Therma Testa

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A Method for the Development of Thermal Clay Tiles

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1 Thermal clay tiles with developed bespoke and modular form and developed green glazing of articulated surfaces.

ABSTRACT

This study investigates and demonstrates a method and process for the development of thermal clay tiles, with a focus on cooling properties. The study is based on a craft-computation approach, combining clay-ceramic manual techniques with parametric design-simulation methods, using thermal flux and computer fluid dynamic simulation procedures.

From the experimental studies, novel clay-glaze prototypes are proposed and tested for temperature and air properties, which effectively impact building thermal environments and energy consumption in a warming world.

The studies find that thermal performances can be significantly steered by the specific material-form articulation presented, that the suggested modular assembly and simple fabrication procedure support a feasible integration, and that the proposed tiles illustrate a rich, articulated material-form characterization that presents both qualitative and quantitative perspectives for further studies.

INTRODUCTION

In the built environment, buildings use 20% of the total energy on cooling (International Energy Agency 2018). With global temperatures predicted to rise significantly, with regional and local increases to more than 5 degrees Celsius within the next 100 years (IPCC 2021), buildings designed and constructed today must consider and implement novel thermal methods. The objective is to utilize methods that do not use fossil-fuel-based power that presently causes climate problems.

The challenge of thermal modulation is fundamental to human survival and the everyday making of experiences through thermal sensation. Hence, development of thermal design through material organization lies at the core of the current energy-climate crisis and within the history of the built environment (Parsons 2002). The mere activity of building is, in principle, the construction of artificial thermal environments, which intent to be different from the ambient, too hot, or too cold, natural environments. Therefore, the problem is not new, but fundamental, and with a historical presence in architectural and design interventions.

Despite the ingenuity and inventions of ancient and vernacular thermal design (Moe 2013), the invention of heat, ventilation, and air-conditioning (HVAC) systems based on electro-mechanical structures prevails today through increased technical advancement and widespread technical integration (Hawkes 2020). These systems have, for decades, become a preferred use in design processes and thinking of thermal engineering (Banham 1984; 1980). This has led to the enormous success in HVAC practical application across different climatic regions, building typologies, and use cases (Gissen 2009), whereas material and form-based passive strategies often have become less favored. The success of these systems relies on the idea of full thermal control and fulfilment of narrow thermal comfort bands (van Hoof 2008; Djongyang, Tchinda, and Njomo 2010; Nicol, Humphreys, and Roaf 2012; Schaudienst and Vogdt 2017) coupled with relatively low prices for energy used in these systems, which, in turn, almost exclusively are based on the use of fossil fuel energy. With energy consumption of buildings becoming a massive and central factor in a transition to a sustainable environment, the focus on rethinking, reinventing, and reapplying material-form solutions for thermal modulation becomes favorable again. This may be geared by an additional increased awareness of using local materials to reduce transport energy, and to increase the relationship between a building's articulation, and the locality of materials and fabrication processes into designed form.

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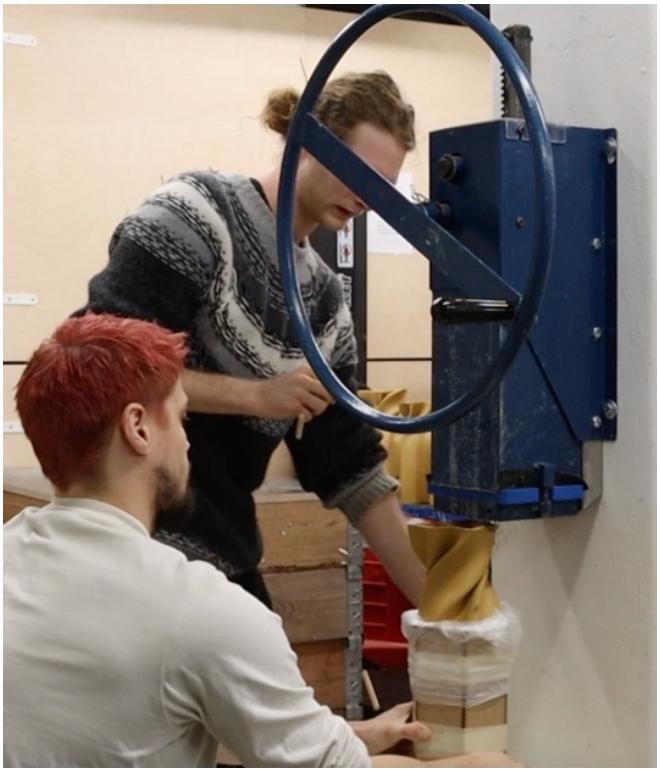

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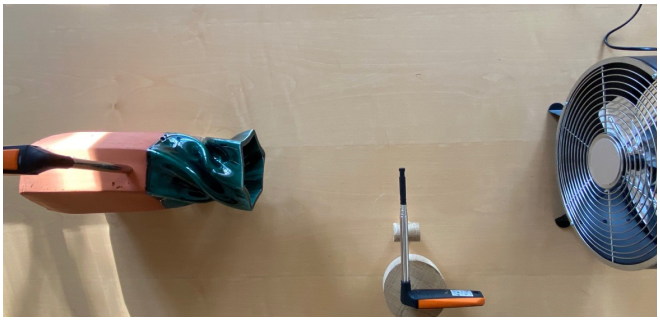
2 Prototype experiments with material, form, and fabrication procedure.

3 Basic extruder with shiftable form tools for controlling the geometry. This is paired with a developed holding and turning tool/process, which creates the final tile forms.



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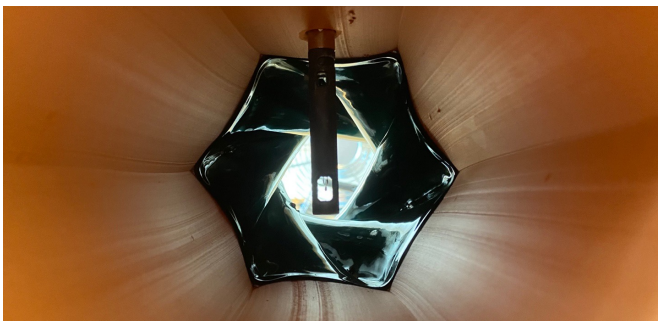

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As a response, this study investigates relationship between material, form and thermal performances to increase the warming and cooling capacity of the built environment without, or by reduction of, electro-mechanical systems.

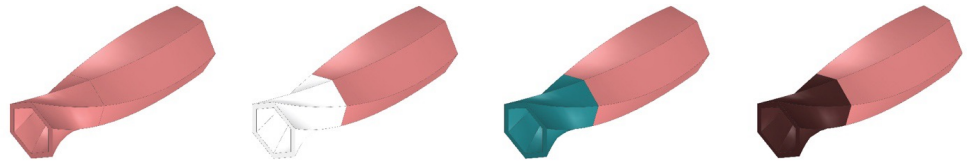
The background on previous solutions and studies is predominantly found prior to the widespread adoption of HVAC systems, where building designs for hot climates were needed to increase cooling. Thermal modulation is seen across continents, most often by convective means, such as increasing air velocity by wind (Kabosova et al. 2019), cross-ventilation strategies, convective floor cooling, and also by use of water-cooling mechanisms that have been adapted in newer projects (Foged 2015). Solar radiation, and therefore the reduction of irradiance, has been a central discussion in urban conditions, since concrete, asphalt and dark roof tiles all absorb solar energy, thereby increasing the surface temperatures significantly (Wines 2000; Tilley et al. 2012). This has led to an increased focus on green roofs, green facades, and green streets, the geometry of elements to increase shade casting, the direct cooling of elements by water, and brighter color schemes of building elements (Foged 2017). All of these material strategies help to reduce the need for energy demanding cooling systems. Within the background of solutions and previous studies (Foged 2013; Andreani and Bechthold 2017; Foged 2016), several factors of investigations are continued, including 1) geometries' ability to steer air flow, 2) a surface's capacity to reflect/absorb solar radiation, 3) a geometry's properties of self-shading, 4) a modular tile-based systems capacity to be configured in respect to a specific locality, and 5) material-fabrication processes that reduce material usage and is not limited by lack of advanced fabrication technologies, ultimately creating a barrier in locations without access or means for such fabrication processes.

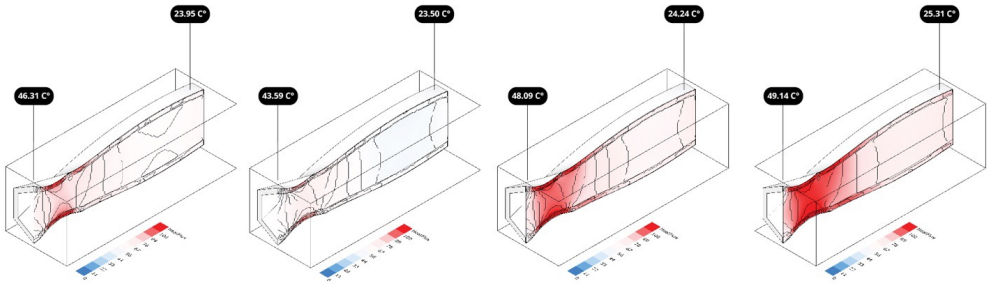
This investigation studies the relationship between the factors for potential solutions by means of physical and computational prototyping, using clay-ceramic, craft-based techniques coupled with digital-driven investigations, coupling thermal simulations with a focus on solar radiation analysis, thermal transfer analysis, and fluid dynamics analysis. The objective is to understand and increase the cooling potential of a clay-based, modular assembly by means of material and form articulation; to formulate a design method based on analogue-computational processes; and to illustrate the performances of the investigation and method through demonstration and testing.

This paper presents the investigations and computational framework applied, together with manual clay-ceramic craft techniques, for the development and testing of bespoke thermal clay tiles. Following the method and specific experimental investigations conducted, results of the novel tiles and associated thermal performances are presented and discussed.

METHODS

This study uses a mixed-method approach, with computational studies for explorative design processes coupled with thermal simulations based on heat transfer and





Material	Roughness	Thickness	Conductivity	Density	Specific Heat	Thermal Abs.	Solar Abs.	Vis. Abs.
White	Rough	0,50	0,68	1300,00	878,00	0,20	0,20	0,50
Green	Rough	0,50	0,68	1300,00	878,00	0,70	0,70	0,50
Brown	Rough	0,50	0,68	1300,00	878,00	0,90	0,90	0,50

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4 Air flow registrations of a single tile with anemometer placed inside/outside tile.

5 Air flow registrations of a single tile with anemometer placed inside/outside tile, with the anemometer inside the tile.

6 Material and fabrication explorations of thermal tiles with clay and glazing.

7 Computational studies focused on form and color versioning coupled with dedicated thermal simulations for singular tiles. Table shows simulation properties of materials.

computer fluid dynamic analysis (CFD) methods, paired with material, fabrication, prototype, and measurement studies. The latter group of investigations serves to inform the computational design studies, and as grounds for thermal and airflow testing in the developed prototypes.

Material, Fabrication and Prototyping

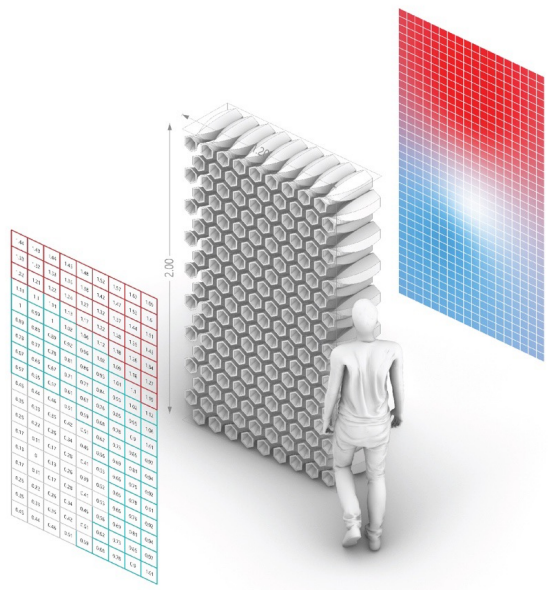
The research focuses on clay and glazing materials (Figure 1). Clay is a naturally occurring and local material in large parts of the world, and is extracted in Germany for this study. The clay has been pre-processed by the clay manufacturer, meaning that small elements have been crushed to form a consistent material quality and viscosity. This is a common process for clay-based tiles, particularly for extrusion processes. Focusing on extrusion forming and fabrication processes, a series of explorative, manual, form-extrusion investigations are conducted with a small extruder with shiftable-form geometries (Figures 2 and 3).

This approach is directly transferable and scalable using industrial extrusion machinery and/or industrial robot fabrication processes. The clay extrusion investigations are paired with a digital twin to inform parametrization and computational exploration, and simulations of thermal transfer processes. Glazing experiments are carried out with 3 color variations, focused on white, brown and green nuances (Figure 6). The color variations influence the solar energy absorption of the geometries which, in turn influence the combined thermal properties together with the geometric studies. The glazing is based on bespoke mixtures, but employs only industrially accessible raw materials. Explored clay forms and glazing color processes are fired in a two-phase kiln process.

Exploration and Simulation

In parallel to material-based investigations, computation-based studies are conducted by parameterization of form and color by versioning at the tile and assembly scale, coupled with thermal simulations. The aim is to understand and advance the coupled investigation method (material -computation) and the understanding and application of thermal performances of the clay-glazing tiles. The computational studies use the Rhinoceros-Grasshopper-Ladybug infrastructure, with the simulation engines Therm (thermal flux simulation for thermal transfer analysis of the tiles), Radiance (solar irradiance simulation for surface temperature analysis), and OpenFoam (computer fluid dynamics simulation for air flow analysis). The key material properties used in the simulations are listed in Figure 7.

The procedural approach of thermal simulations follows the following order: a) simulate temperature increase on air inlet area of tiles with color variations; b) pass this dataset into the thermal flux simulation of the bespoke tile to investigate and understand the heat movement through the tile to the air outlet area of the tile; and c) map the resulting outlet air temperature of the tile (on the inside of the assembly) into the geometric tile model to complete the temperature investigation of inlet temperature ('outside' of assembly) to outlet temperature ('inside' of assembly), (Figure 7). The geometric and material versioning enters above the investigation loop, where the specific thermal



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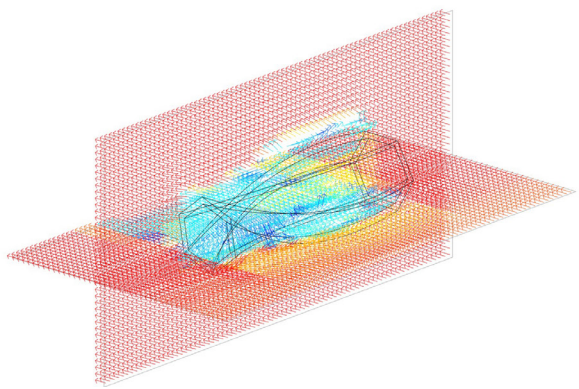

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8 Computational prototype assembly with integrated thermal performance dataset from previous investigation of temperature increase based on coloration. Wall dimensions of 2x1.2m, including 162 tiles.

9 Computer Fluid Dynamics analysis of airflow and air velocity patterns based on air movement perpendicular to the tile.

performance of inlet and outlet air can be observed in the design-simulation model. The models are developed to provide both numerical and visual feedback, which allows understanding of both the determining temperature values, and the heat flow and distribution through the development of the unique tiles. The new dataset combining form, material, and thermal descriptions is then embedded into the investigation model, allowing the exploration and understanding of thermal performances across a wall assembly dependent on specific form-material combinations (Figure 8).

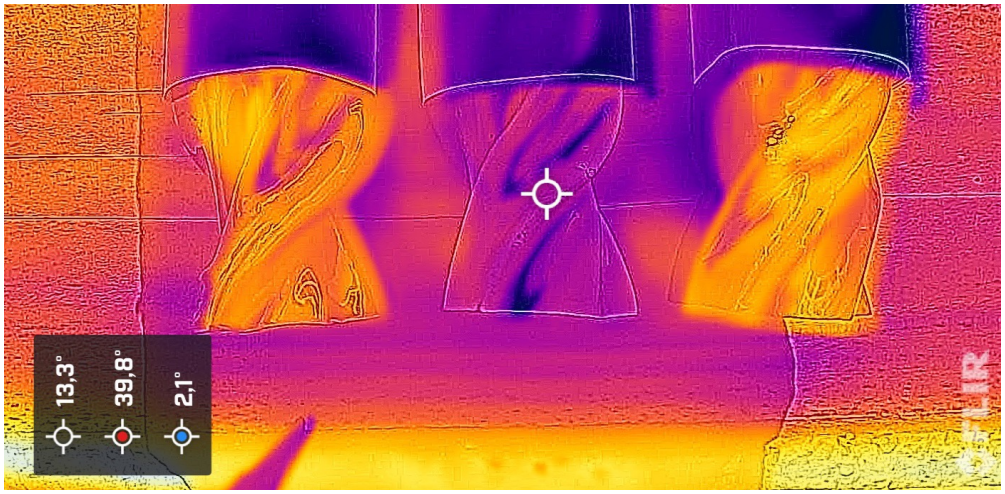
A parallel investigation airflow is studied by modifying the air velocity in two directions in a virtual wind tunnel, respective to the tile direction. In air direction, (a) the airflow vector is parallel to the tile (pointing directly into the inlet/outlet area), and in (b) the airflow vector is perpendicular to the tile (Figure 9 and 11). The airflow simulations are mapped across two intersecting planes of 1.5x1.5m, for high resolution visual analysis of flow phenomena, illustrating the flow regime patterns produced by the tile geometry at different velocities. As an input to the CFD simulation model, we used the extracted surface temperature data for all three color variations and imported it as inlet air temperature for the wind analysis study. The investigation included ten air velocities from 1 to 10 m/s, across two vector directions, resulting in a matrix where comparative analysis was performed (Figure 11). From the simulations, air velocities are extracted for the maximum/minimum values of the tiles in both air direction studies. The aim is to understand how the heated air from the first simulation process is moved by the geometry of the tile in relation to surrounding air movements.

Measurements and Observations

Following the explorative studies, based on computational and material prototyping processes, thermal measurements are conducted by thermography, a thermometer, and infrared anemometer. Thermography is done using a Flir One Pro thermal camera with Vernier Thermal Analysis software to record and log data.

Thermography registrations are used to capture and analyze the complex surface temperature dynamics of the clay tile parts that are color glazed. Three developed tiles, with white, green, and dark brown glazing, are placed in the sun, with the glazed end facing in a southeasternly direction (Figure 10). Thermographic registrations were taken from 9.00 to 10.30am, on May 12, 2023, in Copenhagen, Denmark, under a clear sky. The tiles' glazed surfaces are exposed to air movement, with a measured velocity of 2 to 3 m/s.

Air velocity movement through the cavity of the clay tiles is investigated by the use of two Testo infrared anemometers, model 405i. One anemometer is placed inside the tile, centered in the cross-section (Figures 4 and 5). The second anemometer is placed outside the tile. In a controlled environment condition, with maximum 0.1 m/s ambient air velocity movement, measurements are made of the internal and external air velocities, when air velocity around the tile is increased to 2.5 and 3.5 m/s. To drive the external



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10 Thermography registrations of glazed surfaces by solar radiation exposure from 9.00 to 10.30am, May 12, 2023, Copenhagen, Denmark. Green glazing to the left, white in center and dark brown to the right.

air movement, and resulting internal air movement, a fan is used to construct a steady and directed airflow to provide stable analysis conditions for understanding the correlation between the developed prototype tiles, the simulation investigations, and the resulting performance of the airflow based on the clay tile geometry (Figure 12). In addition to the airflow registration, temperatures are measured both inside the tile cavity, and outside, next to the anemometer sensor. The data streams (air1, temperature1, air2, temperature2) can then be used to understand the performances of resulting tiles based on the explorative material-form methods.

RESULTS

Results from the experimental studies are based on computation-based and craft-based investigations. The results from the two modes of investigation are described as complimentary findings, and cover both qualitative and quantitative material-formal-thermal results.

Material and Form

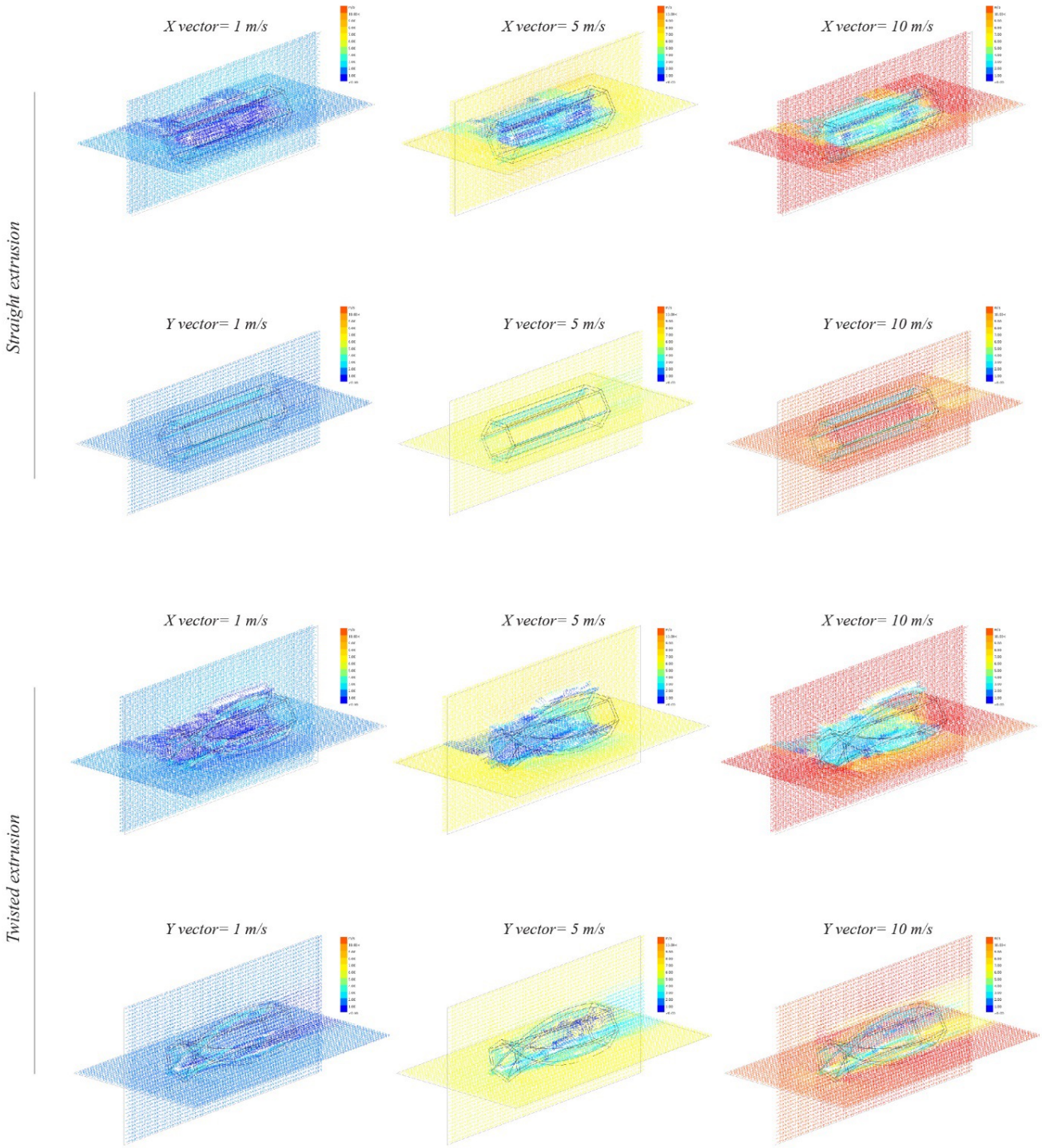
The characterization of the unique and modular tiles is based on the coupling of advanced design-modeling-simulation processes, and low technological and manual fabrication processes. The material-form articulation of the tiles is achieved by a single extrusion and turning motion of the clay, producing a sophisticated form in less than 30 seconds. The form can be described as a platonic, hexagon geometry that gradually develops into a varied, non-rational but defined curved surface with folds. While the form develops continuously from the center of the tile, both ends remain a hexagon at their periphery, albeit with distortion in the curved end of the tile. The continuum and gradient development of two distinctively different geometric expressions appear only possibly by the performed and developed combination of design and fabrication methods. Following the same logic of fast and simple material fabrication processes with coloration, tiles are glazed by dipping them into a color bath, creating the surface coat with varied depths depending on the specific curvature geometry of each tile. In this process, material-form relations are controlled, in alignment with the computed geometry studies, but retain freedom in adjustments in the material-form composition. Such play of material-form development enables variation and repetition in tandem, which arguably is different to a fully automated, robotic-based fabrication process of complex formwork, whereby explicit geometry is a necessity during making. Hence, the coupling of advanced computational design processes with craft-based low-tech fabrication processes demonstrates the capacity to develop advanced, thermally performative clay-tiles that are formed in seconds (Figures 14 and 15).

Airflow

When we observe the results from the airflow and air velocity studies, the anemometer measurements show a modest air flow increase (Figure 13). This is the case for both source airflows, 2.5 m/s and 3.5 m/s, creating only an outward airflow velocity of 0.05-0.1 m/s in the tile cavity. While this number is relatively small, the ventilation airflow volume through the tile will be 3 m3/h (averaged from registered air flow flux) per tile. With a total of 80 tiles per m2 wall, the resulting ventilation rate with low continuous airflow would result in 240 m3/h.

DISCUSSION

This research investigates the direct relations between qualitative craft methods and quantitative computational design methods. This is done by firstly establishing


Straight extrusion
X vector= 1 m/s
X vector= 5 m/s
X vector= 10 m/s
Y vector= 1 m/s
Y vector= 5 m/s
Y vector= 10 m/s
Twisted extrusion
X vector= 1 m/s
X vector= 5 m/s
X vector= 10 m/s
Y vector= 1 m/s
Y vector= 5 m/s
Y vector= 10 m/s

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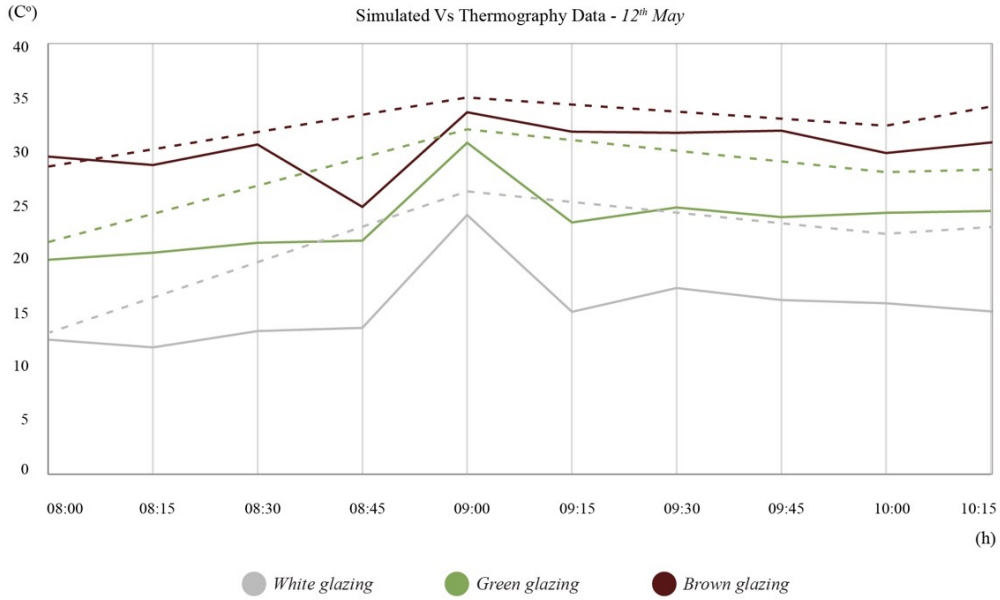

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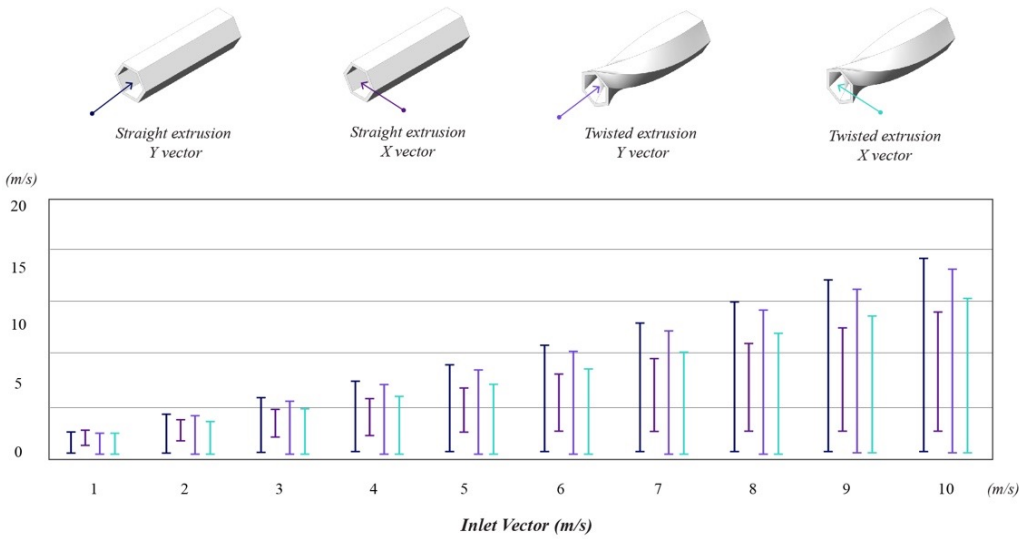

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11 Computer Fluid Dynamics investigation matrix of different air directions and at different air velocities.

12 Graph of the measured surface temperature development over 90 minutes, and the simulated results.

13 Graph of simulated air flow velocities at different air directions.

a craft-based fabrication procedure allowing material sensibility and engagement to take place through visual and tactile feedback during exploration. Then, these developments and insights are paired with the development of a computational design framework based on material-environment-thermal simulations to advance geometry and material compositions. The former can be perceived as of a less rigorous and diffuse development process, while the latter is based on mathematical modeling and structured numerical versioning as methods of investigation and mapping of results. While this is correct for the computational studies, it also applies to the craft-based studies that inform the computational model development. While the tiles are somewhat unique in their specific formal definition, they are based on a precise and distinct execution of material viscosity control, extrusion speed, rotation speed, rotation angle, cutting process, and extraction from the hexagon support structure, glaze mixture, glaze thickness, glaze dipping process, drying, and firing. If any of these procedural steps are off the developed process, the resulting tile will not be able to nest as a modular system into the assembly, nor would the coloration have the desired thermal performances aimed for. Despite such controlled, exact execution of manual steps, the result suggests a humanistic, non-mechanical and rich material-formal articulation in both tile and wall assembly. That, combined with the tiles being formed in seconds, suggest that existing, relatively simple, craft-based fabrication

techniques are competitive in producing qualitative, future formal and material articulations.

The question to future advancements of material-fabrication methods and processes, then, is how we further our abilities to meaningfully combine such craft-based techniques to sophisticated computational design methods and automated fabrication processes, to support the richness in making and the efficacy of producing.

The objective to investigate and develop a method and prototypes using clay for thermal modulation of buildings, through designed temperature and airflow, has been demonstrated. However, generalizing results would be preemptive, as the thermal performances studied are tied to the context of investigation and the simulation variable space described. The computational studies are based on climate data from location, which was Copenhagen, whereas the field measurements logically are influenced by hyper local conditions, both in terms of events close to the samples, such as increased airflow due to surrounding buildings, or far away conditions, such as a temporary cloud cover. Hence, the simulation and measurement results are not intended for comparative analysis of results, but as complimentary studies and results.

To advance this line of investigation, studies could be pursued by exposing the tiles to climate chamber conditions, where heat radiation and airflow can be controlled and isolated. This will obviously lead to non-polluted variables and the ability to perform sensitivity studies of the influencing factors that impact thermal performances. It will, however, also produce results that are most likely never comparable and present in the messy world of the built environment. In contrast to studies of structural behavior, material-environmental phenomena are always in open exchange with its context. The performances are based on its context.

CONCLUSION

The presented research investigates, develops, and demonstrates how computation and craft-based methods can be combined to understand and produce novel modular tiles for thermal modulation. The specific thermal performance depends on the color chosen, the number of tiles embedded into a wall structure, and a number of environmental context conditions that drive the thermal effect, such as the solar radiation potential and airflow potential. These factors will determine the airflow volume and, hence, natural ventilation impact for convective cooling processes. To generalize the low sample and experimental findings of this study, further versioning studies should be conducted, in both lab and field conditions. Such studies may also support the further development of the geometry to steer air flow and the self-shading properties to further decrease the effective surface temperatures in warming climates.

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14 Resulting tile assembly as an expressive, color-clay-based building ventilator.

15 Resulting tile as an expressive, color-clay-based modular building ventilator.

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IMAGE CREDITS

All drawings and images by the authors.

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Vasiliki Fragkia is a Research Assistant at The Royal Danish Academy, Institute of Architecture and Design, holding Master's in Architectural Engineering and Computational Design. Through theoretical investigations and design experimentation, her work focuses on how material performances can be integrated in design and digital fabrication, as an aspect of sustainability.