovered a peak in the droplet production for a bubble diameter range of 2- to 2.5 mm [15]. Some authors, [142], consider this peak as an artefact of the facility used by Blanchard et al. but the results could be reproduced by Resch and Afeti [108]. Spiel, [130], suggests an explanation for this peak based on observations with a high speed camera. For bubbles smaller than 3 mm, the bubble film does not disintegrate but roll up, forming a toroidal ring that gains mass as it advances toward the film edge. The film drops are created when this rolled-up mass hits the edge of the film. As the rolled mass is proportional to the bubble diameter but the rolling speed inverse proportional to it, the energy for the collision has a maximum value for bubble diameters laying around 2 mm. The number of droplets obtained by Spiel’s model is lower than the counts measured by Blanchard et al. However, there is a satisfying agreement between the shape of the distribution obtained with the model and the experimental data.

The formation of jet droplets is also the object of experimental, ([13], [129]), and numerical investigations ([16], [80], [132]). It is shown that for bubble diameters larger than 5 mm, the energy due to the pressure in the bubble is no more high enough to build a fine jet and jet droplets are no more released.

So, there is a competition between the number of produced film droplets (increasing with \(d_b\)) with the production of jet droplets (decreasing with \(d_b\)). However, the jet droplets, although less in number, contribute mainly to the mass quantity of entrained fluid. Thus, the entrainment processes for region closed to the water surface is determined by the burst of bubble smaller than 5 mm.
Eventually, due to the sedimentation of droplets with a terminal velocity higher than the gas velocity and due to evaporation effects, the droplet size distribution depends on the height over the pool surface. The mechanisms controlling the transport of the produced droplets from the gas-liquid interface to the containment atmosphere is discussed later in this work. (See Chap. 5).

2.3.2 Splashing

When a droplet impinges on the surface of a deep liquid it either quietly coalesces with the receiving liquid or splashes. In the first case a vortex ring travelling downward through the pool is produced and in the latter case, a deep crater is produced after the impact. At its rim a crown-like cylindrical liquid film is ejected out of the crater. Small droplets are normally shed from this film. Similarly to the burst of a small bubble, a liquid column rises out of the centre of the collapsing centre and instabilities cause the separation of one or more droplets from the tip of the jet.

The transition between the coalescing and the splashing regime can be characterized by the Weber-number which describes the ratio of the inertia- to the surface tension forces (Eq. 2-10) and the Froude-number which expresses the ratio of inertia- to gravity forces (Eq. 2-11). Droplets splash when the Weber number exceeds a threshold which is a function of the Froude number ([72],[107]).

\[
We = \frac{\rho_t \cdot w^2 dr \cdot \sigma}{\sigma} \quad \text{(2-10)}
\]

\[
Fr = \frac{w^2 dr}{g \cdot d_{dr}} \quad \text{(2-11)}
\]

Although splashing phenomena have been studied for more than one century (Worthington took breathtaking pictures of splashing droplets already in 1887! [142]), the mechanisms in the transition between coalescence and splashing regimes are still not fully understood.

Recently, Rein presented a thorough study of the different regimes during the transition in water-water systems [107]. His results are repre-
sented in Fig. 2-5. Above a critical Weber number characterising the coalescence region, a central jet rises out of the crater and a vortex ring no longer appears. The cases of jetting are divided into several regions. At small Weber numbers a very short thick jet appears. Secondary droplets are not formed. The region of so called regular entrainment follows. In this region, a single gas bubble is pinched off at the bottom of the crater and a thin high-rising jet is ejected out of the crater. From the tip of the thin jet little secondary droplets are detached. At Weber numbers above this region the central jet is thick again. It now rises to greater heights and one or more droplets break off from the tip. Up to this stage, secondary droplets are due to disintegration of the central jet only. Hence, only a few tip droplets are generated. Vigorous splashing causing the formation of many secondary droplets that are shed from the rim of a cylindrical liquid sheet appears only when the Weber number is further increased. Those secondary droplets are usually smaller than their mother drops and usually coalesce when they fall back into the ejecting fluid. Their trajectories are mainly a function of the diameter and velocity of the primary droplet as well as the depth in the pool [3].

<table>
<thead>
<tr>
<th>Coalescence</th>
<th>Splashing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical crater collapse</td>
<td>Mainly lateral crater collapse</td>
</tr>
<tr>
<td>Vortex ring</td>
<td>Jetting</td>
</tr>
<tr>
<td>Thick jet</td>
<td>Bubble and thin jet</td>
</tr>
<tr>
<td>No tip droplet</td>
<td>Tip droplets</td>
</tr>
<tr>
<td>No crown</td>
<td>Crown</td>
</tr>
</tbody>
</table>

Fig. 2-5: Characteristics of different flow patterns ordered according to the Weber number [107].

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Finally, other flow patterns as those described above like floating or rolling of the droplet on the liquid surface can be observed if the droplets are released very close to the pool or impinge the surface with a small angle [21].

2.4 Droplet production by spontaneous condensation

The term spontaneous condensation describes the formation of a condensing disperse phase in supersaturated or supercooled gaseous phase. The suspension of liquid or solid particles formed during this process are called aerosols.

The process of aerosol formation can be split into three steps [117]:

- supersaturation
- nucleation
- particle growth

2.4.1 Supersaturation

Supersaturation occurs when two kinds of saturated gases are mixed or steam is injected in a saturated atmosphere or during a rapid adiabatic expansion (e.g. venting). The degree of saturation is defined as:

\[ S = \frac{p_{\text{cond}}}{p_{\text{cond},s}(T)} \]  

(2-12)

\( p_{\text{cond}} \) is the total pressure of the condensable components and \( p_{\text{cond},s} \) is the total pressure on the saturation curve corresponding to the prevailing temperature. Supersaturation is defined for states with \( S > 1 \). The presence of inert gas does not influence the definition of the degree of saturation [135].

2.4.2 Nucleation

When a pure vapour or a gas mixture which is free of foreign nuclei exceeds the saturation, vapour condenses on embryos (groups of mole-
cules of condensable vapour formed by fluctuation in the gas). This process is called homogenous nucleation.

During homogeneous nucleation, the embryos (also called cluster) are meta stable elements unless the degree of saturation exceeds a critical value, \( S_{\text{crit}} \). This critical value depends on the way supersaturation is reached and on the presence of other components in the atmosphere. By homogeneous nucleation, \( S_{\text{crit}} \) typically equals value between 2 and 4. For \( S > S_{\text{crit}} \), the clusters are stable and their amount growths rapidly.

In the classical nucleation theory, the cluster production, \( J \), is given in the following form:

\[
J = k \cdot e^{\frac{\Delta G}{k_B T}}
\]

(2-13)

Note that the latent heat released during the condensation reduces the degree of saturation close to the cluster. However, if inert gases are present, this heat can be removed without that the degree of saturation is too much affected. Hence, the nucleation rate in presence of inert gas is higher than for the same degree of saturation by pure steam atmosphere. This effect is taken into account with the coefficient \( k \) in Eq. 2-13. According to Feder et al. [46], this coefficient is mainly a function of the cluster concentration and of the ratio of condensable gas in the mixture.

When large concentration of particles are present, condensation takes place on the existing particles without formation of new nuclei. This process is called heterogeneous condensation [144]. The process of condensation is similar but, as long as enough nuclei are present, the needed degree of saturation is much lower and close to 1.

### 2.4.3 Particle growth

A condensation nucleus remains unstable until it reaches a critical radius, \( r_{min} \). After this critical size is reached, the nucleus can only grow if the latent heat released during the condensation can be removed from the droplet. Otherwise, the temperature in the nucleus
increases and the droplet evaporates. Therefore, the growth rate is directly connected to the heat transfer at the droplet surface:

\[
\frac{dr}{dt} = \frac{\dot{q}}{\rho_l \cdot \Delta h_{l,v}} = \frac{\alpha \cdot (T_d - T_\infty)}{\rho_l \cdot \Delta h_{l,v}} \tag{2-14}
\]

The heat transfer coefficient \( \alpha \) summarizes the heat transfer in the Knudsen region (or free molecular flow conditions) and in the continuum. The resistance to the heat transfer due to the presence on non-condensable gas has also to be considered.

Gyarmathy [58] suggested the following particle growth equation:

\[
\frac{dr}{dt} = \frac{1}{\rho_l} \cdot \frac{1 - r_{\text{min}}}{r} \cdot \frac{\ln S_\infty}{\Delta h_{l,v}} \cdot \frac{p_{\infty} - p_{\text{cond},s}}{\lambda \cdot R_v \cdot T_\infty^2} + \frac{p_{\infty}}{p_{\infty} - p_{\text{cond},s}} \cdot \frac{R_v T_\infty}{\rho_v D_v} \tag{2-15}
\]

The heat conduction terms on the right hand side of Eq. 2-15 considers the presence of the non-condensable gas and disappears if there is a pure steam atmosphere \((p_{\infty} - p_{\text{cond},s} = 0)\). Furthermore, \( dr/dt \) is only positive if the nucleus radius is larger than the critical radius \( r_{\text{min}} \).

2.5 Aerosol behaviour in gas flow

2.5.1 Aerosol motion

The Knudsen number

In order to describe the motion of an aerosol in its surrounding, one has to distinguish how the fluid “views” the particle. For this purpose, the Knudsen-number is used:

\[
Kn = \frac{2 \cdot \Lambda}{d_p} . \tag{2-16}
\]

If the aerosol diameter, \( d_p \), greatly exceeds the mean free path, \( \Lambda \), the surrounding fluid appears to the particle as a continuum. Thus, when \( Kn \ll 1 \), one says that the particle is in the continuum regime and the
usual equations of continuum mechanics apply. When the mean free path of the carrier gas molecules substantially exceeds the particle diameter, the particle exists in a more or less rarefied medium, and its transport properties must be obtained from kinetic gas theory. This region characterised by $Kn \gg 1$ is called the free molecule or kinetic regime. The particle size range intermediate between these two extremes is called the transition regime [124].

**The drag coefficient**

First, the motion of a particle in the continuum regime is considered. If the aerosol velocity is different from the fluid velocity, the fluid exercises a drag force on the particle. This force (Eq. 2-17) is proportional to the dynamic pressure and is a function of the particle Re-number (Eq. 2-18-Eq. 2-20, [68]).

$$F_{drag} = \zeta_d \rho_d \frac{w^2}{2}$$  \hspace{1cm} (2-17)

$$\zeta_d = \frac{24}{Re_d} \quad Re_d < 1 \hspace{1cm} (2-18)$$

$$\zeta_d = \left( \frac{24}{Re_d} \cdot 1 + \frac{Re_d^{2/3}}{6} \right) \quad 1 < Re_d < 1000 \hspace{1cm} (2-19)$$

$$\zeta_d = 0.44 \quad Re_d > 1000 \hspace{1cm} (2-20)$$

The region under $Re_d < 1$ is called the Stokes’ region and Eq. 2-18 is known as the Stokes’s law.

When the particle diameter, $d_p$, approaches the same order as the mean free path of the suspending fluid, the resisting force offered by the fluid is smaller than that predicted by the Stokes’ law. To account for the non-continuum effects, the Cunningham correction factor, $k_{slip}$, (also called slip correction factor) is introduced.

$$\zeta_d = \frac{24}{Re_d \cdot k_{slip}} \quad Kn \geq 1. \hspace{1cm} (2-21)$$

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The Cunningham factor is mainly a function of the mean free path and of the particle diameter. It becomes more and more important as the particle diameter decreases.

**Brownian diffusion**

Brownian motion is the irregular random motion of an aerosol particle that is due to bombardment by surrounding fluid molecules. This movement of the particles can be characterized as a diffusion process in a concentration gradient and can be described by the Fick’s first law:

\[ J = -D_p \cdot \nabla N. \quad (2-22) \]

The diffusion coefficient of an aerosol particle can be expressed in terms of particles properties by the Stokes-Einstein derivation. In this derivation, the force on the particles that causes their net motion is equated to the force exerted by the gas resisting the particles motion [68]. The aerosol particle diffusion coefficient is then:

\[ D_p = \frac{k_{Bolzmann} \cdot T \cdot k_{slip}}{3 \cdot \pi \cdot \eta_g \cdot d_p}. \quad (2-23) \]

The importance of Brownian diffusion compared to gravitational settling can be judged by comparing the distances that a particle travels in both cases. At 20°C and over a time of 1 second, a 1 μm radius particle diffuses a distance of the order of 4 μm, while it falls about 200 μm under gravity. A 0.1 μm radius particle, on the other hand, diffuses a distance of about 20 μm in 1 second compared to a fall distance of 4 μm [124]. Therefore, Brownian diffusion can be almost neglected for particle radius much larger than 1 μm.

**Phoretic effects**

Phoretic effects produce a directional preference in the Brownian diffusion of aerosol particles due to a difference in momentum imparted to a particle by molecules coming from different direction.

One phoretic effect is thermophoresis. In this case, the particle motion is caused by higher energy molecules on one side of the particle. A gradient in molecular energies is associated with a macroscopic temperature gradient, so the particles diffuse away from warmer regions.
toward cooler regions. Similarly, photophoresis results when incident radiation heats one side of a particle more than the other, leading to differences in the energies of the gas molecules adjacent to the surface of the particles. Eventually, diffusiophoresis occurs in the presence of a gradient of a gas component which molecules are either lighter or heavier than the surrounding fluid molecules. (For further development on phoretic effects, see [10], [68] and [141]).

2.5.2 Aerosol coagulation and deposition

Coagulation is the process whereby aerosol particles collide with each other due to relative motion between them and adhere to form larger particles. The net result is a continuous decrease in number concentration and an increase in particle size. Coagulation is classified by the kind of the force causing the collision: Brownian coagulation, turbulent coagulation, gradient coagulation, electrical coagulation, acoustic coagulation, coagulation due to different settling velocity under gravity or centrifugal force, etc. [144].

When the relative motion between particles is due to Brownian motion the process is called thermal coagulation. An comprehensive review of the work on Brownian coagulation is given by Fuchs [48]. When the relative motion arises from external forces such as gravity or electrical forces or from aerodynamic effects, the process is called kinematic coagulation. This latter process becomes more and more important as the particle mass increases.

The coagulation phenomena apply not only between particles themselves but also between particles and a surface close to the fluid. This is called deposition. Coagulation among the particles plays an important role for deposition phenomena, as larger particles have higher settling velocities (sedimentation processes) and their momentum increases. When the flow speed of the carrier gas increases (e.g due to an obstacle located in the flow), those heavier particles deviate from the streamlines of the fluid and may intercept the surface located in the flow. This effect is called inertial impaction. The efficiency of this separation mechanism is described with the Stokes number:
The efficiency of separation is an S-shaped curve indicating a sharp size cutoffs at a critical Stokes number. Below this value, there is almost no deposition [141].

Extensive reviews on the deposition and impaction phenomena are given by Fernandez de la Mora [47], Fuchs [48], Hinds [68] and Williams [141].

2.6 Free convection in an enclosed space

One talks about free convection (also called natural convection) when a flow is not driven by an external pressure gradient, but by differences in density in the system in question itself. The driving force is then the body force, or more exactly, the differences in the body force due to differences in density. These may be due to changes both in temperature and in composition of the fluid.

Assuming that gravity is the only external body force, one can therefore rewrite the momentum equation in the vertical direction:

\[ \rho(T) \left( w_x \frac{\partial w_z}{\partial x} + w_z \frac{\partial w_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \eta \left( w_x \frac{\partial^2 w_z}{\partial x^2} + w_z \frac{\partial^2 w_z}{\partial z^2} \right) - \rho(T) \cdot g \]  

(2-25)

In order to simplify the calculations, the liquid properties are considered constant and are calculated for the bulk temperature. The temperature dependency is only considered for the density in the buoyancy term in the right side of Eq. 2-25. It is approximated by

\[ \rho(T) = \rho(T_{bulk}) \cdot (1 - \beta \cdot (T - T_{bulk})) \]  

(2-26)

These simplifications are known as the Boussinesque’s approximations. For a gas mixture behaving like an ideal gas, the thermal coefficient of volumetric expansion, \( \beta \), is given by \( \beta = 1/T_{bulk} \).

Using these assumptions and writing the mass- momentum- and energy balances in a dimensionless form [52], one sees that for free convect-
tion, only the three dimensionless groups, Re-number, Pr-number and Grasshof-number, appear in the balance equations.

\[ \text{Re} = \frac{\rho \cdot L \cdot w}{\mu} \]  
\[ \text{Pr} = \frac{C_p \cdot \mu}{\lambda} \]  
\[ \text{Gr} = \frac{H^3 \cdot g \cdot \beta \cdot \Delta T \cdot \rho^2}{\mu^2} \]

In free convection problems, the momentum balance is coupled with the energy balance and both equations have to be solved simultaneously. Analytical solutions are therefore complicated.

Hence, mostly correlations based on measurements are used to describe the heat transfer. Usually, they are given in the form:

\[ Nu = \frac{\alpha \cdot L}{\lambda} = f(Gr, Pr) \]

(2-30)

For a vertical plate and under laminar conditions, Eq. 2-30 takes the form:

\[ Nu_{lam} = A \cdot Ra^{1/4} \cdot f(Pr) \],

(2-31)

where \( Ra \) is the Rayleigh-number and is defined as \( Ra = Gr \cdot Pr \).

For turbulent regimes, the heat transfer is enhanced and the Rayleigh-number is in the power one-third (for the coefficients \( A \) and \( f(Pr) \), see Churchill and Chu, [30] or Rohsenow [112]).

\[ Nu_{turb} = A \cdot Ra^{1/3} \cdot f(Pr) \]

(2-32)

Note from Eq. 2-32, that due to the one-third power, the heat transfer coefficient is no more dependent on the height, \( H \), of the vertical plate.

According to Parker et al. [99], the transition from the laminar to the turbulent flow regime at a vertical plate is given by the criterion:
For vertical cylinders, the heat transfer correlations for vertical plates can be used as well as long as the diameter fulfills Eq. 2-34 [99]:

\[
\frac{D}{H} \geq \frac{35}{Gr^{0.25}}.
\]  

The free convection flow phenomena inside an enclosed horizontal space are more complex and involve two distinct situations. If the upper plate is maintained at a higher temperature than the lower plate, the lower-density fluid is above the higher-density fluid and no convection occurs. On the other hand, when the lower plate has a higher temperature than the upper plate, convection flow begins and for low Ra-numbers, a pattern of hexagonal cells is formed. These patterns are called Bénard cells [8]. In an enclosed space, turbulence starts earlier than for a vertical plate \((Ra > 10^5, [71])\) and destroys the cellular pattern. From that point, the convection flow is three dimensional and can no more be simulated with 2D-codes [98]. A considerable amount of works on Bénard problems can be found in the literature. A good overview over the relevant experimental, calculational and theoretical studies is given by Nourgaliev and Dinh [98] and Siggia [127]. Furthermore, Dinh [43] compared recently the advantages and limits of a wide variety of computational models for simulating free convection in large vessels.

Eventually, the situation where free convection as well as forced convection occur is considered. This situation can be split into three regimes described by the ratio \(Gr/Re^2\) [99]:

\(a)\) \(Gr/Re^2 < 1\)

In this case, the influence of the forced convection predominates and the buoyancy forces are negligible. As a result, the Grasshof-number does not appear in the corresponding equations for heat- and mass transfer.

\(b)\) \(Gr/Re^2 \gg 1\)

In this case, the motion of the fluid is mainly determined by the buoyancy forces, usually confined to a thin layer near the heated or cooled
As a result, the Reynolds-number does not appear in the corresponding equations for heat- and mass transfer.

c) $Gr/Re^2 \approx 1$

This case is called mixed convection. Both phenomena, free and forced convection, play a similar role for the heat transfer and both have to be considered. According to measurements of Churchill [29], a component equation for the mixed Nusselt-number can be formulated.

If the forced flow acts in the same direction as the buoyancy, the resulting Nusselt-number is enforced and given by Eq. 2-35, otherwise by Eq. 2-36.

$$Nu_{mixed} = 3 \sqrt[Nu_{forced} + Nu_{free}]{3}$$

$$Nu_{mixed} = 3 \sqrt[Nu_{forced} - Nu_{free}]{3}$$

### 2.7 Determination of the entrainment factor

#### 2.7.1 Local measurements

The number of droplets produced by the burst of one single bubble with diameter $d_b$ is described by the distribution $\Phi_{dr}(d_{dr}|d_b)$. The total volume of ejected droplets for this bubble is then:

$$V_{dr}|d_b = \frac{\pi}{6} \cdot \int_0^{d_{dr, crit}} n_{dr} \cdot \Phi_{dr}(d_{dr}|d_b) \cdot d_{dr}^2$$

$d_{dr, crit}$ is the upper limit of droplet radius which will be carried off by the gas flow above the pool. Furthermore, if $\Phi_{b}(d_b)$ describes the distribution of the bubbles in the pool, the total flow of entrained droplets is given by Eq. 2-38:

$$V_p = \frac{\pi}{6} \cdot \int_0^{\infty} \int_0^{d_{dr, crit}} n_b \cdot \Phi_{b}(d_b) \cdot n_{dr} \cdot \Phi_{dr}(d_{dr}|d_b) \cdot d_{dr}^3$$

The droplet size distribution can only be obtained in experiments with uniform bubble size distribution. However, this is not possible in a
boiling pool and \( \Phi_{d r}(d_{d r}|d_b) \) has to be averaged over all the bubble sizes:

\[
\Phi_{d r}(d_{d r}) = \int \left( \Phi_{d r}(d_{d r}|d_b) \cdot \Phi_b(d_b) \right) d d_{d r}
\] (2-39)

The gas flow in the pool can be described with the amount of bubbles crossing the boiling surface by unit of time,

\[
\dot{V}_g = \frac{\pi}{6} \cdot \int_0^\infty \dot{n}_b \cdot \Phi_b(d_b) \cdot d_b^3 d d_b
\] (2-40)

Using Eq. 2-4 and rearranging Eq. 2-38 to Eq. 2-40, one obtains for the entrainment factor:

\[
E = \frac{\int_0^{d_{p, crit}} \Phi_b(d_b) \cdot \Phi_{d r}(d_{d r}) \cdot d_{d r}^3 d d_{d r} \cdot \rho_l}{\rho_g} \cdot \frac{\rho_l}{\rho_g}
\] (2-41)

For a single bubble size, Eq. 2-41 can be rewritten as:

\[
E = \frac{V_{d r}^o}{V_b} \cdot F(d_{p, crit}) \cdot \frac{\rho_l}{\rho_g}
\] (2-42)

where \( V_{d r}^o \) is the total volume of liquid droplets ejected for each bubble of volume \( V_b \) and \( F(d_{d r, crit}) \) represents the fraction of ejected droplets with diameters smaller than \( d_{p, crit} \) [53].

Several attempts have been done in order to determine the ratio \( V_{d r}^o/V_b \) for a given bubble size. Some consider that all of the volume enclosed within the film cap of a bubble is converted to entrained droplets [134]. Similar approaches basing on the oscillation disturbance of the bubble film driven by acoustic noise in the liquid pool [6] were developed and eventually several measurements of the amount and size distributions of droplets for single bubble size have been carried out (See Section 2.3).
2.7.2 Integral measurements

If the droplets and/or the bubble distributions used in Eq. 2-41 are not available, one can describe the entrainment using an integral definition.

Therefore, tracer material like soluble salts or solid particles is put in the boiling pool. If the atmosphere above the sump is saturated and in thermodynamical equilibrium with the pool, no condensation nor evaporation effect occur at the surface of the droplets. It can be assumed that the tracer concentration in the droplets, \( C_{dr} \), is then the same as the concentration in the pool, \( C_{BP} \) (see Fig. 2-1). Part of the atmosphere gas is removed from the containment and the steam and the entrained droplets are condensed and collected in a condenser. The concentration of the tracer material in the condensate, \( C_{cond} \), is given by Eq. 2-43:

\[
C_{cond} = \frac{\dot{m}_{l, cond} \cdot C_{BP}}{\dot{m}_{v, cond} + \dot{m}_{l, cond}} \quad (2-43)
\]

In the following chapters the relationship between the concentration in the condensate and the entrainment factor \( E \) will be investigated for different atmosphere conditions.

**Pure steam atmosphere**

Here, the gas flow is only produced by the evaporation of water and no non-condensable gas are supplied into the boiling pool. Eq. 2-4 can be simplified and the entrainment factor is:

\[
E = \frac{\dot{m}_{l, cond} + \dot{m}_{l, w}}{\dot{m}_{v, cond} + \dot{m}_{v, w}} \quad (2-44)
\]

One assumes that the entrained droplets are small enough to follow the vapour flow and that there is no slip between the liquid and the gas phase. The ratio between the liquid and the gas flow can then be considered as constant everywhere in the containment:
Using Eq. 2-43 and considering that \( \frac{\dot{m}_{l, \text{cond}}}{\dot{m}_{v, \text{cond}}} \) is expected to be very small, one obtains:

\[
\frac{C_{\text{cond}}}{C_{BP}} = \frac{\dot{m}_{l, \text{cond}}}{\dot{m}_{v, \text{cond}}} = \frac{\dot{m}_{l}}{\dot{m}_{v}} = E \quad (2-46)
\]

The entrainment factor by pure steam atmosphere equals the ratio of tracer concentration in the condensate resp. in the boiling pool.

**Gas-steam atmosphere**

Is a non-condensable gas supplied into the pool, new considerations have to be done. Due to partial condensation effects at the wall, the composition of the gas in the venting pipe is not the same as in the containment. The homogeneous gas density changes and the critical sedimentation diameter is affected.

Furthermore, phase separation occurs in the condensate tank. The gas flow, \( \dot{m}_{ncg} \), leaves the tank and the condensed steam and the droplets are pumped back into the boiling pool, \( \dot{m}_{c} \). As the gas flow leaves the condensate tank without condensing, Eq. 2-46 does not apply any more. The tracer concentration in the condensate is then given by the ratio of the tracer mass flow divided only by the vapour flow instead of the total gas flow. The measured concentration is therefore higher than the entrainment factor \( E = \frac{\dot{m}_{l}}{\dot{m}_{g}} \).

In order to have a fair estimate of the real entrainment factor, assumptions have to be done.

\textit{a) 1st (rough) approximation}

If one assumes that the condensation effect at the containment wall are negligibly small, Eq. 2-4 becomes:

\[
E = \frac{\dot{m}_{l, \text{cond}}}{\dot{m}_{v, \text{cond}} + \dot{m}_{ncg}} \quad (2-47)
\]
Rearranging Eq. 2-43 and substituting $\dot{m}_{l,\text{cond}}$ in Eq. 2-47, one obtains for the entrainment factor:

$$ E = \frac{C_{\text{cond}}}{C_{BP}} \cdot \frac{\dot{m}_{v,\text{cond}}}{\dot{m}_{v,\text{cond}} + \dot{m}_{\text{ncg}}} = \frac{C_{\text{cond}}}{C_{BP}} \cdot (1 - x_{\text{cond}}) \quad (2-48) $$

where $x_{\text{cond}}$ is the ratio of non-condensable gas in the venting pipe.

One can see that the real entrainment factor by a gas/steam ratio of 50% is twice as low as the measured concentration ratio.

\textit{b) 2nd (fine) approximation}

In this case, the condensation effects at the wall are considered.

However, one assumes that the concentration of non-condensable gas is constant in the containment, this means:

$$ \rho \neq f(r, \theta, z) \quad (2-49) $$

This assumption is especially adequate in the bulk of the containment where the gas phase is ideally mixed. So, the concentration in the water film at the wall is nearly the same as in the condensate flow:

$$ C_w = C_{\text{cond}} \quad (2-50) $$

Therefore, one can rewrite Eq. 2-4, substituting $\dot{m}_{l,\text{cond}}$ and $\dot{m}_{l,w}$ from Eq. 2-43, resp. Eq. 2-50 and obtains:

$$ E = \frac{C_{\text{cond}}}{C_{BP}} \cdot \frac{\dot{m}_{v,\text{cond}} + \dot{m}_{v,w}}{\dot{m}_{v,\text{cond}} + \dot{m}_{v,w} + \dot{m}_{\text{ncg}}} \quad (2-51) $$

In Eq. 2-51, the liquid flow to the wall does not appear any more. The gas flow $\dot{m}_{v,\text{cond}}$ and $\dot{m}_{\text{ncg}}$ are measured at the output of the venting pipe. However, $\dot{m}_{v,w}$ has to be estimated through the heat loss in the upper part of the containment. The heat loss there is mainly due to the release of the latent heat of the condensing steam. The cooling of the water film at the wall in comparison can be neglected.
\[ \dot{m}_{v,w} \equiv (\dot{Q}_{h_l,w})/\Delta h_{l,v} \quad (2-52) \]

Finally, one can see that both, Eq. 2-48 and Eq. 2-46 can be obtained from Eq. 2-51 by setting \( \dot{m}_{v,w} = 0 \cdot g/s \) resp. \( \dot{m}_{ncg} = 0 \cdot g/s \).
3 Experimental set-up and measurement techniques

This chapter provides a detailed description of the experimental set-up which had been used previously by Müller in the frame of the REVENT program [96]. For this work, modifications of the facility were undertaken in order to observe the boiling pool and to enhance the free convection in the containment. Section 3.1 focuses on the design criteria and the features of the modified facility, whereas Section 3.2 describes the measurement techniques and the data analysis. At the end of this chapter, the course of a typical experiment is presented (Section 3.3).

3.1 The facility

3.1.1 Dimensioning criteria

The experiments are carried out in a pilot plant (see Fig. 3-1) which is a scale-down of a Swiss reference nuclear power plant (NPP). The reference plant uses a pressurised water reactor of the type built by Westinghous. A scaling factor of 1:20 was chosen.

The experimental facility is designed so that, similarly to a real NPP, turbulent natural convection always prevails in the containment atmosphere. Considering a fixed geometry, this is possible when the Rayleigh number exceeds a critical value $Ra > 5 \cdot 10^5$ [71] (See Section 2.6).

The model containment was designed to always fulfil this criterion. With the chosen dimensions (see Tab. 3-2) turbulent natural convection is expected even for a vertical temperature difference of 0.1 °C.

However, matching the Rayleigh-number alone is not sufficient to allow a scaling-up of the experimental results to existing NPP containments. Further criteria, as the specific energy input due to the decay heat, have to be also considered.

To simulate the decay heat of the molten core, an electrical heating plate with a heat power of 20 kW is installed in the containment pool. A heat source of 3 MW in a water pool of 30 m² was assumed for the determination of the prototypical heat flux. This heat source corre-
sponds to approximately one third of the decay heat released twelve hours after the begin of the accident, the remaining energy being used up in the molten core-concrete interaction (MCCI) [28]. At that time the decay heat is about 0.6 percent of the thermal power of the reactor during normal operations [64]. Tab. 3-1 compares the parameters of a reference NPP and the model containment.

During the MCCI, non-condensable gas as carbon dioxide and hydrogen are released in the boiling pool. For the reference scenario, it has been estimated that at the beginning of the venting, a mass flow of 0.12 kg/s CO₂ and of 0.006 kg/s H₂ were to be expected [96]. Using the ratio of the decay heat in the reference power plant, $Q_{\text{decay}}$, to the power of the heating plate, $Q_{\text{heat plate}}$, as a scaling-factor

$$\eta = \frac{Q_{\text{heat plate}}}{Q_{\text{decay}}}$$  \hspace{1cm} (3-1)

one obtains for the pilot plant a non-condensable flow of $m_{\text{n cg}} = \eta \cdot 0.12 \text{ kg/s} = 0.84 \text{ g/s}$. This mass flow, which is simulated with compressed air in this work, is fed back into the lower part of the facility.

The facility is designed for pressures up to 12 bar and for temperatures up to 200°C. Experiments under relevant accident conditions can therefore be carried out. Tab. 3-2 shows the characteristics of the pilot plant resulting of these scaling considerations.

<table>
<thead>
<tr>
<th>Nuclear Power Plant</th>
<th>Specific Energy Input in Containment</th>
<th>Heat Flux between Core Crust and Water</th>
<th>Rayleigh Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>model Containment</td>
<td>0-4000 W/m³</td>
<td>0-100 kW/m²</td>
<td>$Ra &gt; 10^{10}$</td>
</tr>
<tr>
<td>a) 600 W/m³</td>
<td>400-600 kW/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) 4 hours after start of accident, b) MACE MO and WETCORE experiments in [38]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3-1: Scaling parameters
Fig. 3-1: Pilot plant containment with condensation system and phase separation tank

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Volume</td>
<td>5 m³</td>
</tr>
<tr>
<td>Wall surface</td>
<td>18 m²</td>
</tr>
<tr>
<td>Design pressure</td>
<td>1.2 mPa</td>
</tr>
<tr>
<td>Heating power</td>
<td>20 kW</td>
</tr>
<tr>
<td>Wall material</td>
<td>1.4571</td>
</tr>
</tbody>
</table>

TABLE 3-2: Characteristics of the pilot plant

Chapter 3 Experimental set-up and measurement techniques
3.1.2 The experimental set-up

The facility consists of an insulated pressure vessel which represents the containment of a nuclear power plant. (See Fig. 3-2). The diameter of the stainless steel vessel (wall thickness: 0.01 m) is 1.5 m and its height is 3.5 m. The vessel has an inner volume of 5 m$^3$. The outer surface of the walls is insulated with a 0.1 m thick layer of glass wool and a shield in aluminum against splashing-water.

In the lower part of the vessel, water boils above an electrical heating plate, (1) in Fig. 3-2, which simulates the decay heat of the molten core. The heating plate, with a diameter of 0.55 m and thickness of 0.06 m is built in an aluminum alloy. Six electrical resistances, molten in the plate, provide a constant power of approximately 20 kW.

At its lowest level, the diameter of the pool is 0.6 m and the cross-sectional area equals 0.28 m$^2$. Above the level of 0.6 m, the containment enlarges up to a diameter of 1.5 m. At this location, the pool surface is maximum and is equal to 1.77 m$^2$. By adjusting the height of liquid in the sump, the pool volume and the pool surface can be varied. The height of the sump is measured using a level gauge (18).

By heating the water up to boiling temperature, steam is produced and the pressure in the containment increases.

In order to carry out the experiments under steady-state conditions, part of the produced steam is removed from the vessel through a venting pipe (2). The pipe, with an inner diameter of 0.06 m, is located on the centre line of the containment and dips 0.6 m below the top of the vessel (about 2m above the pool surface). The pressure in the containment can thus be kept at a constant level (1-12 bar). The removed steam passes through an orifice (3) (diameter 0.01 m) and a control valve (4) where it expands to atmospheric pressure and condenses in a falling-film condenser (5). The condenser is 2 m high and has an outside diameter of 0.14 m. The steam is led through nineteen tubes (inner diameter: 0.021 m) which are cooled with tap water. Because of their vertical disposition, the tubes are kept clean and aerosol deposition on the wall is reduced. The condensate leaves the condenser and is collected in the phase separation tank (6) where the non-condensable gas are separated from the liquid phase.
The condensate is fed back into the boiling pool with a membrane pump (8). The sump volume and the concentration of model substances in the pool can so be kept constant. The gas flow however cannot be recirculated and leaves the facility through a flow meter (7).

In order to keep the air/steam ratio in the containment constant, gas has to be supplied continuously into the sump. The air is fed under the heating plate through an orifice (9) (inner diameter: 3mm). By varying the pressure before the orifice, the gas flow into the containment and therefore the composition of the containment atmosphere can be adjusted.

With a cooling coil (10) located in the upper part of the containment the vertical temperature gradient can be varied and the natural convection can be enhanced. The cooling coil is operated with compressed air. The inlet \( T_{\text{cool\_in}} \) and outlet \( T_{\text{cool\_out}} \) temperatures of the cooling air are measured by resistance thermometers (Pt-100) and the air flow is determined with a rotameter (22). By varying the pressure in the cooling coil as well as the mass flow of the air, the heat removal can be adjusted to values between 0 kW and 20 kW.

Several temperature sensors are installed inside and outside the pressure vessel. Pt-100 are used to obtain the temperature of the electrical heating plate \( T_{\text{HP}} \), in the steam atmosphere \( T_1 \), in the boiling pool \( T_2 \), in the condensate \( T_3 \) and in the air leaving the condensate tank \( T_4 \). Thermocouples are used to measure the temperature at the outer surface of the vessel wall \( T_{W_1} \) as well as the temperature of the thermal shield \( T_{S_1} \) at three different distances from the pool surface. The pressure inside the vessel is measured with a piezoresistive transducer.

Optical windows are arranged around the circumference of the vessel and provide visual access in the upper part of the containment atmosphere (6 windows, a-f), onto (g) and in the boiling pool (3 windows, h-k).
Experimental set-up and measurement techniques

Chapter 3
3.2 Measuring techniques

3.2.1 Entrainment measurement

In order to determine the entrainment factor (see Section 2.7), the concentrations of fission product simulants (FPS) in the condensate flow as well as in the boiling pool have to be quantified. In the following section, the sampling and measurement methods for soluble and non-soluble model substances are presented.

Soluble model substances

In a first step, experiments with soluble model substances were carried out. The main advantage of soluble substances is that no concentration gradient over height or radius of the boiling pool occurs. The samples can therefore be taken anywhere in the pool and no special stirring is requested.

In an hypothetical accident in the chosen reference power plant about 2000 m$^3$ water would overflow ca. 2000 kg of molten material [37]. This would build a sump with an initial concentration of about 2 g/l. Due to the molten core-concrete interaction (MCCI) additional material will be suspended in the pool. Furthermore, due to the continuous evaporation of the sump water, the concentration of soluble and solid substances will increase. Therefore concentrations between 2-10 g/l are expected in the boiling pool. Based on the Deutsche Risiko Studie B [51], the expected entrainment factors $E$ are in the order of $10^{-4}$. The concentration in the condensate tank will thus reach values in the order of 0.1 ppm.

The detection of such low concentrations requires very sensitive measuring devices which can only be used for specific substances. Consequently, the fission product simulants have to be chosen according to available measuring methods. Furthermore, other functional specifications have to be fulfilled.
Especially, the model substance shall:

- not evaporate under the prototypical temperature,
- be soluble in the concentration range of 2-15 g/l and over a temperature range from 10 °C up to 180°C,
- not be surface active (foam formation, no wall effect in the venting pipe),
- not react with the containment material or other components in the boiling pool,
- not be toxic for the operator nor for the environment.

Furthermore, it would be desirable that the model substances are available at moderate costs and measurable at reasonable time and financial expenses.

Salts containing iodine fulfil these criteria. Cesium iodide (CsI), for instance, occurs in the containment during a real accident and is therefore of particular interest. However, potassium iodide (KI), which has similar chemical and physical properties as CsI, is less expensive (See Tab. 3-3) and was therefore used for most of the experiments.

<table>
<thead>
<tr>
<th>Name</th>
<th>Solubility a) [kg/l]</th>
<th>Price [$/kg]</th>
<th>Measuring method</th>
<th>Measurable range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cesium iodide (CsI)</td>
<td>0.440</td>
<td>440.-</td>
<td>Ion Selective Probe</td>
<td>8E-3 ppm-166 g/l</td>
</tr>
<tr>
<td>Potassium iodide (KI)</td>
<td>1.275</td>
<td>35.-</td>
<td>Ion Selective Probe</td>
<td>0.013 ppm-260 g/l</td>
</tr>
</tbody>
</table>

TABLE 3-3: Comparison of iodine-salt as potential fission product simulants a) values for 273 K [40].

The concentration in the condensate is measured by taking a samples of 200 ml through a valve (11) located at the very bottom of the condensate tank (6) in Fig. 3-2.

Before opening the valve, the tank is emptied so that only condensate which has just gone through the condenser is collected. The emptied water is fed back into the facility over the tank (15), so that the sump volume remains constant.
As the expected concentrations are very low (0.1 ppm), special care is given to prepare the sample containers. An important issue was the possible interaction (adsorption) between the tracer salt and the container wall which could alterate the concentration in the probe.

Scanning tests were carried out in order to determine the effects of the wall properties and to investigate the influence of surface in contact compared to the sample volume. A solution with I- standard (0.164 mg I-/l) was prepared and filled in different containers consisting of polyethylene or glass and having various volumes. (See Tab. 3-4).

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume</th>
<th>Surface</th>
<th>Surface/Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>polyethylene HDPE</td>
<td>250 ml</td>
<td>201 cm²</td>
<td>0.80 m⁻¹</td>
</tr>
<tr>
<td>polyethylene HDPE</td>
<td>1000 ml</td>
<td>354 cm²</td>
<td>0.53 m⁻¹</td>
</tr>
<tr>
<td>glass</td>
<td>80 ml</td>
<td>87 cm²</td>
<td>1.09 m⁻¹</td>
</tr>
</tbody>
</table>

TABLE 3-4: Characteristics of sampling containers.

The containers were kept in a refrigerator during 24 hours and measured in random order (see the procedure below). The results showed no significant influence of the material of the container nor of the surface in contact with the sampled liquid (Fig. 3-3). For the presented experiments containers in polyethylene HDPE with a volume of 250 ml are used.

In order to avoid impurities in the samples, the PET-containers are thoroughly washed before sampling: two times with purified water (filter: Millipore-RO Plus 10) and once with high purified water (filter: Millipore-Qplus 185).

The containers containing samples from the boiling pool need less attention, as the salt concentration are much higher. The containers are cleaned twice with tap water.

Samples of 200 ml are taken out of the pressurised containment just below the heating plate. Due to the pressure drop over the sampling valve ((12) in Fig. 3-2), flash boiling occurs and water evaporate out of the sample. The measured concentration shows then a higher value than the concentration prevailing in the pool. In order to correct this effect, one assumes that the change of state over the valve is an isenthalpic expansion from the pressure inside the containment down
to atmospheric pressure. The percentual amount of evaporated steam can be read in a Mollier-diagram and the original pool concentration can be determined (Eq. 3-2).

\[ C_{BP} = k_{is} \cdot C_{BP,measured} \]  

(3-2)

Tab. 3-5 gives the correction factors for different operation pressures in the containment (steam properties from [119]).

<table>
<thead>
<tr>
<th>Pressure [bar]</th>
<th>Enthalpy of water by containment pressure [kJ/kg]</th>
<th>Corresponding quality by 1 bar [kg/kg]</th>
<th>Correction Coeff. ( k_{is} ) ( C_{BP}/C_{mes} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>504.70</td>
<td>3.9%</td>
<td>0.9614</td>
</tr>
<tr>
<td>3</td>
<td>561.43</td>
<td>6.4%</td>
<td>0.9363</td>
</tr>
<tr>
<td>4</td>
<td>604.67</td>
<td>8.3%</td>
<td>0.9171</td>
</tr>
<tr>
<td>5</td>
<td>640.12</td>
<td>9.9%</td>
<td>0.9014</td>
</tr>
<tr>
<td>5.5</td>
<td>656.07</td>
<td>10.6%</td>
<td>0.8945</td>
</tr>
<tr>
<td>6</td>
<td>670.42</td>
<td>11.2%</td>
<td>0.8880</td>
</tr>
</tbody>
</table>

TABLE 3-5: Correction factors for isenthalpic depressurization

Finally, a special handling is needed for taking the samples in the sump. As the valve (12) is located at the bottom of the facility, material
can sediment or concentrate in the pipeline leading to the valve. To guarantee that the concentration in the sample is the same as the concentration in the boiling pool, the pipeline is flushed before the samples are taken. By taking several samples of 200 ml one after another, it could be shown that the concentration did not vary any more after one litre of sample has been taken. Therefore, before samples of the sump are taken, one litre of sump water is first removed and pumped back into the facility through the tank (15). One litre corresponds to twice the volume of the pipe where the sample are taken.

The concentrations of the soluble model substances, both in the condensate and in the boiling pool, are measured with an ion selective probe. Here, an ion selective electrode with crystal membrane (Metrohm, model 6.0502.160) with a reference electrode with Ag/AgCl cartridge and ceramic diaphragm (Metrohm model 6.0733.100) is used.

This device delivers a voltage signal which is proportional to the logarithm of the ion’s activity [23]. The latter is proportional to the ion concentration and the coefficient of proportionality almost equals 1 at low ion concentrations [123]. By measuring the voltage obtained with solutions of known concentration, a calibration curve can be drawn. (See Fig. 3-4).

In order to enhance the accuracy of the measurement, two calibration curves are determined, one for a very low concentration range, (condensate: 0.05 ppm - 0.1 ppm I), and one for higher concentration range, (boiling pool: 1 g/l - 10 g/l I”). The calibration solutions in the ppm range are prepared shortly before the measurements.

The samples are tempered at 30 °C and mixed with a buffer solution (Ion Strength Adjustor, KNO₃, 2 mol/l) in a ratio of 1:1. The ion selective probe and the reference probe are dipped into the solution which is agitated with a magnetic stirrer (1000 rpm). The voltage signal reaches a stable value at the latest after 1 minute for high ion concentrations and after around 3 minutes for low ion concentrations. Similar laps of time to reach a stable signal were observed by other authors, [1], [88]. In this work, voltages are always measured after 4 minutes. Applying this procedure, a reproducibility of 4% is reached.
Non-Soluble model substances

The requirements for the properties of non-soluble substances (solid particles) are similar to the ones for soluble substances. Instead of the solubility criterion, density close to water is requested in order to limit sedimentation effects. According to Müller [96], no particles larger than 3 μm are carried out of the boiling pool. Therefore, particles with very fine median diameter were sought. As shown in Tab. 3-6, silicon carbide and alumina were considered. Their particle size distribution are shown in Fig. 3-5.

<table>
<thead>
<tr>
<th>Name</th>
<th>median diameter $d_{50,3}$</th>
<th>Density [kg/m$^3$]</th>
<th>Price [$/kg$]</th>
<th>measuring method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon carbide (SiC)</td>
<td>3.2 μm</td>
<td>3200</td>
<td>13.-</td>
<td>Gravimetry, SEM-analysis</td>
</tr>
<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td>1.8 μm</td>
<td>3950</td>
<td>11.50</td>
<td>Gravimetry, SEM-analysis</td>
</tr>
</tbody>
</table>

TABLE 3-6: Comparison of solid particles as potential model substances

Fig. 3-4: Calibration curve for low concentrations (condensate probe)
Due to the lower median particle diameter, the experiments are carried out with alumina (Norton Ltd, precision alumina 7921).

\[
\text{CO}_x \rightarrow w \rightarrow \text{CD} \rightarrow \text{H} \rightarrow \text{O}
\]

\( n \times \rightarrow \)

Fig. 3-5: *Particle size distribution (reproducibility: 1.5%) measured with laser light diffraction (Sympatec Ltd., Model Helos II 5.3.3).*

Samples from the boiling pool are taken with the same procedure as for soluble substances. The determination of the solid concentration is done by gravimetry.

The sample is treated in an ultrasound bath (25 kHz) for 1 minute in order to avoid coagulation among the particles. After this, the suspension is agitated with a magnetic stirrer (1000 rpm) and 50 ml are taken out of the sample with a glass pipette and put in an Erlenmeyer flask. The content of the Erlenmeyer flask is evaporated in a drying cupboard at 110 °C during at least 8 hours. The probes are then cooled down in a desiccator during 2 hours. By measuring the mass of the dry residue with a analytical balance (Mettler Toledo, Type AT 400), the concentration can be calculated. For solid concentrations of about 5 g/l the reproducibility is below 0.2%. However, due to the sedimentation processes during the different steps of the measuring chain, the accuracy of this method is 3%. Here too, the obtained results have to be corrected in order to compensate the evaporation due to flash boiling during sampling.
Using the same samples, the particle size distribution of the alumina in the boiling pool can be determined with laser diffraction (Helos system, Sympatec GmbH). Here too, the samples are treated in an ultrasonic bath during one minute before the suspension is fed into the measuring device. With this device, the particle size can be measured in a range from 0.1 μm to 8750 μm. However, this is only possible if the particle concentration is high enough (O[1 g/l]). This method is therefore not suitable for particle size analysis in the condensate.

For the determination of the concentrations in the condensate a different procedure is used. Due to the very low mass of re-entrained particles, samples of only 200 ml, as for soluble substances, would contain too less particles to be detected accurately with laser diffraction. Therefore, part of the condensate is continuously by-passed and pumped by a gear pump, (13) in Fig. 3-2, through a membrane filter (14). The filter consists of modified polyvinylidene fluoride and have a pore size of 0.22 μm (Millipore, GVWP 047 00). According to the particle distribution of the alumina, they retain over 98.5% of the particle mass. The filtrate is fed back into the facility through the tank (15) in Fig. 3-2, so that the sump volume is kept constant.

By measuring the weight difference, \( \Delta M_{\text{filter}} \), of the filters before and after the sampling period and by measuring the filtrate mass, \( M_{\text{filtrate}} \), with a balance located after the filters, the concentration of particles in the condensate can be determined. (Eq. 3-3).

\[
C_{\text{cond}} = \frac{\Delta M_{\text{filter}}}{M_{\text{filtrate}}} \tag{3-3}
\]

Before each weighing operation, similarly to the handling of the Erlenmeyer flask containing sump samples, the filters which are laid in weighing glasses are dried in a cupboard at 110 °C during at least 8 hours. The filters are then cooled down in a desiccator during 2 hours. After that, a cap with ground joint is put on the weighing glass in order to keep the remained humidity constant in the filters, avoiding any drift during the weight measurement.

As the weight differences are very low (O[1 mg]), special attention has to be paid to the handling of the filters. If the filters contain impurities, these could be taken away during the experiment and the filter would
loose weight, distorting the results. Therefore, the filters are washed before weighing with one litre distilled water in order to remove possible impurities. Tests show that if distilled water is passed through filters having undergone this handling, no weight difference are observed for filtrate quantity up to 30 litres. The weighing glasses are handled only with rubber gloves to avoid fat to be deposited on the walls and change the weight. An analytical balance (Mettler Toledo, Type AT 400) with a precision of ± 0.1 mg was used for the measurements.

It is assumed that the weight difference is only due to the entrained particles in the condensate. Depending on the entrainment factor and on the amount of filtrated condensate, the accuracy of this method varies between 2% (high entrainment and large amount of filtrate) and 33% (low entrainment factor and low amount of filtrate.) The condensate flow through the filter is a function of time and of the pressure difference over the filter. After two hours in operation, the filter plugs gradually and the flow rate decreases drastically. In order to shorten the experiment and to improve the accuracy of the measurement during a given experiment duration, two filters are used during 2 hours each and one after the other. However, less material will be collected on one filter in two hours than in 4 hours. The difference of mass will be too close to the precision of the balance and no accurate measurement are possible. Therefore, both filters are always weighted together in order to keep the ratio of the precision of the balance to the mass difference of the filters equal or smaller than the ratio obtained for one single filter used during 4 hours.

A second method to determine the concentration in the condensate is used. Pictures of the surface of the filters are taken with a scanning electron microscope (HitcheD S-2500C using a Voyager image acquisition system, acceleration voltage 15kV). On these pictures, the main axes $d_1$ and $d_2$ as well as the number $n$ of alumina grains are determined manually on a surface of given size $A_{measured,j}$. Using $m$ pictures for each filter resp. for each experiment, a statistically significant amount of particles can be counted. Assuming that the particles are elliptic, that the thickness of one particle is equal to its smaller main axe, and, assuming that the particles are deposited homogeneously over the hole filter surface $A_{filter}$, the particle concentration in the con-
densate can be determined. (Eq. 3-4). With this method, particles size
distribution in the condensate can also be determined.

\[
C_c = \frac{1}{M_{\text{filtrate}}} \cdot \frac{1}{m} \sum_{i=1}^{n} (\pi \cdot d_{1,i} \cdot d_{2,i}) \\
\sum_{j=1}^{m} \frac{A_{\text{measured},j} \cdot \rho_p \cdot A_{\text{filter}}}{j}
\]  

(3-4)

3.2.2 Composition of the containment atmosphere

The amount of non-condensable gas in the containment atmosphere
can be determined by monitoring the temperatures inside the contain¬
ment (T1 and T2 in Fig. 3-2). Assuming that, due to the turbulent flow,
the gas and steam are perfectly mixed everywhere in the vessel, the
temperature of the mixture is only a function of the partial steam pres¬
sure present in the vessel. Knowing the total pressure in the contain¬
ment, the steam/air ratio can be determined.

Air-steam experiments
(Al₂O₃ as FPS)

Fig. 3-6: Comparison between the air/steam ratio in the containment
and in the venting pipe
Furthermore, assuming that the air/steam ratio prevailing in the containment is identical to the ratio of air and steam flux leaving the containment, the above method can be crosschecked if the gas flux are known.

The air flow is measured through a rotameter (7) located after the phase separator (6). In order to determine the condensate flow, the water level in the tank (6) is lowered by leading the water into tank (15) where the water is pumped back into the pool. Then, the valve (16) is closed and the increase of the water level in the tank (6) is measured during a fixed period of time. Knowing the cross section of the tank, the condensate mass flow can be calculated.

Fig. 3-6 shows good agreement between both methods. The air/steam ratio measured in the containment and in the venting pipe differ less than 10%.

3.2.3 Bubble size distribution

In order to determine which of the bubble break-up mechanism dominates in the boiling pool (jet vs. film droplets formation, see Section 2.3.1), the bubble size distribution has to be investigated.

A multiplicity of methods for measuring the size and velocity of bubbles is given in the literature [9], [66]. Movie and photographs count among the approved methods as far as optical accessibility is ensured. They provide an instantaneous measurement of a bubble population and are non-intrusive. Laser-Doppler Anemometry (LDA) and holography also enable non-intrusive measurements. However, LDA allows only bubbles smaller than 0.5 mm to be measured and, as holography, is quite complex.

Most of the intrusive methods like binary probes (e.g. reflection probe [9], [24], [25], resistive [84] or capacitive probe [65]) have the advantage of enabling the simultaneous measurement of the size and velocity of the bubbles. However, like with systems using isokinetic suction probes [89], the bubbles are deformed during the measurement and the bubble path is influenced by the probe. Furthermore, statistical analysis is required as the information given is local and corresponds to the measurement of chord length, which are not necessarily as long as the bubble diameter. The measured signal is therefore dependent on the
shape, on the size and on the velocity of the bubble and on the location where the bubble is cut.

Keeping this in mind, and considering the cost and complexity of those methods, measurement using photographs are chosen for this work.

The bubbles are photographed through an optical window (d = 125 mm) made of borosilicate glass (BK-7, thickness 30 mm). The window is located on the side of the boiling pool, a couple of centimetres above the heating plate (viewport (h) in Fig. 3-2). Through an identical window situated on the opposite side of the containment, an halogen light source (1 kW) illuminates the bubbles from behind. The pictures are taken on a black and white film (Kodak Tmax 400 pro, 400 ASA) with a Nikon F-301 camera with a macro objective (micro Nikkor, f = 55 mm, 1: 2.8).

With this light intensity and film sensitivity, exposure time between 1/500 and 1/2000 sec were possible. This velocity is necessary in order to freeze the movement of the rising bubble [19], [59]. However, the distance between the light source and the camera is long (0.6 m). The bubbles shatter each other, making the contours of the bubbles difficult to recognise. Even if the focus depth is small, the sharpness of the bubble shapes is insufficient for a software supported recognition. Only an human eye is able to distinguish a bubble from the background and therefore the bubble diameter have to be measured manually.

A convenient and rapid method to determine the Sauter mean bubble diameter, known as “pin-drop technique” [22] consists in placing a line of a length equal to about ten bubble diameters in a random fashion over the photograph and counting the number of hits and cuts. The number of hits is defined as the number of times the ends of the line are totally enclosed by the perimeter of a bubble, and the number of cuts is defined as the number of times this line is cut by the surface of a bubble. From those numbers it is possible to calculate the equivalent Sauter diameter, but no bubble size distribution can be determined. Therefore, if one needs information about the size distribution, the bubble have to be measured individually.

In order to enhance the “objectivity” of this manual measurement, a grid is laid on the photographs. (See Fig. 3-7). The chord length of the bubble are measured along the vertical lines of the grid above the hori-
horizontal line. Only bubbles touching those lines are considered. So it is ensured that the same areas on the photographs are considered with the same attention over all the experiments. The chord lengths were measured using an image analysis program (Image Tool [139]). This program enables to measure the distance in pixels between to points on the computer screen. By measuring a line of known length, a calibration can be done and distances can be measured without regard on the magnifying factor of the original picture. This allows small bubbles to be measured more accurately on the computer screen. As suggested by Buchholz [18], four to six pictures are used for each experiment, and the distance between two grid lines is set so that a total of over five hundreds bubbles is measured. This amount is necessary in order to get significant statistical results. By measuring the same images several times on different days, it could be shown that the reproducibility of this method is below 10%.

Using a method described by Clark [32], the chord length distribution can be transformed into the actual bubble diameter distribution. His model is particularly interesting as it only needs two simple assumptions:

- all the bubbles have the same shape,
- the bubble shape is not dependent on the size of the bubble.

If these assumptions are granted, the chord length distribution has to be divided in \( n \) finite classes. The probability of finding a chord length between \( y_i \) and \( y_{i+1} \) is then \( W_{i,\text{chord}} \). To each subdivision of the chord length distribution corresponds a class in the diameter distribution. All the classes in one distribution have the same width, \( \Delta y \) for the chord length, resp. \( \Delta d \) for the diameter distribution. The probability of finding a bubble diameter between \( d_j \) and \( d_{j+1} \) is then \( W_{j,\text{diam}} \). Is \( W_{\text{chord}} \) the vector containing the \( W_{i,\text{chord}} \) and \( W_{\text{diam}} \) the one containing the \( W_{j,\text{diam}} \), then the relationship between both probability distributions is then given by Eq. 3-5:

\[
W_{\text{chord}} = C \cdot W_{\text{diam}} \cdot \Delta d
\] (3-5)

The matrix \( C \) is a \( i \times j \) triangular matrix with zero above the diagonal. The remaining coefficients are only a function of the chosen bubble shape. (e.g. spheric, elliptic etc.). However, the calculation of
the inverse of the matrix $\tilde{C}$ might become unstable if the number of subdivisions is increased beyond a certain point. The instability results from the fact that for each subdivision there must exist a representative number of data points within the region. This problem can be partly overcome by transforming the chord length data to a local bubble size distribution directly by using a Parzen window function [87]. However, the resulting distribution depends on the width of the Parzen window and higher computing time are needed. In regard to the needed accuracy, the simpler method described by Eq. 3-5 is used in the present work (see Appendix. 8.3).

![Fig. 3-7: Grid for the determination of bubble chord length.](image)
3.2.4 Void fraction in the boiling pool

The void fraction in the pool is defined as:

$$
\varepsilon = \frac{V_g}{V_{pool}} \quad (3-6)
$$

and the amount of gas depends on the production rate of bubbles, \( \dot{n}_b \), and their residence time, \( \tau \).

$$
V_{gas} = \dot{n}_b V_{bubble} \cdot \tau \quad (3-7)
$$

The residence time is a function of the height of the pool, \( H_{pool} \), and of the bubble rising velocity, \( w_b \).

$$
\tau = \frac{H_{pool}}{w_b} \quad (3-8)
$$

However, the use of photographs does not allow the determination of the bubble rising velocity. Inversely, if the void fraction and the mean bubble diameter in the pool are known, the mean rising velocity can be calculated. (Eq. 3-9)

$$
\langle w_b \rangle = \frac{\dot{n}_b V_b H_{pool}}{\varepsilon V_{pool}} \quad (3-9)
$$

A multiplicity of methods for measuring the void fraction in gas-liquid flows is given in the literature. Hewitt [67], Barthels [7] and more recently Medes de Moura et al. [93] and Wilkinson et al. [140] give an overview over the advantages resp. disadvantages of intrusive and non-intrusive methods.

Due to the rough condition prevailing in the boiling pool (high temperature and high pressure), intrusive methods for the void fraction measurement were left beside. For the non-intrusive systems, three measurement methods were considered: gamma-ray absorption [85], impedance [65] and differential pressure measurements [50], [91], [138].

Because of the large diameter of the boiling pool (0.6 m), the impedancce method cannot be used in the non-intrusive mode (capaci-
tor outside of the containment). Also due to the geometry of the sump, the ray absorption method would require expensive gamma-sources with very high radiation intensity implying important safety appliances. The pressure difference method, however, can easily be used in our system.

The principle of this method is shown in Fig. 3-8. The tube outside of the containment contains only water (no gas) with density $\rho_l$ and in the pool the homogeneous density, $\rho_m$, prevails (Eq. 3-10)

$$\rho_m = \varepsilon \cdot \rho_g + (1 - \varepsilon) \cdot \rho_l$$  \hspace{1cm} (3-10)

The pressure $p_1$ and $p_2$ are given by Eq. 3-11 and Eq. 3-12:

$$p_1 = p_\infty + p_{stat, 1} = p_\infty + \rho_m \cdot g \cdot L$$ \hspace{1cm} (3-11)

$$p_2 = p_\infty + p_{stat, 2} = p_\infty + \rho_l \cdot g \cdot L$$ \hspace{1cm} (3-12)

![Fig. 3-8: Differential pressure method](image)

The difference in the static pressures $p_{stat, 1}$ and $p_{stat, 2}$ depends only on the difference of densities prevailing in both tubes.
Arranging Eq. 3-10 to Eq. 3-12, one obtains for the void fraction:

$$\varepsilon = \frac{p_2 - p_1}{g \cdot L \cdot (\rho_f - \rho_g)} = \frac{\Delta p}{g \cdot L \cdot \Delta \rho} \quad (3-13)$$

In the facility, the pressure difference is measured with a piezoresistive transducer fixed on a ceramic membrane (deltabar S PMD 230, Endress + Hauser), no. 17 in Fig. 3-2. The lower pipe connected to the transducer is located 5 cm above the heating plate. The distance, $L$, between the two pressure measurement locations is 0.4 m. With a precision of 0.05 mbar of the pressure measurement device, a difference in void fraction of maximum 0.001 m$^3$/m$^3$ can be detected. Due to the oscillation of the pressure signal however, the resolution of the void fraction might be lower [138].

### 3.3 Experimental procedure

As the venting of the reference power plant during an hypothetical accident is very slow, (two bar in two hours = 30 Pa/s), the flashing effect can be neglected in comparison with the “normal” boiling phenomena. Therefore, each transient point on the depressurisation curve (see Fig. 3-9 above) can be simulated in the pilot facility under steady state conditions and so, be investigated during a long time, enhancing the accuracy of the measurement.

This section will give a detailed description of the course of an experiment to allow both; repeating the measurements under identical steady state conditions and comparing the present experiments with experiments performed in other facilities.

On the day preceding the experiment (see Fig. 3-9 below), the lower part of the facility is filled with cold tap water. The amount of liquid in the sump is determined by measuring the pool level with the gauge (18) in Fig. 3-2.

The pipeline connecting the pressure difference measuring device (17) are flushed, so that the density of the liquid on both side is identical. The pressure difference is therefore nil and the device can be calibrated.
The electrical heating is switched on and the desired temperature of the heating plate is set to 120 °C. When this temperature is reached, the heating power is controlled in order to keep this temperature constant. So, during the night, the sump slowly heats up and starts boiling. Steam is produced and the pressure increases. Due to the steam condensation on colder surfaces and due to conduction from the pool, the containment walls also heat up.

On the next day, the heating plate temperature is set to 250 °C ensuring that maximal heat power is always delivered. The pressure and the temperatures in the containment start to increase again.

During that time, the fission product simulants are fed into the facility as solution (solubles) or as suspension (particles) through the tank (15).

As the desired pressure is reached, the valve (4) opens and the released condensate is pumped back into the sump. The membrane pump (8) has to be controlled manually so that the liquid level in the tank (6) is kept constant. This tuning is very sensible and has to be checked every twenty minutes.

If experiments with air/steam atmosphere are carried out, compressed air is fed through the orifice (9) and if enhanced convection is desired, the cooling coil (10) is also operated.

From that moment, the air and steam flow, as well as the temperatures in the containment are monitored. Increasing condensate flow reveals that the walls of the pilot plant have not yet reached their final temperature. Decreasing air flow indicates that there is still air in excess in the vessel and, inversely, increasing air flow denotes that the supplied compressed air have not yet supplant enough steam. Eventually, creeping temperatures reveal that thermodynamical equilibrium is not attained in the containment atmosphere.

As soon as all these parameters oscillate only in a narrow band, steady state conditions prevail in the facility. From the moment the pressure control valve opens until steady state conditions are reached, almost two hours for experiment with pure steam atmosphere and more than three hours for experiments with air/steam atmosphere have elapsed.
Fig. 3-9: Typical course of two experiments with air steam atmosphere and top cooling.
When the facility operates under steady state conditions, samples of the sump water and of the condensate are regularly taken and put into polyethylene containers.

Usually four to five samples for each experiment are taken with a time interval varying between 30 and 60 minutes. In the case of experiments with solid tracer material, the samples of the condensate are replaced with the continuous filtration of part of the condensate flow. The filter is changed during an experiment as soon as 15 litres condensate have been filtered or after round two hours in operation.

If there is time left, new operating conditions are settled (new cooling rate, higher pressure level, etc.) and one has to wait, as described above, until steady state conditions prevail again. Then, a new experiment can be carried out. In Fig. 3-9 below, the described procedure and change of operating conditions are pictured for typical experiments with air/steam atmosphere and operating cooling coil.

Eventually, if experiments have to be carried out on the following day, the desired temperature of the heating plate is set back on 120 °C. Otherwise, the electrical heating is shut off and as soon as the pressure in the containment equals the atmospheric pressure and as the pool temperature is below 80°C, the vessel is emptied and cleaned.

On the following day, the samples are analysed according to the description given in Section 3.2.1. Using this procedure, up to five experiments a week can be carried out.
4 Results

This section reports the experimental results obtained in the facility described in the foregoing chapter. The effect of concentration, pool volume, pressure and natural convection on the entrainment factor are investigated. Results for experiments with soluble model substances (Section 4.1) and for solid model substances (Section 4.2) are presented. At the end of this section, the results for experiments where the boiling pool is totally evaporated are discussed. (Section 4.3).

4.1 Entrainment of soluble substances

4.1.1 Entrainment in pure steam atmosphere

Preliminary remarks

During a severe core melt accident, the pressure increase in the containment is due on one hand to the steam production in the boiling pool and on the other hand to the gases released by the MCCI. Consequently, at the beginning of the venting phase, the atmosphere in the containment consists of approximately 25% of non-condensable gases and of 75% of steam. When the venting valve opens, the gas/steam mixture is released into the filter system. Since the steam production is about ten times higher than the release of non-condensable gas, the air in the containment is gradually supplanted until the atmosphere is totally filled with steam. Experiments concerning the very beginning of the venting phase will be discussed later in this chapter. In this section, experiments to simulate the end phase of the venting, where the atmosphere consists only of pure steam, are discussed.

Experiments with pure steam atmosphere and with soluble model substances have two main advantages:

First, soluble substances, in the concentration rate considered in this work, are ideally mixed in the boiling pool. The concentration of tracer material is neither dependent on the radial location nor on the height in the pool. Therefore, the droplets entrained from the pool have all a uniform chemical composition.
Secondly, if a pure steam atmosphere prevails in the vessel, the boiling pool and the atmosphere above it are in thermodynamical equilibrium. Therefore no mass transfer occurs at the surface of the entrained droplets. If a droplet is transported by the steam flow above the pool, its mass remains unchanged as long as no coalescence occurs. Furthermore, no temperature gradient occurs above the boiling pool. If there were a heat sink in the facility, the steam would condense immediately and the pressure would adjust to the new equilibrium state. However, under steady state conditions, the pressure in the system is kept constant by a control valve. The temperature in the atmosphere is equal to the saturation temperature at this pressure.

Due to the absence of a temperature gradient, the flow in the containment is mainly driven by the steam flow produced in the boiling pool and leaving the vessel through the venting pipe. The atmosphere is rather calm and steady state conditions are reached more rapidly.

In the present set of experiments, cesium iodide and potassium iodide are used as soluble fission product simulants. The pool volume, the pressure and the cooling of the containment are used as parameters. Tab. 4-1 shows the matrix of the experiments which are discussed in this section. Furthermore, the sump concentration is varied from 3 g/l

<table>
<thead>
<tr>
<th>Substance</th>
<th>Pressure Vsump</th>
<th>2 bar 137 litre</th>
<th>4 bar 137 litre</th>
<th>6 bar 137 litre</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>KI</td>
<td>No cooling</td>
<td>KIS.4-7 137 litre</td>
<td>KIS.5 137 litre</td>
<td>KIS.6 137 litre</td>
<td>KIS.10-KIS.14 137 litre</td>
</tr>
<tr>
<td></td>
<td>cooling</td>
<td>KIS.7 137 litre</td>
<td>KIS.8 137 litre</td>
<td>KIS.16, KIS.19 137 litre</td>
<td>4</td>
</tr>
<tr>
<td>CsI</td>
<td>No cooling</td>
<td>CsIS.23 367 litre</td>
<td>CsIS.24 367 litre</td>
<td>CsIS.25-CsIS.26 367 litre</td>
<td>CsIS.27-CsIS.28 367 litre</td>
</tr>
<tr>
<td></td>
<td>cooling</td>
<td>CsIS.29-CsIS.30 367 litre</td>
<td>CsIS.26 CsIS.31-CsIS.32 367 litre</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5 367 litre</td>
<td>2 367 litre</td>
<td>4 137 litre</td>
<td>11 137 litre</td>
</tr>
</tbody>
</table>

TABLE 4-1: Experiment matrix for experiments with soluble model substances and pure steam atmosphere.
KIS: KI as FPS in pure steam atmosphere;
CsIS: CsI as FPS in pure steam atmosphere.
to 10 g/l for the experiments at 4 bar and is kept around 5 g/l in the other cases.

During scanning experiments, it was observed that, when the top cooling was operated, large drops (O[2 mm]) detached from the cooling coil and fell to the boiling pool. The issue was risen if those drops, colliding with the micro droplets produced in the sump, would wash out the atmosphere and reduce the entrainment. In order to investigate this assumption, ten experiments were carried out with various cooling rate. The heat removal was varied from 0.0 kW to 9.4 kW.

From Fig. 4-1, it is apparent that the cooling rate has no significant effect on the entrainment factor. The amount of falling drops is probably too low in comparison with the one of the rising droplets and the impact between the large and small droplets only has a marginal influence.

**Fig. 4-1:** Effect of top cooling on the entrainment.

In Fig. 4-1, one can also observe that the choice of the model substances has no significant influence on the entrainment factor. Results obtained with potassium iodide or with cesium iodide show no difference. This was expected, as both substances are perfectly soluble in the temperature range considered. Alone the effect of those chemicals on the surface tension of the sump water could modify the mechanism of
the droplets production. However, Fig. 4-2 shows that, at least for temperatures below 100 °C and for the concentrations used in this work, the iodide salts have no effect on the surface tension, which confirms our expectations.

![Diagram](image)

Fig. 4-2: Effect of salt concentration and temperature on the surface tension. The surface tension are measured with an interfacial-tensiometer, device K8600, Kriiss Ltd.

From Fig. 4-1, one can assess the reproducibility of the experiments. The standard deviation of the entrainment factor for one single experiment varies between 4% and 49%, the average being at 18%. On one hand, this can be explained by the design of the facility. As suggested by Garner et al. [49], there are possibly dead zones in the venting pipeline and in the condenser. There, the condensate is gathered and forms a pool of liquid which can be blown at irregular intervals into the condensate tank. This causes erratic variations in the concentration of the salt in the condensate. On the other hand, one has to keep in mind that even for experiments with smooth liquid-gas interface and for one single bubble diameter (see Section 2.3.1), the amount of ejected droplets varies over two orders of magnitude. In the present work, the pool is boiling resp. splashing and the diameters of the bubbles rising to the surface have a large distribution. Regarding this, an average standard deviation of 18% is better than expected.
Furthermore, for almost identical conditions (e.g. P: 4 bar, no top cooling, boiling pool volume: 367 litre), the entrainment factor for different experiments can vary up to 40% from the mean value (standard deviation = 27%). First, it was thought that these variations were due to differences in the thermophoretic effects in the heat exchanger (5) in Fig. 3-2. However, the temperature changes in the cooling water are small and as measurement from Günther et al. [57] have shown, the mean droplet diameter is about 3 µm. At that size, the effect of Brownian diffusion can be almost neglected (see Section 2.5.1) and the changes in entrainment must have other causes. Therefore, the differences in entrainment can possibly result from different ambient conditions like temperatures and humidity. Both have an influence on the heat loss through the containment wall. The ambient temperature determines the temperature gradient through the wall and the humidity can change the conductivity of the glass wool of the insulation outside of the containment. If the heat losses across the containment varies, the steam flow also changes leading possibly to different entrainment mechanism in the atmosphere.

**Effect of concentration**

As the tracer substances have no effect on the surface tension of the sump water, it can be expected that the salt concentration in the boiling pool has no effect on the entrainment. Experiments with salt concentrations varying between 3.8 g/l and 11.7 g/l confirm this assumption (See Fig. 4-3).

Note that the entrainment factor is defined as the ratio of mass flow of entrained liquid divided by the mass flow of the carrier gas. (see Eq. 2-4). The entrainment factor, therefore, describes the transport mechanism of the droplets but gives no information on the amount of tracer material which is carried out of the containment. Hence, by doubling the salt concentration in the sump, the concentration in the entrained droplets will be also doubled, even if the entrainment factor remains constant. The absolute amount of tracer substances released from the containment is therefore directly proportional to the concentration in the boiling pool, even if the entrainment factor is constant.
**Pure steam atmosphere**

\( P = 4 \text{ bar}, V_{BP}=137-367 \text{ litre}, C_{BP}=3.8-11.5 \text{ g/l} \)

---

**Fig. 4-3:** Effect of the tracer material concentration in the boiling pool on the entrainment factor.

---

**Effect of the pool volume**

Due to the curved geometry of the containment, the surface of the pool increases with increasing sump volume. The heat power however remains constant. The bubbles are formed on the upper surface of the heating plate where the containment is narrower. The diameter of the cross section there is only 0.6 m. The bubbles rise first in this “tube” (see Fig. 4-4) and only after a distance of 0.3 m the bubble swarm can expand as a cone in the larger cross section (diameter: 1.5 m). Observations of the surface of the boiling pool reveal that the angle of the bubble cone is very acute. The area where the bubbles burst remains almost identical to the surface of the heating plate, no matter how large the sump surface is.

Furthermore, one can assume that, at identical conditions (pressure and concentration), the production rate of bubbles remains constant. Therefore, even if the surface available for the break-up of the bubbles...
increases, the number of bubbles bursting remains constant and though, the amount of produced droplets should not vary.

On the other hand, the behaviour of the surface might be different for the large pool area (diameter: 1.5 m). Starting from the centre, waves undulate to the side of the pool where the surface is more calm. Enhanced splashing is observed as the waves hit the containment wall.

\[
\text{Fig. 4-4: Schematic expansion of the bubble bed above the heating plate.}
\]

Still, it seems that this effect does not influence significantly the entrainment mechanism. As shown in Fig. 4-5, the entrainment factor is not dependent on the volume of the boiling pool.

**Effect of pressure**

As shown in Fig. 4-6, the entrainment factor increases with increasing pressure in the containment. Even if the standard deviation for the experiments at 2 and 6 bars is slightly higher than at 4 bar (2 bar: \( s = 36\% \), 6 bar: \( s = 54\% \)), the trend remains unequivocal.

This result does not comply with our expectations. With increasing pressure, the density of steam increases too. As the heating power is constant for all the experiments, the mass of water evaporated remains almost constant. Actually, the mass flow augments slightly as the heat of vaporisation decreases with increasing pressure. On the other hand, the bulk temperature is higher at higher pressures, so that the temperature gradient across the walls increases. This enhances the heat losses and more steam condenses at the containment wall. The heat loss effect
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Fig. 4-5: Effect of the sump volume on the entrainment factor.

Fig. 4-6: Effect of pressure on the entrainment factor.
predominates the effect of the change in heat of vaporisation and the superficial velocity, $j_g$, in the containment decreases if the pressure is higher. (see Tab. 4-2). Hence, the critical droplet diameter, which can just be carried by the steam flow, diminishes. A lower number of large droplets are entrained from the containment and one would expect that the entrainment factor decreases.

<table>
<thead>
<tr>
<th>Pressure [bar]</th>
<th>$\dot{m}_{cond}$ a) [g/s]</th>
<th>$\rho_g$ [kg/m$^3$]</th>
<th>$j_g$ [cm/s]</th>
<th>$d_{p, crit}$ b) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>6.5</td>
<td>1.13</td>
<td>0.271</td>
<td>8.3</td>
</tr>
<tr>
<td>4</td>
<td>5.4</td>
<td>2.16</td>
<td>0.141</td>
<td>6.2</td>
</tr>
<tr>
<td>6</td>
<td>5.1</td>
<td>3.17</td>
<td>0.096</td>
<td>5.3</td>
</tr>
</tbody>
</table>

TABLE 4-2: Influence of the pressure on the critical sedimentation diameter. a) average of measured condensate flow. b) Stokes’ law was assumed for the determination of the friction coefficient.

Fig. 4-7: Effect of pressure on the median bubble diameter.
Obviously, this is not the case. It seems that the behaviour of the atmosphere is not the governing factor but much more the phenomena occurring in the boiling pool.

Fig. 4-7 shows the median bubble diameter for the considered pressure range. Even if there is no significant indication that the bubble diameters depend on the pressure, it is noteworthy that the median diameter is close to 2 mm. As seen in Section 2.3, there is a significant peak in the droplet production for bubble diameters close to that size. Besides, in this diameter range, the film droplet production competes with the mechanism of jet droplet production. It might be, even if not measurable in this work, that a slight shift in the bubble size distribution has severe consequences in the production of aerosols. This would explain the increase of the entrainment factor with increasing pressure in the containment.

### 4.1.2 Entrainment in air/steam atmosphere

In this section, the very beginning of the venting is simulated. At that moment, the air/steam ratio is about 25% and the production of steam in the boiling pool is ten times higher than the release of non-condensable gas. As the atmosphere in the pilot plant is no more only filled with steam, the temperature gradient in the containment can be adjusted by the use of the cooling coil and by varying the air flow into the facility. By varying these two parameters, the effect of enhanced natural convection can be investigated. The resulting experiment matrix is shown in Tab. 4-3.

<table>
<thead>
<tr>
<th>Substance</th>
<th>air flow</th>
<th>2 bar</th>
<th>4 bar</th>
<th>5.5 bar</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>KI</td>
<td>No top cooling</td>
<td>KIA.4</td>
<td></td>
<td>KIA.7-KIA.8</td>
<td>KIA.9-KIA.10</td>
</tr>
<tr>
<td>KI</td>
<td>Medium top cooling</td>
<td>KIA.5</td>
<td></td>
<td>KIA.11</td>
<td></td>
</tr>
<tr>
<td>KI</td>
<td>High top cooling</td>
<td>KIA.6</td>
<td></td>
<td>KIA.12-KIA.14</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

**TABLE 4-3:** Experiment matrix for experiments with soluble model substances and air/steam atmosphere.

KIA: KI as FPS in air-steam atmosphere.
Effect of concentration and of pool volume

Experiments with salt concentration in the boiling pool of 4.1 g/l to 8.6 g/l were carried out. Similar to the experiments with pure steam atmosphere, no significant effect of the tracer concentration could be observed.

The sump volume was also varied (137, 280 and 367 l) for experiment at 4 bar. Like for experiments with pure steam atmosphere, the pool volume, resp. the pool surface has no influence on the entrainment factor.

Effect of pressure

Oppositely to the precedent section, the entrainment factor decreases clearly with increasing pressure. (See Fig. 4-8). The trend is particularly pronounced if only the experiments carried out without top cooling (solid symbols) are considered. If the cooling coil is operated, the facility obtains one more degree of freedom. Even small variations of the cooling power (for instance due to pressure oscillations in the compressed air system) lead instantly to temperature changes in the containment atmosphere close to the cooling coil. Due to these changes, steam condenses resp. evaporates and the pressure in the containment becomes unstable. This effect is clearly observed by monitoring the movements of the pressure control valve. The oscillations of the control valve increase distinctly, both in amplitude and in frequency, as soon as the cooling coil is operated. This explains the broader scattering of the results with top cooling (open symbols). Inversely, experiments without top cooling are well reproducible.

The fact that the entrainment factor decreases with increasing pressure is consistent with our expectations as discussed in the precedent section (see Section 4.1.1). The measurements of the void fraction for both, experiments with or without air in the atmosphere, indicate no significant differences. This suggests that the pool behaves similarly in both cases and therefore, that the entrainment mechanism for air/steam atmosphere is governed by the conditions prevailing in the atmosphere.
Effect of the Rayleigh-Number

There are two possibilities to vary the conditions in the containment atmosphere. First, the air/steam ratio can be controlled by adjusting the air flow into the boiling pool and keeping the pressure in the containment constant. If the air/steam ratio is varied, the temperatures in the pool and in the atmosphere have to change to be equal to the saturation temperature of the corresponding partial pressure of the steam.

Secondly, the containment atmosphere can be cooled by operating the cooling coil. The partial condensation of steam is increased and the air/steam ratio shifts to higher values. Consequently, the temperature decreases to stay in accordance with the new lower partial pressure of the steam.

Fig. 4-9, above, shows the effect of both the top cooling and the air/steam ratio on the entrainment factor. Obviously, these parameters do not influence directly the entrainment factor. Although they affect the conditions in the containment atmosphere, they do not entirely describe the flow characteristics in the pressure vessel.

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Fig. 4-9: Effect of the top cooling resp. of the air ratio on the
entrainment factor (above) and on the Rayleigh number
(below).
The adequate variable for natural convection problem (See Section 2.6) is the Rayleigh-number $Ra$.

$$Ra = \frac{H^3 \cdot g \cdot \beta \cdot \Delta T \cdot \varrho_{hom}}{\mu_{hom}^2} \cdot Pr$$  \hspace{1cm} (4-1)

The characteristic height, $H$, is set as the distance from the surface of the boiling pool to the top of the containment and depends on the pool volume. The term $\Delta T$ is defined as the difference between the sump temperature ($T_2$ in Fig. 3-2) and the containment temperature ($T_1$ in Fig. 3-2).

As shown in Fig. 4-9 below, the Rayleigh-number depends strongly on the top cooling and the air/steam ratio in the containment. Note the influence of the top cooling on the air ratio (Fig. 4-9, below right hand). The experiments without additional heat removal are marked with solid symbols.

The influence of the Rayleigh-number is observed in Fig. 4-10. With increasing Rayleigh-number, the entrainment factor decreases. As for the effect of pressure described in the precedent section, the trend is particularly pronounced if only the experiments without top cooling (solid symbols) are considered.

This confirms the assumption that the entrainment at air/steam atmosphere is governed by the behaviour of the gas flow above the pool.

### 4.1.3 Comparison of the experiments with soluble model substances

Before one compares the experiments with air/steam atmosphere and those with pure steam atmosphere, the results obtained for air/steam atmosphere have to be adjusted. As shown in Section 2.7.2, the concentrations measured in the condensate of air/steam experiments are too high and have to be corrected by a factor $k_{as}$. This factor is a function of the air flow into the boiling pool and of the heat losses through the wall of the upper part of the containment (see Eq. 2-51).

The overall heat loss of the facility is estimated by measuring the energy and enthalpy flow into resp. out from the facility and by writing
Fig. 4-10: Effect of the Rayleigh-number on the entrainment factor.

down the energy balance equation \( \text{Eq. 4-2} \). The corresponding control volume is shown in Fig. 4-11.

\[
\dot{Q}_{hl} = \dot{Q}_{el} + \dot{m}_{\text{cond}} \cdot (h_{\text{cond}} - h_{\text{v}}) + \dot{m}_{\text{air}} \cdot (h_{\text{air, in}} - h_{\text{air, out}}) + \dot{m}_{\text{cool air}} \cdot (h_{\text{cool air, in}} - h_{\text{cool air, out}}) \tag{4-2}
\]

For the determination of the correction factor however, the heat loss only in the containment atmosphere has to be known. Based on an estimation of the different heat loss sources (natural convection outside of the pressure vessel, radiation from the aluminum coating and from the optical windows), it was assessed that 60% of the heat losses occurs in the upper part of the vessel containing the steam atmosphere. The remaining 40% are lost through the walls wetted by the boiling pool [114].

The influences of the air flow and of the heat losses on the coefficient \( k_{as} \) are shown in Fig. 4-12. Note that the mean heat loss over the facility is around 5 kW and that for experiments with top cooling, the heat removed through the coiling coil is also considered as a heat loss for the calculation of the correction factor \( k_{as} \). The hatched zone in
Fig. 4-11: Control volume for the energy balance over the experimental facility.

Fig. 4-12 corresponds to the experiments discussed in this section, where the correction factors, $k_{as}$, varies between 0.77 and 0.85.

In Fig. 4-13, the corrected results between experiments with air/steam and pure steam atmosphere are compared. It should be noted that the order of magnitude is the same for low pressures in the containment, whereas at higher pressures, the difference is almost one order of magnitude.

For the venting strategy of a nuclear power plant, this has two possible consequences:

If the strategy consists in waiting until the venting pressure is reached and then keeping the pressure constant, the release of radioactive elements to the environment is kept to a minimum. However, the entrainment factor increases as the air content in the containment atmosphere
Fig. 4-12: Correction coefficients for the determination of the condensate concentration in air/steam atmosphere. Note: 5 kW is the average heat loss of the facility. 10 kW resp. 15 kW correspond to the heat removal through the cooling coil without resp. with heat losses through the containment wall. Hatched area: experiments discussed in this section.

is supplanted by the steam and at the end, the entrainment factor is maximum. (See strategy a) in Fig. 4-13).

On the other hand, (strategy b) in Fig. 4-13), if the venting strategy consists in depressurizing the containment down to 2 bars, the amount of released gas and aerosol is higher. The entrainment factor increases also, but the end value is two times lower than the one achieved by the constant pressure strategy.

In order to evaluate which strategy is more appropriate, one has to keep in mind that the entrainment factor is defined as the ratio of the entrained liquid divided by the gas mass flow. Depending on the venting strategy, this vented mass flow can vary over a large range. Therefore, the product of the vented mass flow with the entrainment factor has to be considered. Furthermore, the duration of the venting and the
4.2 Entrainment of solid substances

4.2.1 Entrainment in pure steam atmosphere

Preliminary remarks

Unlike with soluble model substances, it cannot be assumed that solid particles are homogeneously dispersed in the boiling pool. Due to sedimentation, the concentration and particle size distribution can vary with the height in the pool. Additionally, although a stirrer below the heating plate is used (no. 19 in Fig. 3-2) and despite the fact that the boiling sump is very agitated, the concentration at the same location in the sump water occasionally decreases with time. In this work, the time average of the sump concentration is used for the calculation of the entrainment factor.
Furthermore, solid particles have finite dimensions. An infinitesimal volume of the sump water does not necessarily contain solid particles in it. This means that not all the droplets produced by the bursting of bubbles contain an equal amount of particles. Even more, measurements of the aerosol diameter distribution in the upper part of the pilot containment at 4 bar and pure steam atmosphere [57] revealed that the mean droplet diameter is approximately 3 μm. Assuming that all the droplets have this mean diameter and that all the solid particles are uniformly distributed with a diameter $d_p = d_{p, 50}$ (see Fig. 3-5), one obtains that only every 260 droplet contains one particle. For this estimation, the average condensate flow and the mean entrainment factor $E = 3.5 \cdot 10^{-5}$ of the experiments at 4 bar with soluble model substances were used. Therefore, the concentration of tracer substances in the droplets can no more be considered equal to the concentration prevailing in the boiling pool.

Finally, due to the sedimentation in the sump and in the pipes, the sump water still contains remainders of the particles from the precedent experiments and therefore the concentration of solid particles in the pool cannot be well controlled. Nevertheless, the experiments can be split into three categories; low concentrations ($C_{BP} < 1.5 \cdot g/l$), medium concentrations ($1.5 \cdot g/l < C_{BP} < 3 \cdot g/l$) and high concentrations ($C_{BP} > 3 \cdot g/l$). The resulting experiment matrix is shown in Tab. 4-4.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>2 bar</th>
<th>4 bar</th>
<th>6 bar</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>low $C_{BP} &lt; 1.5 \cdot g/l$</td>
<td>ALS.3-ALS.4</td>
<td>ALS.8-ALS.12</td>
<td>ALS.17</td>
<td>8</td>
</tr>
<tr>
<td>medium $1.5 \cdot g/l &lt; C_{BP} &lt; 3 \cdot g/l$</td>
<td>ALS.5</td>
<td>ALS.13</td>
<td>ALS.18-ALS.20</td>
<td>5</td>
</tr>
<tr>
<td>high $C_{BP} &gt; 3 \cdot g/l$</td>
<td>ALS.6-ALS.7</td>
<td>ALS.14-ALS.16</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>9</td>
<td>4</td>
<td>18</td>
</tr>
</tbody>
</table>

**TABLE 4-4:** Experiment matrix for experiments with non-soluble model substances and pure steam atmosphere.

ALS: Alumina as FPS in pure steam atmosphere.
Effect of pressure

Fig. 4-14 shows the influence of the pressure on the entrainment factor. The results scatter strongly over almost two orders of magnitude. Even for similar conditions (e.g. 4 bar, low concentrations), the standard deviation of the entrainment factor varies between 50% and 75%. Nevertheless, similarly to the experiments with soluble substances, there is a very slight trend that the entrainment increases with increasing pressure. However, Fig. 4-14 demonstrates that the effect of the sump concentration is much more important than the influence of the pressure.

Effect of concentration

The effect of the concentration of the model substance in the boiling pool is particularly significant. Surprisingly, the entrainment factor decreases with increasing concentrations. This means that even more alumina is at disposition at the surface of the pool, the amount of entrained solid particles does not increase as expected. Even more, the concentration of particles in the condensate seems to remain constant, independently of the concentration in the boiling pool. In Fig. 4-15, the
A dashed-dotted curve is drawn for a constant concentration equal to the average condensate concentration of all the experiments discussed in this section. The curve fits suitably the experimental results. Similar phenomenon was already observed by Bunz et al. [20] and Sakai et al. [116] but the reason for this constant concentration in the condensate is still not well understood. However, some hypotheses can be formulated:

a. the concentration very close to the gas-liquid interface remains constant, independently from the bulk concentration in the boiling pool,

b. the break-up mechanism of the bubbles at the pool surface is affected by the presence of particles,

c. the sedimentation mechanism in the containment atmosphere is influenced by the presence of particles in the droplets.

In the following paragraphs, an attempt is made to support these hypotheses.

---

**Fig. 4-15:** Effect of the model substance concentration in the boiling pool on the entrainment factor.
The concentration close to the gas-liquid interface remains constant

Experiments, [90], as well as simulations, [132], indicate that the liquid forming the jet droplets is provided by a very thin liquid layer around the bubble floating at the surface of the boiling pool. The concentration in this layer is influenced by two phenomena. On one hand, sedimentation processes remove the heaviest particles down to the bottom of the containment. On the other hand, particles which are lifted by rising bubbles (similar to flotation effects) and which are not entrained after the bubbles have burst remain close to the surface.

In order to identify the sedimentation process in the boiling pool, samples were taken at different levels. The samples were taken below the heating plate (valve no. 12 in Fig. 3-2), just above the heating plate (valve no. 20) and in the upper part of the pool (valve no. 21). As the volumetric flow of the steam varies by a factor three between experiments at 2 bar resp. at 6 bar, the concentration profiles and the particle size distributions were measured for different operation pressures. The results show that the concentrations remain constant over the three sampling locations and no significant shift in the particle distribution can be observed (see Fig. 4-16). Furthermore, the suspension of the particles seems not to be dependent on the gas flow through the pool and the median particle diameter, $d_{50, 3}$, remains for all three pressures equal to 1.8 μm. This means that the particle larger than the critical sedimentation diameter drops below the valve no. 12 in Fig. 3-2 and that the remaining particles are ideally mixed in the bulk of the pool. However, based on these observations, extrapolations to the concentration in layers very close to the surface cannot be made and one cannot exclude that, due to the lifting processes of the bubbles, the concentrations and particle distributions there are different.

If the concentration close to the pool surface increases, the probability that the particles coagulate increases as well and new formed, larger particles sediment. This acts like a self purification and possibly the concentration close to the surface stays almost constant, independently from the bulk concentration in the boiling pool.

Furthermore, the collection of particles by the rising bubbles brings continuously new particles close to the surface and leads to an enrichment in the droplets ejected from the pool surface [20]. Enrichment
factors of several hundreds are mentioned in the literature [14], [116], [137]. This mechanism appears to be very effective and is possibly the cause for the independence of the mass release rate on the sump concentration. At higher sump concentrations the surface of the bubble becomes saturated with particles and the content of particles in the droplets becomes independent on the sump concentration.

Both phenomena, sedimentation and enrichment could explain why the measured concentration in the condensate remains constant, even if the concentration in the pool increases.

Fig. 4-16: Effect of pressure and of the sampling location on the particle size distribution
b) Break-up mechanism

If the presence of solid particles affects the surface tension of the water, the break-up mechanism could be influenced. The surface tension of suspensions containing 0.5, 1.0, 2.5 and 4.0 g/l alumina and for temperature up to 70°C were measured with an interfacial tensiometer\textsuperscript{1} and with a DSA-device\textsuperscript{2}, but no influence of the particle concentration was noticed.

![Diagram](image)

Fig. 4-17: Liquid film above a bubble at the pool surface.

Furthermore, if particles are in the thin liquid film covering a bubble at the surface of the pool, the critical thickness, $\delta$, at which the film ruptures can be influenced (see Fig. 4-17). The disintegration of this film is responsible for the production of the film droplets and its thickness is a function of the bubble size, of the surface tension and of the liquid density. For bubble diameters between 1.5 mm and 3 mm, the thickness is about 1 $\mu$m [130]. The diameters of the particles contained in this film can not be larger than the thickness of the film. With the alumina used in this work, less than 10% of the particles are small enough to fulfil this criterion. The larger particles have to be carried out by jet or splash droplets, although most of them are too large and too heavy to be carried out of the containment.

Assuming a mean bubble diameter of 3 mm, the height, $z$, to the summit of the cap formed by a floating bubble at the pool surface is 0.6 mm and the surface of the film above the water level is 2.4 mm$^2$ [134]. The film volume can be calculated and, assuming a mean particle diameter of 0.5 $\mu$m, one obtains that for the concentration range used in the present experiments, 70 to 500 particles could be contained in

---

\textsuperscript{1} Interfacial-Tensiometer using the Lecomte du Nouy principle. Device type K8600, Krüss Ltd., Hamburg.

\textsuperscript{2} Droplet Shape Analysis (DSA) method. Device type G10, Krüss Ltd., Hamburg.
the film. If the bulk concentration in the pool increases, the amount of particles in the film increases too and the film breaks up earlier than without particles. At this moment, the bubble is deeper in the water and the film surface is smaller. Consequently, less film droplets containing particles are produced. So, if the bulk concentration in the boiling pool is increased, the film droplet production is reduced. On the other hand, the jet drops contain higher amount of particles. Assuming that the jet drops production is not affected by the presence of the solid tracer substance, more particles are entrained. Possibly, the two effects, the reduced production of film droplets and the higher tracer concentration in the jet drops, neutralize each other.

c) sedimentation of droplets containing particles.

As the solid particles have finite dimensions, one cannot assume that the concentration of alumina in the pool is the same as in the droplets. For instance, if a droplet contains a solid particle with a diameter similar to its own diameter, the mass concentration in the droplet is then much higher than in the sump. Consequently, the density of this solid/water droplet increases remarkably and the critical sedimentation diameter decreases. Fig. 4-18 shows the influence on the critical sedimentation diameter of a droplet containing one entrained solid particles of diameter $d_p$. A drag coefficient according to the Stokes' law, [11], was used for the calculation of the critical sedimentation diameter (see Eq. 4-3).

$$d_{dr, crit} = \frac{18 \cdot j_g \cdot \eta_g}{\eta \left( \rho_{dr} - \rho_g \right) \cdot g}$$  \hspace{1cm} (4-3)

One can see that no particle larger than 3.3 μm can be entrained into the condensate at 4 bar. The analyse of the particle sizes in the condensate with a Scanning Electron Microscope (SEM) confirms this and was already observed by Müller [96]. So, if the particle concentration near to the surface increases, more “heavy” droplets which are larger than the critical sedimentation diameter are produced and fall back to the sump. Assuming that the size and the amount of the produced droplets is not dependent on the solid concentration, less droplets are eventually carried out in the venting pipe. Similar effects (reduced
entrainment by higher droplet density) were observed for the entrainment of solution with high tracer concentration by Heger et al. [62].

\[ P: 4 \text{ bar, pure steam atmosphere} \]
\[ j_g: 0.15 \text{ cm/s (top of containment)} \]
\[ \text{particles: } \mathrm{Al}_2\mathrm{O}_3 \]

Fig. 4-18: Effect of the presence of one solid particle of diameter \( d_p \) in a droplet on the critical sedimentation diameter \( d_{dr,crit} \) compared with the particle diameters present in the pool.

It is difficult to assess which of these phenomena dominates and determines the concentration in the condensate. Possibly, all three effects work together and act so, that the particle concentration in the condensate is not dependent on the bulk concentration in the boiling pool.

**4.2.2 Entrainment in air/steam atmosphere**

Similar to Section 4.1.2, the entrainment of solid particles in an air/steam atmosphere is investigated. The matrix of the experiments discussed in this section is given in Tab. 4-5.

**Effect of concentration**

Alike the experiments with pure steam atmosphere, the entrainment factor decreases with increasing particle concentration in the boiling pool (see Fig. 4-19). Again it seems that the concentration in the condensate remains constant independently of the bulk concentration in the sump water. However, four experiments in the lower concentration
range do not fit well with the other results. As the experiment course and the handling of the filters were identical for all the experiments, one has to assume that those differences stem from a degradation of the filter material. It might be that, despite the handling described in Section 3.2.1, the filters lost weight during the operation and that therefore the results are biased.

**Effect of pressure and of the Rayleigh-number**

Here, the effect of the pressure on the entrainment factor is more pronounced than for experiments with pure steam atmosphere. Alike with soluble substances, the entrainment decreases with increasing pressure (Fig. 4-20). Similarly, the entrainment mechanism of solid particles at air-steam atmosphere is governed by the flow in the containment. Fig. 4-21 represents the effect of the Rayleigh-number on the entrainment factor and confirms this presumption.

### 4.2.3 Comparison of the experiments with non-soluble model substances

Alike in Section 4.1.3, the results obtained for air-steam atmosphere have to be corrected in order to be comparable with those for pure steam atmosphere. In this case, the correction coefficient, $k_{as}$, varies between 0.82 and 0.89.
The scattering of the experiments with non-soluble substances is much larger than for the experiments with soluble model substances. Consequently, the effect of pressure at different atmospheres can hardly be compared and one can no more distinguish the consequences of the two venting strategies discussed in Section 4.1.3.

Though, the most important parameter influencing the entrainment of solid particles is the concentration of fission product simulant in the sump water. Fig. 4-22 shows a comparison between pure steam and air/steam atmosphere. If the three outliers at low sump concentrations are neglected, one can see that the trends are similar but that the results for a mixed atmosphere are shifted to the right. This means that due to the higher turbulences in the atmosphere, larger droplets can be entrained and the entrainment factor is enhanced. Therefore, for an identical concentration of solid material in the sump, the entrainment is higher at the beginning of the venting, where the atmosphere is mixed with air, than at the end where the steam has supplanted the air in the containment.
Chapter 4 Results

**Fig. 4-20:** Effect of pressure on the entrainment of alumina particles.

**Fig. 4-21:** Effect of the Rayleigh-number on the entrainment of alumina particles.
4.3 Entrainment during the evaporation of the sump

An important aspect of the scenario of severe nuclear accidents is the issue whether water will cover the molten core. If this is not the case, the cooling of the molten reactor decreases drastically and large additional amount of radioactive particles are produced.

In the case considered in this work, this situation occurs if the sump water covering the molten core boils out. If this happens, the pool volume decreases gradually and the heating power per cubic meter increases proportionally. As the sump volume is close to nil, the bubbles behaviour (production rate, coalescence, rising velocity, etc.) will change remarkably. Furthermore, as the water at disposition evaporates, the concentration of impurities in the sump increases and higher amount of entrained particles is expected.

Fig. 4-22: Comparison of the corrected entrainment factors for pure steam and for air-steam atmosphere.
In this section, experiments are carried out in order to simulate this scenario. Hence, the facility is initially filled with 140 litres water, warmed up and brought under quasi steady state conditions. (See Experimental procedure in Section 3.3). As these conditions are reached, the pump no. 8 in Fig. 3-2 is switched off and the condensate is continuously removed out of the facility. The amount of removed water (78 litres until the plate is uncovered) is determined by weighing the condensate flow.

At regular intervals, samples from the boiling pool as well as from the condensate are taken. As these experiments are no more under stationary conditions, gravimetry methods for the determination of the particle concentration in the condensate are no more adequate and only soluble model substances could be used.

The experiments are carried out until the heating plate is no more covered by water. At that moment, the pressure control valve is kept in a constant position and the heating power is switched off in order to avoid damages to the heating plate. However, samples are still taken, as the produced droplets are still in suspension and have not yet reached the venting pipe. After 30 further minutes, the experiments are aborted.

Fig. 4-23 shows the dimensionless concentrations in the sump and in the condensate. The values are divided by the concentration at the beginning of the experiments. Basing on the amount of evaporated water, the expected concentration in the boiling pool are calculated. Assuming a constant entrainment factor during the experiment, the concentration in the condensate should increases in the same manner as the concentration in the sump water.

In Fig. 4-23, there is a good agreement between the expected and the measured concentrations, and this both for the condensate and sump measurements. As the heating plate is uncovered the concentration in the condensate first increases before falling down sharply. The increase is due to the intense boiling shortly before the water film has fully evaporated. Observations of the pool at that moment revealed a kind of foaming layer of ca. 1 cm on the heating plate. Due to the residence time in the facility, the corresponding concentration increases in the condensate can be measured only 20 minutes after the heating plate
Evaporation of the sump
(pure steam atmosphere, p: 4 bar, KI as FPS)

Fig. 4-23: Concentration progression in the condensate and in the boiling pool during the evaporation of the sump water.

was uncovered, explaining the shift to the right in Fig. 4-23. As soon as the heating plate is uncovered, there are logically no bubbles left to burst and to produce droplets. Consequently, the concentration of the model substance decreases instantly in the condensate. This decrease however can be only considered qualitatively as at that moment, the heating power is switched off, less sump water is evaporated and the pressure decreases in the containment. However, the speed with which the concentration decreases proved that the governing effect is the disappearance of the boiling pool.

Eventually, the average entrainment factor for the evaporation experiments is \(<E> = 5.8 \times 10^{-5}\) which is slightly higher as for experiments under steady state conditions (e.g. P: 4 bar, pure steam atmosphere: \(<E> = 2.38 \times 10^{-5}\)). This is due to the fact that during the evaporation experiments, the condensate is not fed back into the pool. Therefore, the specific heat power in the boiling pool is higher than during experiments under steady-state conditions and more steam resp. more bubbles are produced increasing the amount of entrained tracer substances.
5 Modelling

In this chapter, existing deterministic and semi-empirical models are presented and compared with the results obtained in this work. At the end of the chapter, a new correlation is given which takes into account the effects of free convection and of the type (soluble vs. solid) of fission products.

5.1 Deterministic models

Basing on the momentum and energy balance around a bursting bubble and using a drag coefficient for the produced droplets according to Chao, Covelli et al., [36], developed a model predicting the entrainment of droplets in a bubbling pool. Müller, [96], implemented this model in order to adapt the drag coefficient for a swarm of particles.

The Müller’s model is based on the following assumptions:

- the bubble diameters of all the bubble in the pool are uniform \( (d_b = \text{cst}) \),
- the bubble terminal velocity is a function of the bubble diameter and is identical for all the bubbles,
- the burst of one bubble releases only one large droplet with a diameter equals to the critical sedimentation diameter,
- the droplets are uniformly distributed,
- the flow over the pool is a plug flow corresponding to the steam flow produced in the pool,
- there is no slip between the droplets and the gas flow.

Using the control volume shown in Fig. 5-1, one obtains for the energy balance,

\[
\dot{m}_g \cdot \frac{w_{g, \text{burst}}^2}{2} = \dot{m}_g \cdot \left[ \frac{l_g^2}{2} + g \cdot \Delta z \right] \\
+ \dot{n}_{dr} \cdot \left[ \sigma \cdot \pi \cdot d_{dr}^2 + V_{dr} \cdot \rho_l \cdot \frac{w_{dr}^2}{2} + V_d \cdot \rho_l \cdot g \cdot \Delta z \right]
\]

\[5-1\]
and for the momentum balance:

\[ \Delta p = \rho_g \cdot \frac{w_{g,\text{burst}}^2 - j_g^2}{2} + \rho_g \cdot g \cdot \Delta z, \]  

(5-2)

where \( w_{g,\text{burst}} \) is the velocity of the gas being ejected by the burst of a bubble, \( j_g \) is the superficial gas velocity in the containment and \( \Delta p \) is the pressure difference between the inside of a gas bubble and its surrounding (see Eq. 2-8).

If the steam mass flow and the mean bubble diameter are known, Eq. 5-1 and Eq. 5-2 can be rearranged and the droplet production rate \( n_{dr} \) can be solved. Knowing this, the mass flow of ejected droplets and therefore the entrainment factor can be determined.

Furthermore, assuming that the concentration of tracer substances in the droplet is the same as in the bulk of the boiling pool, the concentration of FPS in the condensate can be calculated. Fig. 5-2 (from [96]) shows the results obtained with this model by varying the bubble diameter between 5 and 8 mm and by setting the height of the control volume equals to the bubble radius.

One can see that the concentration of tracer substances in the condensate, and so the entrainment factor, decreases with increasing bubble diameter. \( \text{(Pro memoriam } E = C_{\text{Cond}}/C_{BP} \text{ and therefore the entrainment factor equals the slope of the lines in Fig. 5-2). This is due to the fact that small bubbles have more specific energy than large bubbles.} \)
Fig. 5-2: Concentration in the condensate as a function of the boiling pool concentration. The experimental results are compared with the model prediction for different bubble diameters [96].

(see Section 2.3.1) and consequently, more droplets per bubble can be produced.

Since Müller had no optical access in the boiling pool, he assumed that the bubble diameters lay between 5 mm and 8 mm relying on estimations according to a correlation of Peebles and Garber [100]. This correlation gives the bubble diameter in an air-liquid bubble column as a function of the bubble rising velocity. The latter was calculated with a correlation of Harmathy [60].

In this work, however, the REVENT facility was modified in order to enable bubble size measurements (see Section 3.2.3). In Section 4.1.1, it was shown that the measured mean bubble diameter is about 2 mm.

By using the measured mean bubble diameter as input into Müller’s model, the calculated values overestimate the entrainment factor by more than one order of magnitude (e.g. for 4 bar and pure steam atmosphere: $E_{calculated}/E_{measured} = 22$). We suppose that the main reason for this overestimation is the assumption that all the energy delivered by the steam bubbles can be perfectly transformed for the
production of droplets which are all entrained by the gas flow. In fact, a large amount of the produced droplets have a terminal velocity higher than the superficial gas velocity and fall back to the sump. The energy and momentum used by those droplets, which do not leave the control volume, is lost as dissipation energy. Therefore, much less droplets leave effectively the containment than estimated by the Müller’s model and the real entrainment factor is lower as predicted.

In order to support this statement, the energy required to produce and to lift the water droplets which really leave the containment is calculated. First, using the average entrainment measured at 4 bar in a pure steam atmosphere and based on the definition of the entrainment factor (see Eq. 2-4), the droplet mass flow leaving the containment is determined:

\[ m_{dr} = m_l = \langle E \rangle_{4 \text{bar}} \cdot \dot{m}_g = \langle E \rangle_{4 \text{bar}} \cdot m_{\text{cond}}. \]  

(5-3)

Knowing this and assuming that all the droplets have the same diameter, \( d_{dr} \), the surface, kinetic and potential energies of the droplet mass flow can be calculated:

\[ E_{dr, \text{surf}} = \dot{m}_{dr} \cdot \frac{\pi}{4} \cdot d_{dr}^2 \cdot \sigma = \frac{\dot{m}_{dr}}{M_{dr}} \cdot \frac{\pi}{4} \cdot d_{dr}^2 \cdot \sigma, \]  

(5-4)

\[ E_{dr, \text{kin}} = \dot{m}_{dr} \cdot \frac{w_{dr}^2}{2}, \]  

(5-5)

\[ E_{dr, \text{pot}} = \dot{m}_{dr} \cdot g \cdot \Delta z. \]  

(5-6)

The total energy transported by the droplet flow is then:

\[ E_{dr, tot} = E_{dr, \text{surf}} + E_{dr, \text{kin}} + E_{dr, \text{pot}} + H_{dr} \]  

(5-7)

Similarly, assuming a constant bubble diameter \( d_b = 2 \text{mm} \) and a bubble terminal velocity of \( w_b = 0.2 \text{ m/s} \), the energy delivered by the bubble flow can be determined:

\[ E_{b, tot} = E_{b, \text{surf}} + E_{b, \text{kin}} + H_b, \]  

(5-8)
where:

\[ \dot{E}_{b, \text{surf}} = \dot{n}_b \cdot \pi \cdot d_b^2 \cdot \sigma = \frac{\dot{m}_{\text{cond}}}{M_b} \cdot \pi \cdot d_b^2 \cdot \sigma \]  

and

\[ \dot{E}_{b, \text{kin}} = \dot{m}_{\text{cond}} \cdot \frac{w_b^2}{2}. \]  

In Fig. 5-3, the orders of magnitude of the different energies of the droplet flow resp. of the bubble flow are shown.

Fig. 5-3: Energy flows calculated for the average bubble and droplet mass flows measured at 4 bar in a pure steam atmosphere. The bubble diameter is assumed constant and set to 2 mm. The height between the pool surface and the venting pipe is \( \Delta z = 2 m \). An average steam flow of 5.4 g/s and an average entrainment factor of \( 2.4 \cdot 10^{-5} \) are used for the calculations.

The thick dashed dotted line is the total amount of energy delivered by the bubble gas flow. Assuming that the enthalpy of the gas remains constant (no steam condensation) and substracting the potential energy required to rise the gas up to the venting pipe, the remaining energy \( \dot{E}_{b, \text{tot}} - \dot{E}_{b, \text{pot}} - \dot{H}_b \) (thick solid line) is the energy which can be used for the production and the transport of the droplets. On the other hand,
assuming that the enthalpy of the liquid remains constant (no evaporation at the droplet surface), the required energy for the droplet flow is represented by the thick dashed line.

There are at least four orders of magnitude between the required energy and the energy at disposal. As mentioned above, the surplus of energy is used for the formation (surface energy) and for the acceleration (kinetic energy) of the large drops with terminal velocities higher than the superficial velocity in the containment. As those drops fall back to the pool, their energy is dissipated. Note that, although the amount of dissipated energy (ca. 1 W) is much higher that the energy needed by the entrained droplets, it is negligibly small compared to the heat loss over the containment wall (up to 5 kW).

Furthermore, one can see that the kinetic energy of the droplet flow is also negligible (ca. $10^{-13}$ W). Therefore, the assumption that there is no slip between the droplets and the gas flow has, from an energetic point of view, almost no influence on the entrainment mechanism. Inversely, the height of the control volume plays an important role. One can see in Fig. 5-3 that the order of magnitude of the potential and surface energies of the droplets are similar for large droplet diameters. There, the surface energy is lower as the total surface $A_{dr,tot}$ decreases with increasing droplet diameter ($A_{dr,tot} \sim d_{dr}^{-1}$).

However, recent PDA-measurements in the containment atmosphere at 4 bar and in a pure steam atmosphere (see Günther et al. [57]) showed that the mean droplet diameter equals $\langle d_{dr} \rangle = 3\mu m$. For such small droplets, the potential energy, compared to the surface energy, can be almost neglected. The height of the control volume however still plays an important role as the potential energy of the gas flow influences sensitively the energy balance (Eq. 5-11).

$$\dot{E}_{b,\text{pot}} = \dot{m}_{\text{cond}} \cdot g \cdot h = 1/E \cdot \dot{m}_{dr} \cdot g \cdot h \approx 10^5 \cdot \dot{E}_{dr,\text{pot}}.$$  (5-11)

Furthermore, for droplet diameters of ca 3 µm, the Knudsen number is smaller than 0.01 and the law of the continuum mechanics apply (see Section 2.5). Assuming that all the droplets have a diameter of 3 µm, the droplet production rate can be estimated: $\dot{n}_{dr} = \dot{m}_{dr} / M_{dr}$. Based on this estimation, it can be shown that less than 4 droplets per cubic millimetre are expected in the containment atmosphere. Therefore, the
trajectories of the droplets are not influenced by the other and the use of the Stokes' law for the drag coefficient seems to be more appropriate than the correlation of Chao (droplet swarm) used in the Müller's model.

Eventually, the energetic considerations made above assumed that the enthalpy of the gas flow remains constant. However, it cannot be exclude that part of the steam flow condenses at the surface of film droplets, for example during the expansion following the burst of a bubble. If this occurs, important amounts of energy could be released which are significantly larger than the energy required for the droplet formation. In that case, the determination of the amount of energy used for the formation and the acceleration of large droplets is hardly possible.

In conclusion, based on the new information gained by the bubble and droplet size measurements and based on the energetic considerations mentioned above, it can be shown that a physical description of the entrainment based only on the overall momentum and energy balances is not appropriate. Too many key factors, such as the amount of energy used by the large droplets or the possible changes of state in the steam flow, cannot be determined accurately with the measurement techniques currently available in the REVENT-facility. Until these parameters can be better assessed, the prediction of the entrainment factor has to be based on semi-empirical models.

5.2 Semi-empirical models

The amount, the velocity and the size of entrained droplets is strongly dependent on the distance, $z$, between the measurement location and the surface of the boiling pool.

Basing on experimental data mainly for air-water systems, semi-empirical relationships are given in the literature ([54], [101], [113]). Those experimental data show that the entrainment is a strong function of the gas superficial velocity, $j_g$, and of the distance to the pool surface. However, those correlations cannot be used in this work as they all consider the region very close to the surface. At that distance, large droplets with settling velocities higher than the rising gas velocity are also considered, even though they will never reach the venting system.
Therefore, a more differentiated model which takes into account the sedimentation of the large droplets has to be considered.

5.2.1 Kataoka and Ishi’s model

Kataoka and Ishi, [78], compared the entrainment measurements of film and jet droplets from various authors. They found that when the entrainment is plotted versus the distance to the pool, \( z \), three regions with different entrainment regimes can be observed. Those are:

- the near surface region,
- the momentum controlled region,
- and the deposition controlled region.

In order to determine these regions independently of the experimental set-up, dimensionless lengths are defined.

First the height \( \hat{z} \) above the pool and the containment diameter, \( \hat{D} \), are introduced:

\[
\hat{z} = \frac{z}{(\sqrt{\sigma/(g \cdot \Delta \rho))}}. \tag{5-12}
\]
\[
\hat{D} = \frac{D}{(\sqrt{\sigma/(g \cdot \Delta \rho))}}. \tag{5-13}
\]

where \( \sigma \) is the surface tension of the liquid and \( \Delta \rho \) is the density difference between the liquid and the vapour phases.

Similarly, the dimensionless superficial gas velocity, \( \hat{j}_g \), is defined as:

\[
\hat{j}_g = \frac{j_g}{4\sqrt{\sigma \cdot g \cdot (\Delta \rho)/\rho_g^2}}. \tag{5-14}
\]

Eventually, the influences of the liquid properties are summarized in the dimensionless gas and liquid viscosity numbers, \( N_{\mu g} \) resp. \( N_{\mu l} \).

\[
N_{\mu g} = \frac{\mu_g}{(\rho_g \cdot \sigma \cdot \sqrt{\sigma/(g \cdot \Delta \rho)})^{1/2}}. \tag{5-15}
\]
In the following paragraphs, the entrainment in the different regions is discussed.

\[ N_{\mu l} = \frac{\mu_l}{(\rho_l \cdot \sigma \cdot \sqrt{\sigma/(g \cdot \Delta \rho)})^{1/2}} \]  

(5-16)

\[ z_{nsr} = 1.038 \cdot 10^{-3} \cdot j_g \cdot N_{\mu g}^{0.5} \cdot D^{-0.42} \cdot \left( \frac{\rho_g}{\Delta \rho} \right)^{-0.23} \]  

(5-17)

In this region, the entrainment factor is not dependent on the superficial gas velocity and can be given by Eq. 5-18:

\[ E_{nsr} = 4.84 \cdot 10^{-3} \cdot \left( \frac{\rho_g}{\Delta \rho} \right)^{-1} \]  

(5-18)

\[ z_{mcr} = 1.97 \cdot 10^{-3} \cdot N_{\mu g}^{1/3} \cdot D^{-0.42} \cdot \left( \frac{\rho_g}{\Delta \rho} \right)^{-0.23} \]  

(5-19)

In this region the entrainment factor decreases with height until all the droplets whose terminal velocities are higher than the superficial velocity fall back into the sump. One distinguishes two cases: entrainment by low gas flux (Eq. 5-20) and entrainment for intermediate gas flux (Eq. 5-21, according to Sterman in [78]).

\[ E_{mcr_{low}} = 2.21 \cdot N_{\mu g}^{1.5} \cdot D^{1.25} \cdot \left( \frac{\rho_g}{\Delta \rho} \right)^{-0.31} \cdot \frac{j_g}{z} \]  

(5-20)
The transition from the low to the intermediate gas flux is given by Eq. 5-22.

$$\dot{j}_g \leq 6.39 \cdot 10^{-4} \cdot \dot{z}$$

(5-22)

c) Deposition controlled region:

In this region, the deposition of the droplets at the containment wall becomes the main factor determining the amount of entrained particles. In this regime, the entrainment consists of droplets whose terminal velocity is lower than the gas velocity. The entrainment decreases gradually with $z$.

The entrainment factor in this region is:

$$E_{dcr, deposition} = 7.13 \cdot 10^{-4} \cdot \dot{j}_g \cdot N^{0.5}_{\mu g} \cdot (\frac{\rho_g}{\Delta \rho})^{-1} \cdot e^{-0.205 \cdot \frac{z}{D}}$$

(5-23)

If the deposition term can be neglected, the entrainment factor is no more dependent on $z$ and remains constant over all the deposition controlled region. Eq. 5-23 can be simplified and one obtains:

$$E_{dcr} = 1.99 \cdot 10^{-3} \cdot \dot{j}_g \cdot N^{0.5}_{\mu g} \cdot (\frac{\rho_g}{\Delta \rho})^{-1}$$

(5-24)

Using Eq. 5-17 to Eq. 5-24, the heights of the near surface region and of the momentum controlled region for different pressures and different containment atmospheres were calculated (See Tab. 5-1).

One can see that the height of the momentum controlled region decreases with increasing pressure. This is mainly due to the fact that with increasing pressure, the density of the gas increases and, as the mass flow of evaporated water is almost constant, the gas superficial velocity decreases accordingly. Therefore, the drag force exercised by the rising gas is reduced and the large droplets with settling velocities higher than the gas velocity fall back earlier.
TABLE 5-1: Height of the near surface region, $z_{nsr}$, of the momentum controlled region, $z_{mcr}$, and calculated resp. measured entrainment factors as a function of the pressure and of the composition of the atmosphere.

<table>
<thead>
<tr>
<th></th>
<th>$P$ [bar]</th>
<th>$z_{nsr}$ [mm]</th>
<th>$z_{mcr}$ [cm]</th>
<th>$E_{mcr}(z_{mcr})$ [kg/kg]</th>
<th>$E_{dcr}(2\ m)$ [kg/kg]</th>
<th>$&lt;E_{measured}&gt;$ [kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure steam</td>
<td>2</td>
<td>0.175</td>
<td>23.3</td>
<td>2.60E-05</td>
<td>8.67E-10</td>
<td>1.89E-05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.080</td>
<td>18.1</td>
<td>1.20E-05</td>
<td>9.14E-11</td>
<td>2.38E-05</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.053</td>
<td>15.5</td>
<td>8.12E-06</td>
<td>2.85E-11</td>
<td>3.66E-05</td>
</tr>
<tr>
<td>Air steam</td>
<td>2</td>
<td>0.211</td>
<td>24.2</td>
<td>3.30E-05</td>
<td>1.39E-09</td>
<td>4.07E-05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.107</td>
<td>19.1</td>
<td>1.55E-05</td>
<td>1.90E-10</td>
<td>1.65E-05</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>0.074</td>
<td>16.7</td>
<td>1.20E-05</td>
<td>6.91E-11</td>
<td>7.48E-06</td>
</tr>
</tbody>
</table>

Furthermore, as the height where the air-steam atmosphere is removed from the containment into the venting pipe is approximately $z \approx 2\ m$, the vented droplets originate from the deposition controlled region (see Tab. 5-1). The entrainment factors in this region are calculated with Eq. 5-24 ($E_{dcr}(2\ m)$). In Eq. 5-23, the deposition term $e^{-\left(0.205 \cdot z/D\right)}$ equals ca. 0.75 and the deposition at the wall can be almost neglected. The entrainment is therefore also calculated at the upper limit of the momentum controlled region ($E_{mcr}(z_{mcr})$, see Eq. 5-20).

Although the results obtained with both equations should be almost identical, there is a striking difference between the two models. The calculated entrainment factors with the equation for the deposition controlled region show values which are 5 orders of magnitude lower than the value measured in the REVENT facility. This is due to the fact that Eq. 5-24 was obtained on the base of experiments from Golub and Garner (in [78]), where the gas superficial velocities are higher than 50 cm/s (pro memoriam, in the REVENT facility $0.5\ cm/s < j_g < 2.7\ cm/s$). Obviously, this correlation cannot be used for conditions such as those prevailing in this work.

On the other hand, the values calculated at the upper end of the momentum controlled region, $E_{mcr}(z_{mcr})$, are in good agreement with the measured entrainment factors, $E_{measured}$. For experiments with air-steam atmosphere, not only the range of the calculated entrainment but also the decreasing trend by increasing pressure is described correctly by the Kataoka’s model (see Fig. 5-4).
Furthermore, the results obtained with Kataoka’s model are higher for an air-steam atmosphere than those for a pure steam atmosphere. This is mainly due to the fact that during the air steam experiments, the same amount of steam is produced as during the pure steam experiments (the heating power is constant) but in addition, compressed air is supplied into the containment. Consequently, the total gas flow is higher: more bubbles resp. more droplets are produced and the superficial velocity is increased allowing larger droplets to be entrained out of the containment.

However, for experiments with pure steam atmosphere, the calculated entrainment factors are in the same order of magnitude as the measured results but the trend given by the model (decreasing entrainment factor by increasing pressure) does not correspond to the measurements.

This discrepancy between the model and the measurements is probably due to the fact that the Kataoka’s correlation in the momentum controlled region is mainly based on experiments with air-water systems (see [78]). Therefore, the model fails to take into consideration the importance of the sump behaviour as it was described in Section 4.1.1.
Furthermore, the Kataoka’s model is not appropriate to describe the entrainment of solid fission product. As shown in Section 4.2.1, the entrainment of solid tracer substances depends mainly on the particle concentration in the boiling pool. This effect is not taken into account by the model of Kataoka and Ishi (see Eq. 5-20). Therefore, new models considering the composition of the atmosphere above the boiling surface and taking into account the concentration of solid material in the sump water have to be developed.

5.2.2 Own correlations

In this section, an attempt is given to predict with one equation the entrainment factors obtained in pure steam and air-steam atmosphere. The different entrainment mechanisms of soluble and solid model substances are considered by adapting the set of constants used in the new correlation.

For this purpose, a dimensional analysis according to Buckingham (in [102]) is used. The Buckingham’s method is based upon the premise that if \( n \) dimensionless quantities, \( \Pi_1, \Pi_2, \Pi_3, \ldots, \Pi_n \), are involved in a certain physical phenomenon, their mutual dependence may be expressed as a power product of the following type:

\[
\Pi_1 = k_1 \cdot \Pi_2^{k_2} \cdot \Pi_3^{k_3} \ldots \cdot \Pi_n^{k_n}
\]  

(5-25)

where the \( k_i \) are dimensionless constants.

In Eq. 5-25, \( \Pi_1 \) is the quantity of principal interest. The other \( \Pi \)'s include all the variables known to influence the particular phenomenon. Therefore, the dimensionless groups which might describe the entrainment mechanism will be discussed in the following paragraphs.

First, the stability of a droplet can be characterised by the Weber number (Eq. 5-26), which describes the ratio of the inertia force to the surface tension force.

\[
We_{\text{cont}} = \frac{j_{g,\text{cont}}^2 \cdot D_{\text{cont}} \cdot \rho_1}{\sigma}
\]  

(5-26)
Furthermore, the sedimentation behaviour of the entrained droplets can be described by the Froude number. This number represents the ratio of inertia to gravity forces:

\[ Fr_{cont} = \frac{j_{g, cont}}{g \cdot D_{cont}} \]  (5-27)

In Eq. 5-26 and Eq. 5-27, the diameter of the containment is used as characteristic length. The superficial velocity, \( j_{g, cont} \), is calculated by dividing the measured condensate and air flow in the venting pipe by the cross section of the containment and by the homogeneous gas density. The latter is given by Eq. 5-28:

\[ \frac{1}{\rho_{hom}} = \frac{x_{ncg}}{\rho_{ncg}} + \frac{1-x_{ncg}}{\rho_v} \]  (5-28)

Müller [96] suggested for the description of the following type:

\[ x_{Cond} = k_1 \cdot x_{BP} \cdot We_{cont}^{k_3} \cdot Fr_{cont}^{k_4} \]  (5-29)

where \( x_{Cond} \) resp. \( x_{BP} \) are the model substances concentration in [g/kg].

In order to take into account the effects of the free convection in the containment atmosphere, Eq. 5-29 is completed by the Rayleigh number.

\[ Ra = \frac{H^3 \cdot g \cdot \beta \cdot \Delta T \cdot \rho_{hom}^{2}}{\mu_{hom}^{2}} \cdot Pr \]  (5-30)

whereby the homogenous viscosity is defined as:

\[ \mu_{hom} = \gamma_{ncg} \cdot \mu_{ncg} + (1-\gamma_{ncg}) \cdot \mu_v \]  (5-31)

The characteristic height, \( H \), is the distance from the surface of the boiling pool to the top of the containment and depends on the pool volume. The term \( \Delta T \) is defined as the difference between the sump tem-
perature \( (T_2 \text{ in Fig. 3-2}) \) and the containment temperature \( (T_1 \text{ in Fig. 3-2}) \).

The resulting equation for the determination of the concentration in the condensate is then:

\[
x_{\text{Cond}} = k_1 \cdot x_{BP}^{k_2} \cdot W_{e, \text{cont}}^{k_3} \cdot F_{r, \text{cont}}^{k_4} \cdot (1 + Ra)^{k_5} \quad (5-32)
\]

For experiments with pure steam experiments, the sump and the containment temperatures are identical as the steam and the boiling pool are in thermodynamical equilibrium. Therefore, the expression \( 1 + Ra \) is used instead of \( Ra \) in order to avoid that the right hand of Eq. 5-32 disappears if there is no temperature difference in the containment atmosphere.

<table>
<thead>
<tr>
<th>soluble fission products</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_3 )</th>
<th>( k_4 )</th>
<th>( k_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.954E-09</td>
<td>0.3636</td>
<td>1.1968</td>
<td>-1.3057</td>
<td>-0.0216</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>solid fission products</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( k_3 )</th>
<th>( k_4 )</th>
<th>( k_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.095</td>
<td>0.000</td>
<td>-0.0997</td>
<td>0.0153</td>
<td>0.0060</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 5-2:** Coefficient \( k_i \) in the Eq. 5-32 for the prediction of the entrainment of soluble or solid fission product simulants.

The five coefficients \( k_i \) in Eq. 5-32 are determined by minimizing the differences between the measured entrainment factors \( E_{\text{meas}} = k_{as} \cdot x_{\text{cond, meas}} / x_{BP, \text{meas}} \) and the calculated entrainment factors \( E_{\text{fit}} = x_{\text{cond, fit}} / x_{BP, \text{meas}} \) with the method of the minimal squares.

As the entrainment mechanisms for soluble and non-soluble model substances are different (see Chapter 4), two sets of constants were determined. The results can be seen in Tab. 5-2 and are valid if the conditions given in Tab. 5-3 are fulfilled.

Note that for experiments with solid fission product simulants, the coefficient \( k_2 \) was set to zero, as the tracer concentration in the con-
TABLE 5-3: Range of application of Eq. 5-32. for soluble and solid model substances.

<table>
<thead>
<tr>
<th></th>
<th>Soluble model substances</th>
<th>Solid model substances</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sump concentration</strong></td>
<td>$3.8 \ g \leq x_{BP} \leq 11.7 \ g \ kg$</td>
<td>$0.2 \ g \leq x_{BP} \leq 4.9 \ g \ kg$</td>
</tr>
<tr>
<td><strong>Weber number</strong></td>
<td>$0.017 \leq W_{e_{cont}} \leq 0.400$</td>
<td>$0.016 \leq W_{e_{cont}} \leq 0.469$</td>
</tr>
<tr>
<td><strong>Froude number</strong></td>
<td>$4.42 \cdot 10^{-8} \leq F_{r_{cont}} \leq 1.11 \cdot 10^{-6}$</td>
<td>$4.15 \cdot 10^{-8} \leq F_{r_{cont}} \leq 1.31 \cdot 10^{-6}$</td>
</tr>
<tr>
<td><strong>Rayleigh number</strong></td>
<td>$0 \leq R_{a} \leq 2.34 \cdot 10^{11}$</td>
<td>$0 \leq R_{a} \leq 1.27 \cdot 10^{11}$</td>
</tr>
</tbody>
</table>

**Fig. 5-5:** Comparison of the calculated and measured entrainment factors for experiments with soluble tracer substances. (42 data points).
Experiments with solid model substances

Fig. 5-6: Comparison of the calculated and measured entrainment factors for experiments with solid tracer substances. (34 data points).

densate is not dependent on the bulk concentration in the boiling pool. Furthermore, although the coefficient $k_5$ is smaller than $k_3$ and $k_4$, this does not mean that the Rayleigh number is less important than the Weber and Froude numbers. But, as the Rayleigh number varies between zero at pure steam atmosphere and up to $10^{11}$ at air-steam atmosphere, the term $1 + Ra$ has to be damped for experiments with air-steam atmosphere.

In Fig. 5-5 and Fig. 5-6 the predicted entrainment factors, $$E_{fit} = \frac{x_{cond, fit}}{x_{BP, meas}}$$ and the measured entrainment factors $$E_{meas} = k_{as} \cdot \frac{x_{cond, meas}}{x_{BP, meas}}$$ are compared.

As Fig. 5-5 shows, there is a good agreement between the predictions and the measurements for experiments with soluble model substances.
The scattering on both sides of the 45° line has to be explained by the relative large standard deviations of the measured entrainment factors. As shown in Section 4.1.1, the standard deviation for experiments with identical conditions can vary up to 50%.

Fig. 5-6 shows also a good agreement between the model and the measurements with solid tracer substances. However, some points are wider scattered than for soluble model substances. This had to be expected as the entrainment range for experiments with solid FPS is much larger (from $E = 5.2 \cdot 10^{-5}$ to $E = 5.1 \cdot 10^{-4}$) than for experiments with soluble FPS (from $E = 4.0 \cdot 10^{-6}$ to $E = 7.1 \cdot 10^{-5}$).

In conclusion, the correlation given by Eq. 5-32 allows the scaling-up of the results obtained in the REVENT-facility on larger boiling pool as far as the following conditions are fulfilled:

- the pool and containment geometry of the model and of the full scale plant are similar,
- the removal of the containment atmosphere in the venting pipe happens in the deposition controlled region (see Section 5.2.1), and
- the Weber, Froude and Rayleigh numbers respect the limits given in Tab. 5-3.
6 Discussion

In this section, the results obtained in this work are compared to values given by other authors. As mentioned in Chapter 1, only a few experimental works on the entrainment of droplets were carried out under prototypical conditions of a severe nuclear accident and, in the same time, consider the entrainment above the momentum controlled region. Therefore, the following sections focus on the results of Bunz et al. [20], Garner et al. [49], Kudo et al. [82] and Müller [96]. A table comparing the different considered facilities is given in Appendix 8.1.

6.1 Preliminary remarks

The main difficulty in order to compare the different results is to find a common variable which is a) known or at least can be easily determined in all the facilities and b) which is representative for the entrainment process.

In this work, the superficial gas velocity was chosen as characteristic variable. Its relevance for the determination of the flow regime in the boiling pool, its influence on the sedimentation process in the containment atmosphere and its simple determination made this variable the most convenient to be used. However, we are aware that this variable does not describe such effects as the relative humidity, the viscosity and the natural convection.

Therefore, the following considerations serve mainly a qualitative comparison of the different works available in the literature. The main objective of this sections is to show the order of magnitude of the different results and possibly to indicate possible research directions for a more comprehensive understanding of the entrainment phenomena.

6.2 Experiments with solutions

Fig. 6-1 shows the entrainment factor for experiments with soluble substances as fission product simulants (FPS). Since the considered superficial velocities range from 0.0015 m/s up to 1.18 m/s, a double logarithmic scale has to be used.
Comparison of the entrainment factors for soluble model substances as a function of the pool superficial velocity based on data from this work and from Bunz et al. [20], Garner et al. [49], Kudo et al. [82] and Müller [96].
Although the entrainment factors of the different authors show slightly different trends, the entrainment factor increases with increasing gas velocity in the boiling pool. Especially, the results obtained by Garner et al. are strongly dependent on the gas velocity and show substantially higher values than the other authors. Indeed, the gas velocities prevailing by Garner (from 0.46 m/s up to 1.40 m/s) are much higher than those in the other works. Already for the lowest velocity of 0.46 m/s, the critical sedimentation diameter $d_{dr, crit}$ (see Eq. 4-3) is about 104 μm (compared to $d_{dr, crit} = 6.2 \mu m$ at 4 bar in the REVENT-facility). Therefore, the produced steam flow can entrain droplets with an inner volume almost 5000 times larger than those observed in this work. Furthermore, even at the lowest velocity occurring in the Garner's facility, the flow in the boiling pool is close to the upper limit of the bubbly regime. According to the criteria of Ishii (in [78]) or of Rozen et al. (in [78]), churn turbulent flow is even expected. In this regime, the gas flow builds channels through the liquid phase and ligaments are formed on the surface (see Fig. 6-2). The shear stress due to the

![Diagram](image)

**Fig. 6-2:** Detachment of droplets from a liquid ligament in the churn turbulent flow regime [78].

streaming gas detaches large droplets from the liquid which are carried out into the containment atmosphere. Therefore an increase of the entrainment is expected and could explain the entrainment factor in the order of $E \cong 10^{-3}$ observed for high velocities in Fig. 6-1.

The entrainment factors obtained for experiments with gas velocities between 0.1 cm/s and 10 cm/s are significantly lower than the values
obtained by Garner and lay between $E = 4 \cdot 10^{-6}$ and $E = 3 \cdot 10^{-4}$. At those velocities and for the pool geometry used in those experiments, bubbly flow prevails. Despite the large scattering for identical superficial velocities, the values obtained by one single author are usually spread within one order of magnitude.

The experiments carried out by Müller (pro memoriam, $P = 4$ bar, pure steam atmosphere) show a good agreement with the results obtained for the pure steam atmosphere experiments in this work. The slightly lower values obtained here can be explained by the geometry change in the pool of the REVENT facility. In Müller’s facility, there was only a very small gap between the heating plate and the containment wall (ca. 5 mm). The steam produced below the heating plate was therefore caught and large bubbles were built. These bubbles had to escape through the small interstice between the plate and the containment wall. Due to the shear stress resulting from the high flow velocities, the bubbles were torn and small bubbles were produced. For this work however, new optical windows were built in order to observe the bubble behaviour at the level of the heating plate. These windows provide additional room on the side of the plate through which the large bubbles from below the heating plate can pass without being disintegrated (see Fig. 6-3). The overpressure in these large bubbles ($d_b = 5\text{cm}$) is low and no jet droplets can be produced. In the same time, the steam flow used by the large bubbles lacks for the production of small bubbles ($V_b(d_b = 5\text{cm}) = 15000 \cdot V_b(d_b = 2\text{mm})$) and consequently, less droplets are produced leading to lower entrainment factors.

Furthermore, note that for the experiments of Bunz et al., the entrainment factor decreases with increasing gas velocity. In the REST facility, the higher gas velocities are obtained by increasing the heating power in the boiling pool. According to Bunz et al., the increase in heating power leads to a greater amount of large coalesced bubbles. As described above, the presence of such large bubbles leads to a reduced droplet production.

Eventually, as shown in Fig. 6-1, the results obtained by Bunz et al. in the REST facility and by Kudo et al. in the ALPHA facility are in the same order of magnitude as in the present work. This assessment is particularly important as the entrainment factors measured by these
two other authors were obtained in both, a smaller boiling pool (REST-experiments) and a larger boiling pool (ALPHA-experiments). The good agreement with those data makes the results presented in this work particularly suitable for the validation of thermal-hydraulic codes and constitute a useful database for scale-up considerations.

6.3 Experiments with suspensions

Fig. 6-4 shows the entrainment factors for experiments with solid substances as fission product simulants. Similar to Section 6.2, the entrainment increases with increasing superficial velocity.

However, although the gas velocities are in a much narrower range than in the previous section, the entrainment factors scatter much more for almost identical steam flow than this was the case for soluble substances. The factors vary between \( E = 5 \cdot 10^{-5} \) and \( E = 3 \cdot 10^{-3} \). Even by considering the different authors separately, the spreading of the measured entrainment factors is larger than for the experiments with soluble model substances.

Here too, the comparison between the values obtained by Müller with silicon carbide and the results presented in this work with alumina
Fig. 6-4: Comparison of the entrainment factors for solid model substances measured in this work and by Bunz et al. [20] and Müller [96] as a function of the superficial velocity in the pool.

shows a very good agreement. In both cases, the average entrainment factor is approximately $E \approx 3 \cdot 10^{-5}$. The larger scattering observed in this work is mainly due to the wider range of tracer concentration in the boiling pool. The width of this range is particularly evident in Fig. 6-4.

In Section 4.2.1, it was described that the tracer concentration in the containment atmosphere is not dependent on the bulk concentration in the boiling pool. The results from Müller and from Bunz et al. confirm this assumption. In Fig. 6-5, the solid lines correspond to the calculated entrainment factors obtained by setting a constant concentration in the condensate equal to the average condensate concentration of all the experiments of the considered series:

$$E = \frac{\langle C_{Cond} \rangle}{C_{BP}}$$

The resulting fit is unequivocal for all authors and all model substances. Undoubtedly, the concentration in the containment atmosphere does not depend on the bulk concentration of the boiling pool. Possible explanations for this phenomena were already discussed in Section 4.2.1.
Fig. 6-5: Comparison of the entrainment factors for solid model substances measured in this work and by Bunz et al. [20] and Müller [96] as a function of the solids concentration in the boiling pool. The solid lines correspond to the calculated entrainment by setting the condensate concentration equal to the average of the concentration in the condensate for the considered set of experiments. (See Eq. 6-1).

However, the concentration in the containment atmosphere differs for the various authors. The diverse average concentrations, $\langle C_{\text{cond}} \rangle$, which are statistically significantly different, are shown in Tab. 6-1. The reason for those different levels of concentration is not yet well understood and will be discussed here.

As suggested at the beginning of this section, it seems that an increasing superficial gas velocity leads to higher concentrations in the containment atmosphere. This is particularly evident if the results obtained by Bunz et al. (solid diamonds) are compared with the other authors in Fig. 6-5. This assumption is also confirmed by the observations made in this work, where the measured entrainment of alumina for air-steam atmosphere (open triangles) is slightly higher than for pure steam atmosphere (solid triangles). As mentioned in Section 5.2.1, the steam flow in both, pure steam and air-steam experiments, is almost constant.
but the gas flow is enhanced by the supply of compressed air during
the air-steam experiments.

Furthermore, the lower entrainment factors obtained by Müller in
almost the same facility and for similar superficial velocities as in this
work are particularly interesting. Since these differences are statisti-
cally significant, this might indicate that the type of tracer substances
also plays an important role. Müller used two types of silicon carbide
particles. The first one had a mean diameter \( d_{50,3} \) of 0.98 \( \mu m \) and the
other one of 3.83 \( \mu m \).

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Remark} & \text{d}_{50,3} & \text{density} & \langle C_{\text{cond}} \rangle & \text{Stdev} \\
& [\mu m] & [\text{kg/m}^3] & [\text{mg/kg}] & [\text{mg/kg}] \\
\hline
\text{Bunz et al.} & \text{BaSO}_4 & - & 4300 & 3.3660 & 2.2653 \\
& \text{SiC} & 0.98 & 3200 & 0.0277 & 0.0143 \\
& \text{SiC} & 3.83 & 3200 & 0.0326 & 0.0101 \\
\text{Müller} & \text{Al}_2\text{O}_3, \text{pure steam} & 1.8 & 3950 & 0.0751 & 0.0404 \\
& \text{Al}_2\text{O}_3, \text{air-steam} & 1.8 & 3950 & 0.1855 & 0.1519 \\
\hline
\end{array}
\]

TABLE 6-1: Averages of the model substance concentration in the
condensate obtained by Bunz et al. [20], Müller [96] and in this
work.

However, the differences between the average concentrations \( \langle C_{\text{cond}} \rangle \)
obtained with the smaller or with the larger distribution are stochastical
(see Tab. 6-1). The particle diameter is therefore, at least in the consid-
ered diameter range, not a governing variable.

Furthermore, one could expect that silicon carbide particles with a
lower specific density should be more easily entrained than the alu-
mina particles. Obviously, as shown in Fig. 6-5, this is not the case as
the entrainment factors observed with silicon carbide are lower than
with alumina.

Eventually, the differences might be explained by different hydrophilic
behaviours of the solid particles. These could influence the collection
of the particles by the rising bubbles as well as the coagulation effects
at the gas-liquid interface. However, no data (e. g. surface tension, wet-
ting angle) for the investigated substances could be gathered up to now
in order to confirm this assumption.

Discussion
7 Conclusions and outlook

In this work, the entrainment of droplets from a boiling pool was determined in a pilot scale facility. The experiments were carried out under prototypical conditions of a severe core melt accident in a nuclear power plant and the measurements were made far above the surface of the boiling pool in the so-called deposition controlled region. The investigated boiling pool contained soluble fission product simulants (KI, CsI) or non-soluble fission product simulants (Al₂O₃).

7.1 Experiments with soluble fission product simulants

The experiments with soluble model substances showed neither an influence on the entrainment factor of the concentration of tracer material in the boiling pool nor of the water volume contained in the sump. However, the pressure in the model containment has a significant effect on the entrainment of water droplets. Depending on the composition of the atmosphere above the pool, different trends for the entrainment factors are observed by increasing containment pressure. On one hand, if the atmosphere is composed of air and steam as it were the case at the very beginning of a venting scenario, the entrainment factor decreases by increasing pressure. On the other hand, if the containment is only filled with pure water steam, as it were the case at the end of the containment venting, the trend is opposite and the entrainment factor increases by increasing pressure. Although the entrainment factors are similar at pressures of 2 bar, they differ in more than one order of magnitude at pressures of 6 bar.

It seems that those differences are due to a shift in the importance between the droplet production (source term) and droplet sedimentation (sink term) phenomena. In a containment with an air-steam atmosphere, the entrainment is mainly determined by the velocity of the gas flow above the boiling pool. In a pure steam atmosphere however, the gas velocity as well as the turbulence intensity are much lower than in an air-steam atmosphere. Consequently, the bubble behaviour in the boiling pool and therefore the droplet production becomes the governing parameter. In order to confirm this assumption, the distribution of
the bubble sizes in the boiling pool was measured for varying pool volumes and at different operating pressures. Although no significant difference could be notice, it was observed that the mean bubble diameter is close to 2 mm. As shown in [15] and [108], there is a sharp peak in the droplet production for bursting bubble having a diameter in this range. Therefore, a slight shift in the bubble size distribution, which is not measurable in this work, might lead to considerable changes in the droplet production. The consequences of this shift is important enough to dominate the effects due to varying gas velocities above the pool.

Furthermore, the results obtained in this work are in good agreement with those given in the literature for comparable operative conditions. At similar superficial gas velocities in the boiling pool, the entrainment factors are in the same order of magnitude. If the boiling pool is in the bubbly flow regime, the mean entrainment factor is approximately $\langle E \rangle \approx 3 \cdot 10^{-5}$ and the maximal measured value is $E = 1.5 \cdot 10^{-4}$. Note, that the source term calculation in the Deutsche Risiko Studie B, [51], assumed an entrainment factor of $E = 1 \cdot 10^{-4}$ and was therefore rather too conservative in its estimations. In the churn turbulent flow regime however, as shown by Garner et al. [49], the entrainment factor is one order of magnitude higher than in the bubbly flow regime.

Eventually, even if the water of the boiling pool comes to be totally evaporated, the resulting stronger sparkling occurring shortly before the heating plate is no more covered by water has no influence on the entrainment factor. However, due to the continuous evaporation of the sump water, the concentration of soluble substances in the boiling pool is increased and leads to higher concentrations in the produced droplets, even if the entrainment rate remains constant.

### 7.2 Experiments with solid fission product simulants

Unlike in the preceding section, the experiments carried out with solid fission product simulants show no significant influence of the containment pressure on the entrainment factor. Furthermore, it was observed that the concentration of tracer substances in the containment atmosphere is not dependent on the bulk concentration in the boiling pool. Similar effects and entrainment rates could be observed by other...
authors [20], [96]. However, the reasons for these constant concentrations are not well understood. Three possible causes might be at the origin of this phenomenon:

- the concentration very close to the gas-liquid interface remains constant, independently from the bulk concentration in the boiling pool,
- the break-up mechanism of a bubble at the pool surface is affected by the presence of particles,
- the sedimentation mechanisms in the containment atmosphere are influenced by the presence of particles in the droplets.

Furthermore, the concentration of solid particles in the containment atmosphere varies for different experimental set-ups and for different substances. A comparison with the results of Bunz et al. [20] and Müller [96] shows that the concentration in the containment atmosphere increases by increasing superficial gas velocity in the boiling pool. Furthermore, there are indices that the hydrophilic behaviour of the solid particles also plays an important role on the entrainment factor.

### 7.3 Recommendations

The results obtained in this work for soluble and solid fission product simulants are in good agreement with literature data and this for entrainment factors measured in both, smaller boiling pool (REST-experiments, [20]) and larger boiling pool (ALPHA-experiments, [82]). Therefore, the results presented in this work are particularly suitable for the validation of thermal-hydraulic codes and constitute a useful database for scale-up considerations.

In the latter case, the semi-empirical model of Kataoka [78] gives a very satisfying estimation of the entrainment of soluble model substances in an air-steam atmosphere. In pure steam atmosphere however, the order of magnitude of the entrainment is fairly well predicted but the effect of pressure is not described correctly. Furthermore, using the mean bubble diameter measured in this work as input value, the deterministic model of Müller [96] overestimates by more than one order of magnitude the entrainment factor and is therefore not appropriate for systems such as the REVENT facility. On the other hand, the
**7.4 Outlook**

In this work, the influences of macroscopic parameters such as the containment pressure, the composition of the atmosphere, the pool volume or the type of tracer substances have been investigated. In this task, the entrainment factor was determined with the integral method described in Section 2.7.2. This method has proved to be appropriate in order to scan the most influent parameters and to reveal the phenomena which are dominant in the entrainment process. However, a further understanding of this process requires the investigation of microscopic phenomena such as the course of the bubble burst, the production of jet and film droplets and the enrichment of solid particles in the ejected droplets.

At this point however, the integral method have reached the edge of the technical possibilities. First, the long measuring chain consisting of the droplet production at the pool surface, the transport of the aerosols through the venting pipe and the condenser and eventually, the collection of samples in polyethylene containers is a large source of uncertainty. Deposition effects in the sampling path can be hardly controlled nor estimated. Furthermore, the large difference in scale between the investigated object \( (d_{dr} \approx 3\mu m) \) and its surrounding system \( (D_{cont} = 1.5m) \) stretches over six orders of magnitude for the length scale and eighteen orders of magnitude for the volume scale! Despite a particularly careful handling, taking samples under such conditions is a formidable and sensitive operation which inevitably leads to important measurement variations. Finally, the particularly low concentrations in the condensate in the range of 0.1 ppm for both, soluble and solid model substances, are at the lower limit of the measurement capacity.

*semi-empirical* model of Müller [96] based on the dimensionless Froude and Weber numbers was adapted in this work with a correction term containing the Rayleigh number in order to consider the effects of free convection (see Eq. 5-31). This enhanced model gives fully satisfying results for the determination of the entrainment factor in both, air-steam and pure steam atmospheres. Using different set of constants in Eq. 5-31, this new correlation enables the prediction of the entrainment of soluble substances as well as solid particles.
Therefore, time and local resolved measurement methods are required for further research of the entrainment phenomenon.

Two major areas should be especially further investigated.

First, the droplet production (source term) and the sedimentation processes in the containment atmosphere (sink term) have to be closer studied under prototypical conditions of a severe accident in a nuclear power plant. For such conditions, there is still a lack of knowledge on the droplet ejection height and ejection velocity in the region close to the boiling surface, the so called momentum controlled region. Possible means to get this information \textit{in situ} in a pilot plant facility are Phase Doppler Anemometry (PDA) or light sheet techniques. In contrast to PDA, which provides only information in a tiny measurement volume, the light sheet techniques have the valuable advantage to enable instantaneous measurements of a full velocity flow field. With such a technique, the flow pattern but also the large scale vortexes can be measured as well close as high above the air-liquid interface. Such measurements would deliver valuable information for the determination of the transport and sedimentation phenomena.

A second field of investigation should aim at a better understanding of the entrainment of solid particles. Although comprehensive researches with soluble substances have been done, there is a profound lack of knowledge on the entrainment processes of non-soluble particles. Especially, a better understanding of the causes of the enrichment factor (higher particle concentration in the droplets than in the bulk of the boiling pool) is strongly needed. Furthermore, the origin of the constant particle concentration in the containment, independently from the particle concentration in the pool, has to be investigated. Therefore, experiments with clearly defined boundary conditions such as bubble size, bubble production rate and particle distribution have to be carried out. The influence of parameters such as the diameter, the density and the hydrophilic behaviour of the particles but also the effects of the liquid and bubble properties should be investigated separately in a laboratory scale facility before other experiments are carried out under conditions comparable to those prevailing in a severe core melt accident.
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## 8 Appendix

### 8.1 Comparison of the set-ups of entrainment experiments

Tab. 8-1 gives a comparison of the main dimensions of the facilities used by Bunz et al. (REST-Program, [20]), Garner et al. [49], Kudo et al. (ALPHA-Program, [82]) and Müller (REVENT-program, [96]). The type and concentrations of the tracer substances are also presented as well as the average entrainment factor $\langle E \rangle$.

<table>
<thead>
<tr>
<th>Facility</th>
<th>$H_{\text{cont}}$ [m]</th>
<th>$D_{\text{cont}}$ [m]</th>
<th>$V_{\text{cont}}$ [m$^3$]</th>
<th>$H_{\text{BP}}$ [m]</th>
<th>$D_{\text{BP}}$ [m]</th>
<th>$V_{\text{BP}}$ [litre]</th>
<th>$P$ [bar]</th>
<th>Tracer</th>
<th>$C_{\text{BP}}$ [g/l]</th>
<th>$\langle E \rangle$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA [82]</td>
<td>5.70</td>
<td>3.9</td>
<td>50.0</td>
<td>2.0</td>
<td>1.00</td>
<td>400-800</td>
<td>1-15</td>
<td>Na$_2$SO$_4$</td>
<td>70.3</td>
<td>9.2E-05</td>
</tr>
<tr>
<td>Garner [49]</td>
<td>1.37</td>
<td>0.3</td>
<td>0.53</td>
<td>0.61</td>
<td>0.305</td>
<td>45</td>
<td>1</td>
<td>KNO$_3$</td>
<td>0-165</td>
<td>6.35E-04</td>
</tr>
<tr>
<td>REST [20]</td>
<td>1.50</td>
<td>1.5</td>
<td>3.7</td>
<td>0.14</td>
<td>0.108</td>
<td>1.3</td>
<td>1</td>
<td>Fluorescine</td>
<td>3-30</td>
<td>4.66E-05</td>
</tr>
<tr>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>BaSO$_4$</td>
<td>3-30</td>
<td>5.6E-04</td>
</tr>
<tr>
<td>REVENT [96]</td>
<td>3.00</td>
<td>1.5</td>
<td>5</td>
<td>0.5-0.8</td>
<td>0.6-1.5</td>
<td>135-370</td>
<td>4</td>
<td>Na$_2$SO$_4$</td>
<td>1.6-7.7</td>
<td>8.86E-05</td>
</tr>
<tr>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>KI</td>
<td>3.0-8.2</td>
<td>6.69E-05</td>
</tr>
<tr>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>CsI</td>
<td>1.6-7.2</td>
<td>5.18E-05</td>
</tr>
<tr>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>SiC</td>
<td>0.8-2.4</td>
<td>2.09E-05</td>
</tr>
<tr>
<td>This work</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>KI</td>
<td>3.8-9.2</td>
<td>1.88E-05</td>
</tr>
<tr>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>CsI</td>
<td>4.5-11.7</td>
<td>2.04E-05</td>
</tr>
<tr>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Al$_2$O$_3$</td>
<td>0.2-4.9</td>
<td>8.88E-05</td>
</tr>
</tbody>
</table>

TABLE 8-1: Comparison of the geometry of the different facilities for the determination of the entrainment factor in the deposition controlled region and under conditions comparable to those prevailing during a severe core melt accident.
8.2 The Student-distribution for the interpretation of two sample means

Consider two samples which are characterised by the parameter $x$. By measuring $n_1$, resp. $n_2$ times $x$ in both samples, the mean value, $\langle x_1 \rangle$ and $\langle x_2 \rangle$, with the corresponding standard deviations, $s_1$ and $s_2$ are calculated. Assuming that the variance of the two measurements are identical, a two-sided t-test can be used in order to determine if the two sample means are different.

Therefore, the test statistic $t$ is defined:

$$ t = \left| \frac{\langle x_1 \rangle - \langle x_2 \rangle}{s_d} \right| \cdot \sqrt{\frac{n_1 \cdot n_2}{n_1 + n_2}}, \quad (8-1) $$

where $s_d$ is given by:

$$ s_d = \sqrt{\frac{(n_1 - 1) \cdot s_1^2 + (n_2 - 1) \cdot s_2^2}{n_1 + n_2 - 2}} \quad (8-2) $$

The test statistic is compared with the $t$-distribution of Student, $\Phi_t\left(1 - \frac{\alpha}{2}, df\right)$, with a level of significance of $\alpha/2$ (two-sided test). The degree of freedom is $df = n_1 + n_2 - 2$.

In this work, the rules suggested by Dinkloh et al., [44], were used to describe the sample means differences:

$$ t < \Phi_t\left(1 - \frac{0.05}{2}, df\right) \quad \text{the difference is stochastical,} $$

$$ t < \Phi_t\left(1 - \frac{0.01}{2}, df\right) \quad \text{the difference is likely,} $$

$$ t < \Phi_t\left(1 - \frac{0.001}{2}, df\right) \quad \text{the difference is significant and} $$

$$ t < \Phi_t\left(1 - \frac{0.0001}{2}, df\right) \quad \text{the difference is highly significant.} $$
8.3 Backward transform from a bubble chord length to a bubble diameter distribution

The following FORTRAN-program transforms a chord length distribution into a diameter distribution according to the method described by Clark et al. [32].

Before executing the program, an input file with the name "chordist.txt" must be created in the program directory. This file stores all the chord lengths and its first line must be an integer describing the size of the sample. For example, if the set of data contains 1017 chord lengths, the first line of the input file, "chordist.txt" must be 1017.

After running the program, both, the chord length and the diameter distributions are stored in the output file "result.txt". Make sure that this output file does not exist in the directory where the program is executed, otherwise running errors occur.

Currently, the number of divisions of both distributions is set to twelve. This can be adapted by changing the variable "ndv" in the program and by re-compiling it.

```
parameter (cmx=10000)
parameter (ndv=12)
integer ntfans
integer i
real pdch(ndv),b(ndv),raw(cmx), maxch, minch, delx, delr,tem,chord
```
open(unit=7, file='chordist.txt', status='old')
rewind(7)
read(7,*) ntl
maxch = 0.0
minch = 100000.0
do 10 i = 1, ntl, 1
   read(7,*) raw(i)
   if(raw(i).gt.maxch) maxch = raw(i)
   if(raw(i).lt.minch) minch = raw(i)
10 continue
close(7)
call diam(rmax, rmin, maxch, minch, delx, delr, ndv, cmx, ntl, b, raw, pdch)

open(unit=8, file='result.txt', status='new')
rewind(8)
write(8,*) "Chord_Length Distribution"
   tem = 0.00000
   do 20 i = 1, ndv
      tem = tem + b(i)*2*delr
20 continue

chord = minch - delx/2
   do 25 i = 1, ndv
      chord = chord + delx
   write(8,*) chord, pdch(i)
25 continue

write(8,*) "Diameter Distribution"
da = 2*rmin-delr
   do 30 i = 1, ndv
      da = da+2*delr
   write(8,*) da, b(i)/tem
30 continue
adia = adia/tem
stop
end

******************************************************************************
** This subroutine is for preparing the chord length distribution
** function and the matrix of multiplication. Within this subroutine,
** gaussj is called for inverse the coef(i,i) for computing the bubble
** diameter distribution.
** b(i) ------ the chord length distribution before gaussj is called,
** it converted to diameter distribution after returned
** from gaussj
** coef(i,i) - is the coefficient matrix of conversion.
******************************************************************************
subroutine diam(rmax, rmin, xcmx, xcmn, delx,
+ delr, ndv, cmx, ntl, b, raw, pdch

integer ntl, iend, cmx
integer ndv
real delr, delx, xcmx, xcmn, alpha, Q, tem, rad, ym, yn, count
real rmax, rmin, coef(50, 50), b(ndv), raw(cmx), pdch(ndv)
integer i, k

data alpha/1.000/
data Q/1.0E0/
delx = (xcmx - xcmn) / real(ndv) ! neu
delr = delx / (alpha * (1 + Q))
rmax = xcmx / (alpha * (1 + Q))
rmin = rmax - delr * real(ndv)
iend = ntl
do 50 i = ljend
    tem = raw(i) - xcmn
    k = int(tem / delx) + 1
    if(k.le.ndv) b(k) = b(k) + 1.000
50 continue

count = 0.0e0
do 60 i = 1, ndv
    pdch(i) = b(i) / ntl / delx
    count = count + b(i)
    ym = xcmn + float(i - 1) * delx
    yn = xcmn + float(i) * delx
    tem = yn * yn - ym * ym
    do 70 j = i, ndv
        rad = rmin + float(j - 1) * delr
        coef(i, j) = tcm / (rad * rad)
    70 continue
60 continue

do 80 i = 1, ndv
    b(i) = b(i) / count
    call gaussj(coef, ndv, b)
80 continue

subroutine gaussj(a, n, b)
parameter (NMAX=50)
integer*2 n
integer icol, i, j, k, ll, indxc(NMAX), indxr (NMAX), ipiv(NMAX)
real a(50, 50), b(50)
real big, dum, pivinv

** The integer arrays ipiv, indrr, and indrc are used for bookkeeping on the pivoting.
*********************************************************************
* Linear equation solution by Gauss-Jordan elimination,
* equation (2.1.1) above. a(1:n, 1:n) is an input matrix stored
* in an array of physical dimensions np by np. b(1:n, 1:m) is

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an input matrix containing the m right-hand side vectors,
stored in an array of physical dimension np by mp. On output,
a(l:n,l:n) is replaced by its matrix inverse, and b(l:n,l:m)
is replaced by the corresponding set of solution vectors
Parameter: NMAl is the largest anticipated value of n.

```
do 11 j=l,n
   ipiv(j)=0
11 continue

********** This is the main loop over the columns to be reduced**********
do 22 ni=l,n
   big=0.

********** -p^jg js me outer loop of search for a pivot element**********
do 13 j=l,n
   if(ipiv(j).ne.1)then
      do 12 k=l,n
         if (ipiv(k).eq.0) then
            if (abs(a(j,k)).ge.big) then
               big=abs(a(j,k))
               irow=j
               icol=k
            endif
         else if (ipiv(k).gt.1) then
            pause 'singular matrix in gaussj'
         endif
      12 continue
   endif
   ipiv(icol)=ipiv(icol)+1
   if (irow.ne.icol) then
      do 14 i=1,n
         dum=a(irow,l)
         a(irow,l)=a(icol,l)
         a(icol,l)=dum
      14 continue
      dum=b(irow)
      b(irow)=b(icol)
      b(icol)=dum
```

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endif
 indxr(i)=irow

****** We are now ready to divide the pivot row by the pivot
 indxc(i)=icol

****** element located at irow and icol
 if(a(icol,icol).eq.0) pause'singular matrix in gaussj'
 pivinv=1./a(icol,icol)
 a(icol,icol)=1.
 do 16 l=1,n
 a(icol,l)=a(icol,l)*pivinv
 16 continue
 b(icol)=b(icol)*pivinv

* Next, we reduce the rows.. except for the pivot one, of course.

* This is the end of the main loop over columns of the reduction.
* It only remains to unscramble the solution in view
* of the column interchanges. We do this by in-
* interchanging pairs of columns in the reverse order
* that the permutation was built up.

do 21 l=1,n
 if((l ne icol).then
   dum=a(l,icol)
   a(l,icol)=0.
 do 18 l=1,n
   a(l,l)=a(l,l)-a(icol,l)*dum
 18 continue
 b(l)=b(l)-b(icol)*dum
 19 continue
 endif
 21 continue
 22 continue

* (C) Copr. 1986-92 Numerical Recipes Software !+iS")+),c
8.4 Experimental data

In the following section, the main data of the experiments carried out in this work are sorted by the type of tracer substances (soluble salts or solid particles) and by the kind of atmosphere prevailing above the boiling pool (pure steam vs. air-steam atmosphere).

Each experiment is listed twice. In a first table, the controllable parameters such as the operation pressure $P$, the pool volume $V_{BP}$, the heat removed with the cooling coil $Q_{cool}$, etc. are given together with the corresponding concentration in the containment atmosphere and with the average entrainment factor.

In a second table, resulting parameters such as the temperatures in the boiling pool and in the atmosphere as well as the dimensionless numbers used in the semi-empirical model (see Eq. 5-31) are listed.
### 8.4.1 Experiments with soluble model substances and pure steam atmosphere

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<tr>
<th>Exp.</th>
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<th>( P ) [bar]</th>
<th>( V_{BP} ) [litre]</th>
<th>( \dot{Q}_{\text{cool}} ) [kW]</th>
<th>( \dot{m}_{\text{cond}} ) [g/s]</th>
<th>( \dot{m}_{\text{air}} ) [g/s]</th>
<th>( \dot{w}_{\text{air}} ) [kg/kg]</th>
<th>( C_{BP} ) [g/l]</th>
<th>( \text{Std dev} )</th>
<th>( C_{\text{cond}} ) [mg/l]</th>
<th>( \text{Std dev} )</th>
<th>( E = k_{\text{as}} \cdot \frac{C_{\text{cond}}}{C_{BP}} ) [kg/kg]</th>
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**TABLE 8-2**: Experiments with soluble model substances and pure steam atmosphere: controllable parameters.
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<th>$\dot{m}_{\text{cond}}$ [g/s]</th>
<th>$\dot{m}_{\text{air}}$ [g/s]</th>
<th>$w_{\text{air}}$ [kg/kg]</th>
<th>$C_{BP}$ [g/l]</th>
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<th>$\text{StdDev}_{\text{C,c,o n d}}$ [mg/l]</th>
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TABLE 8-2: Experiments with soluble model substances and pure steam atmosphere: controllable parameters.
<table>
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<th>Exp.</th>
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<th>$T_2$ [°C]</th>
<th>$T_3$ [°C]</th>
<th>$T_4$ [°C]</th>
<th>$T_{HP}$ [°C]</th>
<th>$T_{cool, in}$ [°C]</th>
<th>$T_{cool, in}$ [°C]</th>
<th>$\varepsilon$ [-]</th>
<th>$M_{filter}$ [kg]</th>
<th>$j_{g, pool}$ [cm/s]</th>
<th>$j_{g, cont}$ [cm/s]</th>
<th>$W_{e_{cont}}$ [-]</th>
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**TABLE 8-3:** Experiments with soluble model substances and pure steam atmosphere: resulting parameters.
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<th>$T_3$ [°C]</th>
<th>$T_4$ [°C]</th>
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<th>$T_{cool, in}$ [°C]</th>
<th>$T_{cool, in}$ [°C]</th>
<th>$\varepsilon$</th>
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<th>$j_{g, pool}$ [cm/s]</th>
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TABLE 8-3: Experiments with soluble model substances and pure steam atmosphere: resulting parameters.
### 8.4.2 Experiments with soluble model substances and air-steam atmosphere

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<th>$\dot{m}_{air}$ [g/s]</th>
<th>$w_{air}$ [kg/kg]</th>
<th>$C_{BP}$ [g/kg]</th>
<th>$Stdev_{C_{BP}}$ [mg/l]</th>
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**TABLE 8-4**: Experiments with soluble model substances and air-steam atmosphere: controllable parameters.
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<th>$T_{cool,in}$ [°C]</th>
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<th>$j_{g, cont}$ [cm/s]</th>
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**TABLE 8-5:** Experiments with soluble model substances and air steam atmosphere: resulting parameters.
### 8.4.3 Experiments with solid model substances and pure steam atmosphere

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<th>( \dot{m}_{cond} ) [g/s]</th>
<th>( \dot{m}_{air} ) [g/s]</th>
<th>( w_{air} ) [g/kg]</th>
<th>( C_{BP} ) [g/l]</th>
<th>( Stdev ) [g/kg]</th>
<th>( C_{cond} ) [mg/l]</th>
<th>( Stdev ) [mg/l]</th>
<th>( E = k_{as} \cdot C_{cond} / C_{BP} ) [kg/kg]</th>
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**TABLE 8-6: Experiments with solid model substances and pure steam atmosphere: controllable parameters.**
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<tr>
<th>Exp.</th>
<th>Tracer</th>
<th>$P$ [bar]</th>
<th>$V_{BP}$ [litre]</th>
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<th>$\dot{m}_{\text{cond}}$ [g/s]</th>
<th>$\dot{m}_{\text{air}}$ [g/s]</th>
<th>$w_{\text{air}}$ [kg/kg]</th>
<th>$C_{BP}$ [g/l]</th>
<th>$\text{Stdev}<em>{C</em>{BP}}$ [mg/l]</th>
<th>$C_{\text{cond}}$ [mg/l]</th>
<th>$\text{Stdev}<em>{C</em>{\text{cond}}}$ [mg/l]</th>
<th>$E = k_{as} \cdot C_{\text{cond}} / C_{BP}$ [kg/kg]</th>
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<td>0.17</td>
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**TABLE 8-6**: Experiments with solid model substances and pure steam atmosphere: controllable parameters.
<table>
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<tr>
<th>Exp.</th>
<th>$T_1$ [°C]</th>
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<th>$T_4$ [°C]</th>
<th>$T_{HP}$ [°C]</th>
<th>$T_{cool,in}$ [°C]</th>
<th>$T_{cool,in}$ [°C]</th>
<th>$\varepsilon$ [-]</th>
<th>$M_{\text{filter}}$ [kg]</th>
<th>$j_{g,\text{pool}}$ [cm/s]</th>
<th>$j_{g,\text{cont}}$ [cm/s]</th>
<th>$We_{\text{cont}}$ [-]</th>
<th>$Fr_{\text{cont}}$ [-]</th>
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**TABLE 8-7:** Experiments with solid model substances and pure steam atmosphere: resulting parameters.
### 8.4.4 Experiments with solid model substances and air-steam atmosphere

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<tr>
<th>Exp.</th>
<th>Tracer</th>
<th>$P$ [bar]</th>
<th>$V_{BP}$ [litre]</th>
<th>$Q_{cool}$ [kW]</th>
<th>$m_{cond}$ [g/s]</th>
<th>$m_{air}$ [g/s]</th>
<th>$w_{air}$ [kg/kg]</th>
<th>$C_{BP}$ [g/l]</th>
<th>$Stdev$</th>
<th>$C_{cond}$ [mg/l]</th>
<th>$Stdev$</th>
<th>$E = k_{as} \cdot C_{cond}/C_{BP}$ [kg/kg]</th>
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**TABLE 8-8:** Experiments with solid model substances and air-steam atmosphere: controllable parameters.
<table>
<thead>
<tr>
<th>Exp.</th>
<th>Tracer</th>
<th>P [bar]</th>
<th>$V_{BP}$ [litre]</th>
<th>$Q_{cool}$ [kW]</th>
<th>$\dot{m}_{cond}$ [g/s]</th>
<th>$\dot{m}_{air}$ [g/s]</th>
<th>$w_{air}$ [kg/kg]</th>
<th>$C_{BP}$ [g/l]</th>
<th>Std $C_{BP}$ [g/kg]</th>
<th>$C_{cond}$ [mg/l]</th>
<th>Std $C_{cond}$ [mg/l]</th>
<th>$E = k_{as} \cdot C_{cond}/C_{BP}$ [kg/kg]</th>
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**TABLE 8-8:** Experiments with solid model substances and air-steam atmosphere: controllable parameters.
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<th>$T_4$ [°C]</th>
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<th>$T_{cool,in}$ [°C]</th>
<th>$T_{cool, in}$ [°C]</th>
<th>$\epsilon$ [-]</th>
<th>$M_{filter}$ [kg]</th>
<th>$j_{g, pool}$ [cm/s]</th>
<th>$j_{g, cont}$ [cm/s]</th>
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**TABLE 8-9: Experiments with solid model substances and air steam atmosphere: resulting parameters.**
8.5 References


Chapter 8 Appendix


Chapter 8

Appendix


ment: the mechanism of drop formation from gas or vapour bubbles.”,
244-261, 1954.

convection heat transfer in molten metal layer.”, Report
HMTR.ZZ.96, Royal Institute of Technology (KTH), Div. of Nuclear

[99] Parker, J.; Boggs, J.; Edward, E.: “Introduction to fluid mechanics and
heat transfer.”, Addison-Wesley Publishing Company, 2nd edition,
1970.

[100] Peebles, F. N.; Garber, H. J.: “Studies on the motion of gas bubbles in
liquids.”, Chemical Engineering Progress, Vol. 49, No. 2, pp. 88-97,
1953.


from the power burst facility severe fuel damage test 1-4: a simulated
severe fuel damage accident with irradiated fuel rods and control

[104] Powers, D. A.; Bradley, D. R.; Brockmann, J. E.; Copus, E. R.; Green,
G. A.; Burson, S. B.: “Validation of core debris/concrete interactions
and source term models.”, Fission product transport processes in reactor

[105] Prohaska, G: “Containment filtered Venting- The Situation in Swit¬
zeland.”, Proceedings of the 2nd International Conference on Con¬

[106] Rahn, F. J.: “Summary of the LWR aerosol containment experiments


[108] Resch, F.; Afeti, G: “Submicron film drop production by bubbles in
seawater.”, Journal of Geophysical Research, Vol. 97, No. C3,


[134] Toba, Y.: “Drop production by bursting air bubbles on the sea sur-
face.”, The Journal of the Oceanographical Society of Japan, Vol. 15,
pp. 121-130, 1959.


1969.

[137] Wangwongwatana, S.; Scarpino, P. V.; Willeke, K.; Baron, P. A.:
“System for characterizing aerosols from bubbling liquids.”, Aerosol

stiegsgeschwindigkeit in einer Blasensäule eines Wasser-Luft-Gemis-
ches in Abhaengigkeit vom Luftmassenstrom und von der Hoehe.”,
MitteIlung Nr. 94, Institut für Wasserbau und Wasserwirtschaft -
TU Berlin; 1980.

dows.”, version 1.25, Shareware, The University of Texas Health
Science Center, 1996.

fer and bubble size in a bubble column under pressure.”, Chemical

[141] Williams, M.; Loyalka, S.:” Aerosol science: theory and practice with
special applications to the nuclear industry”, 1st edition, Pergamon

of instantaneous photography.”, Philosophical Transaction of the

[143] Wu, J.: “Comment on ‘Film drop production as a function of bubble
size.’ by D. C. Blanchard and L. D. Sysdek”, Journal of Geophysical

neers: condensation, coagulation and dispersion.”, Power Co. Ltd.,
Tokyo, 1979.
8.6 Curriculum Vitae

Jérôme Olivier Cosandey

Date of birth: 18th September 1970
Place of birth: La Chaux-de-Fonds, Switzerland
Citizen of: Sassel, Switzerland


2/1997-9/1998 Post-grade education in "Risk and Safety" at the Swiss Federal Institutes of Lausanne (EPFL) and Zurich (ETH) as well as at the University of St.-Gallen (HSG).


10/1990-7/1995 Graduation as Dipl. Ing. ETH (M. Sc. degree) in the department of Mechanical and Process Engineering, Swiss Federal Institute, Zurich.


08/1982-07/1986 Secondary school, La Chaux-de-Fonds.

08/1977-08/1982 Primary school, La Chaux-de-Fonds.