Design of a Portable Experiment for Demonstrating Air Conditioning Processes

Dr. Robert G. Ryan
California State University, Northridge

Abstract

An air conditioning experiment apparatus was designed and constructed for the undergraduate mechanical engineering laboratory at California State University, Northridge. The purpose of the apparatus is to demonstrate the air-side processes which are fundamental to understanding the design of air conditioning systems for buildings. Electric resistance heaters are used to simulate a heat load in the conditioned space, and dampers are provided for controlling air flow rate and outside air induction. Sample results for temperature and humidity throughout the system are presented. This project was completed with the assistance of a Senior Project Grant from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE).

I. Introduction

The Mechanical Engineering Department at California State University, Northridge (CSUN) requires students to take a laboratory course devoted to thermo-fluids experiments. Some of the equipment supporting this laboratory includes a subsonic wind tunnel, a York Trainer refrigeration system, a pipe flow bench, a centrifugal pump test bed, and a centrifugal fan and duct system. It was decided that the laboratory needed an apparatus designed to demonstrate the thermodynamics of air cooling and mixing processes which commonly occur in building air conditioning systems.

An ongoing challenge for any instructional laboratory is the purchase of new equipment within the typical budgetary limitations of state-supported institutions. The purchase of apparatus designed by vendors specializing in education equipment avoids the development time required to build and refine an effective piece of equipment, but the cost is often difficult to justify due to the many demands put upon the department’s equipment budget. Additionally, the equipment design may not exactly reflect the educational purpose intended by the faculty. Specific educational goals within a manageable equipment budget may be achievable with an apparatus designed “in-house”, but can require a significant input of faculty and student time for construction and development. However, effective integration of the design and construction of the apparatus into projects performed as part of selected senior courses, as well as generous support from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), provided an efficient approach for developing a new experiment for CSUN’s laboratory.

The support from ASHRAE came in the form of an Undergraduate Senior Project Grant in the amount of $3850. The purpose of the Senior Project Grant program is to fund equipment and supplies for undergraduate engineering projects on ASHRAE-related topics. An additional donation of a compressor/condenser unit (originally designed for a drinking water cooler) from

CSUN’s Physical Plant Management department provided a solid foundation for completing this project without significant support from department funds.

The design of the apparatus started with a few overall guidelines:

- The apparatus should be portable for optimum use of laboratory space, and for operation outdoors if desired.
- The apparatus should have the major elements of a building air conditioning system, i.e. a cooling coil, a fan, a conditioned space where temperature and humidity are maintained at desired levels, supply and return air ducting, and a method for introducing outside air.
- Means for a variable heat load in the conditioned space must be provided, to simulate the effect of building occupants, lighting, heat gain through walls and ceiling, etc.
- Motor-driven dampers should be used to control supply air flow and outside air induction.
- Sufficient instrumentation should be included to monitor temperature and humidity throughout the system.
- The apparatus should be capable of “stand-alone” operation, but also have provisions for being interfaced to a computer system for data collection and control.

Most of the apparatus design and equipment specifications were produced by students in a senior level elective course (ME 474, Analysis and Design of Heating, Ventilating, and Air-Conditioning Systems) during the Fall 1997 semester. The students had to designate an overall system configuration, specify an evaporator (cooling coil) compatible with the donated compressor/condenser unit, size the ductwork, and choose a fan to produce the desired air flow through the system.

Assembly of the components and purchase of additional items (e.g. instrumentation) were handled by a student group in a senior laboratory course (ME 491, Experimental Methods in Mechanical Engineering). Additional refinements to the damper control system and computer interface will be a project for a student group in the Spring 2001 ME 491 class. Integration of the development of this apparatus with related courses in the senior curriculum was an important element to the project’s success.

II. Equipment Description

The project began with an application to the ASHRAE Undergraduate Senior Project program. The original proposal described an air conditioning experiment design using an automotive air conditioning unit as the refrigeration source. The intent was to purchase the air conditioning components at an automotive junkyard to reduce costs. Subsequent to the awarding of the project grant in the amount of $3850 from ASHRAE, CSUN’s Physical Plant Management department offered to donate a condensing unit made by Copeland Corporation. The condensing unit (Model No. F3AH-A050) included a compressor, condenser, and a receiver tank mounted on a base with a footprint of 16 by 13 inches, and a height of 12 inches. Since the size of the donated condensing unit was consistent with the project's objectives, it was decided to use it in lieu of an automotive unit. The money saved from this choice provided more flexibility for allocating the remainder of the project budget.

The refrigerating capacity for the condensing unit (using R-22) is 5180 Btu/hr. This capacity established many other related quantities for the design, including the supply air flow rate and the required duct area. Preliminary design calculations confirmed that an air conditioning unit built around the condensing unit could be small enough to be mounted on a rolling cart, and thus be portable. The capacity and corresponding air flow were supplied to a coil manufacturer and a compatible cooling coil design was established. The specified cross-sectional dimensions of the coil were 7.5 inches by 12 inches, which kept the air face velocity below the common design threshold value of 500 feet/minute. The cooling coil and the galvanized drain pan/enclosure were purchased through Southern California Air Conditioning Distributors at a cost of $993.

The volume of the conditioned space is clearly limited by the requirement that the entire apparatus must fit on a portable cart. A small conditioned volume (relative to the supply air flow rate) leads to a relatively short residence time for the conditioned air before it passes to the return air duct. Another consideration for the conditioned space design was the method for providing the variable heat load. Ultimately a box shape with a volume of 18 cubic feet (3 feet tall by 3 feet wide by 2 feet deep) was chosen. Two finned strip heaters from Omega Engineering, Inc. were chosen as the source of the heat load (maximum 1500 watts, approximately equal to the nominal refrigerating capacity of 5180 Btu/hr). The heaters are placed just downstream of the point where the supply air enters the space. This heater placement, coupled with use of internal baffles in the space, was chosen so that the air would be reasonably mixed prior to exiting into the return air duct. This allows a fairly reliable measurement of the space temperature and humidity, which can then be used to control damper positions to adjust the space parameters to a given set point.

With most of the major components now specified, it was possible to design a duct system and a fan to produce the required air flow. Air conditioning ducts are commonly sized using the air flow rate and a desired pressure drop per unit length of duct. Using the values of 300 cubic feet/min (cfm) and 0.1 inch of water per 100 ft of duct, the required duct size was found to be 6 inches by 14 inches. (A rectangular duct was greatly preferred over a circular duct due to space considerations.). Calculations for the total pressure drop in the air flow loop included losses due to bends and the cooling coil, yielding a value of 2.1 inches of water. Using this value it was determined that a Model 207 Inline Duct Blower from Delhi Industries, Inc. with a ½ horsepower drive motor would provide the required flow. This unit was also purchased through Southern California Air Conditioning Distributors at a cost of $641.

A rolling cart was located in the college's inventory which was capable of housing the apparatus. The cart was constructed of a metal frame and was designed to hold two 34 inch by 85 inch shelves. The cart was refurbished by building new wooden shelves covered with Formica. The lower and upper shelves are at heights (above floor level) of one foot and three feet, respectively. The blower, condensing unit, and cooling coil were placed on the lower shelf. The box for the conditioned space was placed on the upper shelf, along with a small panel for instrument readouts and switches. Once the major components were anchored to the cart, design details of the duct system were completed.

The construction of the sheet metal box for the space and the duct system was performed by Physical Plant Management personnel. The front of the space box is enclosed with a removable plexiglass cover, offering visual access while the apparatus is operating and easy removal for repair and maintenance. A damper for controlling supply air flow rate was placed just upstream of the entrance to the space. A second damper was placed in the return air duct to regulate the amount of air that was recirculated relative to the amount of air inducted from the outside. Insulation was used in the supply air duct and the space box to minimize environmental heat gain. After the duct system and space box were assembled, the PPM technicians charged the condensing unit with R-22. The cost for this work, including materials, was $1000.

A schematic drawing of the apparatus is shown in Figure 1. The locations for temperature and humidity sensors are shown by the letters T and H, and are numbered one through four. Temperature and humidity are measured in the space (location 1), blower inlet (2), supply duct (3), and outside (4). Pressure is measured upstream and downstream of the cooling coil (denoted as P1 and P2). The air pressure drop across the cooling coil can be used to measure air flow rate, and also provides a useful feedback for the control of the supply air damper. The sensors, power supplies, and digital displays were purchased from Mamac Systems in Minnesota. Rotary switches are used to read multiple sensors on a single display. The sensor outputs are in the form of DC voltages and thus can be easily connected to a standard analog/digital board for display and collection on a personal computer.

A senior mechanical engineering student is currently designing a circuit to control stepper motors which operate the two dampers. The circuit design will allow the user to operate the damper motors with simple push button switches (for “stand-alone”operation without a computer), or allow a computer to be connected to adjust the dampers to maintain a desired set point for the space temperature.

A summary of the major expenditures for this project is listed in Table 1. The difference of approximately one thousand dollars between the total costs and the Project Grant from ASHRAE was made up with department equipment funds.

Item	Cost
Sheet metal fabrication, refrigerant charge	1000
Inline Duct Blower	641
Cooling Coil / Drip Pan	993
Strip Heaters	132
Instrumentation	1915
Miscellaneous Hardware	200
Total	4881

Table 1 Cost Summary

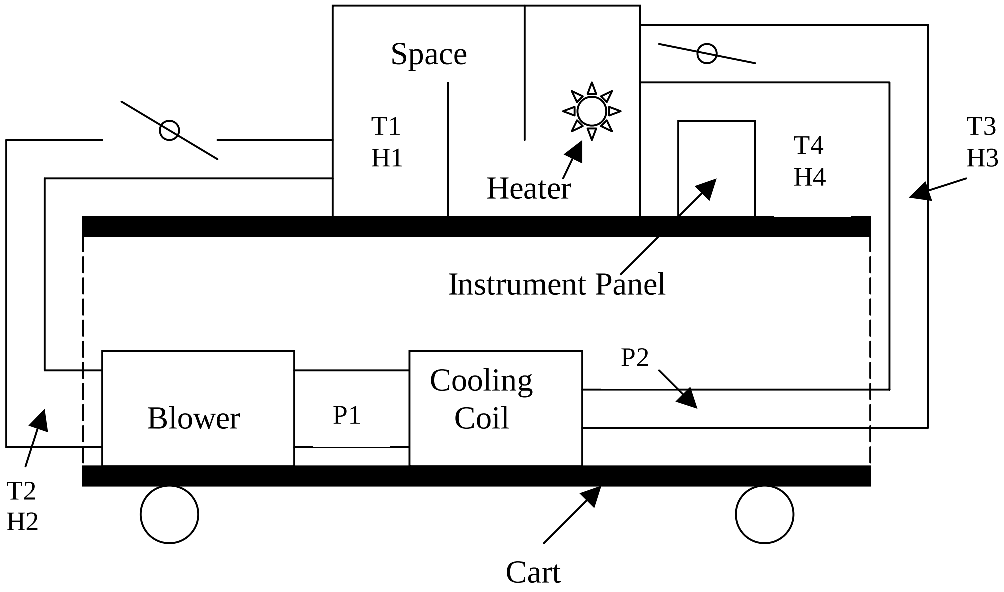

Figure 1   Schematic of Apparatus

III. Sample Results

Preliminary results from the apparatus indicated that the air flow rate was significantly higher than the target of 300 cfm. Conservative assumptions during the design phase regarding pressure losses in the ducting system were the source of this discrepancy. The pulley size on the blower was changed to reduce the rotational speed, and the maximum air flow rate (i.e. with the supply air damper fully open) is now approximately 300 cfm.

The results presented here are from a one hour test cycle designed to demonstrate the operating envelope and dynamics of the apparatus. The settings for dampers and heat load used in the test represent extremes and define practical limits for the space temperature which are achievable when the unit is operated indoors. Temperature and humidity values were recorded every two minutes during the test. The test cycle operation is defined as follows:

- At time zero, the compressor and blower are turned on. The outside air damper is closed (no outside air induction), and the supply air damper is fully open. Operation in this “maximum cooling mode” continues for twenty minutes.

- At twenty one minutes, the outside air damper is fully opened. Essentially all the conditioned air leaving the space is exhausted, and outside air is drawn into the blower inlet. Operation in this “100% outside air mode” continues for ten minutes.

- At thirty-one minutes, the outside air damper is closed. Operation in this mode continues for ten minutes.

- At forty-one minutes, the strip heaters are turned on to their full rating (1500 watts). Operation in this mode continues until the hour is over.

Temperature and humidity values during the test cycle are shown in Figures 2 and 3. The “outside” air temperature and relative humidity (inside the laboratory) for this test were 77 degrees Fahrenheit and 22%, respectively. As the test results indicate, the minimum space temperature achieved was 36.7 ^{o}F, with a corresponding relative humidity of 67.8%. These conditions were achieved after twenty minutes of operation in the maximum cooling mode, when nearly steady conditions had been achieved. Thus there is an approximately forty degree range of achievable temperatures within the space when the apparatus is operated indoors in maximum cooling mode.

Temperature values in Figure 2 between the time of twenty and thirty minutes show the effect of 100% outside air induction. The space temperature increases to 53 degrees at the end of this ten minute period, and would probably reach a steady value of less than sixty degrees in this mode. Thus it is possible to maintain a space temperature of about twenty degrees less than the ambient value in 100% outside air mode.

Between thirty and forty minutes, the apparatus was returned to maximum cooling mode in order to assess the impact of the electric heat load for the remaining portion of the test. The strip heaters were turned on to full capacity at the forty-one minute mark, and the space temperature climbed from 39 to 55 degrees during the last twenty minutes of the test. The steady state temperature in this mode would probably be less than sixty degrees.

It is also interesting to note the interrelationships among the space (T1), blower inlet (T2), and supply air (T3) temperatures during the test cycle. In the maximum cooling mode, the differences in these three values indicate the effect of the environmental heat gain in the space and return air duct. When the outside air damper is opened, the blower inlet temperature approaches the ambient temperature, but it is still being cooled by the thermal inertia of the return air duct. The cooling effect of the return air duct also appears to influence the blower inlet temperature during the last phase of the test cycle.

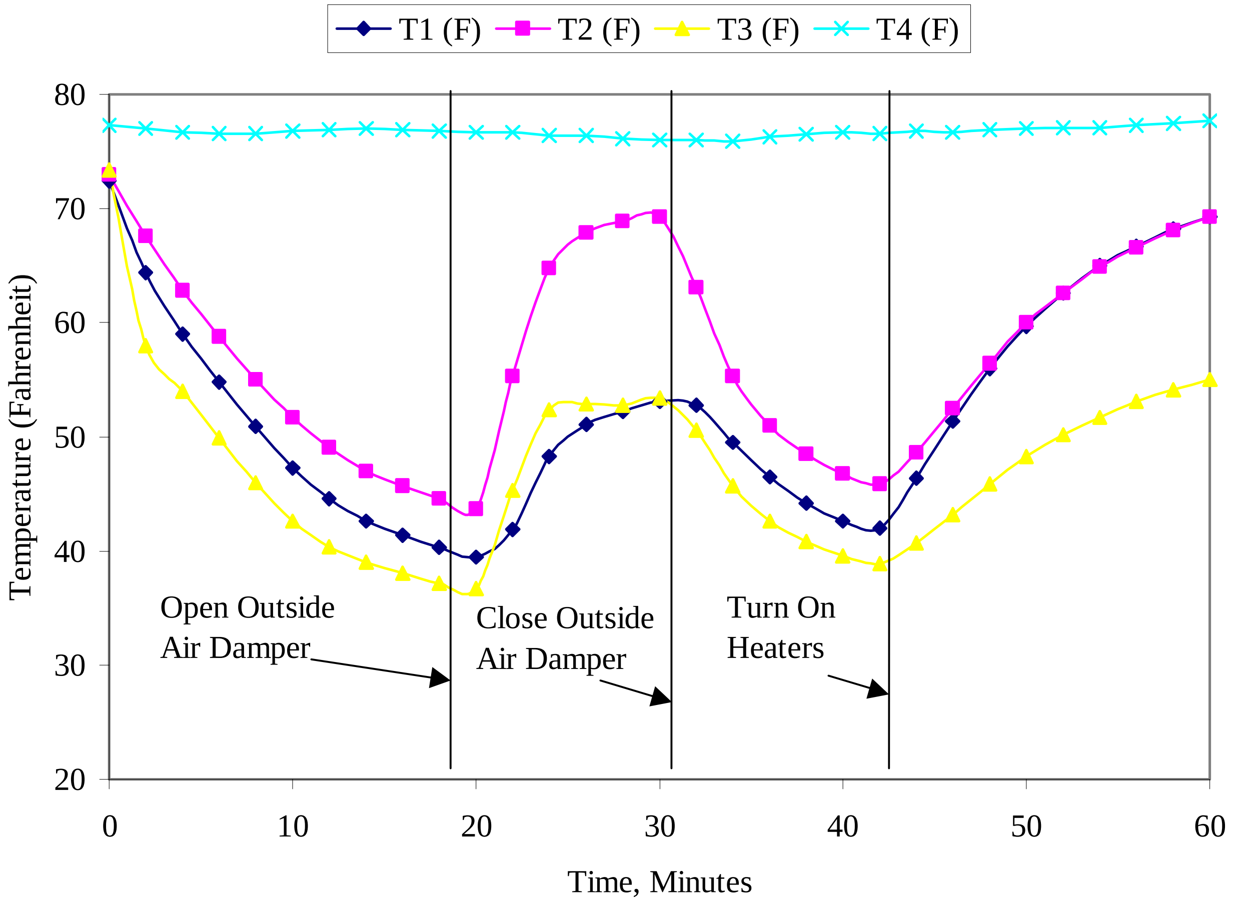

Figure 2 Variation of Temperatures During Test Cycle

The results for relative humidity in Figure 3 show similar trends. As the temperature drops, the relative humidity increases. Clearly a higher ambient humidity would lead to dehumidification as the air passes through the cooling coil, but very dry conditions existed at the time of this test.

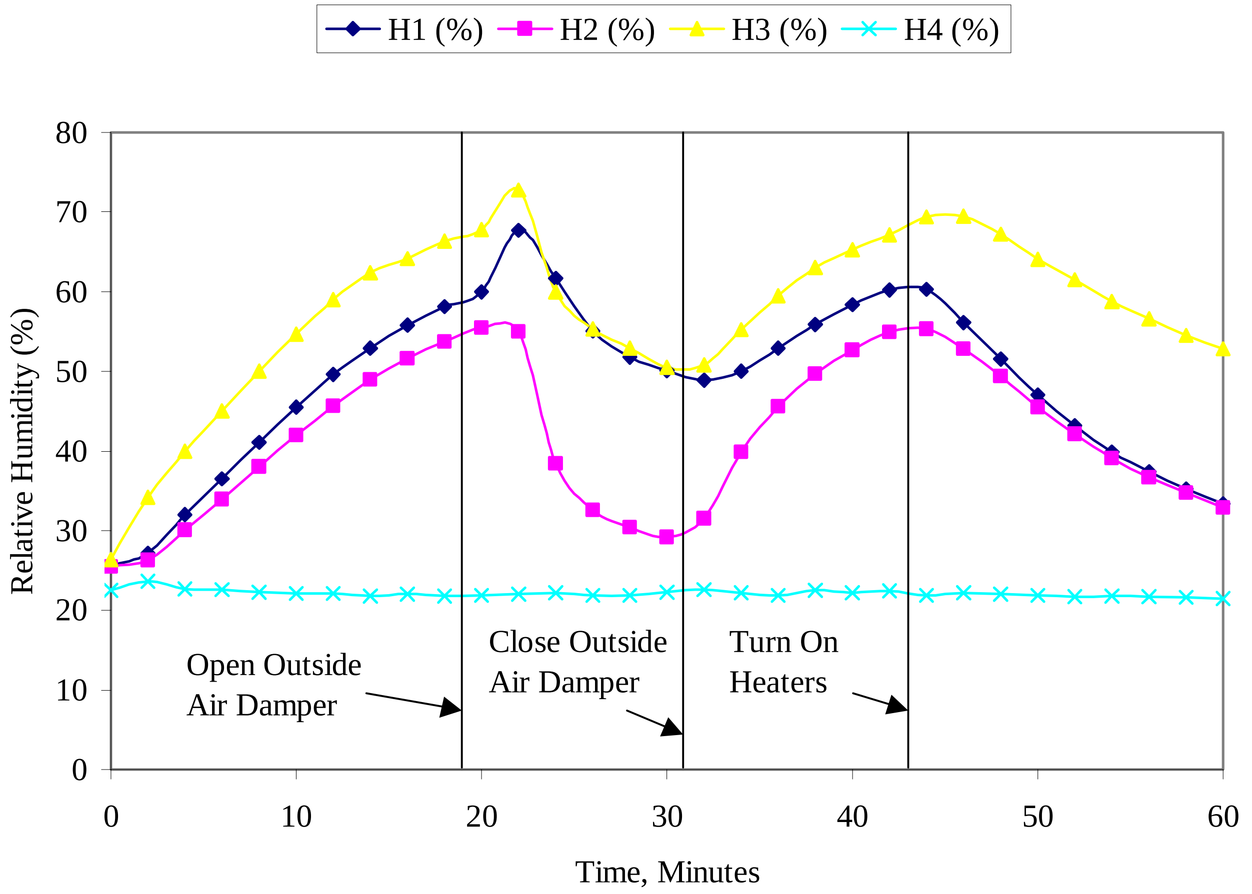

Figure 3 Variation of Humidity During Test Cycle

The results show that the apparatus effectively demonstrates the air cooling and mixing processes that occur in building air conditioning systems. A fairly wide range of space conditions can be achieved by adjusting damper positions and heat load. The dynamics of the apparatus are such that the effect of damper and heat load changes on space temperature and humidity are sensed fairly quickly, although the attainment of truly steady conditions is complicated by the thermal inertia of the sheet metal in the space box and ducting.

IV. Future Plans and Conclusions

The apparatus described in this paper is a valuable addition to CSUN’s thermo-fluids laboratory. Financial support from ASHRAE’s Undergraduate Senior Project Grant program was the key to beginning this endeavor. Integration of the design and construction of the apparatus into related senior courses was educationally valuable and allowed the project to be completed within a reasonable time frame. Thanks are also due to James Valiensi, Bill Sullivan, and Tom Brown of the Physical Plant Management department for the donation of the condensing unit and their expertise. The cost to the mechanical engineering department for this apparatus was approximately one thousand dollars.

The sample results prove that the apparatus is well designed for its intended purpose of demonstrating basic thermodynamic principles of air conditioning processes. Its portability allows the unit to be used for classroom demonstrations, laboratory experiments, and outdoors operation. The use of components from standard vendors simplifies the maintenance and future modifications which may be desired in the future.

Further enhancements will include the completion of the control system and computer interface for automatic operation. The goal is to make the apparatus capable of maintaining a set point for space temperature while the user varies heat load arbitrarily by adjusting the voltage input to the heaters. The computer and its interface will be designed to record the temperature and humidity versus time, while controlling the damper positions and possibly turning the compressor on and off. Thus students will be able to experiment with different control gains to optimize the dynamic response.

ROBERT G. RYAN
Robert Ryan received his PhD degree in Mechanical Engineering from the University of California at Los Angeles in 1994. He is currently a Lecturer in the Mechanical Engineering Department at California State University, Northridge. He is the coordinator for the department’s measurements laboratory and thermo-fluids laboratory.