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Materializing Convection

Lisa Moffitt

ABSTRACT

This essay uses a physical modeling technique from mechanical engineering, the filling box, as a speculative architectural design tool. In the filling box, dyed salt water is injected into acrylic models submerged within a tank of fresh water, simulating the introduction of cold air into a warm environment or, when mirrored, the introduction of warm air in a cooler environment. The models make complex and beautiful convective thermodynamic processes visible, revealing insights about environmental processes taking place within and around buildings. Mirror images of model studies are accompanied by writing that draws on the science of thermodynamics to explore the atmospheric milieu of architecture, aligning an increasingly ubiquitous concept in architectural design discourse – thermal variability – with a design technique that foregrounds this concern.

Introduction

In this essay, photographs of physical models and associated writing together explore reciprocities between thermodynamic concepts and architectural atmospheres. The models use mechanical engineering's experimental technique of the filling tank, which simulates buoyancy-induced airflow, appropriating it as a speculative architectural design tool. The photographs of the models are mirrored about a horizontal axis: upper images depict cold air falling, lower images show hot air rising (Figure 1). The writing asks explicitly for connections to be made between scientific thermodynamic principles and architectural, atmospheric possibilities. Placing the filling tank within its historic and disciplinary context of using physical experiments to test building heating and ventilation principles, the writing also suggests that the models act as devices for more open-ended speculation about the choreography of atmosphere. Considered sometimes purely physically, as literal indications of air flow, sometimes more metaphorically, in terms of gradients or intensities, differentials or equilibrium, the essay proposes that it is often in the mis-readings or failures of models – in this case, in particular, in the unintentional leaks – that potent insights for design's inflections reside.

Figure 1: Filling tank study with movable interior partition. As plumes of dense air fall (or buoyant air rises), new configurations of space emerge where hot and cold meet, creating distinct, shifting “thermal” fronts. Source: Author.

Figure 2: Reid's test tube (left and middle) and tubular apparatus (right) convection-experiments. Source: David Boswell Reid, *Illustrations of the Theory and Practice of Ventilation*, 1844, fig. 161.

Reid's Convection Experiments

Physician David Boswell “The Ventilator” Reid may have been the first to develop a physical model of convection to illustrate architectural principles. In 1844, Reid published *Illustrations of the Theory and Practice of Ventilation*, which focused on the interface between the built environment and the real and perceived effects of air-borne disease. Air was a harbinger of contaminants and its invisibility made developing best ventilation practice challenging.¹ Reid relied on a range of techniques for illustrating and testing the principles of air movement through buildings, including partial and full-scale mock-ups of his ventilation designs, most notably for the debating chambers of the British House of Parliament. His book is peppered with diagrams of conceptualized environmental states, often marked with arrows to indicate expected thermodynamic movement – diagrams still commonplace in technical textbooks. Of particular note are the simple drawings of two experiments that attempt to materialize convection (Figure 2).

The first drawing shows two test tubes filled with dyed water topped up with clear water, one of which is heated from below, the other from above, both by a small naked flame. On either side of the first tube are arrows indicating the movement of the water; the color of the liquid has become uniform throughout the tube. The water in the second tube remains stratified, suggesting stasis. Reid elaborates:

Fig 161 represents a tube with coloured litmus water below, and common water above. A lamp applied above heats and evaporates the water there, and no further change is observed. But if the lamp be applied below, then the cold water there being expanded, the colder colourless water descends below it and pushes up. In this manner, a continuous circulation is maintained, till, from the constant mixture of the ascending and descending currents, a uniform heat is observed.²

Figure 3: Filling tank sectional study with outlets. Denser, dyed water displaces buoyant water as it moves through a series of interconnected spaces, creating distinct atmospheric pockets and zones of inhabitation. Source: Author.

A second, more elaborate experiment applies these principles directly to mechanical heating systems in buildings. Described as a “tubular apparatus,” the experiment is “well adapted for shewing the manner in which hot-water apparatus operates, water being placed in one limb and coloured water in the other. The fluid moves upwards in the limb to which the heat is applied, descending in the opposite limb.”³ The experiment represents a system that is organized as a convective loop; a boiler heats water, convection conveys this heated water through pipes to associated radiators in each room; cooled water descends back to the boiler at basement level where it is heated again, and the process continues.

Shifting focus to the formal configuration of the “tubular apparatus” in Reid’s experiment prompts architectural speculation. Reid’s experiments demonstrate thermal principles that apply also to the movement of air within rooms. It is not unreasonable, then, to imagine the glass tubes as vessels of air. In this interpretation, water represents air, and the convective process takes place as a result of the natural tendency for buoyant (hot) air to rise. This extrapolation of Reid’s experiments invites further speculation. One could imagine a range of iterations of Reid’s “tubular apparatus” as models that test other, more complex, spatial situations – a series of glass apparatuses of increasingly elaborate shapes and configurations, heated at different locations to test thermal exchanges. In these models, dyed water would continue to represent convection, but within air rather than water. The focus of the model would then shift from representing the organization of pipes within a heating system to the organization of architectural space and its associated constructed atmospheres (Figure 3). The tubular glass apparatus becomes a vessel of interconnected spaces and their corresponding thermal exchanges. The model transitions from being a scientific explanatory device to a device for architectural speculation, in which chambers might expand or change shape to create different atmospheric environments.

Reid’s experimental models, reinterpreted as architectural models, reveal the potent ability for such misreadings to open up new imaginative possibilities of what might be in the world. Models are both scale physical artifacts and mental ideals. Those attributes of the “real” world that a model represents are referred to as its “target system.” It is through the dialogue between a model and its target system, between the physical artifact and the ideals it suggests, that potential design insights reside. What makes Reid’s experiments, when read as architectural models, distinct from most conventional architectural models is the incorporation of a particular environmental exchange, that of thermodynamic movement. Incorporating this enables the relationship between buildings and their atmospheric surroundings to be brought into consideration.

The Filling Box Technique

The mirrored images on these pages are contemporary equivalents of Reid’s experiments. They use mechanical engineering’s experimental technique, the filling box, as a speculative architectural design tool. The

Figure 4: Filling tank sectional study without outlets. Water descends and remains caught in low-lying, stratified cold pockets, which slowly drain out through unintentional leaks. Source: Author.

technique is straightforward: plexiglass models with inlets and outlets are submerged within a tank of fresh water. The models are either filled with or, later, injected with dyed saltwater. The differential in density between clear fresh water and dyed salt water induces visible flow patterns. Fresh water represents less dense (warm) air and dyed salt water represents dense (cold) air. In the top image, dyed salt water indicates flow patterns of cold air falling within a warmer environment. When mirrored, the bottom image represents flow patterns of warmer air rising within a cooler environment, simulating buoyancy-induced airflow.

The filling box technique is used by engineers to test both air displacement and the mixing effects of ventilation. Paul Linden, Gregory Lane-Serff, and David Smeed describe their use of the technique to investigate air flow in buildings:

The experiments that we have made have been restricted to a very simple geometry and some idealized sources of buoyancy. Buildings have much more complicated shapes, with multiple zones and levels, and may be connected to the exterior by a number of different openings at different heights. The flows within these buildings are, in general, time-dependent and complex, and yet they are of crucial importance to the correct functioning of the building. In addition, in order to calculate heat losses and temperatures within the building the architect and ventilation engineer need to have a knowledge of the internal flow patterns and the air movement.⁴

While Linden et al's research is limited to fairly basic forms, and to a mode of physical experimentation that relies on a notion of "correct functioning," they acknowledge the value of testing more complex spatial configurations with multiple zones, interconnected volumes, sectional variation, and with variable opening configurations – an open invitation for further engagement and design speculation.

In the filling box, thermal processes become legible material processes, making complex thermodynamic flow patterns visible. Just as Reid's experiments open productive possibilities when misread as architectural models, the filling box models shown here raise productive questions about the relationship between building configuration, temporality, materiality and environmental effects. Warm air rises. At times, it collects in pockets of relative thermal homogeneity, creating distinct zones of occupation. These zones of occupation are not bound fully by physical enclosure but by differentials of hot and cold, suspended in a state of steady stratification (Figure 4). At times, warm air rises and works its way through and around adjacent spaces, escaping from intentional (or unintentional) openings. It escapes either in heavy plumes or in delicate wisps, mixing with its atmospheric

Figure 5: Filling tank sectional study with chimneys. Water is activated as it escapes in wispy plumes, in material contrast to the inert boundaries of the vessel containing and directing it. Source: Author.

surroundings (Figure 5). These wisps and plumes eventually dissipate to adopt a state of subtle stratification, within both the “architectural vessel” (the plexiglass model) and the wider environment (the tank) that houses it. The building becomes simply part of the continuum of its surroundings.

Thermal Variability

The filling tank experiments foreground “thermal asymmetries” and “thermodynamic figurations,” allowing them to become a primary material of design exploration.⁵ If the technique was originally used to test ventilation strategies in the service of establishing codified notions of thermal comfort, some contemporary designers and theorists now view these standards much more speculatively. Thermal variability has gained status in two related domains: architectural design and thermal comfort. Theorist Christopher Hight describes the non-visual dimension of climatic exchanges such as air movement and thermal variation as “somatic architecture,” “a three-dimensional matrix of sensation that is not so much seen as felt.”⁶ Architect Philippe Rahm uses principles of thermal exchange to govern spatial arrangements, maximizing thermal asymmetry. His projects explore “the formal, programmatic, and ecological potential of thermal imbalance and climatic asymmetry.”⁷ Rahm uses convection as a primary determinant of form in many of his projects. His Interior Gulf Stream project, for example, is organized as a convective loop within a small, split-level dwelling, consisting “of an asymmetrical distribution of heat in the house, creating a convection movement in the entire space.”⁸ Iñaki Abalos and Renata Snetkiewicz advocate a thermodynamic conception of architecture that expands the conventional material palette to include thermal exchange.⁹ Kiel Moe uses the term “thermodynamic figuration” to describe how “diverse forms of energy become primary determinants of architectural figuration and performance.”¹⁰ These architectural frameworks are indebted to Lisa Heschong’s *Thermal Delight*, a book first published in 1979 which tests the “hypothesis that the thermal function of a building could be used as an effective element of design.”¹¹

The definition of thermal comfort itself has been changing. Thermal comfort standards as codified in the mid-twentieth century largely assume the desirability of a stable body of cool, still air, its temperature maintained within a narrow range. More recently, however, research has suggested that thermal variability is more desirable than stability. Thomas Parkinson and Richard DeDear argue for models of thermal comfort that acknowledge “alliesthesia,” a term first coined by physiologist Michel Cabanac in 1971 to provide “a conceptual framework to understand the hedonics of a much larger spectrum of thermal environments than the more thoroughly researched concept of thermal neutrality.”¹² Alliesthesia reflects a more nuanced understanding of thermal perception that accounts for the pleasure of occupying heteroge-

Figure 6: Filling tank study without outlets, leaking at seams. Water works its way through a series of interlocking volumes. Interior space is marked by a subtle, shifting gradation that descends as streams escape. Source: Author.

neous rather than homogenous thermal environments.

Understanding the material tendencies and behaviors of environmental exchange, particularly those related to invisible thermodynamic and fluid dynamic processes, is crucial to being able to engage with them as design variables. However, architects have struggled to fully understand and represent such environmental conditions due to thermodynamic complexity and to the attendant scalar questions raised by the attempt to model it.¹³ Moe suggests that architects require new design models that explore “reciprocal conceptions of causality and formation” between a building’s static properties, such as its mass and volume, and its much more variable properties, such as temperature and pressure.¹⁴

Static diagrams and computational fluid dynamics offer two existing strategies for designing with thermal principles in mind. What do the filling tank models viewed as architectural models offer this conversation? They offer an intuitive method for working with fluid and thermal phenomena as architectural materials. Models establish similitude with selected features of the world. Filling tank models establish similitude between air and water. In doing so, they give air a material presence, highlighting its behavioral tendencies. Air (water) is a medium sensitive to disruption, to change, to exchange due to differential in pressure or temperature. Air (water) is material that exerts pressure, that infiltrates, that destabilizes. Air (water) is at times static, at rest, creating particular discernible zones or thermal pockets that are influenced but not entirely defined by conventional building enclosure. Through this materialization of convection, the filling tank models seen as architectural models play a double act, revealing insights about both the environmental performance of spaces and the performances of environmental processes.

Conclusion: The Consequential Leak

Architectural models are potent tools; as scale artifacts, they abstract and distil. They establish relationships between the physical world and mental ideals. Models that make thermodynamic processes evident reveal causal relations between more inert architectural materials and their fluid counterparts. To focus too intently on their role in simulating thermodynamic processes, however, misses the full range of insights the models can provoke. Often the most productive insights for design are revealed through failures or misreadings of the model’s original intent. It is when the model doesn’t quite align with the ideal that new insights emerge. A central feature of the filling tank models, like the architectural ideals they represent, is that they leak in unintended places (Figure 6). Neither simulations nor diagrams

Figure 7: The filling tank contextualizes buildings as objects submerged within the “tank” of the sky dome, leaking, and eventually establishing equilibrium with their surroundings. Source: Author.

leak; it is the leak that makes the filling tank distinct. The filling tank models leak, slowly, persistently, eventually reaching a state of equilibrium with their surroundings.

The significance of the leak is three-fold. First, the leak reminds us that the physical model is distanced from the mental ideal. As Ulricke Passe and Francine Battaglia note, “a homogenous interior climate as imagined by Buckminster Fuller or Yves Klein in the 1960s is an illusion and does not comply with the physics of fluid flow and motion.”¹⁵ Conceptions of architecture as containers for thermodynamic processes are models in the sense that they are theoretical constructs. Just as the plexiglass model is not fully watertight, inevitably leaking at seams and intersections, no building is completely airtight. No building operates as an entirely contained closed-loop system, and even those filling tank models with no intentional outlets, like the supposedly airtight buildings they represent, leak, inaugurating exchanges with the environments in which they are immersed.

Second, the persistent leak reveals the tendency for the system to move towards equilibrium. When viewing the filling tank photographs, it is tempting to focus on the swirling plumes and wispy trails marking thermodynamic differential; these effects and their strange figurations are beguiling. However, the swirling plumes are but station points to a state of equilibrium. After the initial disruption induced by injecting saline solution into the model, a slow and steady process of dispersal begins. In its final state, the architectural model sits within a subtle static gradient of dyed water. The architecture of the filling tank transitions from being a vessel of charged thermal differential to a vessel held in equilibrium within its surroundings, draining and receding from view.

Third, leaks shifts focus from the source of the leak to the destination of the leak. Filling tank models represent nested environments in which buildings are metaphorically “tanks” submerged within the “tank” of the skydome (Figure 7). The models remind us that buildings are in constant collusion with and are often destabilized by their atmospheric surroundings, requiring tethering, anchoring, or grounding for stability. The filling tank models leak, and they leak somewhere, and that somewhere leaks beyond, inaugurating a series of cascading environmental effects. In doing so, they establish connections across a vast range of scales of atmospheric exchange. The leak places buildings within a context of possibility and consequence, acting as reminders of Evangelista Torricelli’s observation in 1644 (when describing his discovery of the sensitive air-weighting instrument, the barometer) that “we live submerged at the bottom of an ocean of the element air.”¹⁶

Endnotes

1 David Boswell Reid, *Illustrations of the theory and practice of ventilation, with remarks on warming, exclusive lighting, and the communication of sound* (London: Longman, Brown, Green, & Longmans, 1844).

2 Reid, D.B, *Illustrations of the theory and practice of ventilation*, 245-6.

3 Ibid.

4 P. Linden et al., "Emptying filling boxes: the fluid mechanics of natural ventilation," *Journal of Fluid Mechanics* 21 (1990): 331.

5 Christopher Hight, "The New Somatic Architecture," *Harvard Design Magazine* 30 (2009): 25.

6 Philippe Rahm, "Climatic Constructions: Thermal Asymmetry in Architecture," *Harvard Design Magazine* 30 (2009): 34.

7 Ibid.

8 Inaki Abalos and Renata Snetkiewicz, *Essays on Thermodynamics: Architecture and Beauty*. (Actar, 2015).

9 Kiel Moe, *Thermally Active Surfaces in Architecture*. (Princeton Architectural Press, 2010:119.

10 Lisa Heschong, *Thermal Delight in Architecture* (MIT Press, 1979): vii.

11 Thomas Parkinson and Richard de Dear, "Thermal Pleasure in built environments: physiology of alliesthesia," *Building Research and Information* 43, no. 3 (2015): 288.

12 Hight, "The New Somatic Architecture," 26.

13 Kiel Moe, "Energy and Form in the Aftermath of Sustainability," *Journal of Architectural Education* 71, no. 1 (2017): 89.

14 Torricelli, 1644 cited in J.B. West, "Torricelli and the Ocean of Air: the First Measurement of Barometric Pressure," *Physiology* 28, no. 2(2013): 66-73.

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