The fluid dynamics of air flow in free flow open spaces: An architectural approach to energy efficient buildings

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Introduction
The rising prices of natural gas and electricity in the United States, and the concerns that our natural resources will be depleted, motivates research to explore how society uses energy. More than 70% of the energy used in the U.S. is consumed by homes, businesses, schools and industries. One approach taken to address energy concerns is the development of alternative fuels. The approach used in this research is to consider how buildings utilize energy through the architectural design. Ideally, if natural ventilation systems can achieve the same climate as mechanical heating (furnace) and cooling (AC) systems, then building designs that use natural ventilation would not consume natural gas and electricity for energy needs.

We investigated the relationship between spatial volumetric layout of building interiors (free flow open space) and the required building energy consumption. These buildings utilized natural ventilation, i.e., natural convection of air, to control the interior building climate, whereby a building was cooled or heated by using the building’s spatial layout, such as connecting rooms, windows and vents. A coupled approach between architectural design analysis and computational fluid dynamics (CFD) was used to analyze the effects of volumetric spatial composition on natural airflow and temperature changes within the building. The temperature stratification in a building indicated how well the building design controlled the flow of air during the cooling and heating processes.

Background
A literature survey was conducted to determine suitable architectural designs that utilize natural ventilation. Case studies were considered based on the work of pioneering architects, who elaborated the architectural concept of free flow open space in the first half of the 20th century, during a time before mechanical air conditioning systems were heavily utilized. The case studies were selected to bring a range of building typologies and types of volumetric interconnectivity of double height spaces in different climatic settings into the research.

A survey on CFD techniques and efforts was also conducted to determine what methods, if any, have been used to simulate airflow within buildings. It was found that very little research has focused on simulating full size buildings; typically, simulations were for one or two connecting rooms. The research presented herein is one of the first studies that not only considers airflow within a large building, but studies the importance of spatial volumetric layout and natural ventilation.
Research Methods

Architectural Design Analysis

To be able to understand the effects of convection within free flow open spaces, we started with an analysis of the architectural design of specific buildings in order to abstract certain patterns of spatial composition. Five buildings were selected for the case studies whose typology used vertical air movement by natural convection. The airflow is enhanced through vertical connection between two or more levels of the building. Three of the selected buildings, the Esherick House, the Viipuri Library and the Des Moines Art Center, were previously visited by Passe and were found to be particularly applicable to this study. The How House and the Schwartz House were also added because of their unique spatial designs. Further information on the architectural designs considered and schematics can be found in Appendices B and D.

After the case study selection process was concluded, we developed a tool for spatial analysis to determine volumes of spaces and how they are geometrically composed. The strategy for spatial analysis through drawings was to highlight the volumes and show their overlapping quality by filling the interlock with layers of colored transparency. The hypothesis was that the area with the most overlapping quality would best enhance the spatial air flow. Figure 1 shows the five selected buildings as axonometric drawings analyzing their spatial composition. To test this hypothesis, the Esherick house was studied extensively due to connecting double height space that the building forms.

The digital drawings were produced after working drawings were extracted from literature or other archival resources. We digitally reproduced drawings of the five selected buildings and produced three-dimensional digital models in ‘Inventor’, which was chosen as the software to produce interior volumes that could then be used in the CFD analyses. Thus we established a way to transfer an architectural design into a format that can be read by gridding software and used in a CFD platform.

Computational Fluid Dynamics

The software FLUENT was selected as the computational framework to solve the fluid dynamics and thermal conditions for natural ventilation in a building. The software Gambit, which creates a grid of the building to be imported into FLUENT, was also compatible with the digital models created in Inventor. FLUENT has a broad range of mathematical models that are useful in simulating conditions such as wind through an open window or modeling a wood-burning fireplace. For this study, the relevant equations to describe natural ventilation included conservation of mass, momentum (fluid motion) and energy (temperature changes). The resulting simulation provides information on the velocity, pressure and temperature changes with respect to time. Pressure does not vary significantly; however, velocity and temperature can have significant changes depending on the specified conditions. Further details on the CFD models and efforts can be found in Appendix C.

Simulations of the Esherick House were conducted to show how the spatial layout affected airflow for passive cooling and heating. For the case of passive cooling, it was assumed that
one side of the building was subjected to solar radiation (analogous to direct sunlight on a hot summer day). The front door and lower window on opposite sides of the building from the direct sunlight were open to allow for a mild breeze (0.5 m/s = 1 mph) to enter the building. For the case of heating, all windows and doors were closed and it was assumed that both fireplaces were operating. Results of these simulations will be discussed next.

**Key Findings**
Two conditions representing passive cooling and heating will be presented for the Esherick house. Simulations were run to demonstrate airflow and temperature changes for a time lapse of 2 minutes (120 seconds). It is worth noting that the CFD simulations were computationally intensive and limited the number of simulations that were performed.

The case for passive cooling did not have many windows open and demonstrated that airflow within the building is minimal. Figure 2 shows four views of the Esherick house and the temperature changes at key locations. For example, the upper two frames are cross-sectional views (looking down on the house) for the lower (y=2.5 m) and upper level (y=4.0 m), respectively. The variable y indicates the height within the building from ground level. The variable x is the length of the building and z is the perpendicular direction. As expected, the first level of the Esherick House (y=2.5 m) maintained temperatures between 20–24°C (68–76°F), which is a very comfortable interior climate in the summer. Interestingly, the lower left side of the building was 4°C cooler than the right side; the lower temperatures can be attributed to the spatial layout that formed a large open space from floor to ceiling. The second level (y=4.0 m) was significantly warmer, with temperatures ranging from 25-29°C (77–84°F). The other two views (x=6.75 m and z=4.8 m) show side views of the house and the lower right view indicates the location of the other views with the labeled black lines. The side views demonstrate how the air temperature stratifies vertically, where the warmest air is closest to the ceiling of the second level. Figure 3 shows four frames of the same side view at different times to demonstrate how the airflow affects air temperature over a 2 minute time interval.

**Conclusions**
The preliminary research based on this project demonstrated that CFD can be integrated into the architectural design process and can be used as a tool to predict performance of complex spatial building configurations. Future work will open a huge new field of inquiry into the relationship of how energy transfers relative to the building layout. However, simulating a full three-dimensional building requires experience and expertise, and most importantly, large computational times. The benefit of using CFD is that it will be possible to gain more knowledge on best practices of how spatial proportions enhance/impede airflow for effective ventilation.

The simulations of the Esherick house demonstrated that intuition does not always reflect the complex situation. For example the simulations showed that the height of space (floor to ceiling) has an enormous effect on the air movement and consequently, the temperature stratification of the air in the room between the single and double height spaces. Another
conclusion was that only a whole building simulation can predict the complexity of natural ventilation in a multilevel spatial composition where spaces interconnect and intertwine. Effects such as solar radiation or a mild breeze and cross-flow can not otherwise be detected. Further studies to verify the influence of spatial composition of the Esherick House and the other 4 buildings are necessary to compare different ventilation settings and will be conducted as part of a Master’s thesis at Virginia Tech. The research will continue and our team is confident that they will find further funding with the results of these initial findings.
Figure 1. Spatial analysis as axonometric drawings of case studies: Esherick House, Schwartz House, How House, Viipuri Library and the Des Moines Art Center (Saarinen wing) highlighting the composition of free flow open space.
Figure 2. Cross-sectional views of the Esherick house for passive cooling 120 seconds after the front door and downstairs window are open. Each frame shows the temperature variation within the building. The view labeled $z=4.8$ m is at the center of the building. Also identified in the view are 3 black lines that correspond to the 3 planes shown in the other views.

Figure 3. Cross-sectional view at the midplane ($z=4.8$ m) of the Esherick house for passive cooling. Each frame shows how the temperature of the air within the building changes every 30 seconds after the front door and downstairs window are open.
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Appendix A: Bibliography


Appendix B: Spatial Analysis Drawings

This section elaborates on the performed spatial analysis of the selected architectural precedence and their volumetric composition. Eliel Saarinen (1873-1950) worked as an established architect in Finland, where he built the central railway station in Helsinki, and in the Midwest of the U.S., where the Cranbrook Art Institute is his major work. From his mature work we chose the Des Moines Art Center in Des Moines, Iowa (est. 1947) which demonstrates a linear connection of various volumetric heights culminating in a center space at the intersection of two courtyards. Although the adjacent galleries are air-conditioned, this central space can be cross-ventilated and enhances air flow across the courtyard pond in the hot and humid Iowan summers as shown in Appendix D Figure IV.

Alvar Aalto (1898-1976) was one of the pioneers of the Modern Movement whose designs used free flow open space in a very sensitive relationship to the harsh climate of Finland. We chose the Viipuri Municipal Library in Vyborg, Russia (est. 1935) in spite of the fact that it was designed for mechanical ventilation. Its historical fate was war damage and partial reconstruction, and thus the consequential failure of its mechanical forced air system. Thus, the library operated for decades exploiting natural ventilation along the free flow interlocking spatial volumes. The spatial composition elaborates on the interlocking of two main cubic volumes with three split levels, connecting the main lobby with the library reading areas and facilitating the circulation of air and people as shown in Appendix D Figure Vd. We studied all design stages of the library as shown in Appendix D Figures. Va-c, as the free flow open space evolved during this important work of Aalto’s career.

From the realm of residential typology, we added three different patterns. From the work of Frank Lloyd Wright (1857-1959), whose designs established an architectural standard for the Midwest climate, we chose the Bernhard Schwartz House in Two Rivers, Wisconsin (est. 1939), where two horizontally-layered cubic volumes are placed at right angles as if sliding past each other. The two volumes form a double height open space at their intersection as shown in Appendix D Figure III.

The second house selected is the Esherick House in Chestnutt Hill, Philadelphia, Pennsylvania (est. 1961) by Louis I. Kahn (1901-1974), where its spatial composition is intentionally designed for natural ventilation and the façade elaborates wooden shutters to modify the flow. The spatial composition explores the connection of two single and one double height spaces incorporated within a compact volume as shown in Appendix D Figure I.

As a third residential project, we analyzed the How House in Los Angeles, California (est. 1925) by Rudolph M. Schindler (1887-1953), one of his most spatially complex buildings, where he elaborated on the ‘Raumplan’, initiated by the Viennese architect Adolf Loos (1870-1933), to compose spatial flow within the connection of cubic volumes along a diagonal composition of cubes. The building is composed of cubic volumes of various heights and scale-aligned on a diagonal as shown in Appendix D Figure II. At the central junction, a vertical shaft or well is bolted through all other main volumes opening the house to the elements, thus enhancing
natural ventilation on this mountain site. This is a unique feature in architectural composition possible only in this mild Californian climate with little precipitation. His work is especially important in this context as he strongly considered the relationship to air flow and space as a health issue in his theoretical text.

The spatial analyses conducted through the drawings showed that five different types of overlapping free flow open spaces can be differentiated and defined as follows:

1. INCORPORATED SPACE: the connecting double height space is incorporated in an all encompassing volume (Esherick House as shown in Appendix D Figure I)
2. BOLTED SPACE: the main ventilation space acts as a bolt joining various levels of the building. (How House as shown in Appendix D Figure II)
3. SLIDING SPACE: two perpendicular spaces are sliding past each other on different heights with the double height volume opening up where both volumes meet. (Schwartz House as shown in Appendix D Figure III)
4. CULMINATING SPACE: a linear sequence of horizontal spaces culminates in a double height space, which allows for visual connection and cross ventilation between two exterior court spaces. (Des Moines Art Center Saarinen Wing as shown in Appendix D Figure IV)
5. INTERLOCKING SPACE complex interlocking of intertwined split level volumes in a holistic composition (Viipuri Library as shown in Appendix D Figure Va-d)
Appendix C: Computational Fluid Dynamics Modeling and other Results

The computational modeling is a very important aspect of any CFD simulation. There are many commercial software tools available but the user requires experience to be successful. In order to simulate complex flows such as air movement through a whole building, the appropriate models and boundary conditions must be specified in the computational software. Furthermore, it is important to establish that the simulation is predicting physical and (mathematically) accurate results.

The computational software chosen for this research was FLUENT, which is a very popular CFD tool. Before a simulation proceeds, a grid of the building must be constructed. The software GAMBIT was chosen to create the grid because it is compatible with FLUENT. Also, the CAD software, Inventor, used to create the architectural building designs, can be exported with an “igs” extension to be read by GAMBIT. Thus, a file with an igs extension is imported into GAMBIT where a mesh is created and boundaries are specified. The grid is exported to FLUENT where additional models are specified so that the mathematical equations which describe fluid dynamics and heat transfer.

Significant time was spent determining the appropriate grid cell size and CFD models to accurately represent the physics of the air movement within the buildings. The grid, or mesh as sometimes referred, is composed of millions of small parallelepipeds adjacent to each other and filling the volume of the building. An example of the mesh used for the Esherick house is shown in Fig. 4. Ideally, the grid resolution, i.e., number of cells, should be increased systematically to determine the number of cells such that the CFD solution is not affected; this process is known as finding a “grid-independent” solution. The final grid used to simulate air flow in the Esherick house was composed of more than 600,000 cells (Fig. 4).

There were five partial differential equations necessary to solve that included conservation of mass, 3 equations for the fluid motion in 3 dimensions, and the energy equation, thus providing information about velocity, pressure and temperature. Two more additional equations are required to model turbulence. FLUENT allows the user to select what methods to use to solve the equations. The set of equations are solved simultaneously for every grid cell in the mesh and for every advance in time. Another challenge with obtaining an accurate CFD solution is ensuring that the solution is converged, that is, the overall answer satisfies mathematical and physical principles. As the simulation advances in time (e.g., simulating 1 second, 2 seconds, 3 seconds, etc.), care was taken to make sure that the solution converged. Thus, simulating air flow in a full size building is computationally intensive when the grid is composed of many cells and the problem is time-dependent.

The example of heating by way of fireplaces is shown in Figure 5 at a time of 120 s after the fireplaces were turned on. The lower level tends to remain at a constant temperature of 20°C. The second level is definitely warmer than the lower level (20–40°C); however, it is important to note that for this preliminary study, heat loss through the building walls was not modeled. It is expected that once heat loss is included in the simulation, the temperatures will remain at a
more comfortable level. As further evidence of how the air moves, Figure 6 shows four frames of the side view at different times to demonstrate how the natural convection affects air temperature over a 2 minute time interval. It is important to recognize that there are no windows or doors open. Thus, the air movement is a direct consequence of buoyant effects, which implies that lower density fluids such as warm air rise and higher density fluids such as cooler air (relative to the warm air) descend.

Figure 4. The upper left figure shows the full grid define for the Esherick house and the right view is an enlargement of the mesh to show the grid cells that compose the volume of the house
Figure 5. Cross-sectional views of the Esherick house for heating 120 seconds after the fireplaces are turned on. Each frame shows the temperature variation within the building. The view labeled $z=4.8$ m is at the center of the building. Also identified in the view are 3 black lines that correspond to the 3 planes shown in the other views.

Figure 6. Cross-sectional view at the midplane ($z=4.8$ m) of the Esherick house for heating. Each frame shows how the temperature of the air within the building changes every 30 seconds after the front door and downstairs window are open.
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Appendix D

I. Louis Kahn: Esherick House 1" : 20'

II. R.M. Schindler: James How House 1" : 20'

III. Frank Lloyd Wright: B. Schwartz House 1" : 75'

IV. Eliel Saarinen: Des Moines Art Center 1" : 75'

V. Alvar Aalto: Viipuri Library
   a. Phase I 1" : 50'
   b. Phase II 1" : 50'
   c. Phase III 1" : 75'
   d. Phase IV 1" : 50'

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IV. Eliel Saarinen: Des Moines Art Center
IV. Eliel Saarinen: Des Moines Art Center
IV. Eliel Saarinen: Des Moines Art Center
V.A. Alvar Aalto: Viipuri Library Phase I
V.A. Alvar Aalto: Viipuri Library, Phase I
V.A. Alvar Aalto: Viipuri Library, Phase I
V.A. Alvar Aalto: Viipuri Library, Phase I
V.A. Alvar Aalto: Viipuri Library, Phase I
V.A. Alvar Aalto: Viipuri Library, Phase I
V.B. Alvar Aalto: Viipuri Library Phase II
V.8. Alvar Aalto: Viipuri Library, Phase II
V.8. Alvar Aalto: Viipuri Library, Phase II
V.8. Alvar Aalto: Viipuri Library, Phase II
V.8. Alvar Aalto: Viipuri Library, Phase II
V.c. Alvar Aalto: Viipuri Library, Phase III
V.c. Alvar Aalto: Viipuri Library, Phase III
V.c. Viipuri Library: Phase III
V.C. Alvar Aalto: Viipuri Library Phase III
V. D. Alvar Aalto: Viipur Library, Phase IV
V.D. Viipuri Library: Phase IV