AC 2008-1835: CONSTRUCTION OF A RADIANT COOLING AND CONTROL DEMONSTRATION UNIT FOR USE IN ENGINEERING COURSES

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I. INTRODUCTION

Radiant cooling is a method commercially used to provide a level of human comfort without relying solely on forced convection. Operating under the same basic principles as radiant heating, this method functions by providing a cooled surface which will absorb radiated heat from other objects, such as a person. While radiant cooling exhibits several advantages few applications of this technique are available for students to study. Few engineering students, therefore, have heard of the technique or know anything about it. The intention of this project was to produce a radiant cooling demonstration unit which can be used to introduce radiant cooling techniques. Additionally, acquisition of sensor signals and computer management of the equipment will allow students to explore methods of controlling a simple HVAC system.

Through a grant from the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) the demonstration unit was designed and constructed as part of an undergraduate senior project during the 2005-2006 academic year. The unit is fully instrumented through the LabVIEW software package for a variety of uses. A graduate student is currently performing characterization experiments with the unit in an environment chamber. For the next stage of development appropriate automatic control software will be written using LabVIEW. This paper will detail the design and construction of the demonstration unit and will present basic data on its use.

II. BACKGROUND

Radiant cooling is a method commercially used to provide a level of human comfort without relying solely on forced convection. The basic principles of radiant cooling are similar to that of radiant heating. Radiant cooling works by providing a chilled surface that will absorb radiated heat from surrounding objects. An object that is hotter in temperature than the cooling surface will emit a net thermal radiation to the cool surface. As the thermal energy is received it is transferred to a secondary medium, in this case chilled water, to be removed. Convective heat transfer will also occur between the air and the cool surface of the panel. The performance of the system depends on how well it can receive energy by the combination of thermal radiation and convective heat transfer from the air. However, radiant cooling panels are defined as a source of cooling which has at least 50% of the heat transfer via radiation [6]. Cooling panels can be made in various forms but are generally designed to replace existing drop down ceiling panels. They are ideally suited for applications which already have access to a chilled water distribution system.

The benefits of radiant cooling panels mainly derive from a reduction in the required air flow rate for the HVAC system. As more of the cooling load is handled by the panels the air flow rate can be reduced to the point of simply satisfying ventilation requirements. From an energy perspective, the pump work is much less than the fan work so radiant panels tend to be more energy efficient. There are also advantages in terms of comfort. The thermal comfort of an room occupant is decided by a combination of parameters including air temperature, humidity, operative temperature, mean radiant temperature, and air velocity. A radiantly cooled room can have a higher dry-bulb temperature because thermal comfort for an occupant is largely driven by the mean radiant temperature [6]. As Feustel and Stetiu point out, radiation is the most important aspect when analyzing heat loss from occupants. At the same time the largest complaint for systems is the fluctuation in air velocities [3]. Since radiant panels improve radiant transport and reduce air velocity they are, therefore, an attractive alternative to forced air systems. Vangtook & Chirarattananon have also stated that ceiling radiant cooling panels achieve a smaller vertical temperature difference when compared to conventional systems [4].

The main disadvantage of radiant cooling is the formation of condensation on the cooling panels if the temperature of the panel drops below the dew point temperature. Condensation can be a thermal comfort issue, a liability for damaged equipment, and even allow the infestation of bacteria. Condensation can be avoided by keeping the mean water temperature above the dew point temperature. However, in climates with high dew point temperatures the difference in mean water temperature and the ambient air is small resulting in a low efficiency for the system. Experimental studies of the condensation problem are limited but some results have been published. For instance, Mumma looked at the problem of steady state condensation with a test run that included an occupancy that exceeded the design by 100%. After one hour a 5/10,000 inch layer of water formed. Mumma also states that a 3°F (1.7°C) difference between the inlet panel temperature and space dew point temperature will require 90 minutes to 14 hours to form a layer of condensation the diameter of a human hair [1].

III. STUDENT DESIGN EXPERIENCE

Students were presented with the general concept shown in Figure 1 and were given several design requirements for the apparatus at the start of the project.

- The ability to move between class rooms (i.e. fit through standard doors)
- The cooling panels should be capable of multiple orientations such as horizontal and vertical mounting
- A refrigeration system should be included that produces sufficient chilled water for the radiant cooling panels
- A budget of $5,000 was specified
- All sensor outputs should be outputted to a DAQ board and computer with appropriate signal conditioning
- Instrumentation should allow monitoring of water heat gain and room psychometric conditions
- A movable heat flux sensor should be included

The minimum sensing and control requirements of the system were the ability to measure or determine the following values.

- Water temperature into the cooling panel
- Water temperature out of the cooling panel

- Flow rate of the water
- Ambient temperature of the room
- Relative humidity of the surroundings
- Heat flux at a particular point surrounding the panel
- Control of the water flow rate into the panel

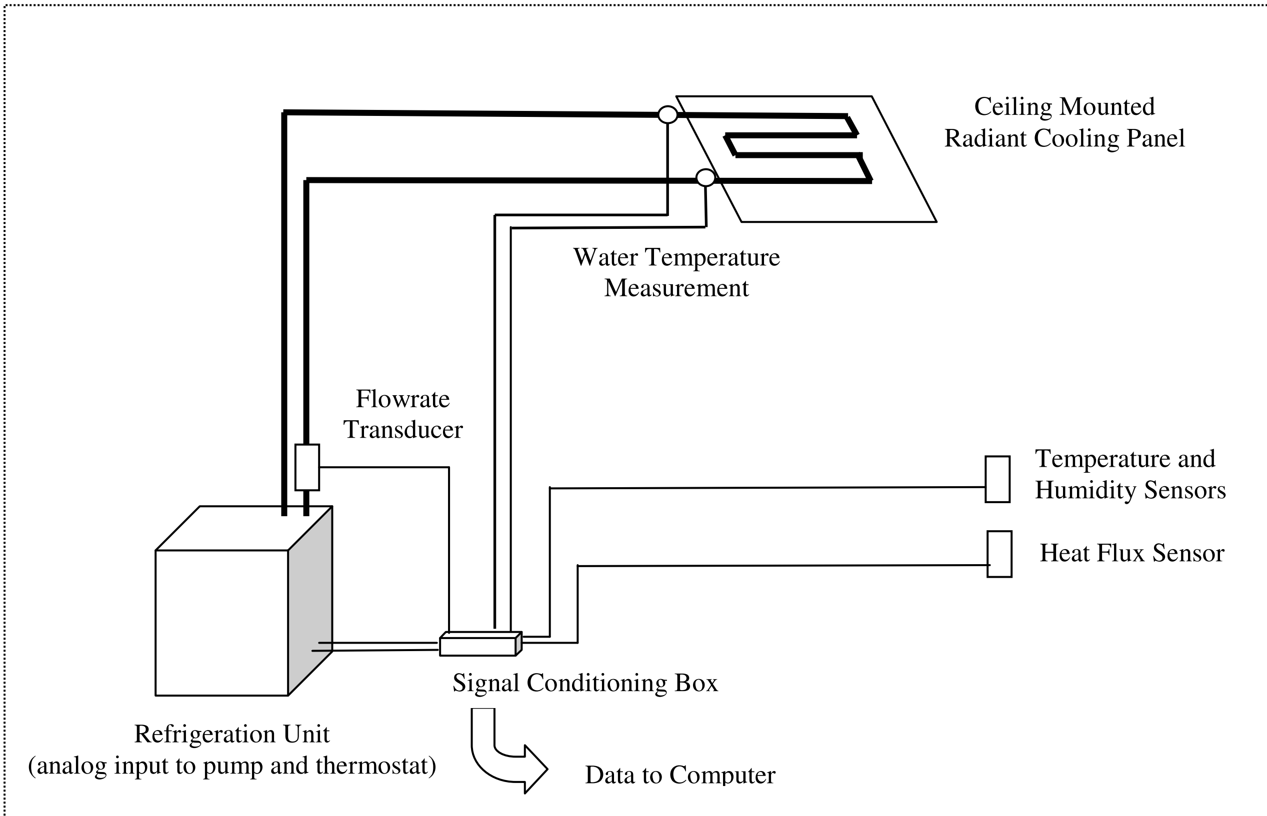

Figure 1: Block diagram of the Radiant Cooling Demonstration Unit.

The student design team consisted of four mechanical engineering seniors. The project was conducted over the course of approximately 1 ½ semesters. The students chose to divide the project into three main sections. Each student selected a primary section, of which they were responsible for, with two students sharing the mechanical equipment section. Respective designs were presented at bi-weekly meetings, allowing feedback from the group as well as from the faculty advisor. This allowed concurrent development of the system but maintained student involvement in the overall design. Progress presentations and reports were made at the end of each semester.

In addition to design responsibilities, the students had to acquire material quotes from vendors and interact with University administration on the procurement of all products. At the conclusion of the project the students were responsible for preparing a complete bill of materials and a final project report for submission to ASHRAE.

Mechanical Equipment	**Control Equipment**	**Structural Assembly**
- Refrigeration Unit - Pumps - Valves - Cooling Panels	- DAQ Equipment - Control Sensors - Software	- Unit Frame Configuration - Construction Material

Figure 2: Division of tasks amongst student design group.

IV. MECHANICAL COMPONENT SELECTION

The choice of cooling panels was influenced by the desire to represent an actual HVAC application of radiant cooling. The 2' x 2' modular panel design is the same one that would be used in a ceiling grid application. These panels are the same design as radiant heating panels and can be used for that purpose as well. The Sterling modular panel meets the design criteria, and had a cost of $66.00 per 2' x 2' panel. The approach taken was to design a system that would support up to three 2' x 2' panels. The chilled water lines were attached with quick connect couplings to allow panels the panels to be changed as needed. This also allows the chiller to be connected to other experiments which may require cooling.

Using a 150 Btu/h per square foot specification, multiplying by 8 ft^2 (the area of three 2' x 2' panels), a cooling load of 1200 Btu/h was calculated. This is the target that the system was sized to. Elkay manufactures a series of point of use chillers that exceeds this specification. The selected refrigeration unit, Elkay Agua-chill ER 5 series, is a small point of use water chiller designed to supply cold water to remote locations. It has a maximum capacity of 1500 Btu/h.

The structural assembly involved the design of the demonstration unit frame needed to house the mechanical and control equipment, as well as a frame structure to hold the cooling panels. The skeletal structure consists of angle iron, steel sheets for shelving, and plywood sides. Everything is mobile by way of attached casters at the bottom of the structure. The panel frame was designed to be detachable and self-standing. This was intended to allow the panels to be detached from the main unit for use in an environment chamber. The panels themselves are held in place by simple pins with possible positions in the range of 0° (horizontal) to 90° (vertical) as shown in Figure 3. The frame itself was made to be collapsible for easy storage and movement of the unit.

The pump selection was delayed until the demonstration structure was nearly complete. This allowed better calculations of the system head loss to be performed. Pump design was based upon the pump head required to circulate the chilled water through the three 2' x 2' radiant cooling panels and the rest of the system. Using the table provided by the radiant cooling panel manufacturer and other head loss coefficient data, an estimate for the required system head was calculated. Using the pump curve provided my the a pump was selected that would provide the appropriate pump head and flow rate to deal with two 2' x 2' radiant cooling panels. The selected pump was a Grundfos recirculating pump.

A three-way proportional control valve was selected to divert the circulating cold water through the panels when the system calls for increased cooling or to loop the water back through the chiller when less cooling is called for. This valve was chosen for its ability to respond to a pulse width modulated signal output by the control equipment. The selection of a specific Belimo control valve, therefore, required choosing a model that worked with the chosen control electronics.

The key system characteristics are shown in Table 1. Additional details of the demonstration unit can be seen in Figure 4.

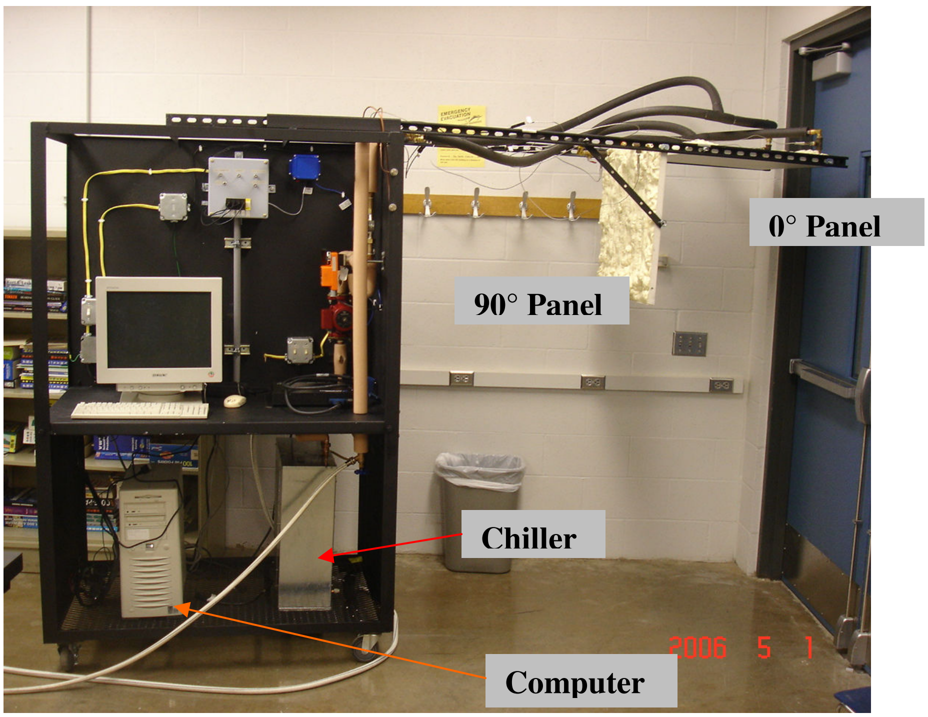

Figure 3: Radiant Cooling Demonstration Unit (panel frame extended).

Table 1 System characteristics

Flow rate (max)	7 gpm
Heat transfer capacity	1500 Btu/hr
Steady state panel temp	50ºF
Time to steady state	45 min
Total System Head	25 feet

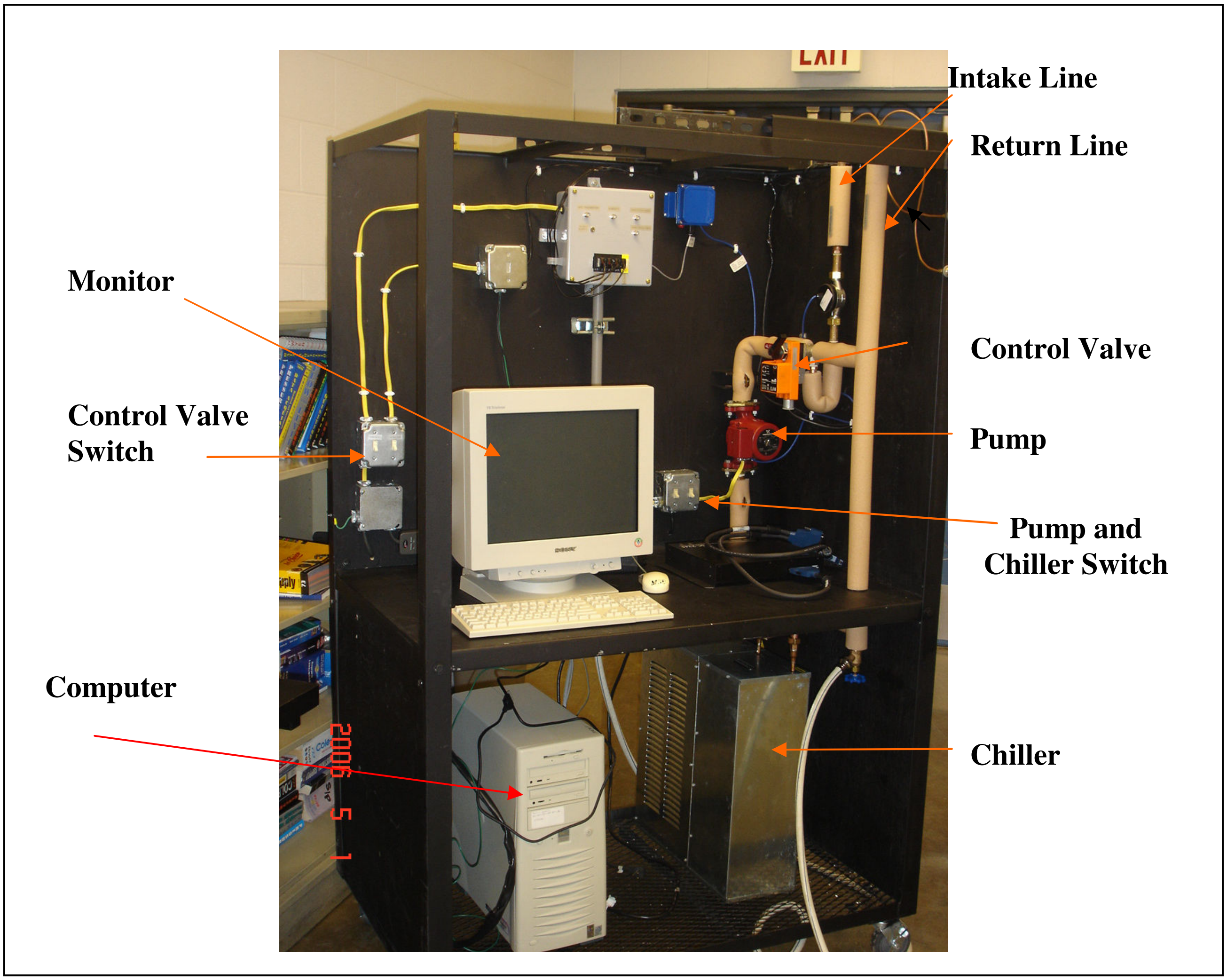

Figure 4: Close-Up of Structure, Controls, Mechanical and Plumbing Features.

V. CONTROL SYSTEMS AND SENSORS

From the initial project specifications the control and sensing system was based around a National Instruments (NI) data acquisition board (DAQ) and NI's LabVIEW graphical programming environment. For the signal conditioning components a custom printed circuit board (PCB) option was initially explored. However, the time required and future technical support considerations eliminated this option. Therefore, the more expensive option of basing the system entirely around National Instrument's compact signal conditioning equipment was selected. A base carrier unit interfaces directly with the NI DAQ board using a 68-pin cable. The sensors and control systems are then connected to the signal-conditioning box through individual interface modules purchased from NI. The down side to this option is price. A module can only interface with one or two sensors based on their type, so almost every sensor in the design required its own module. This drives the total system cost up, limiting the number of configurations that the system can be used for. A block diagram of the DAQ and control systems is shown in Figure 5.

The flow rate is measured using a FloCat inline turbine flow meter. This is interfaced directly to the signal-conditioning unit by a FloCat frequency-to-analog converter. The output is a 4-20mA current measured at the SCC chassis.

Heat flux is measured using an Omega thin film heat flux sensor. The sensor consists of two thermopiles separated by a material of known thermal conductivity. The difference in temperature between the two is used to determine the heat flux. There is also a built in k-type thermocouple for temperature measurements at the surface of the object in test. The thermocouple is interfaced into the signal-conditioning unit with a thermocouple module. The differential pair output by the heat flux sensor is input into an instrumentation amplifier module with a static gain of 100.

Humidity is measured using a Humirel relative humidity sensor. This takes in a 5-volt DC supply and outputs a DC voltage between 1 and 4 volts that is proportional to the relative humidity of the environment. A NTC thermistor is included in the same sensor housing. This is used to measure the ambient temperature by way of a voltage divider circuit.

Fluid temperature is measured using Omega pipe probe thermocouples with ¼" NPT fittings. Each signal is input into an individual thermocouple module located in the signal-conditioning chassis.

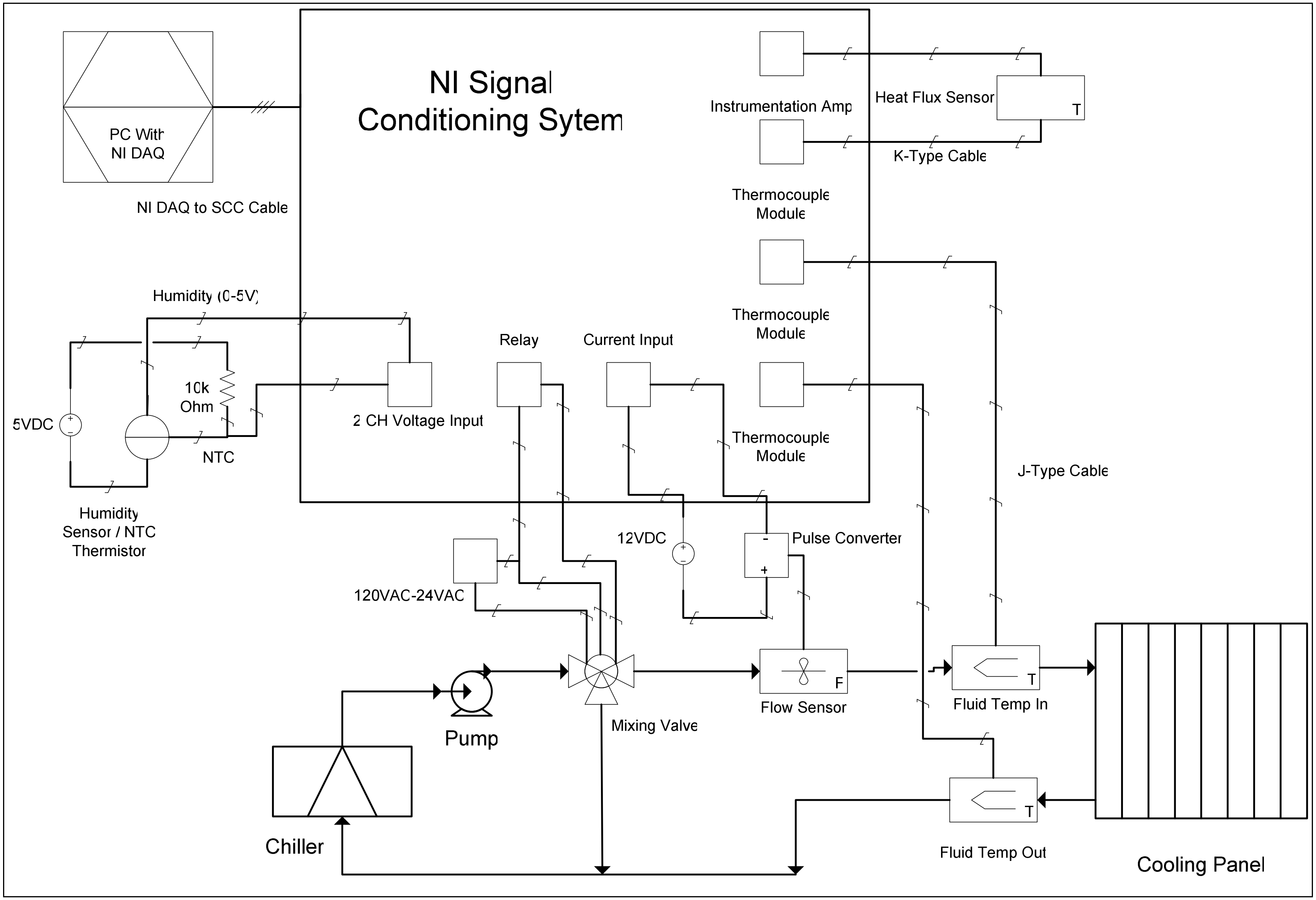

Figure 5: Piping and control system schematic.

VI. EQUIPMENT TESTING

After the mechanical portion of the test unit was completed tests were completed by the student design group to gauge the performance of the mechanical systems. The purpose of the tests was to try and show that the radiant cooling panels would indeed absorb heat from a nearby object.

First, a 100 mL graduated cylinder was filled with boiling water and placed under the cooling panels according to the configuration shown in Figure 6. Data was then taken by means of an infrared camera over the course of one hour. This data was then compared with data taken with the radiant panels cooling at an average temperature of 50ºF. By comparing the slopes of the linear approximations for each test run, a 9% increase in the cooling rate was detected.

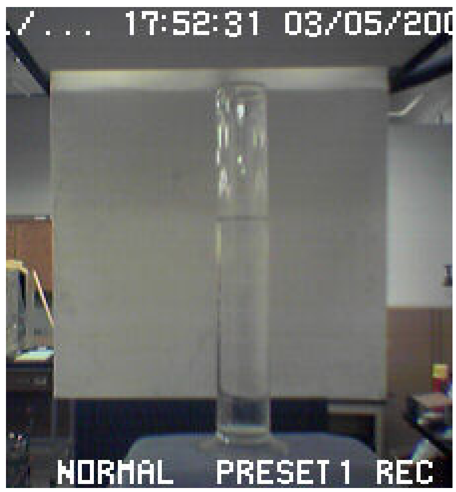

Figure 6: Testing configuration for graduated cylinder of water.

Experimental characterization of the radiant cooling panels is now being conducted within an environment chamber where the air temperature and humidity can be adjusted and controlled. This work is being conducted by a graduate student (Brian Weninger) as part of his Masters research. The panels were erected inside the chamber using the detachable frame and extension lines for the chilled water and electrical connections (Figure 7). In order to analyze the data collected correctly some basic tests were performed on the environment chamber alone. Primarily heat gain/loss of the environment chamber without panels or chamber systems running was measured. This allows later measurements to be corrected for how much of the cooling done when the panels are operating is in fact associated with the radiant cooling panels and not infiltration of the environment chamber. Two other basic types of tests have also been run, including performance tests and condensation tests. Performance testing is used to determine the cooling capacity of the panels under various testing conditions. Each test had a different initial temperature and initial humidity condition. The environment chamber was then turned off and the panels turned on. Each test was run for a minimum of 3 hours. The following graph (Figure 8) shows the effects of the cooling panel on the air temperature of the environment chamber.

Figure 7: Radiant cooling apparatus setup for use in the environment chamber.

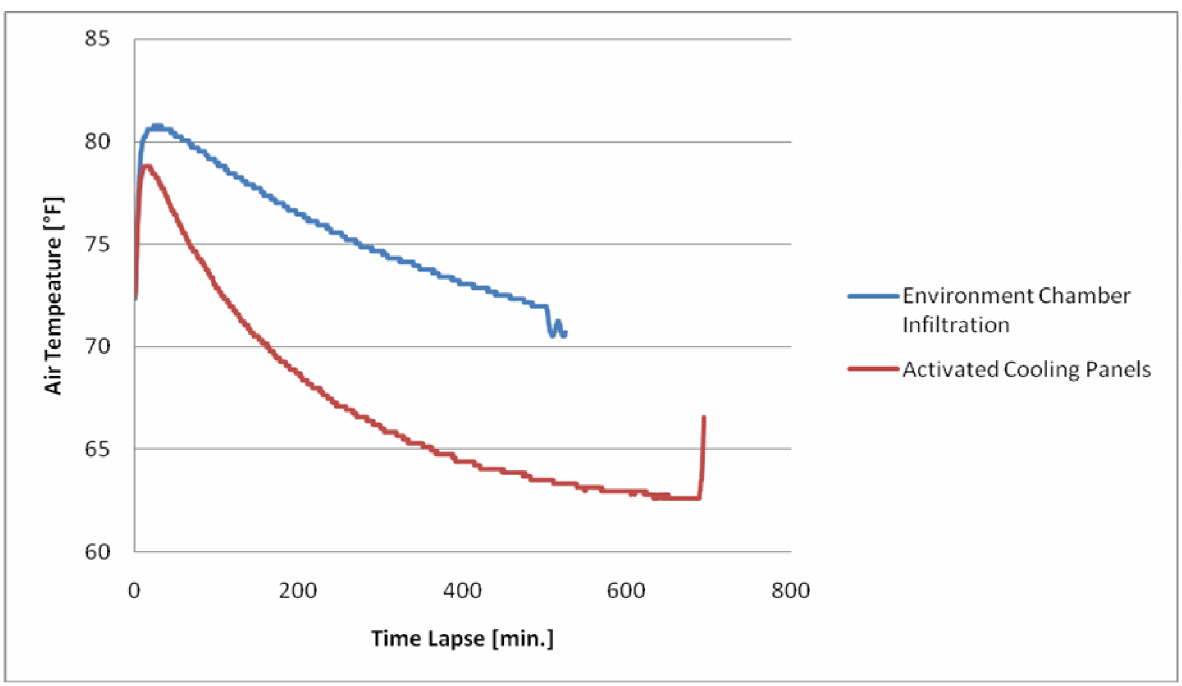

Figure 8: Time variation of environment chamber air temperature.

As the graph shows, the environment chamber is not perfectly insulated. Over an eight hour period, the air temperature dropped from 27°C to 21°C without any interior conditioning. With the cooling panels functioning, the air temperature dropped from 26°C to 17.5°C over an eight hour period. At the end of the test which lasted eleven hours, the final air temperature was 17°C. The heat absorbed by the chilled water can be calculated from the inlet and exit water temperatures. This represents the cooling capacity of the panels. Figure 9 shows the cooling capacity for a long term test. The cyclic pattern present in both water temperatures and heat flux figures are due to the thermostat on the water chiller. The thermostat cycles on and off as the chilled water increases and decreases in temperature.

As mentioned in the Background, condensation on cooling panels is a major complication. To explore whether this could be demonstrated and measured with the demonstration unit experiments have also been conducted to monitor condensation. As shown in Figure 10 condensation can be made to form on the cooling panels by lowering the water temperature below the dew point temperature of the surroundings. The apparatus was originally designed by the students with the capability to control the flowrate of chilled water, and hence the panel temperature, through a LabVIEW program. While this has not been fully tested to date, it is envisioned that an appropriate control scheme will allow the panel temperature to be kept slightly above the dew point, thereby avoiding condensation.

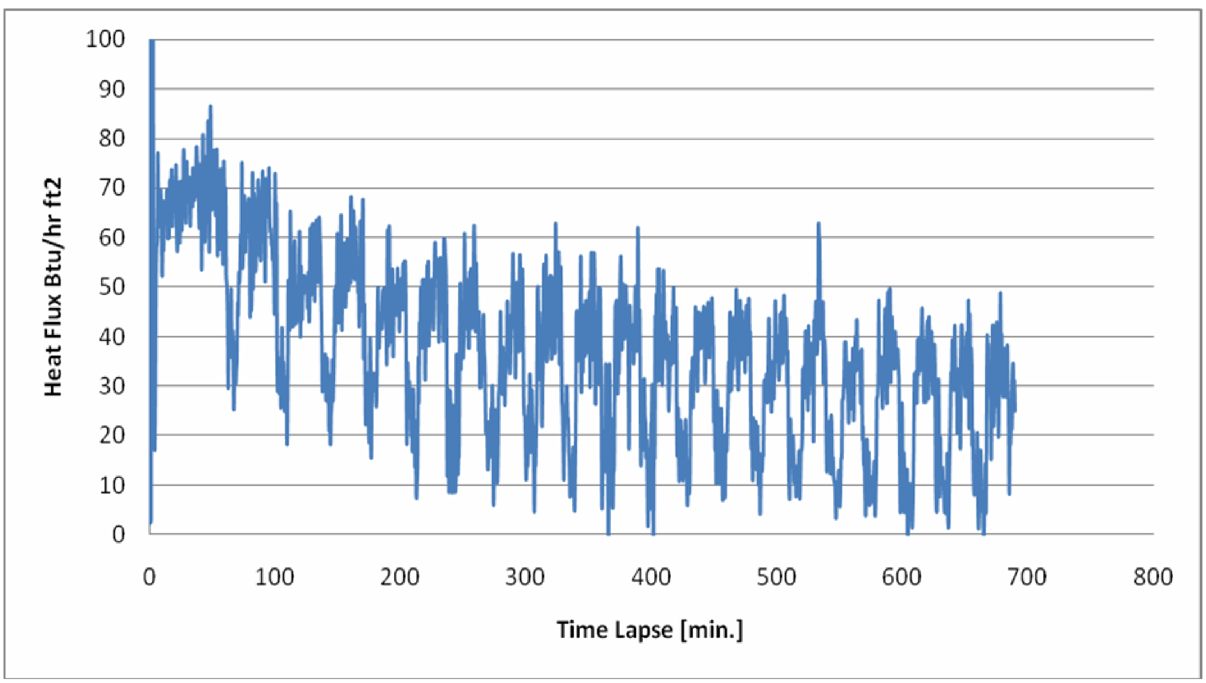

Figure 9: Ceiling Radiant Cooling Panel Cooling Capacity

Figure 10: Photograph of condensation droplets forming on the underside of a horizontally mounted cooling panel.

VII. CONCLUSIONS

A radiant cooling demonstration and test unit has been designed and built as part of an ASHRAE funded senior design project. The final cost of the entire system was $4593, excluding the attached computer and LabVIEW software which was already available.
The unit has undergone preliminary testing with all experiments performed by undergraduate and graduate students. It is expected that experimental work with students will continue in the future. This gives them valuable hands-on experience with both the applied technology and the basic experimentation concepts.

Several potential applications currently exist within the mechanical engineering curriculum for this demonstration unit. In the future it will be integrated into the undergraduate thermo-fluids experimentation course. Students will be expected to take experimental data relating to heat transfer factors as well as to determine the cooling effect. One envisioned experiment will be to compute the thermal performance of the cooling panels. In addition, the equipment has the potential to be used in the Applied Thermodynamics, Air Conditioning (HVAC), and Thermal/Fluid Systems Design courses as a demonstration or experiment. This could include the use of sensors and control theory in HVAC systems. Students will be able to examine an application of their theoretical material which will promote student interest and increase course relevancy to industry.

One concern with radiant cooling is the possibility of condensation on the panels. Monitoring and control of this issue provides an excellent example for students to explore interfacing HVAC systems with computer monitoring and control. Sensors on the system allow room humidity, and hence dew point, to be determined. The flowrate and temperature of the cooling water can then be adjusted to avoid panel condensation and to maintain the correct mean radiant temperature (MRT). The LabVIEW software package will be used to handle all data acquisition from the sensors, perform control calculation, and control the equipment allowing students to explore creating their own control programs. It is possible that this will be integrated into the controls theory experimentation course. However, since a fairly basic control scheme would suffice it is ideally suited for the thermal-fluids experimentation course. This course is also one of the points in the curriculum where students do more LabVIEW programming. Programming the control sequence would reinforce LabVIEW programming, instrumentation, and understanding of the basic processes.

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