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Expanding Boundaries:
Systems Thinking for the Built Environment

CAMPUS AS A LAB: BUILDING- AND SYSTEM-LEVEL AIR MOVEMENT INVESTIGATION

E. Teitelbaum[1]*, S. Urano[2], L. Conlan[1], A. Percival[2], J. Hinson[3], F. Meggers[2,4]

[1]Civil and Environmental Engineering, Princeton University, USA
[2]School of Architecture, Princeton University, USA
[3]Princeton High School, USA
[4]Andlinger Center for Energy and the Environment, Princeton University, USA
*Corresponding author; e-mail: eteitelb@princeton.edu

Abstract

The successful realization of an architectural narrative through engineering is intimately entangled with stochastic events of which advanced models, such as CFD or energy modelling, do not navigate. Through a series of investigations within air spaces around campus buildings at large, i.e. atrium, and small, i.e. double skin facades, scales, this study demonstrates the actual movement of air within these spaces and seeks to compare them with the design narrative and any calculations put forward by engineers prior to construction. Additionally, we propose new, informative methods of visualization for our results, modifying standard arrow conventions to provide more information about the probability of observed performance modes. While such an in-depth computational analysis is only possible with real data available after building completion, we claim that the methods developed in this approach and the associated results may still inform the planning process when sizing equipment and engineering control logic.

Keywords:
Double skin façade; Sensors; Arduino; Air movement; Convection

1 INTRODUCTION

Buildings are often designed to take advantage of natural air movements. This is commonly seen in buildings with large atria and with narrow cross section where thermal free convection and wind-driven cross ventilation are used as strategies to increase comfort without any energy demand. Unfortunately, the design process makes gross assumptions about the reliability of these natural flows, and the implementation often performs in ways not addressed in the design process, and not measured after completion. Natural ventilation is designed using prevailing winds and average wind speeds. But prevailing wind is exactly that: prevailing, not constant. Speeds and direction are highly volatile, and significant periods of time in any location will have non-ideal wind speeds and directions, rendering achieving reliable natural ventilation difficult.

Another aspect that airflow design relies on is free convection, where the height of atria is used to move hot air upward or cool air downward. Unfortunately, the interaction of heat flux and air movement is difficult to predict.

In most cases, airflow inside the building volume is represented by architects as arrows that are essentially estimations based on first principles or heuristics. In the best case, some analysis or simulation has been carried out, but in general they are not representative of the highly dynamic conditions at the interface of air flows inside and outside the building. A post occupancy analysis of airflow in building spaces, which have been designed based on predictions of complex natural ventilation and/or convection, will provide valuable insight into the reality of air movement in buildings and facilitate maximizing performance.

In general, if a natural ventilation system fails to meet comfort criteria, this is easily compensated

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by air conditioning systems (often oversized with large factors of safety). The windows are closed and the system compensates. But in order to reach higher performance levels some buildings strive for completely natural ventilation operation. The Federal Building in San Francisco was built with a design criteria of complete natural ventilation. Unfortunately, in a survey by the US General Administration showed that although the Federal Building had 10% lower operational costs, the occupant satisfaction rate was only 13%, with the next lowest building being 26% [1], showing that the natural ventilation systems was causing significant comfort problems as well as acoustic and lighting problems. Another example is the Sandra Day O'Conner Courthouse in Phoenix, Arizona. A very novel evaporative cooling mist system for the atrium was developed by Arup and analysed by Raman [2], using an extensive CFD modelling process before being installed by ARUP. Yet despite the development of an independent CFD model for the system, predicting the evaporation and free convection was very difficult.

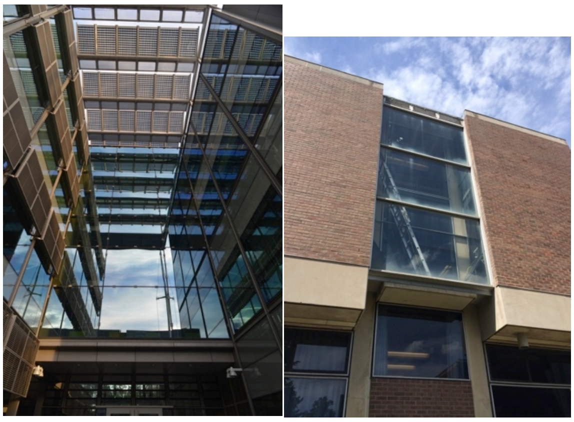

Fig. 1: (a - left) Frick chemistry atrium; (b-right) Double skin façade with a ladder placed inside.

At Princeton we have many buildings that have interesting and complex spaces that were designed with a specific preconception of the airflow in the space. One of the oldest is the lofted studio space of the School of Architecture which was retrofitted with a double skin façade 15 years after the building's opening to address comfort thermal issues (Fig 1b). The new Frick Chemistry Laboratory building (Fig. 1a) has a large atrium designed by Hopkins architects and Arup engineers, which is supplied by outside air that is efficiently first brought in through the adjacent offices. The building also includes radiant heating near the entrances, the operation of which is dependent on the airflows.

The buildings can be analysed using a novel setup leveraging wireless Wi-Fi-enabled networked microcontrollers called Particle Cores. Particle Cores collect data from sensors, such as temperature, humidity, differential pressure, infrared temperature, etc. and publish the values to the Particle Cloud, a privately hosted platform accessible from anyone connected to the internet. Sensor values can be collected by polling the cloud and stored in a database or similar format. They can be battery powered, hung throughout the space, and have temperature and humidity sensors attached to them to track conditions relayed back to our own servers, making an ideally flexible and highly distributed platform to measure the resulting conditions in these airspaces and reconsider the predictions made in their design.

2 METHODS

The study is broken into two primary components, building-level investigations of the atrium space in Frick Chemistry building, and systems-level investigations of the double skin façade (DSF) in the school of architecture. The breakdown reflects the scale of each problem, and while a double skin façade will have impacts on the entire building's energy consumption, we are only concerned with heat transfer within the space. The entire study contains multiple datasets in other buildings around campus for comparisons of similar features in different settings.

2.1 Building-level Atrium study

As mentioned in section 1, the atrium in Frick was the first large atrium space studied as part of the Campus as a Lab investigation. The atrium, approximately 90 m by 10 m by 20 m high, represents a considerable volume of air. The energy-conscious narrative of the building design dictates that for summer operation, air is conventionally cooled upon entering the building on east side, where the majority of the offices are located. Air warms up while moved through the office space, and is directed towards the atrium. Fume hoods and a laboratory air handler unit on the western side of the building circulate the warmed air through the lab space, and out of the building. This allows the atrium to be ventilated as an interstitial space with minimal fan power. But this results in dependency on complex free convection flows.

Engineers ran CFD simulations to predict airflow before the building was constructed. To compare these models with actual data, we placed sensors on floors 1, 2, and 3, at 3 locations (north, central, and south), for the east, west, and central portions of the building. Altogether, 27 sensor locations were used, not including a seldom-polled sensor that remained on the ground floor. This sensor was subject to disturbances by occupants and the lower level café. Air temperature and humidity sensors (DHT22) were attached to handrails as shown in fig. 2.

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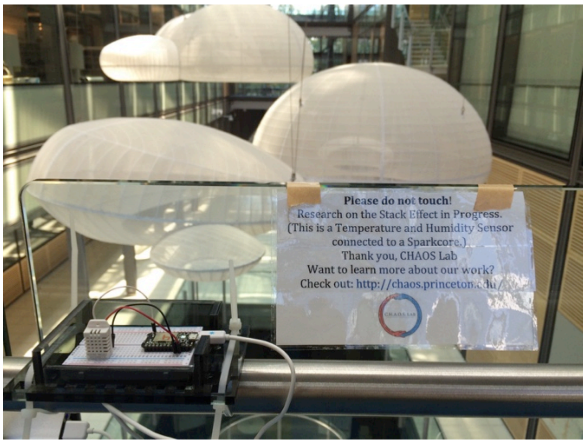

Fig. 2: Air temperature and humidity sensor connected to a Particle Core placed in Frick.

2.2 Systems-level DSF study

The Double Skin Facade in the Princeton University School of Architecture is a particularly interesting space as it is a retrofit to improve energy performance and thermal comfort levels in the building. The large windows were initially designed with large curtains, however the large windows are between 1/3 and 1/2 of the overall wall surface area. During the energy crisis in the 1970s and into the 1980s, a new energy retrofit company cofounded by Harrison Fraker was called upon to design and install moveable skylights and the operable DSF to improve energy performance. The skylights were phased out in subsequent retrofits, but the DSF, while inoperable in most areas, is still in place today.

According to discussions with the designers, some heuristic techniques were employed with 1970s technology to determine the contribution of the DSF retrofit to the energy consumption of the building. The guiding prediction was for winter operation the closed cavity would provide additional insulation, and in summer the vents in the cavity would open and free convection would circulate air through the space to keep it cool. No record exists today of these performance predictions.

To track the air motion, and evaluate the ability of the space to be ventilated by complex free convection in summer, sensors were semi-permanently installed to glass surfaces inside the double skin façade and hard-wired to facilitate data collection. Air temperature and humidity sensors (DHT22) were installed at 19.5”, 77.5”, 116”, and 191”. Air temperature and humidity inside the building were also monitored at the bottom of the system. Surface temperature sensors (Omega ON-409-PP) were installed inside the DSF on the exterior glass, interior glass, and inside the building on the glass at the same height as the two surface temperature sensors to model heat transfer through the space. Additionally, the space was outfitted with a differential pressure sensor (Sensirion SDP610-125PA) at the top of the cavity to track the pressure generated in the cavity. The differential pressure sensor had a range of +/- 125 Pa. A +/- 25 Pa sensor would have sufficed.

A Python script was written to log data for days, at 90 second intervals. Intermittency of the Wi-Fi connection proved fatal to the script frequently, however over the course of several months, a large amount of data was taken.

In addition to sensors that were installed by the authors, Weather Underground information was polled from a nearby weather station. Data used included ambient temperature, humidity, solar radiation, wind velocity, and wind direction. These variables were monitored to provide an understanding for the observations inside the cavity.

Smoke tube imaging techniques were also employed to track air motion for creating diagrams.

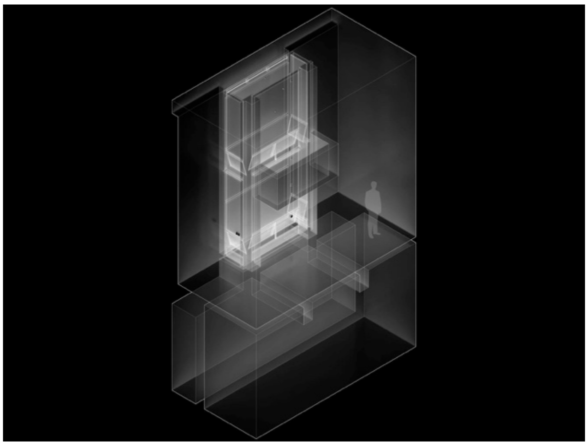

Fig 3: Rendering of the DSF

The results were interpreted to create a realistic figure showing temperature profiles, actual airflow patterns dictated by actual weather patterns.

3 RESULTS

3.1 Building-level Atrium study

Original drawing sets and documentation from the design of the building helped to characterize design intent. From some research into the building design stage, CFD simulations were uncovered which document the anticipated operation of the atrium. These images are shown in Fig. 4.

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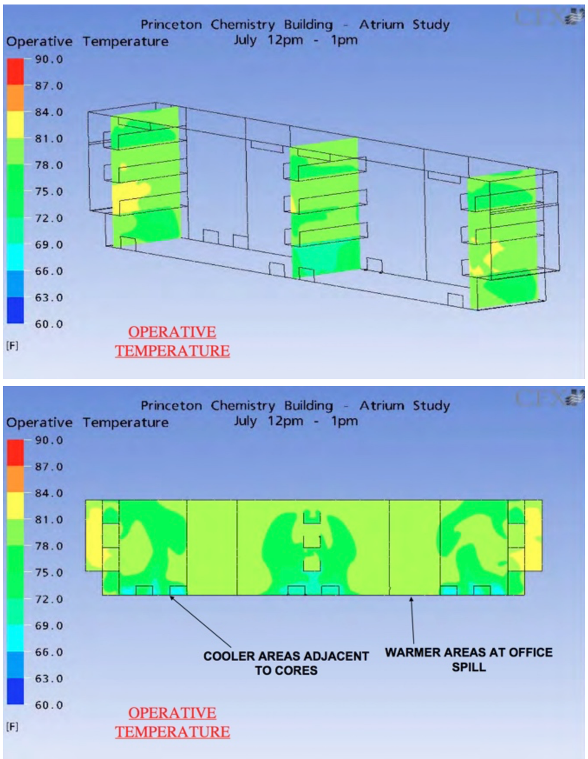

Fig. 4: Transverse and longitudinal cross-sections of temperature profiles from CFD simulations.

It is clear that engineers anticipate the warmest regions being at the north and south ends of the building, with the coolest regions in the centre of the building, with the warm regions being near the “office spill”, i.e. air exiting the offices.

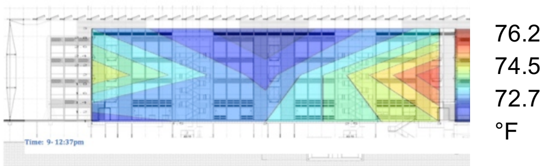

Fig. 5: Measured temperature in Frick Atrium.

Compared to our own measurements shown in Fig. 5, we are in agreement that between 12:00 and 13:00 in July, the warmest regions are at the north and south ends of the building. This image is comprised of averages over a 1 hour period of 10-15 measurements, depending on sensor connectivity. Due to resolution of the sensor mesh, we cannot rule out the existence of the northern and southern cool regions, however our readings confirm cool temperature in the middle of the building. Additionally, fig. 5 shows a decrease of temperature as one goes up in the building. This is a counterintuitive result that is not indicative of buoyancy driven free convection, and could be investigated with a finer resolution sensor mesh. It could be due to the speed of the air intakes that supply the laboratory space near the top of the atrium. This gives an indication that the assumed buoyant airflow and cold-on-bottom hot-on-top may not be as prevalent in the space as considered in the design phase. This is by no means an indication that the space has failed as the space has enough conditioning capacity to meet the demand, but it does demonstrate the challenge in predicting realistic airflow scenarios.

Sensor reliability issues in the large atrium were immediately obvious when taking measurements of air temperatures in this space. Intermittent temperature readings made obtaining a time-series dataset difficult, while this was an original research goal. Future studies may want to consider using a more robust sensing protocol.

3.2 Systems-level DSF Study

The DSF study was to some extent simpler to implement than the atrium study due to the smaller size of the feature. Fig. 6 shows non-uniformity of the daily temperature profiles as height increases. All plots in fig. 6 show data from the spring for the temperature at different heights throughout the day inside the DSF.

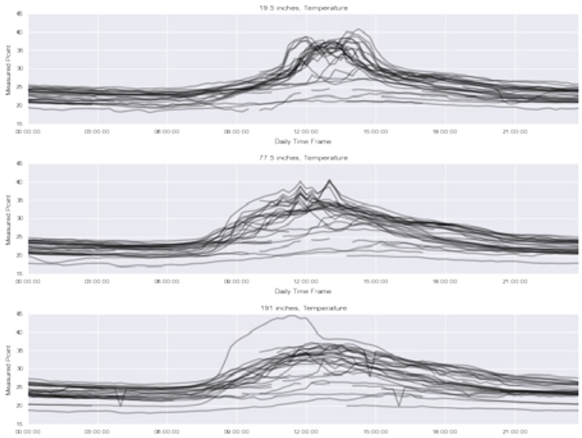

Fig. 6: Spring-time daily temperature profiles inside the DSF at 19.5”, 77.5”, and 191”.

The nonuniformity of the temperature profiles is particularly interesting because it demonstrates the complexity of the feature that cannot be predicted with heuristic design approximations. Fluctuations due to cloud cover, tree shadows, etc. seem to be “smoothed” out as height increases. In other words, the lowest temperature sensor in the DSF was subject to faster fluctuations, whereas the higher temperature sensors generated smoother daily contours.

Conceptually, these leads should be indicative of a buoyancy-driven temperature gradient. More specifically, as air heats up it will rise and exit the space. However, eventually the capacity of the air escape mechanism seems to be exceeded during the warmest parts of the day, and this DSF air turnover rate is no longer able to maintain a smooth profile throughout the space, resulting in even the lower sections heating up.

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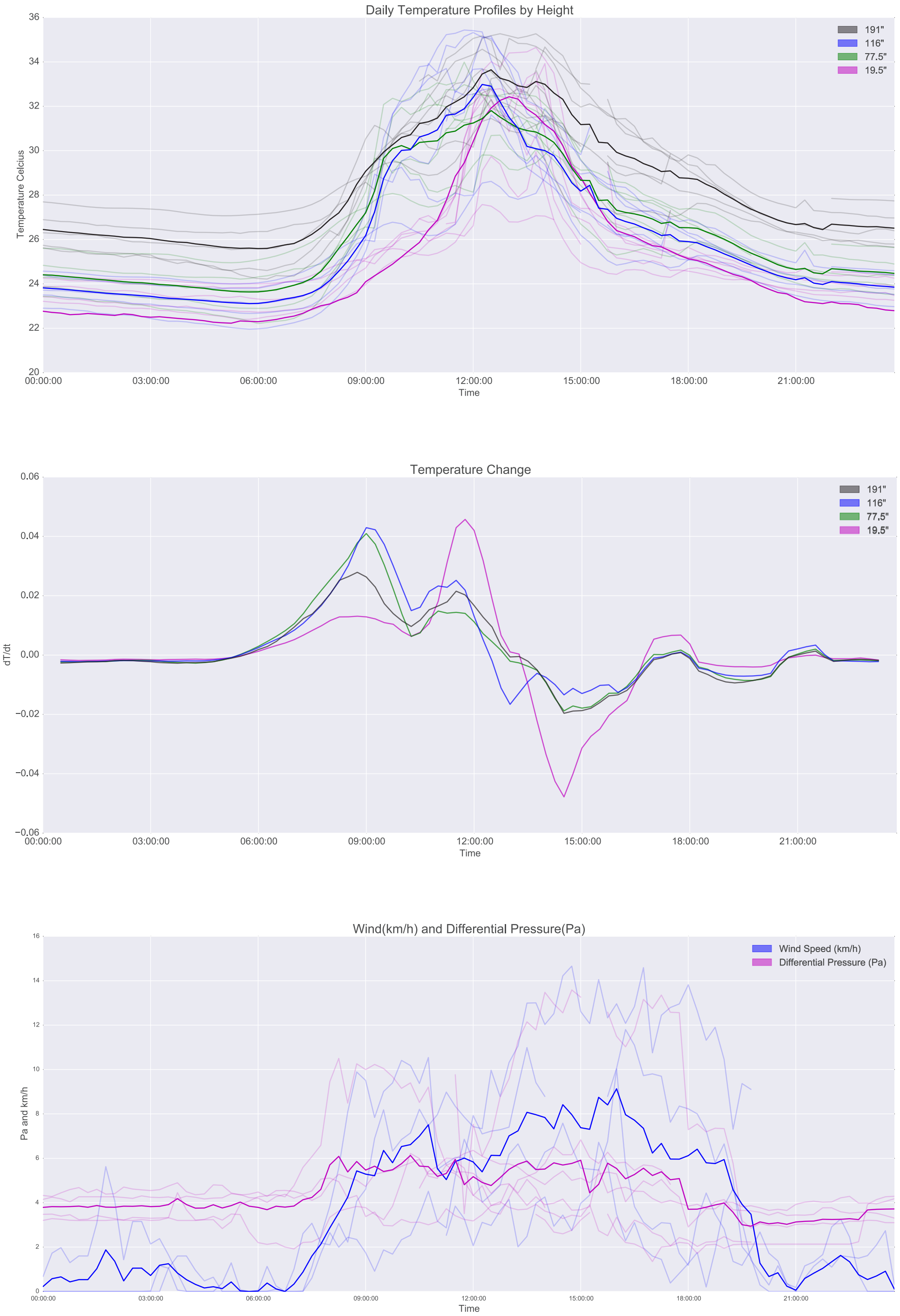

Fig. 7: (a – top) Daily temperature profiles and averages (opaque lines) for spring-time operation of the DSF at varying heights; (b – middle) Time derivative of temperature change throughout the day at each height; (c – bottom) wind and differential pressure averages for the DSF.

Fig. 7a, shows averages as heavier lines, and the lighter lines are actual daily trends. Again, one sees the buildup of temperature throughout the cavity during the day. Initially, the top is the warmest, until the warm air rises and is unable to escape at sufficient velocities.

The time-series derivative reflects this concept as well, shown in Fig. 7b. Initially, the top heats at the same rate as the middle two regions, until the top stabilizes. Eventually, there is a quick spike in the bottom temperature, however this is relatively short-lived. Since the integral of the derivatives must be zero, Fig. 7b implies that the quick increase in temperature at the lowest region is met with a quick decrease in temperature beginning at approximately 13:00.

This conceptual understanding of the space that is provided from high time-resolution of the measurements shows that the cavity's air throughput is significantly undersized. Larger

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vents would allow for faster turnover, and perhaps the sharp temperature increase would not be observed.

Further complexities within the DSF are introduced in Fig. 7c. Again, the opaque lines represent the daily (summer) averages, and the transparent lines represent individual days. Overall, there is a relatively constant pressure difference between the cavity and the exterior. Pressure buildup is mitigated to some extent through the vents. However, short fluctuations in wind speed generate large changes, up to 100%, the equilibrium differential pressure. This is significantly larger than the buoyancy driven flow, and difficult to plan for or control.

Fig. 7c also implies correlation between wind velocity and differential pressure, as the increase in prevailing wind during the day on average tends to be accompanied by an increase in differential pressure. This correlation may not imply causation, as this may also coincide with the building's air handling unit starting up for the day. A separate investigation will need to look at values when it is known the air handler unit is off.

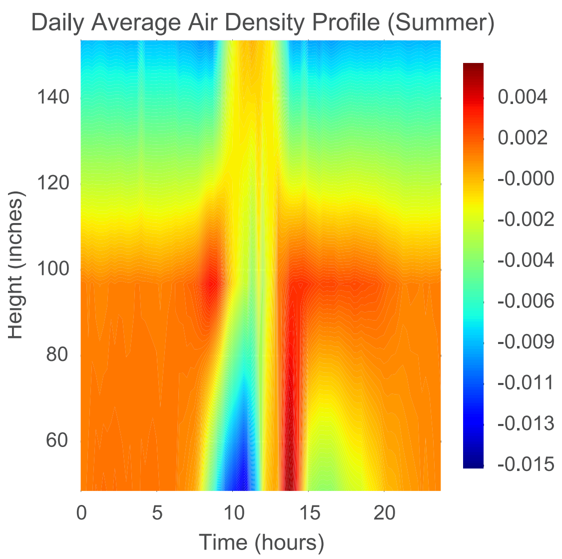

Fig. 8: Daily average air density differences between sensors.

Calculations of air density differences between the temperature sensors to inform Raleigh number calculations to observe the onset of free convection revealed an environment that does not have a characteristic free convection cavity. Instead, a stable conductive space is observed.

Fig. 8 shows air density differences in kg m^{-3}, calculated from the temperature differential between sensor locations. Orange (bottom) through blue (top) represents a density difference that favours natural convection, whereas a blue value at the bottom of the cavity shows air temperatures that will not create a draft in the cavity. By comparing this map to the temperature profile at a given height based on the time on the abscissa, one can see the temperature profile that corresponds to a particular density profile. It appears that despite warm temperatures in the bottom of the cavity after 12:00 from direct sunlight, overall there are frequent changes in the modality of the feature, switching between freely convecting and stagnant.

Fig. 9: Smoke tube test of the DSF.

For visualization purposes, smoke tube tests were performed to see how air moved around the cavity inside the building. This showed the draw of fresh air up into the cavity, and informed imaging of the actual air movement around the space.

4 DISCUSSION AND CONCLUSION

This study was particularly helpful in highlighting failures of a strictly narrative-based approach to design. For instance, when planning a DSF, the guiding principles of hot air rising and performing basic calculations to predict the vents required to maximize air throughput does not sufficiently describe this complex phenomenon.

The results presented in this paper are not meant to strictly inform design, either. It is recognized that complex spaces have a large number of variables that influence air motion, variables that are not isolated in the datasets presented here. Instead, stochastic performance is represented as simply stochastic. The novel part of this examination is that through the proliferation of cheap sensors, complex spaces and buildings of the future may benefit form controls algorithms that are fed high resolution data which is used to open vents, change fan speeds, etc. The possibilities are numerous.

Perhaps the biggest success of this study was using real data to inform imaging. A drawback with standard architectural representations is the lack of precision with arrows and conceptual illustration that oversimplify complex phenomena like airflow. Arrows directing airflow have become ubiquitous, however the exact interpretation is infrequently specified. Fig. 10 shows a figure that shows real daily temperature profiles throughout the DSF, real air movement by arrows that track real smoke test paths, and also specific

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indicators of where the sensors collected the temperature and humidity data.

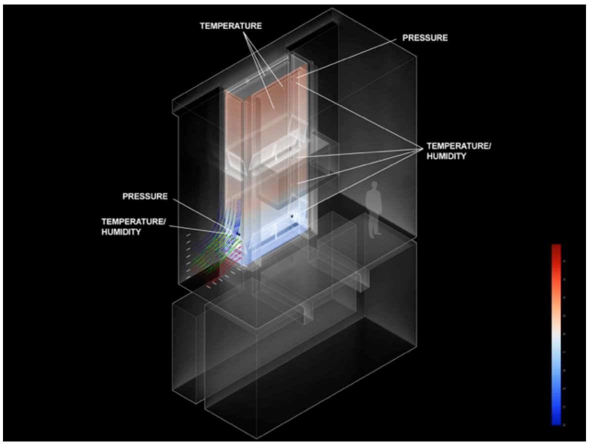

Fig. 10: Air flow and air temperature depiction informed with real data.

The authors would like future depictions of the space to include probabilistic operation as well, i.e. an element of the image that represents the likelihood of the air throughput being sufficient throughout the day. This could be informed partially by the time derivative shown in fig. 7b, however this must be part of a future investigation.

5 ACKNOWLEDGMENTS

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