AC 2011-2607: A COMPREHENSIVE STUDY TO DESIGN HVAC SYSTEMS AND EVALUATE ENVELOPE PERFORMANCES

Ahmed Cherif Megri, University of Wyoming

Dr. Ahmed Cherif Megri, associate professor of architectural engineering at the University of Wyoming (UW), teaches several HVAC and energy courses. Dr. Megri is also teaching a course titled "Comprehensive Performance of Building Envelope and HVAC Systems" for Summer School at UW, and "Smoke and Fire Dynamics" during summer session at Concordia University, Canada. His research areas include airflow modeling, zonal modeling, energy modeling, and artificial intelligence modeling using the support vector machine learning approach. Prior to his actual position at UW, he was an assistant professor and the director of Architectural Engineering Program at Illinois Institute of Technology (IIT). He was responsible for developing the current architectural engineering undergraduate and master's programs at the Illinois Institute of Technology (IIT). During his stay at IIT, he taught fundamental engineering courses, such as thermodynamics and heat transfer, as well as design courses, such as HVAC, energy, plumbing, fire protection and lighting. Also, he supervise many courses in the frame of interprofessional projects program (IPRO).

In few months, Dr. Megri will defend his "Habilitation" (HDR) degree at Pierre and Marie Curie University - Paris VI, Sorbonne Universities.

A Comprehensive Study to Design HVAC Systems and Evaluate Envelope Performances

Ahmed Cherif Megri
Associate Professor, amegri@uwyo.edu
University of Wyoming
Civil and Architectural Engineering Department
Laramie, WY, USA

Abstract:

In this paper, we discuss two types of projects performed by architectural engineering students: design and experimental projects. First, the design project methodology will be discussed, beginning with system selection (fan coil, VAV (Variable Air Volume) terminal box, under floor air distribution system, displacement ventilation and beam system), heating and cooling load estimation, systems sizing, airflow distribution, commissioning and culminating with administrative topics. We demonstrate this methodology through the use of a comprehensive design project.

Secondly, we describe the experimental project. In this project a comprehensive experimental study is conducted by undergraduate students on a number of residential houses to improve the energy efficiency of these houses and identify the most appropriate energy conservation measures. We describe the work performed by students starting from the building instrumentation, the measurement and the monitoring of the energy consumption of the building systems, as well as the use of advanced energy simulation programs such as, Visual-DOE, eQuest and EnergyPlus for energy prediction purposes.

The results of a number of experimental studies, such as duct blaster testing, blower door testing and infrared thermography has been demonstrated. Also, we show how these techniques have been used to improve the students' understanding of different concepts and techniques, such as pressurization, pressure and airflow measurements, duct leakages and building tightness, temperature and humidity distribution within building envelop and HVAC systems.

1. Design Project:

This course is the final course in the building mechanical systems sequence. It incorporates elements of previous design courses by executing the design of a hypothetical building with a concentration on a detailed design of the project's mechanical systems.

During the preliminary phase the budget is estimated based on the cost of equipment and materials, shipping, and labor. Two systems are selected by the students with the guidance of the instructors, based on the building characteristics, the building functions, and the level of comfort requested and evaluated based on economy and effectiveness.

During the final design, the development of an HVAC system design can be divided into several major categories:

- HVAC Design Criteria Manual (DCM)
- Development of the HVAC Diagram
- System selection

- Heating and cooling load calculations and system analysis
- Preparation of an HVAC diagram and associated equipment list
- Preparation of HVAC arrangement, construction and detail drawings
- Pressure drop calculations
- HVAC noise calculations
- Equipment selection and preparation of specifications:
    - AHU analysis
    - Heat exchanger
    - Heat and reheat analysis
    - Boiler analysis
    - Chiller analysis
    - Duct clearance
- Preparation of the HVAC system drawings

The design requirements for varying types of buildings are established using the unique HVAC Design Criteria Manual (DCM), given building specifications and any other pertinent documents. Once these design requirements are determined, the HVAC diagram is created and the heating and cooling load calculations and system analysis are performed, either manually or automatically through the use of several available software packages.

Students create 2-D CAD HVAC diagrams that visually demonstrate the HVAC system arrangements, indicate the spaces served, identify airflow quantities and label HVAC equipment. Throughout this design phase, HVAC equipment lists are prepared to provide all necessary engineering equipment data.

Under the supervision of their instructor, students use AutoCAD to prepare their HVAC detailed design drawings, including the HVAC system component spatial arrangements, construction drawings, installation details, ductwork fabrication sheets and part lists.

Pressure drop calculations are the next step. To calculate these pressure losses within the HVAC system, computer programs are utilized as a student design tool. These programs employ the three main design methods: Equal friction, balanced capacity (balanced system by changing diameters) and static regain methods.

Careful selection and sizing of HVAC equipment can reduce initial costs, increase homeowner comfort, increase operating efficiency, and greatly reduce utility costs. In contrast, over-capacity equipment systems have higher initial costs, operating costs, and may in fact be less effective than optimally sized systems.

Design Considerations:

a. ***Systems selection***

Proper heating and cooling system selection takes into consideration fuel sources (e.g., natural gas and electricity), distribution mechanisms (e.g., air and hydronic), equipment options (e.g., furnace and heat pump), and equipment efficiency.

A life-cycle analysis of various, properly sized HVAC options must be performed in order to select a cost-effective system. Cost considerations include equipment and installation prices, annual heating and cooling expenses, and maintenance costs. Although more difficult to evaluate, equipment reliability, longevity, warranty coverage, and safety are also important.

For example, heating fuel sources directly impact system operating costs. Also, high-efficiency heating equipment often costs more than standard-efficiency models, however they cost less to operate. Therefore, life-cycle cost rather than initial purchase price may make high-efficiency equipment and fuel selection an important economic selection criterion.

HVAC system component options include:

- VAV with terminal boxes
- Fan coils system
- Chilled Beam
- Underfloor Air Distribution Systems
- Hydronic in floor system
- Hydronic baseboard
- Electric resistance baseboard
- Evaporative cooling
- Forced air heating and cooling
- Constant volume forced air w/ evaporation cooling or air washer
- Heat pump
- Geothermal system
- Gas-fired fan coil

b. Mechanical room

The mechanical rooms contain many types of equipment, including boilers, chillers, air handling unit (AHU) systems, ductwork and piping, valves, security devices, expansion tanks, pumps and fans. Typically these rooms are located within or outside the building, or are split between inside and outside of the building. When located inside, they are typically situated either in the basement or on the roof. A design penthouse can be used as a screen for the mechanical room to improve the overall aesthetics of the building while maintaining functionality and providing protection from the effects of both wind and weather. Details included in this type of building design include openings and framing for both louvers and doors. For high-rise buildings, a mechanical floor, mechanical penthouse, or mechanical level is a story of a high-rise building dedicated to mechanical and electronic equipment. They are present in all tall buildings, including the world's tallest skyscrapers which possess significant structural, mechanical and aesthetics concerns. As a rule of thumb, skyscrapers require a mechanical floor for every ten tenant floors (10%), although this percentage can vary widely. In some buildings, they are clustered into groups dividing the building into blocks, whereas in others they can be spread evenly throughout the structure or concentrated at the top.

Mechanical floors are generally counted in the building's floor numbering, as required by building codes, but are accessible only through service elevators. However, in some circles they are excluded from the maximum floor area calculations, leading to significant increases in overall building sizes. In some cases, the building's designer arranges for the mechanical floor to be located on the thirteenth floor, to avoid problems in renting the space due to superstitions about the number thirteen.

c. Equipment selection

Trane Official Product Selection System (TOPSS) is a flexible and powerful software package that helps designers determine what Trane equipment best serves their HVAC needs. TOPSS guides the designer through various steps in order to generate a list of product selections that meet or exceed the determined specifications by using fundamental models to establish equipment performance. Many of these models are rated and certified. For example, ARI 410 establishes a single set of testing and rating requirements for determining capacities on air cooling/heating coils and product performance. If the designer enters a set of conditions and desired performances into TOPSS, the program decides on product configurations that are appropriate for the specified parameters. After performing these calculations, TOPSS provides an online location to review, print, graph, select, export schedules to Microsoft Excel™, and e-mail the designer's equipment selections to the Trane sales engineer.

2. Experimental Project:

In many states, local authorities and state officials spend significant amounts of money, time, and resources each winter to help low income families pay their heating bills. Many weatherization programs exist. However, these programs focus only on adding insulation and sealing major air leaks. Energy efficiency measures are applied with various degrees of comprehensiveness. The capstone design course objective is the conduction of a comprehensive study that includes: health, safety and indoor air quality, high priority energy and long-term efficiencies and comfort. The study conducted within the capstone course focus not only on the building envelope, but focus on all components, such as furnace, boiler, and fan that contribute to the improved energy performance of buildings.

A comprehensive experimental study has been conducted on several residential houses, and one building at the University campus (regarding the University campus building the focus has been conducted on motors efficiency and daylight control plan) to demonstrate the best ways to improve the energy efficiency, and identify the most appropriate energy conservation measures. Students have been involved as follow: about 35 undergraduate students (ARE/ME) have been divided in groups:

- Instrumentation and measurement (temperature, pressure, airflow, combustion analysis, thermography, dew point, duct leakage, equipment efficiency, and so on).
- HVAC system auditing
- Attic Auditing
- Basement Auditing
- Simulation and regression models
-

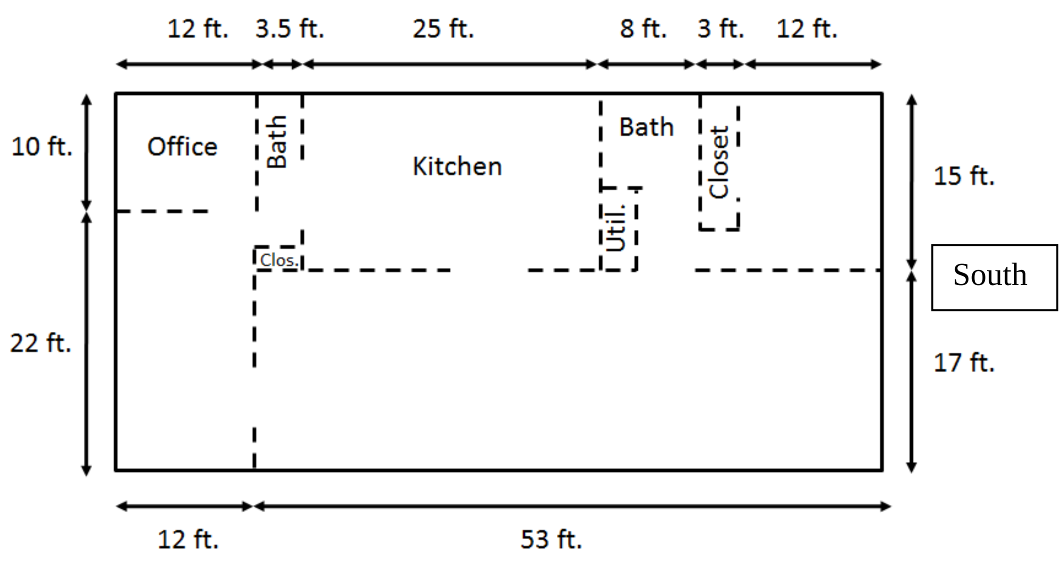

Figure 1: floor plan of the building 1 used as experimental building.

The methodology followed during this project is summarized in the following flow chart (Figure 2).

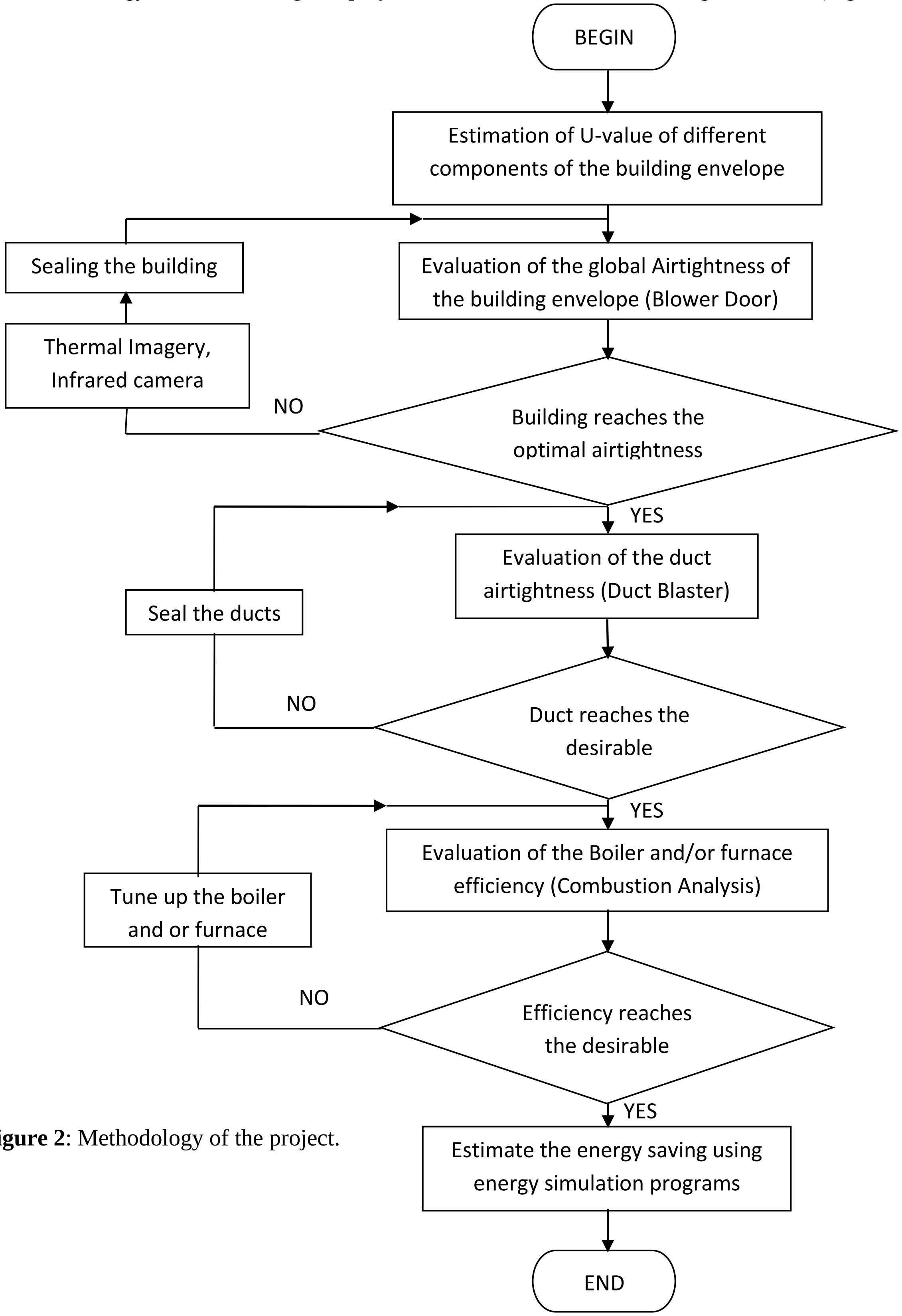

Figure 2: Methodology of the project.

The project methodology:

*S*everal buildings have been used for this study. In this paper, the results of only one building are presented. The building is an old day care center used as an experimental building for architectural engineering students. The building is about 2080 ft^2 and represented in Figure 1.

Thermal comfort and stress analysis:

The following work shows thermal environment measurements (dry bulb temperature, relative humidity and globe temperature) for the selected room (south-east corner room within building 1). These measurements were used to graph the temperature distributions over various heights of the room and to determine the mean radiant temperature. The basic parameter used to describe the radiative conditions in a space is *the mean radiant temperature*, the mean temperature of individual exposed surfaces in the environment. The most commonly used instrument to determine the mean radiant temperature is Vernon's *globe thermometer*, which consists of a hollow sphere 6 in. in diameter, flat black paint coating, and a thermocouple or thermometer bulb at its center. The equilibrium temperature assumed by the globe (the globe temperature) results from a balance in the convective and radiative heat exchanges between the globe and its surroundings. Measurements of the globe thermometer, air temperature, and air velocity can be combined as a practical way to estimate values of the mean radiant temperature:

$$T^4_{mrt} = T^4_g + C.V^{1/2} (T_g - T_a)$$

where:

T_{mrt}: mean radiant temperature, R or K
T_g: globe temperature, R or K
T_a: ambient air temperature, R or K
V: air velocity, fpm or m/s
C = 0.103×10^9 (English units) = 0.247×10^9 (SI units)

From the measured value and known equation, the mean radiant temperature was found for each different case. A Quest Thermal Environment and Heat Stress Monitor was used to take the temperature measurements and can be seen in Figure 3.

A heat stress index is a single number which integrates the effects of the six basic parameters in any human thermal environment such that its value will vary with the thermal strain experienced by the person exposed to a hot environment. The index value can be used in design or in work practice to establish safe limits. Much research has gone into determining the definitive heat stress index, and there is discussion about which is best. For example, Goldman (1988) presents 32 heat stress indices, and there are probably at least double that number used throughout the world. Many indices do not consider all six basic parameters, although all have to take them into conside ration in application. The use of indices will depend upon individual contexts, hence the production of so many. Some indices are inadequate theoretically but can be justified for specific applications based on experience in a particular industry (Parsons, 2003).

The room was split into a 3x3 grid (Figure 4). Measurements were taken in each section of the grid at three heights: 1, 4, and 6 feet. For each location, the dry, wet, and globe temperatures, WBGTI (Wet-

Bulb Globe Temperature Indoor) and WBGTO (Wet-Bulb Globe Temperature Outdoor) indices, relative humidity, and heating stress index were recorded. The obtained values at each position were then used to plot graphs that showed the variance in temperature with respect to location as well as to determine the mean radiant temperature.

Figure 3: The Quest Monitor used to take Measurements

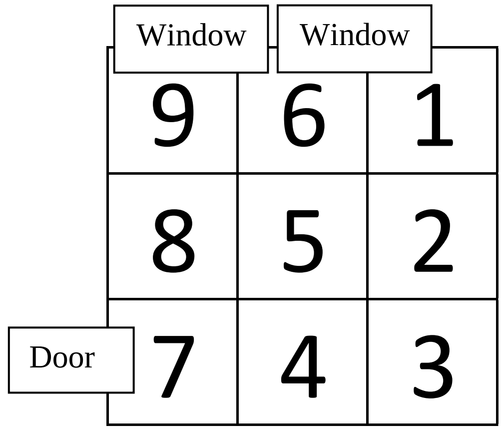

Figure 4: Room split into a 3x3 grid

The data obtained from the experimentations were used in a MATLAB code to plot the temperature distribution throughout the room (See Table 1). From the graphs, it can be seen that the temperatures were lower when the windows were open compared to when they were closed. It was actually warmer near the windows because the heater is positioned below the windows and was therefore overcoming the heat losses due to heat transfer through the windows. The right side of the room was warmer than the left side because the wall on the right was next to the mechanical room.

The thermal environment and heat stress properties of building 1 were measured and evaluated. It was seen that the temperature was cooler by the windows. When the window was open, the room was colder and the relative humidity was lower. The mean radiant temperatures were successfully calculated for each location. The raw measurements taken and respective mean radiant temperature with the windows are closed and opened are given in Tables 1 and 2. Figures 5 (a, b, c, d, e) show the temperature stratificatoin of the dry bulb, wet bulb, and globe values determiend from using the Vernon's globe thermometer with the windows closed or opened.

Table 3: Power law coefficients (C and n)

Building 1	n	C
Un-sealed Room	.78	5448
Sealed Room	.76	5046

Table 4: Estimated Cost Heating Losses for 2,000 Hours in Winter

Building 1	Total Cost
Sealed Room	$900
Un-sealed Room	$1,650

Table 1: Results of building 1 with Window Open

Location	Height (ft)	DB (°C)	WB (°C)	Globe (°C)	WBGTI (°C)	WBGTO (°C)	RH (%)	H Index (°C)	Time	Tmrt (K)	Tmrt (°C)
1	6	22.4	13.1	21.9	15.6	15.6	27.0	20.0	1:48pm	291.0	18.0
	4									273.0	
	1	20.1	10.7	20.9	13.5	13.4	22.1		1:55pm	299.9	26.9
2	6										
	4										
	1										
3	6	20.9	11.9	20.9	14.6	14.6	27.2		1:52pm	293.9	20.9
	4									273.0	
	1	17.8	9.3	18.5	12.0	12.0	25.0		1:59pm	296.9	23.9
4	6	21.1	11.6	20.9	14.5	14.5	25.8	19.0	1:51pm	292.3	19.3
	4									273.0	
	1	17.9	9.4	18.6	12.1	12.1	24.8		1:58pm	297.0	24.0
5	6										
	4										
	1										
6	6	21.7	12.1	21.4	14.9	14.9	26.2	20.0	1:49pm	292.1	19.1
	4									273.0	
	1	19.2	10.1	20.5	13.3	13.2	25.0		1:55pm	303.1	30.1
7	6	21.3	11.9	21.0	14.6	14.6	25.7	18.0	1:51pm	291.7	18.7
	4									273.0	
	1	18.3	9.6	12.5	12.3	12.2	24.3		1:57pm	214.4	-58.6
8	6										
	4										
	1										
9	6	21.5	11.9	21.2	14.7	14.7	26.6	19.0	1:50pm	291.9	18.9
	4									273.0	
	1	18.6	9.8	20.1	12.8	12.7	24.5		1:56pm	304.1	31.1

Table 2: Data Analysis (Results of building 2 with windows Closed)

Location	Height (ft)	DB (°C)	WB (°C)	Globe (°C)	WBGTI (°C)	WBGTO (°C)	RH (%)	H Index (°C)	Time	Tmrt (K)	Tmrt (°C)
1	6	22.8	13.9	22.8	16.7	16.2	30.2	22.0	1:10pm	295.8	22.8
	4	23.3	15.0	23.3	17.1	17.1	32.2	22.0	1:25pm	296.3	23.3
	1	23.2	13.9	23.2	16.6	16.6	29.4	22.0	1:31pm	296.2	23.2
2	6	23.0	13.7	23.1	16.7	16.7	31.0	22.0	1:15pm	296.8	23.8
	4	23.3	15.1	23.3	17.6	17.6	37.4	23.0	1:25pm	296.3	23.3
	1	23.1	13.8	23.0	16.6	16.6	29.8	22.0	1:32pm	295.2	22.2
3	6	23.2	13.8	23.4	16.8	16.9	32.0	22.0	1:17pm	297.9	24.9
	4	23.3	14.6	23.3	17.5	17.5	35.4	22.0	1:25pm	296.3	23.3
	1	23.1	13.8	22.9	16.6	16.6	30.4	22.0	1:33pm	294.4	21.4
4	6	23.2	14.0	23.6	16.9	16.9	30.2	22.0	1:18pm	299.5	26.5
	4	23.2	14.1	23.4	16.9	16.9	32.5	22.0	1:27pm	297.9	24.9
	1	23.0	14.0	22.9	16.6	16.6	30.3	22.0	1:34pm	295.1	22.1
5	6	23.3	13.9	23.5	16.9	16.9	30.7	22.0	1:19pm	298.0	25.0
	4	23.2	14.2	23.4	17.2	17.2	35.9	23.0	1:27pm	297.9	24.9
	1	22.9	13.6	22.8	16.3	16.3	29.1	22.0	1:36pm	295.0	22.0
6	6	23.3	13.8	23.5	16.9	16.9	30.8	22.0	1:20pm	298.0	25.0
	4	23.2	14.3	23.4	17.2	17.1	33.4	22.0	1:28pm	297.9	24.9
	1	23.0	13.7	22.9	16.5	16.5	30.3	22.0	1:35pm	295.1	22.1
7	6	23.3	13.8	23.4	16.8	16.8	29.8	22.0	1:22pm	297.1	24.1
	4	23.2	13.9	23.4	17.0	17.0	30.9	22.0	1:29pm	297.9	24.9
	1	22.8	13.4	22.6	16.1	16.2	29.0	22.0	1:37pm	294.1	21.1
8	6	23.3	13.9	23.3	16.7	16.7	29.4	22.0	1:23pm	296.3	23.3
	4	23.2	13.9	23.3	17.0	17.0	34.0	22.0	1:29pm	297.0	24.0
	1	22.7	13.5	22.6	16.2	16.3	30.0	22.0	1:39pm	294.8	21.8
9	6	23.3	13.8	23.3	16.7	16.7	29.2	22.0	1:23pm	296.3	23.3
	4	23.1	13.9	23.3	17.1	17.1	34.9	22.0	1:30pm	297.8	24.8
	1	22.7	13.7	22.6	16.4	16.4	31.2	22.0	1:40pm	294.8	21.8

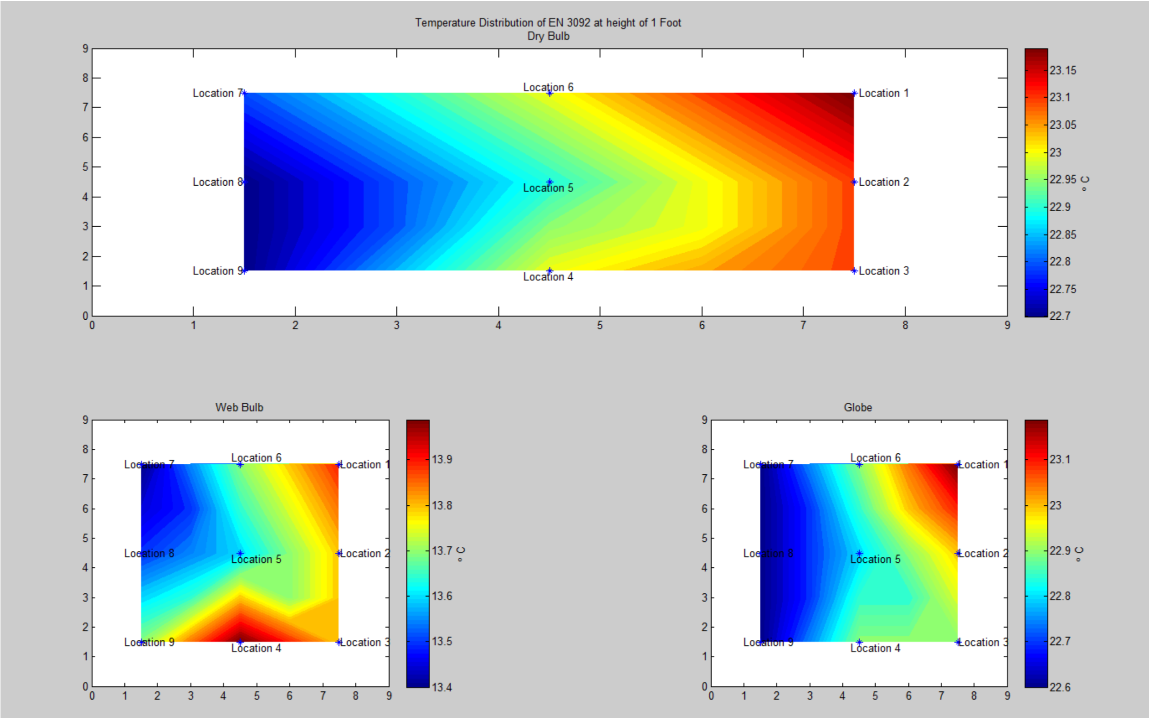

Figure 5a: Temperature distribtion at height of 1 foot (building 1) with window open

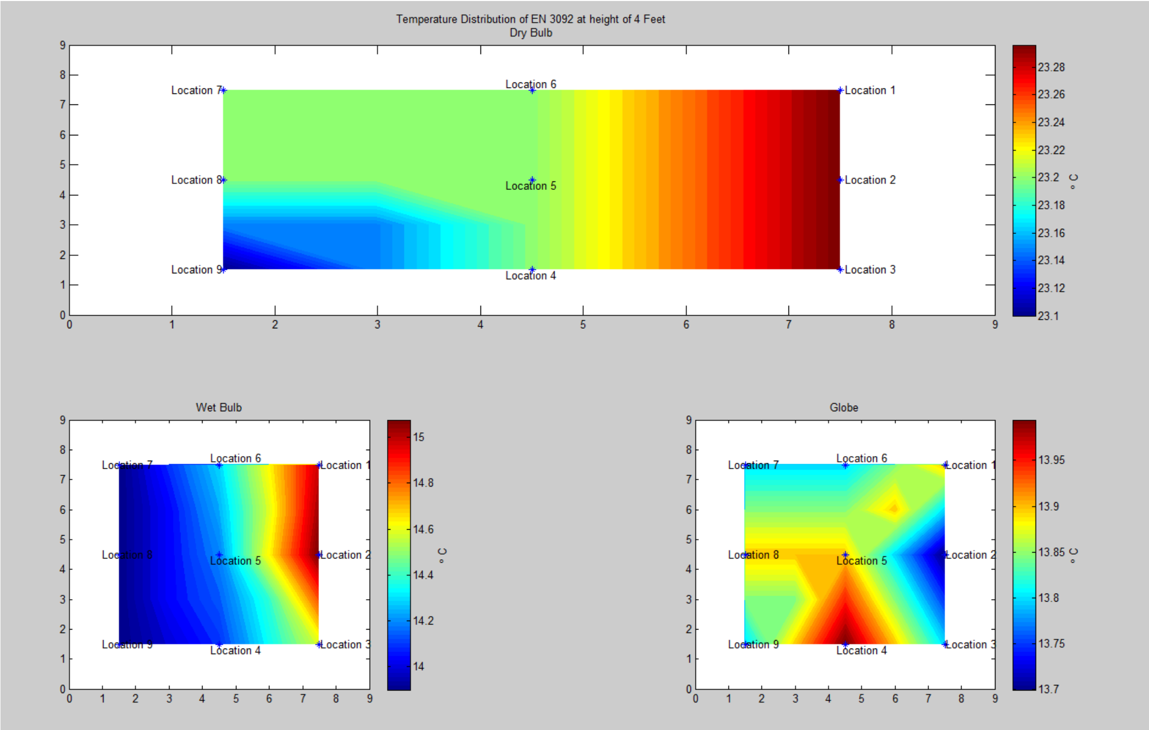

Figure 5b: Temperature distribtion at height of 4 feet (building 1) with window open

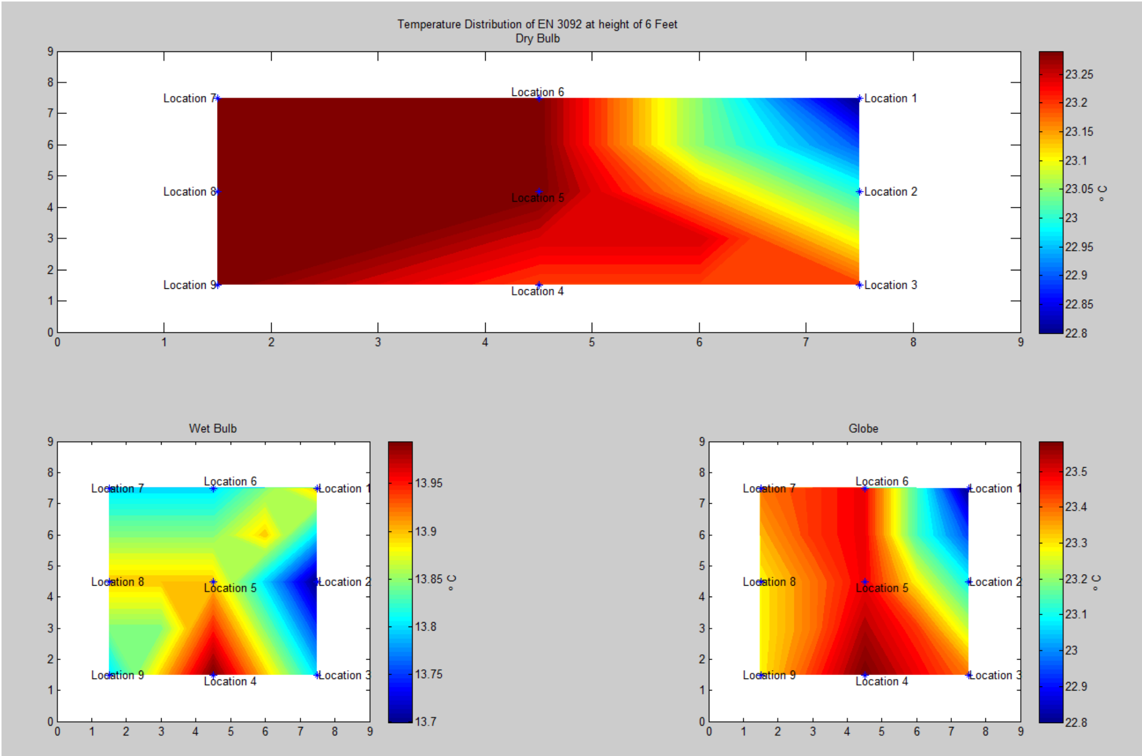

Figure 5c: Temperature distribtion at height of 6 feet (building 1) with window open

Blower Door Systems:

The Minneapolis Blower Door has long been used to predict airtightness of the buildings. It has been used combined with specialized accessories and testing procedures, such as the DG-700 digital pressure and flow gauge (Figure 6). The DG-700 contains 2 precision pressure sensors which provide simultaneous display of both building pressure and Blower Door fan flow readings. It's specialized "Baseline" and "CFM @50" features makes it extremely easy to get quick and accurate airtightness test results. Using a door screen, a variable speed blower was used to change the airflow through the envelope and the electronic monometer (DG-700) was used to record the pressure differentials and air-flow rates between the room and the hallway.

Air infiltration can be calculated using the power law equation where Q is the airflow rate, C is the flow coefficient, ΔP is the pressure differential and n the power coefficient.

$$\dot{Q} = C.\Delta P^n$$

This equation shows how much air is leaked to the outside surrounding and how air infiltration varies with respect to a pressure differential. This relation was used to estimate the cost due to heating losses from infiltration for one winter season.

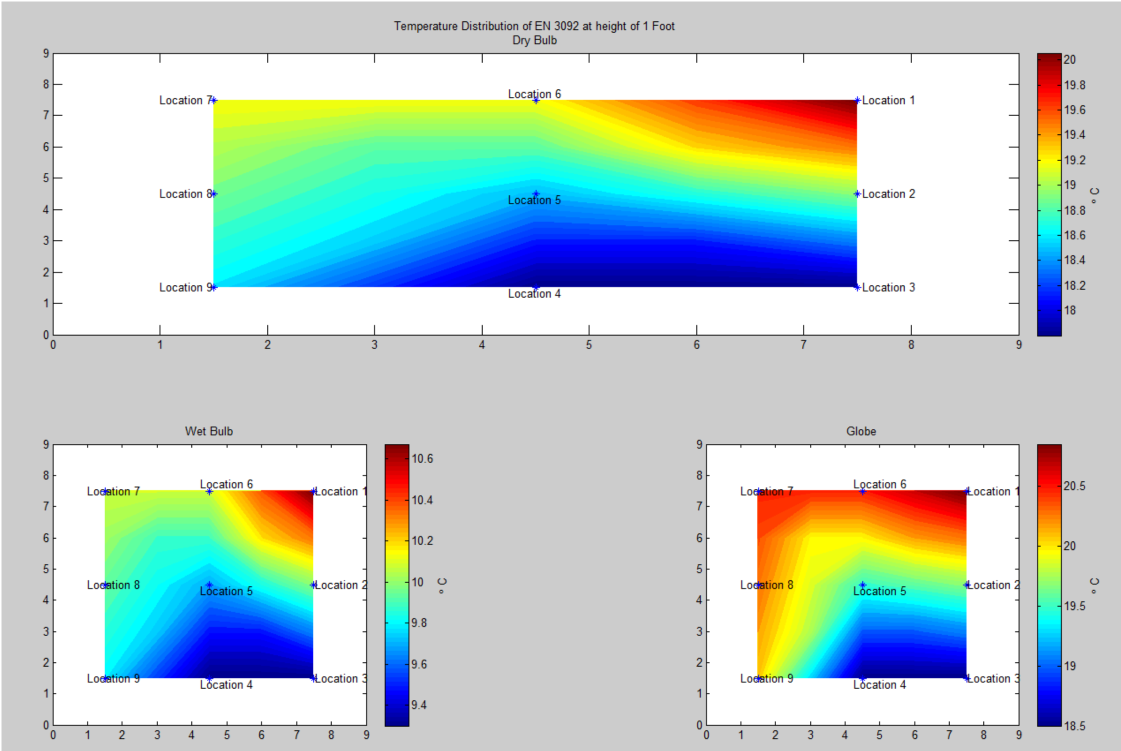

Figure 5d: Temperatures distribtion at the height of 1 foot (building 1) with window close

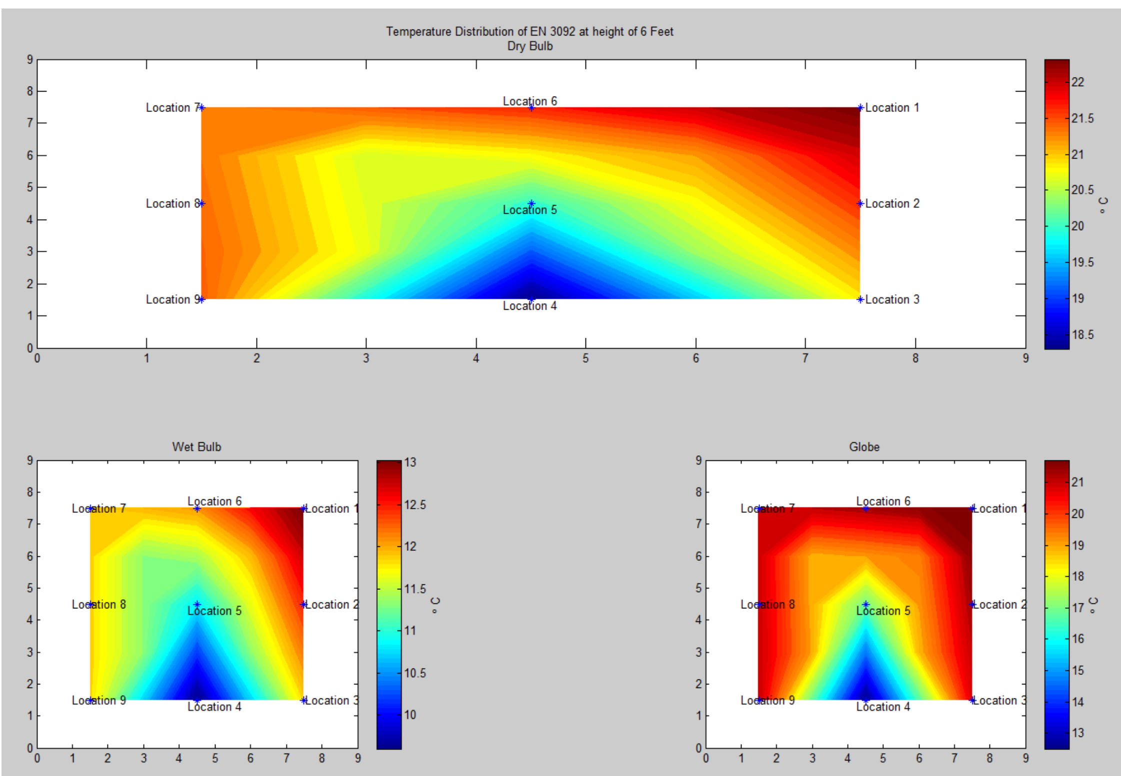

Figure 5e: Temperatures distribtion at the height of 6 feet (building 1) with window close

Figure 6: Blower Door apparatus

To determine C and n, the natrual log is used on both sides of the power law, to get a linear equation:

$$\ln(\dot{Q}) = \ln(C) + n.\ln(\Delta P)$$

The relations used to determine both C and n are:

$$Y = a.X + b$$
$$a = \ln(C) --> C = e^{a}$$
$$b = n$$
$$Y = \ln(\dot{Q})$$
$$X = \ln(\Delta P)$$

The purpose of this lab was to provide the experiments basis for air infiltration or exfiltration of the building 1. The recorded pressure differentials between inside and outside as well as the blower air-flow rates were recorded by varying the blower speed using a speed controller. This method was used to determine and provide an estimated cost for heating losses in building 1, due only to infiltration for one winter season.

From the experimental data, building 1 was found to have an n value, ie. the constant that depends on the flow in the crack, of 0.76 and 0.78 for the unsealed and sealed room respectively. The flow coefficient, C, was determined to be 5,046 and 5,448 for the unsealed and sealed room respectively. The cost for heating losses in the winter was found to be $1,650 for the unsealed building.

Prior to testing, the room was sealed to prevent any unwanted infiltration in the room. From this data, the C and n constants were determined along with the heat lost from the building. The experimental values are listed below in Table 3. The cost for heating losses the room in winter (2,000 hours) was determined (Table 4).

It can be concluded that infiltration plays a major role in building energy cost along with performance of the building envelope. Further investigation into this topic is needed to properly construct a building. The envelope permeability (or flow coefficient), C, was much larger than expected due to the age of the building.

Course evaluation:

In parallel with the self-evaluation of each course by the instructor, we also conduct a course evaluation by students. The course objectives introduced earlier in the course are again provided to the students at the end of the semester. The students' input on whether the materials offered have met the objectives is then complied and used in the program outcome assessment process. Results of instructor course evaluations (conducted by students) are reviewed by the Department Chair and the Dean and shared with the faculty.

Each faculty member also conducts an evaluation of performance of students in his/her courses as part of the Program objectives and outcome assessment process. A summary report on the performance of students (to meet the Program objectives) and compliance with the Program outcomes is prepared and submitted to the Department Chair for the assessment purposes.

Future plans to evaluate the effectiveness of the capstone in term of learning outcomes:

Actions that will be implemented to improve the effectiveness of the curriculum in term of learning outcomes:

- We expanded on the instructors' self-evaluation such that more direct assessment of students' learning outcomes is obtained. A set of standards for instructor's self-evaluation will be prepared by the faculty and the Board of Advisors and will be implemented with the annual assessment cycle. The main point of these standards is that the evaluation of students' performance will based on samples of work in three categories of students: those in the upper 75 percentile, those in the 50 – 75 percentile and those below the 50 percentile populations. Thus the assessment results compiled are based on course performances and grades, exams, projects, presentations of students, and writings as required in some courses. Furthermore, each course specifically addresses the learning outcomes and relation between the course and the Program outcomes, the methods used for the evaluation of students' performance and the relevance of the course materials to the Program outcomes following the standards adopted for the assessment process.
- Students will be provided with the course descriptions including learning objectives and outcomes. Students also will provide their input on the Program outcomes. The results from this instrument are used along with those from the instructors' self-assessment of courses as a means to ensuring compatibility in results obtained.
- A more rigorous process in assessing the learning outcomes of this capstone course will be implemented, which are in parallel with the Program outcomes. The following outlines process will be used for this capstone course assessment.
    - Individual instructor evaluation of the degree of learning achievement of individual students on a capstone team, which includes consideration of the collective achievements of the team.
    - Peer evaluation (optional by instructor).
    - Grading of deliverables by the instructors (project plan, mid-term review, final report, exhibit (and abstract), oral presentation, team minutes, web site if applicable).
    - Teamwork survey.

- Self-assessment.
- Senior Design Symposium judging (with evaluation criteria explicitly indexed to the learning objectives and articulated via rubrics for all measures).

Conclusions:

Two types of projects have been introduced: design and experimental projects. Within the design project, students have the freedom to make their design of the mechanical systems on a real building, under the supervision of an instructor. Student progress is discussed twice a week and during the office hours (UW requires a minimum of 5 office hours a week). Participation in the capstone course provides another opportunity for students to apply knowledge they learned during several other courses. The capstone design course is conducted in parallel with capstone structural design. Both structural and mechanical students collaborate to achieve a final project. For example, the weight of HVAC systems is transmitted from mechanical students to structural students to be considered for mechanical loads and later the structural students transmit the structural design to mechanical students to be considered for duct layout.

Regarding the experimental project, the objective of this work is to expose students to experimental aspects of architectural engineering. Student progress is discussed twice a week and during the office hours (UW requires a minimum of 5 office hours a week). Participation in this comprehensive project provides another opportunity for students to apply knowledge they learned during several other courses. This project is conducted within HVAC systems design courses.

A number of experimental studies have been conducted, such as duct blaster testing, blower door testing and infrared thermography. Our objective was to use these techniques to improve the students' understanding of different concepts and techniques, such as pressurization, pressure and airflow measurements, duct and building leakages and tightness, temperature and humidity distribution within building envelop and HVAC systems.

References:

1. Yu, Y., Megri, A.C., (2010) "The Integration of Attic Model into Building Simulation Program", CLIMA 2010.
2. Soleimani, A., Megri, A.C., (2009) "Computer-based analysis of transient state heat transfer in residential attic space" Roomvent 2009.
3. Parsons K. Human thermal environments. London: Taylor & Francis; 2003.