UNDERSTANDING HEAT TRANSFER PERFORMANCE FOR DESIGNING BETTER FAÇADES

ABSTRACT

This early research focuses on the design of building façades to mediate external and internal thermal conditions. It explores new workflow for accessible feedback into the early design of façade systems. Specifically, this research aims to explore the level of corroboration or the gap between predictions of thermal behavior using digital modeling and simulation, and the empirical measurement of thermal behavior in physical analog models for façade design.
INTRODUCTION

We investigate better integration of thermal performance prediction into the architectural design process as a means to reduce energy consumption. This paper will describe the initial experimental set-up and the results of introducing it in an intensive four-day workshop for designers from practice and academia. The research project involved approximately twenty participants (including industrial professionals, researchers and students from various institutions and practices) in a collaborative design workshop.

We started with the aim of guiding our digital predictions towards a more faithful representation of values gathered in physical experimentation, and arrived at a better understanding of the multiple challenges of both digital and physical simulation of simulation of heat transfer.

The set-up supported the generative exploration of façade shape, pattern, formal arrangement for transmission of light and ventilation, shading, and thermal behavior at a conceptual level.

1 METHODOLOGY: A DUAL APPROACH USING ANALOG AND DIGITAL SIMULATION TOOLS

In this research, we introduced two parallel processes for analyzing façade designs:

i) a set of analog measurements on and around physical prototype models.

ii) a set of digital simulation tools used for the same models but in the virtual computational environment (Figure 1).

Before we could begin a hypothesis-testing exercise, we needed to have a solid grasp of the subject and of the phenomena under study. One of the many dimensions of the experiment is acquiring confidence in our predictions, for example, checking whether our designs meet a standard performance criteria.

While this type of research is exploratory by nature, the following are our preliminary lines of enquiry:

i) Analog testing of physical prototypes will yield a richer data set and need not adhere to the restrictive assumptions made in digital models.

ii) There is a correlation between digital simulation and analog modeling independent of the façade design and the performance aspect that the design is testing.

iii) The system could support models to test different aspects of façade thermal performance: for example varying R-value, varying proportions of transparency and opacity, size and distribution of openings; and effects of patterning and relief in the digital and physical environment.

The methods used to set up the physical boxes were adapted from building physics and used with guidance from building physicists, including using thermo-imaging cameras to monitor surface temperatures (Melcher and Karmazínová 2012) and scaled façade models in a controlled test environment to monitor and measure the performance behavior of the façade (Zollner et al. 2002).

1.1 ANALOG TOOLS

The analog tools were designed and fabricated from the ground up, which included a thermal imaging box and a thermal sensor box.

In each design enquiry, a series of façade prototypes were designed, fabricated and tested using the boxes (Figure 2).

The thermal imaging box was used to understand heat transfer and the phenomena of conduction and radiation by visualizing the distribution of temperature and heat gains or losses across the external and internal surfaces throughout the period of the test for different façade prototypes. The thermal sensor box was used to understand the issue of convection and fluid dynamics by monitoring the changes of air temperature inside the box in response to different façade prototypes. The heat source for the physical test boxes is a 500W halogen lamp, placed directly in front of the opening on one side of the boxes, where the façade prototypes were mounted.

One box is painted black to screen out all interfering light. There are optional mountings included for light sensing using small ordinary cameras, both from the top and from the back of the box. Also, the material and joining of the boxes are made airtight to measure the light air flow (convection) that occurs when the thermal differences increase.

We separated sensors and imaging into two boxes mainly to avoid the visual occlusion of the camera view by the grid of sensors in the space. However, this introduced the issues of:

(a) calibration of setup;

(b) the need to match initial boundary conditions to start measuring the façade temperatures;

(c) the need to set up a homogenous environment to maintain the conditions and behaviors of the two boxes (Figure 3).
1.2 THERMAL IMAGING BOX

The thermal imaging box is 400 mm (depth) x 300 mm (width) x 300 mm (height) in dimension, constructed out of three millimeter thick clear acrylic sheets, then painted black inside. The façade designs are mounted for testing at the front (open) face of the box. The box has a built-in thermal camera (optris® PI160) which captures thermal emissions from the inside faces of the façade prototype. Another thermal camera (optris® PI450) mounted in front of the box measures the external surface temperature of the façade. Both thermal camera images were streamed live to a computer and stored digitally for analysis.

1.3 THERMAL SENSOR BOX

The thermal sensor box (Figure 5) has the same physical dimensions as the imaging box, but with clear surfaces. Within the box, twenty-seven DS18B20 digital thermal sensors were equally distributed and connected to communicate using 1-Wire® technology. With 1-Wire® technology we could dynamically increase and decrease the number of sensors without changing the electrical circuitry, which gave us the option to place additional sensors outside the box, either in front or within a cavity of the façade prototype. Analog sensors (NTC thermistors), which are much smaller (Figure 4) and cheaper, were embedded into the testing façades to sense conductive heat transfer (Figure 10, left). The sensor data was captured using an Arduino and sent to a computer for data logging and analysis.

1.4 DIGITAL TOOLS

The digital workflow (Figure 6) incorporates several software packages that are used by participants to design, segment, analyze and visualize a series of façade design prototypes. Analog testing is difficult to replicate, as it is non-deterministic and non-homogenous, whereas digital simulations are deterministic: the
boundary conditions, while always questionable, can be set to the same conditions at every run.

2 DESIGN CASE STUDIES

In the workshop there were eleven different design case studies (approximately twenty five physical prototypes and at least one digital simulation model for each case in total). Within each of these proposals, variants of the system were tested, introducing modifications to material, pattern and scale. In the context of the workshop, participants were able to model variants in response to the initial simulation, based on physical thermal images and measurements, to test hypotheses about the behavior they were witnessing and explore the factors leading to it (Figure 7).

2.1 CASE STUDY 1

This participant developed a façade system with a relief pattern on the surface. The design of the testing boxes included a square opening for inserting the façade models at the front of the box, allowing them to be rotated by ninety degrees for testing. In this design, raised, undulating ribbons across the façade caused very different behavior whether inserted horizontally or vertically. This was attributable to their interference with the air movement across the front surface of the façade, shifting the heat through convection (Figure 8–11).

2.2 CASE STUDY 2

This participant also investigated patterning and relief, in this case using different materials to inlay the surface pattern. This design combined an undulating cellular network on different layered materials, varying the R-value of the overall façade (Figure 12).

2.3 CASE STUDY 3

This participant experimented with the design for a kinetic façade of opening umbrella-like components, testing it in different states
Analog simulation results visualized

Digital simulation workflow

Physical prototypes for analog simulation – left, with embedded sensors; right, experiment with thermal sensitive paint

Plot of 27 Digital sensor values

Plot of Embedded sensor values

Analog simulation results visualized
of opening and closure. Models were prepared using polypropylene and perforated card for the shading surfaces. From the illustrated results (Figure 13), it is clear that while more information is needed for interpretation of the behavior, successive empirical testing of variants and states of the physical model can develop a useful predictive intuition.

2.4 CASE STUDY 4
A kinetic star-based folding structure was compared to a larger scale detailed investigation of the thermal behavior of the star form including thermochromic paint to achieve a visualization using the model itself (Figure 14).

3 EVALUATION AND CONCLUSION
The outcomes of the project include a better understanding of both the possibilities and limitations of thermal analysis using parallel physical and digital simulation setups. The results also allow for a better understanding of design for inter-disciplinary collaboration in the early design stage in order to collect data, and derive information and feedback of value.

Modeling and analysis of digital and physical models contributed to a rapid understanding of the many issues surrounding the highly complex field of thermal performance analysis. The data from analog tests and digital simulations were difficult to compare owing to the different formats and the variables in the boundary conditions. However, the visual aspects of the analysis seemed to give a richer understanding of the cyclic combination of digital- and analog-based modeling. Moreover, the use of the thermal cameras, thermochromic paint, and visual representation of the sensor data in Matlab and ParaView in particular, provided a useful and rich interface for intuitive feedback. Such feedback affected the general impact of design changes in the analog models with respect to the heat flow across the surfaces, transport through the “façades” and heat transfer within the interior space.

The interpretation of data into the likelihood of convection currents on the surfaces, turbulence inside the box, and significant differences in terms of heat distribution and change over time requires experienced input from building physicists able to read the inference of the effects. However, the sense at the end of these early experiments was that the most relevant analysis is likely to be through pattern extraction. The experience highlighted the extreme complexity of setting up such an experiment. The attempt to achieve consistent physical starting conditions between testing different façades involved having to cool the physical boxes between tests in ways that “over sensitized” the sensors. The room in which the experiment was conducted had relatively stable conditions but was in no way a thermally controlled environment. There is enormous sensitivity to tiny changes in starting conditions so it is likely that the actual figures will need to be manipulated to provide direct comparisons between the tests of different façades with any veracity.

We started with the hypothesis that digital thermal simulation could be verified or calibrated through a comparison with analog results, while understanding the subjective control opportunities in setting the digital conditions. We arrived at the realization that the analog modeling was also subject to enormous vagaries with respect to the precise conditions of the experiment. Future research will include attempts to further refine the testing environment to introduce greater rigor.

Finally, the façade designs tested were consciously simplified for this application to enable simple variations to be assessed.
(rotating patterns at ninety degrees, small elaborations of pattern or changes of scale). There is further work to be undertaken to refine this system including analysis of the outputs before the experiment can be shifted to more detailed, complex or refined façade models.

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