AC 2011-2606: COMPREHENSIVE STUDY TO EVALUATE HVAC SYSTEMS AND ENVELOPE PERFORMANCES

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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.

Comprehensive Study to Evaluate HVAC Systems and Envelope Performances

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Abstract:

In this paper, we describe a comprehensive experimental study 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.

In this paper, 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.

We discuss the capstone design program from students' point of view, and the experience earned in design, experimentation, and also in written and oral communication skills. Future plans to evaluate the effectiveness of this capstone in term of learning outcomes.

Introduction:

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

1) <u>Instrumentation</u>:

Several buildings have been instrumented with sensors placed in attics, on walls and in basements. A power meter has been installed in each building, and a data acquisition system allows the storage of the measured data.

2) <u>Comprehensive Experimental study (HVAC Systems & Envelope)</u>:

This comprehensive study considers the building envelope and the systems. As well, the study takes into account both thermal and airflow aspects of heat transfer in buildings. The building envelope includes walls, windows and doors, attic and floor. Regarding the systems, many aspects have been measured, such as as the thermal efficiency of the furnace and the fans. In particular, the components that have been treated and studied include:

- Sub-floor Assembly and Venting: Check the presence of a vapor barrier for example.
- HVAC – Furnace: Measure furnace efficiency and check the actual condition of the furnace to see if a cleaning and tune up is needed to reduce carbon monoxide levels.
- HVAC – Exhaust/Bath Fan: Check the bath fan to determine the degree to which the moisture level is managed.
- Attic: Check the level of air tightness of the ceiling between the home and attic using a multi-zone blower door. Air seal all penetrations between home and attic, including wall top plates, electrical penetrations and chases, install soffit vent baffles, move open electrical boxes above insulation level, weather strip and insulate attic hatch, and insulate attic with blown cellulose.
- Insulation – Attic, Insufficient Levels: Attic insulation has been studied and corrected if insufficient.
- Attic Air Sealing: Gaps around the plumbing stack are prime candidates for air leakage and should be studied prior to adding insulation.
- Attic Vents: Check the necessity to put baffles on the vents to ensure that insulation doesn't block the vents.
- Pressure Differential Testing – A manometer has been used to measure pressure differences between the inside and the outside of the houses. Pressure differences drive air into or out of your home. In the worst- case scenario, high negative pressure draws dangerous combustion gases back into the home.

- Duct Blaster Testing – A duct blaster pressurizes duct systems to find leaks. Any leakage in an unconditioned area, such as an attic or vented crawl-space, is a huge energy drain. In addition, duct leakage within the home can cause pressure differences that drive air out of or into the home.
- Blower Door Testing – A blower door is a precisely variable speed fan installed in an exterior doorway (or other location to be studied) that depressurizes or pressurizes the home. This diagnostic tool helps quantify air leakages in a home that are otherwise difficult to detect.
- Infrared Thermography – An infrared camera sees temperature difference, which helps to find hot and cold spots in a home, often due to lack of insulation, water leak or the presence of thermal bridges. When used in conjunction with the blower door, the infrared camera demonstrates air leakage pathways.
- Motor replacement: motor energy consumption is the most expensive one comparatively to other system such as lighting (the motor check are in a specific University Campus building).
- Daylight control plan: increase the possibility of using daylight, without increasing the heating/cooling loads, by building envelope modifications, such as increasing the windows opening and placing window shadings using different strategies, through simulations using Ecotect Analysis simulation program.

3) <u>Simulation</u>:

An advanced energy simulation program such as, Visual-DOE (eQuest or EnergyPlus) has been used to determine the most appropriate procedures necessary to improve the building performance. Attic model developed at UW (Soleimani et al., 2008), (Yu et al., 2010) has been tested and comparisons with experimentation have been performed.

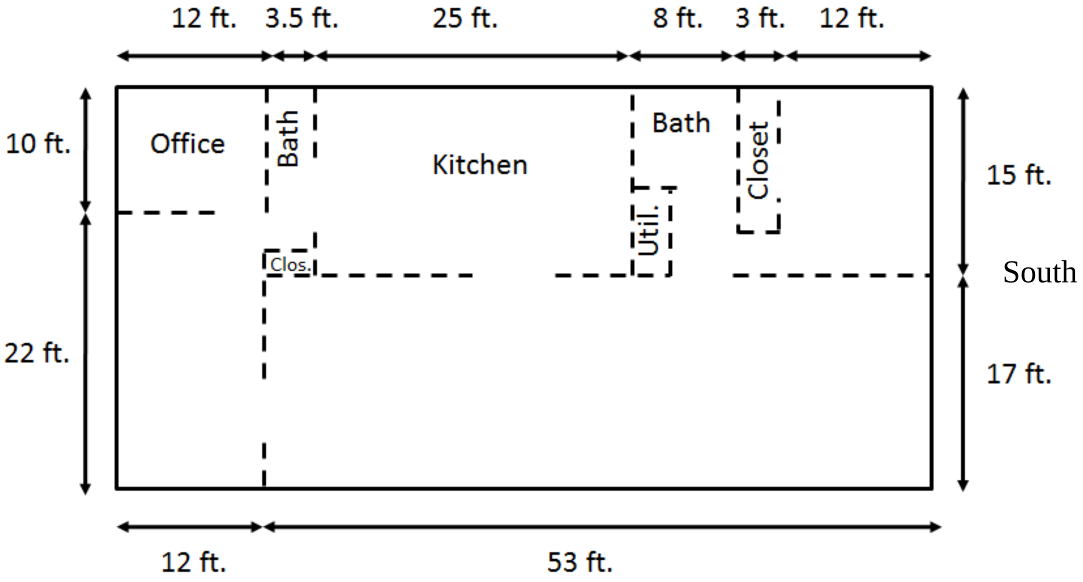

Figure 1: floor plan of the building 1 used as experimental building.

Figure 2: Building 1 used to test the methodology developed

Figure 3: In-situ measurements (air, surface and globe temperatures)

The methodology followed during this project is summarized in the following flow chart (Figure 4).

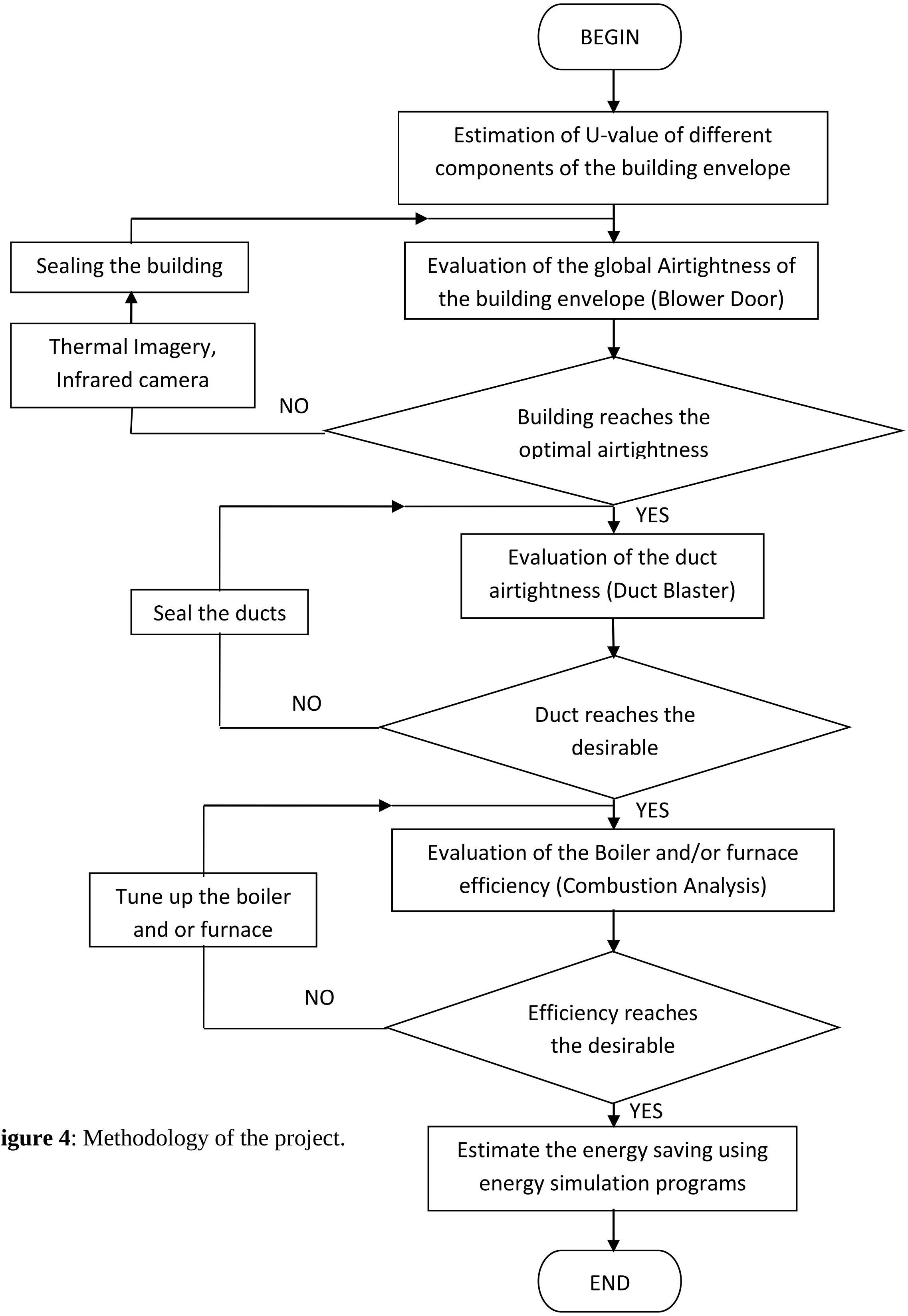

Figure 4: Methodology of the project.

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 Figures 1 to 3.

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 5.

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 6). 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 5: The Quest Monitor used to take Measurements

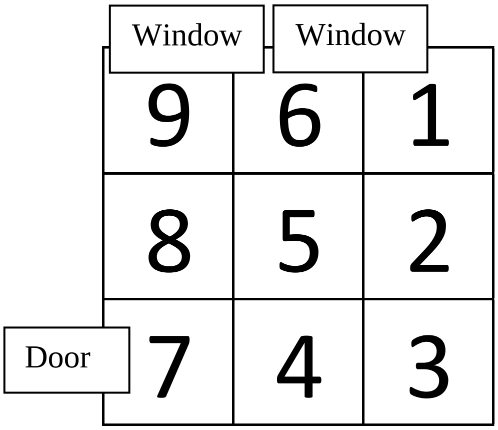

Figure 6: Room split into a 3x3 grid

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 7 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

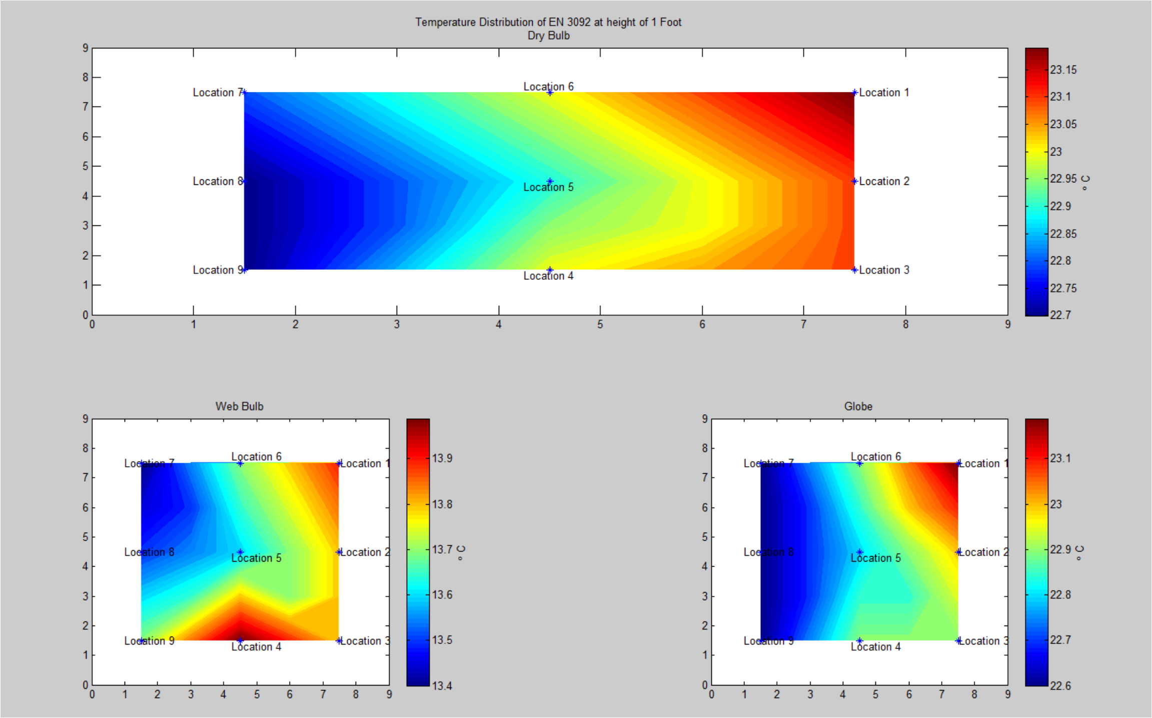

Figure 7a: Temperature distribtion at height of 1 foot (building 1) with window open

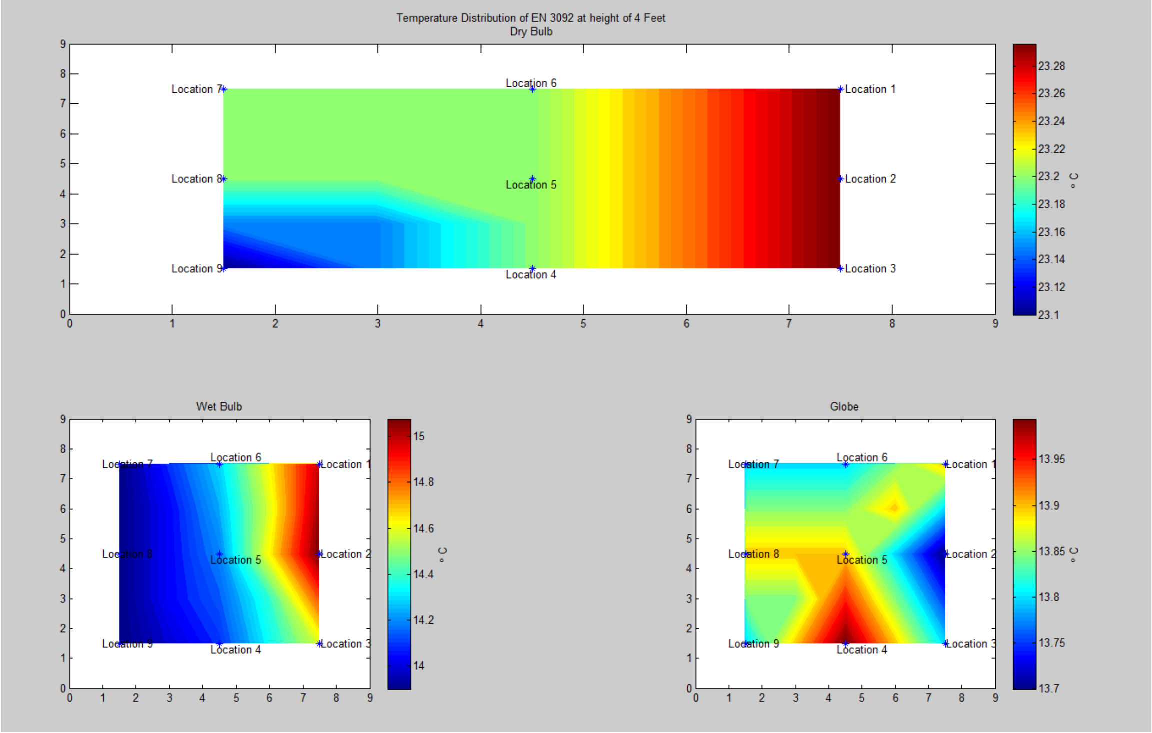

Figure 7b: Temperature distribtion at height of 4 feet (building 1) with window open

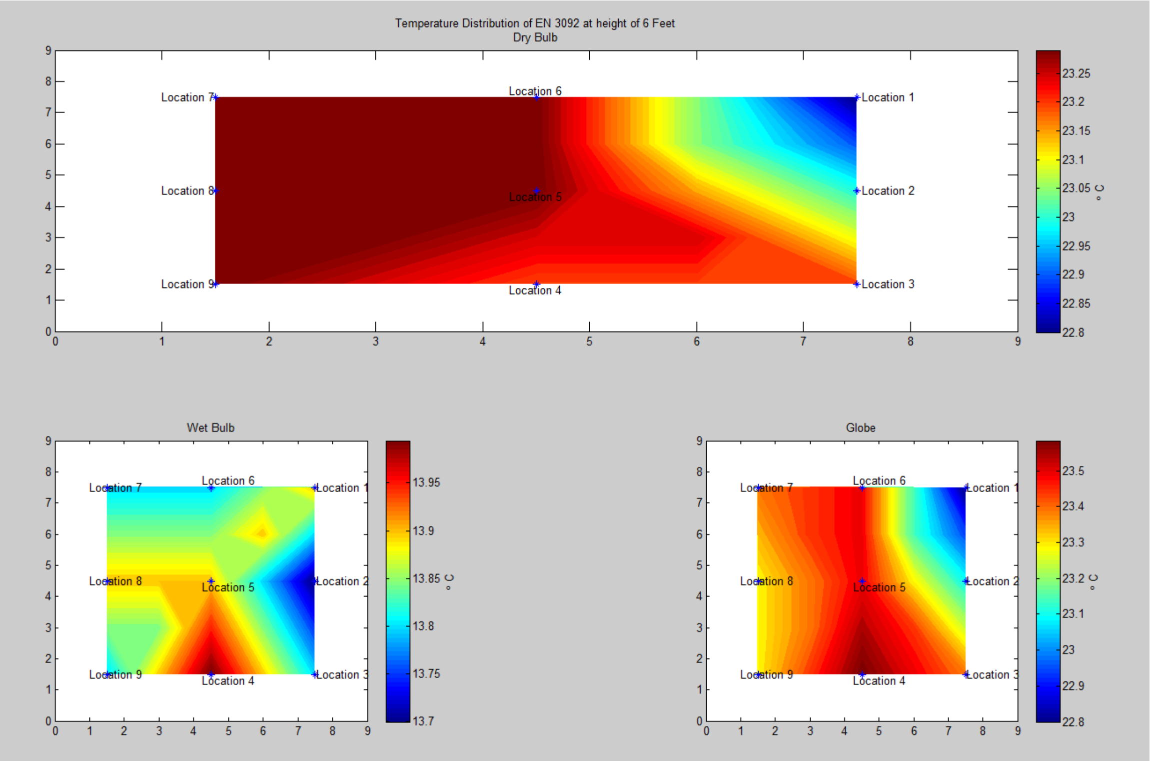

Figure 7c: Temperature distribtion at height of 6 feet (building 1) with window open

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 8). 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.

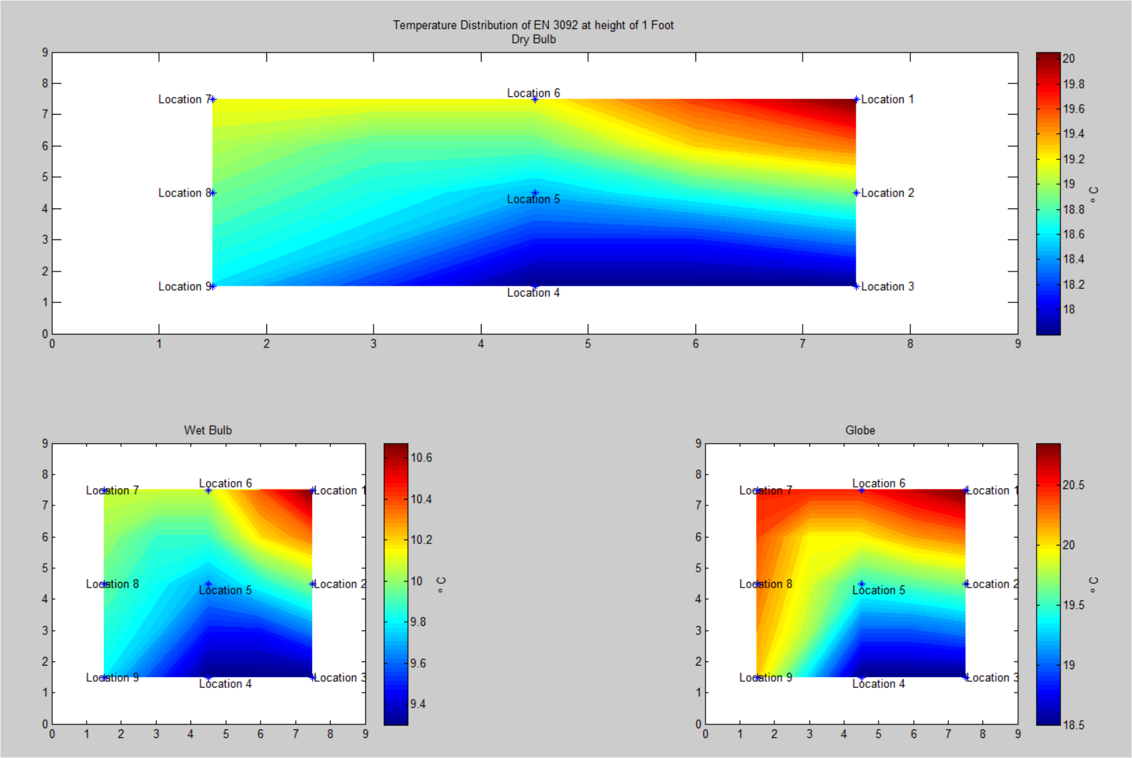

Figure 7d: Temperatures distribtion at the height of 1 foot (building 1) with window close

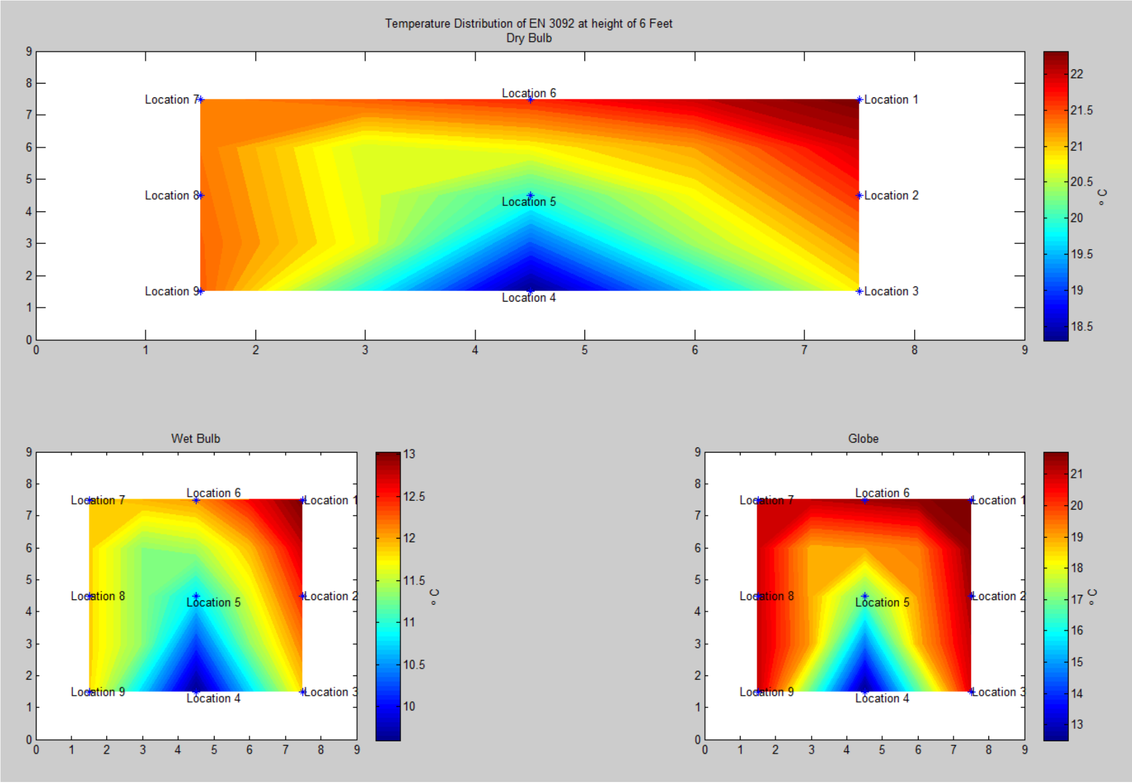

Figure 7e: Temperatures distribtion at the height of 6 feet (building 1) with window close

Figure 8: 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:

The objective of this project 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.

Based on students' course evaluations, and years of observing the way students learn, I have come to realize that a project-based course is the best way to get students to understand the importance, and necessity, of integrating knowledge from several discipline to produce a final product.

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