Developing Thermal Intuition Using Building Thermal Simulations in the Classroom

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INTRODUCTION

Education has commonly been viewed as the most effective path to cure various ills in society and has been used with varying degrees of success to combat problems in diverse subjects. One pressing problem of the near future is energy efficiency in buildings. In the United States, nearly one third of all energy consumed is used to thermally condition the indoor environment. This thermal conditioning requires the use of energy, which is traditionally linked with perceived negative effects on the environment. The overuse of energy in buildings has two effects: first, an increased reduction in the natural resources of the planet and second, a potential reduction in the quality of life for those living on the planet. In general, architects and architecture students have a desire to minimize the negative impact that their designs have on the environment aesthetically and thermodynamically. Much time is spent in the course of an architectural education studying the aesthetic effects of buildings on the surrounding environment. In most cases, some time is also spent on the thermal physics aspects of buildings; however, it is indeed rare that energy conscious design is taught in the classroom as a potential solution to both energy efficiency and environmental concerns.

In spite of the lack of attention given to the subject in the architectural curriculum, it is widely understood that natural resources are limited in nature. We do not have an endless supply of energy to use. Even solar power, which is perceived as a relatively inexhaustible source of energy, has yet to ever be harnessed effectively on a wide scale basis. It is obvious that the faster we consume resources, the faster we will exhaust our limited supply. In addition, the more scarce resources become, the most expensive those resources will become.

Public policy at all levels is requiring that more attention be given to the energy conscious design of buildings. The federal government and the state of California have recently adopted regulations that mandate more energy efficient buildings for public use. Eventually, some form of these guidelines will be adopted by other state governments as well as by local governments. These guidelines will affect both public and private construction to satisfy both economic and environmental concerns.

So, where does one conserve energy in a building and how does one impart to students ways in which they can learn about energy efficiency and be prepared to grow as architects once they have graduated into practice?
Certainly, the production of the building materials and the actual construction of the building consume a large amount of energy. Nevertheless, the life-cycle energy cost of operating the building usually far exceeds the energy cost related to production and construction. This paper will restrict itself to discussing energy conservation during the operational phase of a building.

This leads to two other important questions: how does one save energy during the operational phase and why is the architect responsible for this? The response to the first question has traditionally been the development of technologically advanced heating, ventilating, and air-conditioning (HVAC) systems. Yet, these technologies, in general, are limited, partial solutions that are applied in the post-design phase. Trying to reduce heating and cooling loads in a building by applying more efficient HVAC systems is akin to attempting to close a window by placing a screen over it. One can change the density of the screen or make it technologically sophisticated, but the window is still open. The same is true for the building energy efficiency. Working to increase the efficiency of a heat recovery system from 70 to 80% is certainly worthwhile, but it does not attack the heart of the problem—the cost of human comfort in the form of the building heating and cooling loads.

The real place to have a significant impact on the energy consumption of a building over its lifetime is in the design phase. The integration of energy efficiency into the building design process has the potential to save a considerable amount of energy. Naturally, the exact amount is highly dependent on the structure under consideration, location, environmental factors, etc. However, energy efficient design has an immediate impact on the energy consumption of a building by reducing the heating and cooling loads that the mechanical system has to meet.

Given that the building design and construction are the place where there is the potential to save energy, it follows logically that the architect is in a prime position to design a building that is more energy efficient. This is only possible with some basic understanding of thermal physics and how these principles apply to building heating and cooling loads. The most important place to lay the foundation of such knowledge is during the course of an architect's formal education.

Historical Perspective and Future Trends

The oil crisis of 1973/74 rudely awakened the United States to an unprecedented level of energy consciousness. A flurry of activity at the Federal level resulted in mandated energy efficiency ratings for household appliances, tax incentives to offset the cost of energy conservation measures, and perhaps most significantly, the establishment of the Department of Energy in 1977. Two research initiatives sponsored by the Department of Energy in the late 1970's have proven pivotal in the current trend toward energy conscious design of building systems. These research initiatives resulted in widely available building energy computer programs and low cost solar energy systems. Together these developments at once established the importance of the building fabric in energy efficient design and quantified the energy cost of envelope related design decisions.

Until recently, the impact of these two pivotal research initiatives has been largely lost on the architectural education community. Thermal analysis of the building envelope, once considered the exclusive domain of research engineers has made its way to the architect's desk in the form of neatly packaged computer applications. With these tools come the opportunity and the responsibility to add a new dimension to the building design education process. Thermal intuition, in addition to aesthetic awareness, can and should be considered well within the purview of the architect. This broadening of perspective, however, requires rethinking the educational process.

Historically the education of the architect in the area of mechanical systems has been constrained by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) procedures and standards as well as by the requirements for professional licensure. Educators have understandably been reluctant to deviate from ASHRAE methods in the classroom. In many cases, however, the emphasis on procedures and licensure has resulted in a myopic focus on rote calculations and has failed to develop an intuitive feel for the thermal aspects of the building. The problem has been compounded by the fact that until recently ASHRAE procedures did not support an integrated treatment of the building envelope, the building mass and the mechanical systems. During the last two decades, pragmatic and political considerations resulted in a proliferation of simplified ASHRAE cooling load calculation procedures and chart based system design methods. These procedures were more or less incompatible with the development of thermal intuition in the student.

With the publication of *Load Calculation Principles* in 1998, (Pedersen, et. al.), ASHRAE signaled a clear shift toward fundamentally based procedures that support the development of an integrated approach to the thermal aspects of building design. Thermal models, graphically driven thermal simulation, and characterization of the building's thermal attributes are supported under the new procedures. It is now possible to develop thermal intuition within the context of ASHRAE procedures. The following sections discuss the key features of an undergraduate mechanical systems design course that stimulates the development of thermal awareness in the architect.

Thermal Simulations in a Classroom Setting

As part of a introductory level course dealing with HVAC and associated issues, thermal simulations are capable of advancing a student's knowledge and preparing the student for the lifelong learning experience of architectural practice. This section briefly describes some of the goals for using thermal simulations in a classroom setting and also introduces undergraduate level coursework that has been under development for over a year.

GOALS

Basic Thermal Physics Understanding

In order to understand how various environmental factors will influence the thermal loading of a building, it is imperative that an understanding of basic thermal physics be developed in a methodical, logical manner. Understanding basic thermal physics allows one to isolate parameters and begins to establish cause and effect relationships between changes in environmental factors and the resulting building thermal loads. While the hand calculation techniques formerly used by most practitioners gave some indication of the physics involved, many times the simplified calculation blurs the actual process and any insight that can be gained from it beyond recognition. For example, film coefficients are commonly used to simplify radiation and convection from a surface to the surrounding environment. Yet, this simplification has very limited applicability and obscures what is actually happening at the surfaces. Without an understanding of the basic underlying processes, use of these coefficients can result in a thermally inadequate design.

Introducing a heat-balance based thermal simulation into a classroom setting provides a springboard to discuss both the physical processes and the calculation of the thermal loads. Investigating heat balances at various locations—such as at the outside surfaces, inside surfaces, and air nodes—allows each physical process to be singled out, explained, and understood. An understanding of the basic thermal processes inherent in buildings is crucial to understanding how changes in a building design might alter the thermal loads. Just as it is not possible to build an effective truss without any knowledge of structural theory, it is also not likely that energy efficiency will result without a basic knowledge of thermal physics. In addition, without a basic knowledge of thermal physics, more complex issues such as passive solar, thermal mass, etc., remain abstract concepts that are not applied in the correct circumstances because of the lack of understanding of how they really work.

Introduction to Energy Analysis and Load Calculations

The use of thermal simulations in a classroom setting gives students hands-on experience with some form of energy analysis or load calculation tool. This goes beyond generic computer experience to provide targeted exposure to real world tools already in use by architects and engineers. With energy likely to be at a premium in the new century, experience with thermal simulation programs will be essential from the earliest phases of design. Experience with one such program during the formal education phase of learning provides a basic working knowledge of a particular program. In addition, since most of the thermal simulation programs are similar in nature from the perspective of underlying concepts, this can translate into the ability to get up to speed much more quickly with other tools in the field.

Begin the Development of "Thermal Intuition"

The key role of the architect in the construction process is the synthesis of a wide variety of disciplines through different design stages into one integrated product—the building. At each step during this complex process, the architect uses knowledge, intuition, and modeling to progress to the next level of detail. Aesthetically, the architect uses spatial intuition acquired through the experience of other buildings and personal style to create a desired emotional or intangible response to spaces within a design and to the overall design. This intuition is based on knowledge gathered through a lifetime of learning and is then proven through the creation of models which help to convey the sense of space to others. Similarly, the architect will use structural intuition at key points in the design process to develop a structural plan for the design. Again, this intuition is built on experience with other projects and knowledge gained during the academic years. Moreover, this intuition is validated through structural modeling and calculations. Naturally, the architect must balance all of these potentially competing ideas and arrive at the most optimal solution.

The process of integrating energy efficiency and thermal aspects into the design process needs to follow this same approach. In the ideal situation, the architect will use thermal intuition gained through learning the fundamentals and designing other buildings to fuse energy efficiency into the overall design process as a partner with all of the other aspects of design: space, structure, lighting, sound, etc. Further, just as producing physical models is important to checking spatial intuition, creating thermal models is crucial to checking that the complex interactions of the building's thermal physics has been correctly understood.

It is important to note that thermal intuition is not something that is gained quickly or can be completely "taught". However, it must have a starting point that is based on the fundamental physics associated with the problem so that the thermal intuition has some basis in thermal principles. Thus, the goal of a basic understanding of thermal physics is a crucial prerequisite to developing thermal intuition.

Yet, thermal intuition alone is not enough, and the use of thermal simulations to provide numerical backing to the developing intuition is critical. As a result, the goal of some level of competency in thermal simulation tools is important to checking one's thermal intuition and further developing and honing it. Thus, the development of thermal intuition is a lifelong process that upon successful completion of the first two goals mentioned above can be started during the formal education of the future architect. In addition, having thermal intuition as an architect, allows for the integration of energy concerns throughout the design process so that it can have the greatest impact on the design and can be given proper consideration with all of the other factors that must be balanced in a particular project.

Preparation for Revisions to Licensing Exam

As has been mentioned in the previous section, changes in the methods for calculating thermal loads approved by various professional groups such as ASHRAE are currently underway. This will eventually result in changes within the architectural profession and the licensing exam. Such changes should be anticipated and embraced by courses in the area of HVAC and thermal physics so as to better prepare students for potential changes to the architectural licensing exam. While licensure should not be the single goal of students, it should be a consideration in how courses are taught, especially when the goals of educational program map over to preparation for the licensing exam.

Laboratories

The four goals presented above were the main driving forces behind introducing thermal simulations into the basic undergraduate HVAC course for architecture students. While lectures on thermal simulations provided a solid basis for imparting knowledge about thermal physics to the students, the goals of familiarity with thermal simulation software and the first steps toward the acquisition of thermal intuition can only be obtained through hands-on experience. This was achieved during a 3-4 week period (approximately 10 contact hours) during the semester.

The software package used for these computer laboratories was the BLAST/HBLC program. HBLC is a Windows based user interface that is employed to sketch a footprint of the building, define the physical layout and characteristics of the building, etc. It also serves to create input files for and launch the BLAST (Building Loads Analysis and System Thermodynamics) program. Architects and engineers have been successfully used BLAST since its introduction in the 1970s. The program has undergone continual revision and numerous enhancements since the initial public release. While other programs could also be used with similar success, BLAST/HBLC was chosen due to its availability, its ability to be installed over a campus network, the relative friendliness of the user interface, and its implementation of the heat balance based method for calculating heating and cooling loads that has become the ASHRAE standard.

Using these thermal simulation tools, two exercises were designed to meet the goals of the previous subsection. In both cases, a real building was used as a case study to investigate different aspects of the thermal environment and how the building responds to these various forces. Each of the exercises is described briefly below.

Basic Heating and Cooling Loads (SS vs. Transient)

The first exercise was simple in nature in order to allow the students to gain experience with the software package without being overwhelming in detail. The case study building was modeled as a single thermal zone for typical design day weather conditions. The base case model was compared with a "zero thermal mass" variation on the building. This required the students to calculate R-values for all of the building elements and alter the constructions in the alternative so that the R-value remained the same while removing all thermal mass from the building.

The exercise reinforced the simple sensible heating load hand calculation exercise (since this is a steady state calculation there is no difference between the base case with thermal mass and the alternative which had no thermal mass) and pointed out the problems and potential danger of neglecting thermal mass in a transient problem such as a cooling load calculation. Since this was a simple case where the weather environment was the only thermal driving force being applied to the building, the students were able to visualize the basic thermal physics effects and begin to both interpret results and build intuition.

Thermal Zoning and the Effect of Windows, Internal Gains

The second exercise introduced the concept of thermal zoning and added common thermal effects such as internal gains from people, lights, and equipment to see how these different aspects of thermal modeling affected the cooling loads. The base case model used single pane windows as the glazing system. In the alternative, the only change made in the building was to switch from single pane to double pane windows.

This exercise served to move beyond the basic knowledge of physical processes that occur in a building and start to develop and check their thermal intuition. The students assumed, reasonably so, that the cooling loads would go down when the double pane windows were introduced. This was based on their knowledge that double pane windows would have a higher thermal resistance and would thus tend to reduce the heat gain from the outdoor environment of the various spaces. The use of the thermal simulation program allowed them to test that assumption and show that it was not true in this case. This allowed for fruitful discussions where the students learned that their base assumption was valid for a heating load where steady state assumptions hold but there were other factors to consider with the transient cooling load case.

CONCLUSIONS

The current state of both the methods used to teach architectural students about thermal physics and the shift in focus by the professional societies from hand calculation methods to heat balance based methods for calculating thermal loads offers a historic opportunity to significantly improve the educational experience at both the graduate and undergraduate levels. To address these factors as well as the growing push for the design integration of all disciplines of architecture at the earliest possible levels of education, a different approach to introducing thermal physics and HVAC concepts to students has been proposed.

The goals of imparting a basic understanding of thermal physics and analyzing how the building responses to various environmental factors through the use of simulation can be achieved without radical curriculum changes. When successfully implemented into an undergraduate course on building thermal physics and HVAC, these initial two goals lead to a third goal: the development of thermal intuition which can then be used from the earliest phases of the design process to allow energy efficiency to be considered as a design feature rather than an afterthought. Certainly, energy efficiency is not the only goal of a building. Aesthetics, structural integrity, lighting, emotional response, etc., all play vital roles in the way a building is perceived. Even energy efficiency itself is not a simple bottom line fiscal or environmental concept. A building's thermal environment can influence important concepts such as quality of life and worker productivity. Clearly, a balance must be struck between all of these forces. For that to happen, all aspects of a building must be considered at all stages of the design process. Thermal intuition allows this to take place, and as discussed in the preceding sections, the process of developing thermal intuition can be started even at the undergraduate level.

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