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Author(s):
Seshadri, Bharath; Morroni, David; Hischier, Illias; Masania, Kunal; Schlüter, Arno

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Projected energy savings of a 3D printed selective heat transfer facade

B Seshadri[1], D Morroni[1], I Hischier[1], K Masania[2], A Schlueter[1]

[1] Architecture and Building Systems, ETH Zurich, Switzerland
[2] Shaping Matter Laboratory, Faculty of Aerospace Engineering, TU Delft, The Netherlands
seshadri@arch.ethz.ch, dmorroni@student.ethz.ch

Abstract. Dynamic building facades offer untapped potential for reducing building energy consumption and emissions. However, there is currently a lack of suitable technologies for bespoke components for new and retrofit applications. In previous work, we developed a 3D printed polymer facade component that selectively acts as a thermal conductor or insulator depending on outdoor and indoor conditions. Our experiments demonstrate that the element can achieve effective thermal conductivities as low as 0.03 W/mK and as high as 28 W/mK in insulating and conducting modes. In this work, we assess the potential impact of this technology on reducing heating and cooling energy demand. We conducted a parametric analysis of ten physical characteristics of the facade component. Then, we simulated the façade component employed in 270 building typologies and climate combinations. Our results indicate annual energy reduction of up to 80 kWh/m2 (heating) and 15 kWh/m2 (cooling) for building typology-climate combinations that can benefit the most from this technology.

1. Introduction

The global building stock accounts for 26% of total CO2 emissions, with heating and cooling energy demand contributing a significant portion. By 2040, today's buildings will account for 2/3 of the global building stock, highlighting the importance of optimizing building design to meet current and future energy needs [1]. While for existing buildings, various strategies to reduce energy consumption are employed, building envelopes often fall behind in addressing performance targets [2]. To address this, researchers and building practitioners have identified high-performance adaptive facade elements as a state-of-the-art solution to reduce CO2 emissions.

Digital fabrication workflows and robotic fabrication processes offer a potential means to design, realized and implement innovative facades in the buildings and construction industry [3]. In this research, we contribute to the growing body of work on the dynamic performance of facades. We developed a novel, recyclable polymer-based [4], 3d-printed facade component with selective heat transfer properties [5]. The passive façade component functions as a variable thermal conductivity thermosiphon without mechanical actuation, i.e., selectively acting as a thermal conductor and insulator depending on the outdoor and indoor conditions. The solution, aimed at both new buildings and retrofit applications, aims to speed up the decarbonization of the building sector by reducing its reliance on conventional HVAC systems, as well as reducing their growing complexity. We previously researched the fabrication, critical gas barrier, geometry, and performance testing of 3D printing thermosiphon components in building facades [5]. Here, we incorporate the dynamic thermal performance of a façade with variable thermal conductivity into a simulation matrix to (i) determine the ideal physical and design parameters of such a façade and (ii) the impact of this technology on the decarbonisation of the building sector.

2. A thermosiphon façade component for selective heat transfer

2.1. Working mechanism

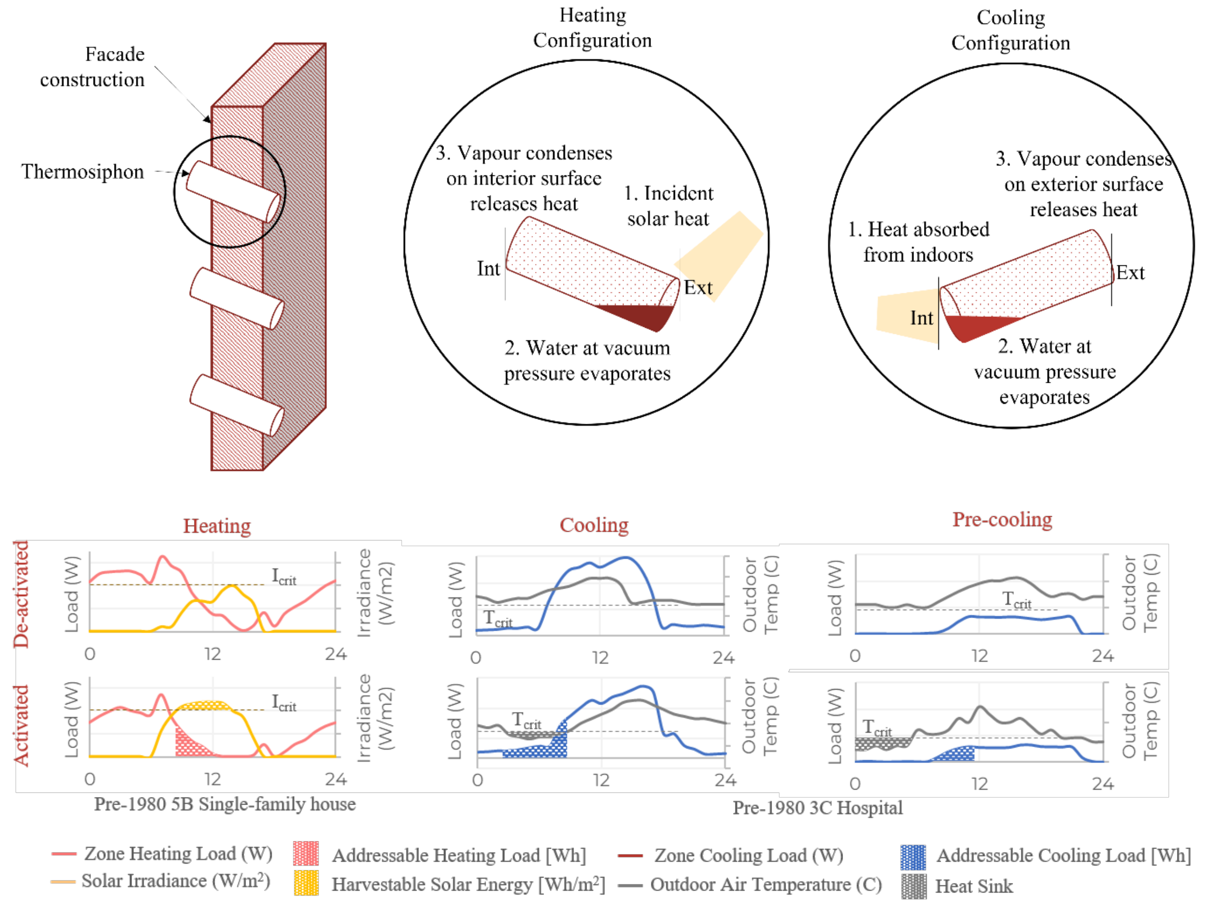

Figure 1. (Top) Construction of a selective heat transfer façade with embedded thermosiphons. The working mechanism in the heating- and cooling- configuration relies on the heat source and a working fluid's subsequent evaporation, flow, and condensation cycle. (Bottom) Simulated energy consumption saved by a selective heat transfer façade. In the heating configuration, when the solar irradiation is greater than I_{crit} (minimum power required to activate the thermosiphon), the façade is in its activated state and transfers the heat to the inside, thus reducing demand for indoor space heating. In the cooling- and pre-cooling- configurations, when the outdoor temperature drops below the indoor setpoint temperature (T_{crit}), the façade is in its activated state and dissipates heat indoors to outdoors hence reducing demand for indoor space cooling. In its deactivated state, the façade functions as an insulator.

A thermosiphon is an evacuated, hermetically sealed container with a small amount of working fluid (typically, water). Due to its orientation and gravity-assisted fluid-flow, it transfers heat in one direction while blocking it in the opposite direction [6]. In this research, we embedded thermosiphons in a façade component to create a thermal diode that selectively acts as a conductor or an insulator depending on the outdoor and indoor conditions. The construction and orientation of the façade determine its heating and cooling configurations.

In the heating configuration, the façade element absorbs solar radiation received on the exterior to heat the indoors while blocking heat loss from indoors to outdoors. When the solar irradiance on the façade reaches a critical value (Icrit), the thermosiphon conducts the heat indoors, reducing the heating load on the building's system. In the cooling configuration, the element rejects heat from indoors to the outdoors during periods of lower outdoor ambient conditions and blocks heat gain from outdoors to indoors when the ambient temperature is hotter. When the outdoor temperature drops below the indoor room temperature (Tcrit), the element conducts indoor heat to the outdoors, and when not, it functions as an insulator. Figure 1 depicts the construction of a façade component with embedded thermosiphons that can be engineered for heating and cooling configurations.

2.2. Experimental measurements of effective thermal conductivity

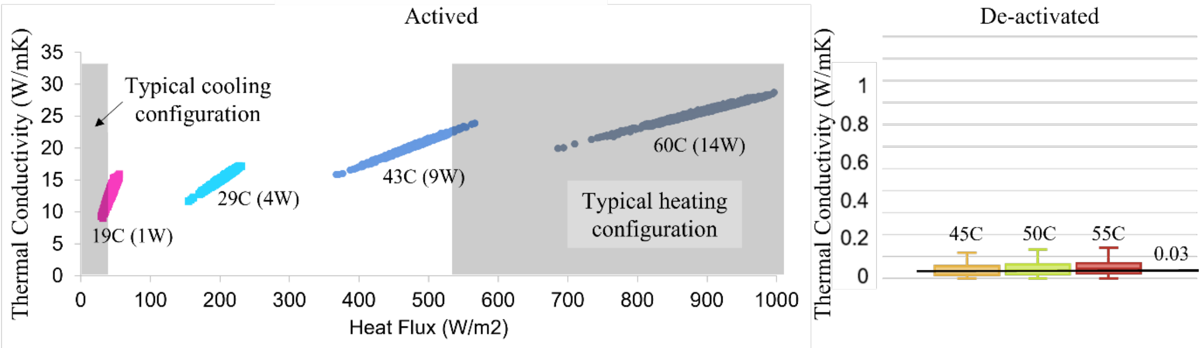

Figure 2. (Left) Effective thermal conductivities of a prototype polymer 3DP printed thermosiphon façade component when activated at various temperatures and input powers. (Right) Thermal conductivities at various temperature under de-activated mode.

We measured the effective thermal conductivity of a 3D printed Φ50mm, 200mm cylindrical thermosiphon façade component under different conditions. When 'activated' at 60^0C (14W), the effective thermal conductivity reached upto 28 W/mK. We de-activated i.e. no fluid is present at the evaporator, the thermosiphon retained an insulating thermal conductivity of a vacuum tube at 0.03 W/mK. We used an evacuated prototype to obtain the 'de-activated' values. A more accurate approach would be to test the activated prototype in reverse orientation. We used these empirical values for the simulation studies in the following section.

3. Simulation methodology

3.1. User-defined thermosiphon facade component

In our research, we have realized a thermosiphon façade component using the Energy Management System (EMS) sensors and actuators functionality in EnergyPlus [7]. The surface construction state actuator was used to represent the thermally conducting and insulating states. The resulting conductivities were area-averaged to the thermosiphon and base-material conductivities. A decision tree was executed at each time-step for each thermosiphon façade surface to switch between the two states. At the beginning of the decision tree, variables in the simulation were sensed at the time-step level, such as evaporator surface and condenser surface temperatures and heat flux. The first step in the decision tree checked if the corresponding zone predicted heating (or a cooling load in the cooling configuration). The surface construction was set to the insulating construction object if the corresponding thermal zone's expected load was zero. Otherwise, the second step of the decision tree was assessed. In this step, the surface temperature difference was calculated. The "on" conductive construction object was applied to the surface if the surface temperature difference would drive favorable heat transfer. Otherwise, the insulating construction object was used. The evaporator side was the exterior surface of the heating configuration, and the interior surface for the cooling configuration.

3.2. Modeling framework

To evaluate the efficacy of our thermosiphon façade component, we utilized a modeling matrix composed of various building types and climate zones obtained from the DoE Commercial Reference buildings and PNNL Residential Prototype buildings database [6]. We compared building models' ideal heating and cooling demands (as represented by the IdealAirLoadsHVAC metric in EnergyPlus) with and without the façade component. Our analysis did not include HVAC systems and control components, and we did not apply efficiency factors to convert space heating or cooling load reduction

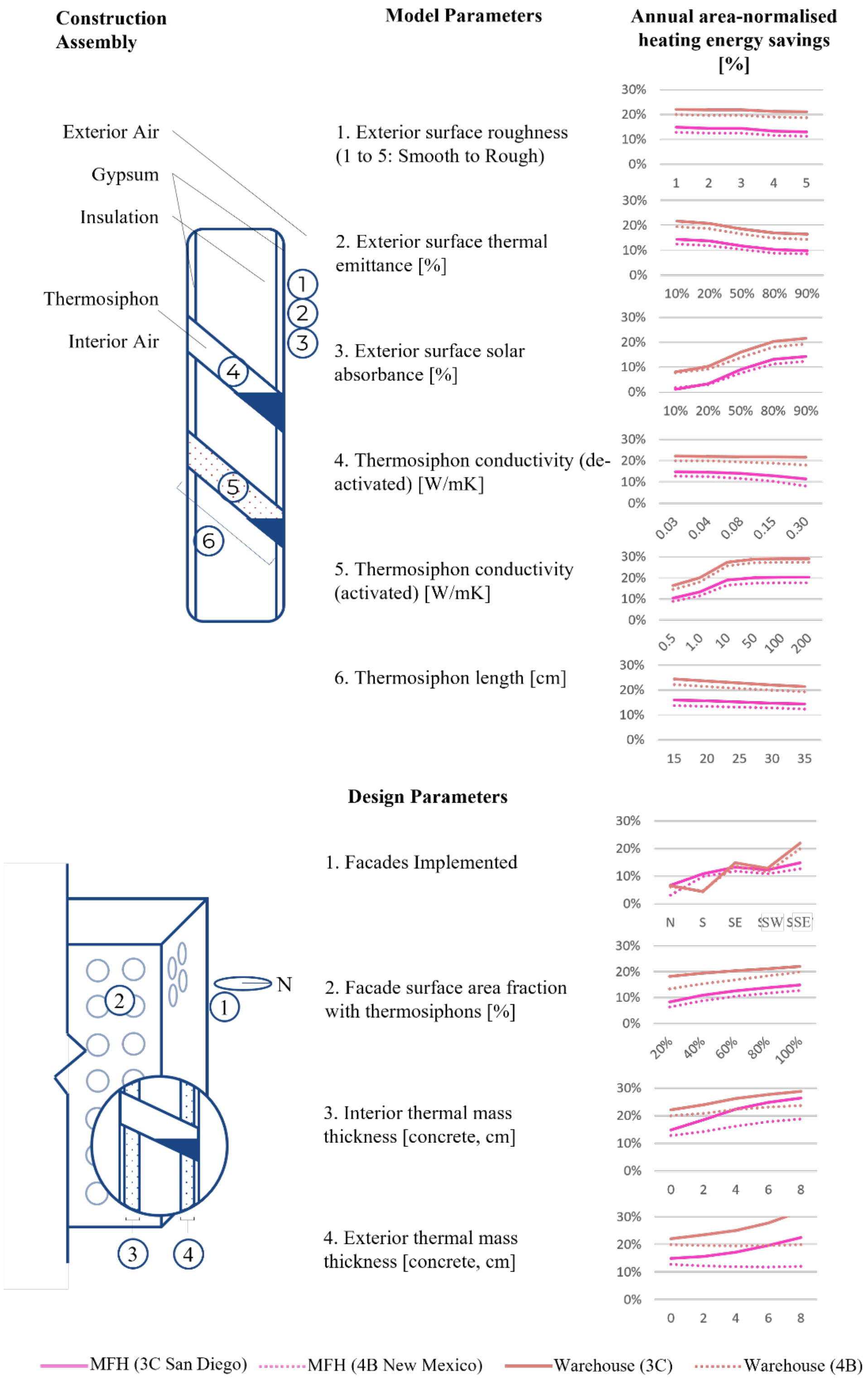

Figure 3. Construction assembly of the thermosiphon façade component, model- (top) and design- (bottom) parameters, and corresponding annual area-normalized heating energy savings for four climates (3C and 4B), building typology (Multi-Family House and Warehouse) combination

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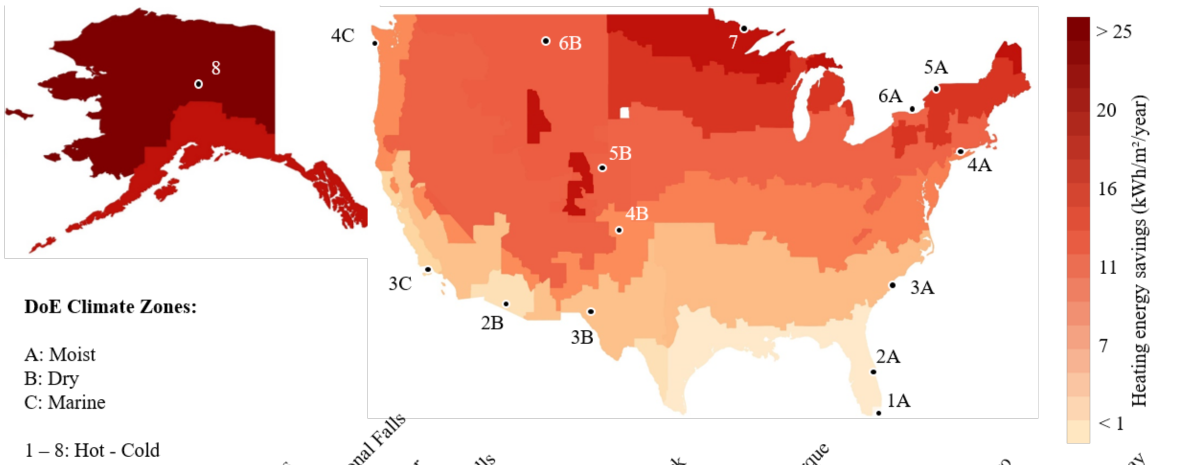
into energy use reduction. TMY3 climate zone representative weather files were used for the simulation framework [8]. To enable the simulation of a large number of models, we employed a time- and resource-efficient strategy. Our software environment in EnergyPlus was built as a Docker image from our code stack's GitHub repository. The resulting image was then uploaded to the cloud and downloaded onto a supercomputer cluster for execution on 16 cores, utilizing the Singularity module and multiprocessing functionality integrated into the eppy Python module.

4. Results and discussions

4.1. Parametric study of the thermosiphon and façade design

Before conducting the simulation matrix, we comprehensively analyzed the parameters that impact the potential for heating/cooling energy savings of the thermosiphon façade. We classified them into two categories: thermosiphon model parameters (such as surface roughness, thermal emittance, solar absorptance, emittance, length, and effective conductivities at the "on" and "off" states) and design parameters (such as façade orientations, the surface area occupied by thermosiphons, and thermal mass). We selected the appropriate building types and climates for our study using a preliminary filtering exercise (illustrated in Figure 1). Figure 3 depicts the heating configuration.



	Fairbanks	International Falls	Rochester	Great Falls	Boulder	Buffalo	New York	Seattle	Albuquerque	Atlanta	El Paso	San Diego	Tuscon	Tampa Bay	Miami
	8	7	6A	6B	5B	5A	4A	4C	4B	3A	3B	3C	2B	2A	1A
Warehouse	80	69	62	61	77	57	56	57	76	52	60	56	41	30	13
Single-family	39	32	29	22	19	26	20	16	11	12	8	4	8	6	1
Stand-alone Retail	34	26	23	21	22	20	17	17	18	13	14	11	8	5	1
Multi-family	24	18	19	17	25	18	19	19	23	15	16	12	8	7	2
Midrise Apartment	34	27	26	22	21	22	19	17	15	12	10	6	5	4	1
Strip Mall	30	26	23	19	18	18	16	14	14	11	10	9	6	4	1
Small Office	30	25	21	20	17	18	15	15	13	11	10	9	6	4	1
Quick Service Restaurant	35	29	25	21	14	21	18	16	9	8	3	-4	-2	0	-1
Supermarket	26	21	18	16	19	15	14	12	14	8	8	2	2	2	0
Full Service Restaurant	24	20	17	15	12	14	11	11	9	8	7	7	5	3	1
Small Hotel	23	19	16	14	11	14	11	10	8	7	5	3	2	2	0
Secondary School	14	11	10	9	8	8	7	7	6	5	4	3	3	2	0
Medium Office	14	12	10	9	8	9	7	7	5	5	4	3	2	1	0
Outpatient Healthcare	15	12	10	9	7	9	7	7	5	5	4	3	2	1	0
Primary School	13	11	9	9	7	8	7	6	6	5	4	4	3	2	0
Hospital	11	9	7	6	4	6	5	4	2	2	1	0	0	0	0
Large Hotel	11	8	8	6	4	7	5	4	2	2	0	-2	-2	-1	0
Large Office	8	6	6	5	3	5	4	3	2	2	0	0	0	0	0

Figure 4. Annual, area normalized, heating energy savings for US DoE climate zones (top) and further classified into building typologies (bottom).

4.2. Building stock simulation

Using the optimal model and design parameters, the simulation matrix assessed the thermosiphon facade's performance across different building types and climates in heating and cooling configurations. To limit the matrix, we utilized one vintage for each dataset: pre-1980 for commercial buildings and 2012 for the PNNL residential buildings. Removing non-overlapping climate zones for these two datasets results in 240 commercial building models (15 climates by 16 types) and 30 residential building models (15 climates by two types). The primary comparison metric for the stock simulation was annual heating or cooling energy savings per square meter of gross floor area.

Across the 15 climates and 18 building types simulated, the average energy savings in the heating configuration were 13 kWh/m2. However, certain building-climate combinations exhibited significantly higher energy savings of up to 80 kWh/m2/year. In particular, warehouses consistently demonstrated higher energy savings across all climates. At the same time, single- and multi-family, mid-rise, and retail buildings also displayed superior energy-saving performance relative to others within the same climate zone. The warehouse building type exhibited the highest wall-to-floor area, floor-to-ceiling height, and low window-to-wall ratios. The coldest climates demonstrated the most significant energy savings due to their larger heating loads and lower solar incidence angles, resulting in greater facade irradiation. No correlation with humidity was inferred. Analogous modeling and analysis of the façade in the cooling configuration were also completed [9] which simulated annual energy savings upto 15 kWh/m2.

5. Conclusion

This work presents a novel thermosiphon facade element with variable thermal properties and a simulation framework to evaluate its energy-saving potential. Through parametric simulations of 270 building type-climate combinations, we identify building types with high facade-to-floor area ratio, low window-wall ratio, and high ceiling heights as having the highest potential for energy savings of up to 80 kWh/sqm/yr in heating. The potential consequences of these findings include reduced energy costs and greenhouse gas emissions. The paper provides empirical data and demonstrates the thermosiphon's dual states of thermal conductivities, which can be used to create EnergyPlus building facade components with variable thermal properties. Our work advances the field by providing new technology for energy-efficient building facades and a simulation framework to evaluate their potential.

The next stage of this research will address aspects which are beyond the scope of this publication, including (i) mass-fabrication and (ii) on-site assembly, (iii) design-, and installation-, of the façade in typologies where both heating and cooling scenarios are relevant, and (iv) longevity and maintenance of the façade.

Acknowledgments

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