FIELD AND LABORATORY STUDY OF A GROUND-COUPLED WATER SOURCE HEAT PUMP WITH AN INTEGRAL ENTHALPY EXCHANGE SYSTEM FOR CLASSROOMS

Ron Domitrovic
Senior Research Associate
University of Tennessee, Knoxville
10521 Research Drive, Suite 300
Knoxville, Tennessee 37932

G. J. Hayzen
Student Researcher
University of Tennessee, Knoxville
10521 Research Drive
Knoxville, Tennessee 37932

W. S. Johnson
Professor, Mechanical and Aerospace Engineering
University of Tennessee, Knoxville
Knoxville, Tennessee

F. C. Chen
Senior Researcher
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

ABSTRACT

School classroom space-conditioning equipment in hot and humid climates is often excessively burdened by the requirement to dehumidify incoming air to maintain proper thermal comfort and air quality. To that end, application of new or modified technologies is needed to increase the dehumidification abilities of equipment without compromising energy efficiency or the need for fresh ventilation air. To study the effectiveness of integrated heat pump and enthalpy exchange equipment, a nominal 4-ton water-source heat pump, coupled with a geothermal water loop and incorporating a forced fresh-air enthalpy exchange system was installed in a typical middle school classroom in Oak Ridge, Tennessee. This project is a joint effort among Oak Ridge School District, Tennessee Valley Authority, Energy Office of the State of Tennessee, and Oak Ridge National Laboratory.

The retrofit classroom, along with a similar baseline classroom (employing a water source heat pump supplied by a boiler/cooling tower loop), were instrumented with an Internet-based system to control and monitor performance, efficiency, and a variety of air states. Those include classroom air, outdoor air, semi-conditioned fresh air, and supply air. Particular attention was dedicated to the humidity content and the carbon dioxide content of conditioned space (classroom) air and to the intake rate of forced fresh air. This field study builds on a previous laboratory study of a water-source heat pump coupled to an enthalpy recovery system. The laboratory work showed good potential for reducing the moisture load from forced ventilation air. At simulated outdoor conditions of 90°F (32.2°C) and 90% RH, the enthalpy recovery wheel in the nominal 2-ton system was able to capture and exhaust 9.9 lb of moisture that would otherwise have to be handled solely by the cooling coil.

INTRODUCTION

Designing an air-conditioning system that can adequately handle the variety of loads brought on by the extremes of hot humid weather is a difficult task. Doing so with a system that minimizes energy use and maintains air quality is a substantially more difficult task. This paper primarily deals with classroom environments, but many of the issues are common to office buildings and other multi-occupant buildings. In a school classroom on a hot humid day, the most unfavorable outdoor conditions come when the classroom is most in need of cooling. The opposite is generally true in the heating season, when the coldest outdoor temperatures come at night when classrooms are unoccupied and the thermostat setpoint is low. Air-conditioning systems designed to satisfy cooling needs during extreme summer conditions are often oversized and thus short-cycle for more ordinary spring or evening summer conditions. This was historically a problem in hotel/motel systems that were oversized so that a guest could quickly cool down a room. Short cycling of the air conditioner does not allow moisture to be condensed out of the air, and eventually the conditioned space will approach saturated humidity levels.

Fresh air ventilation requirements, as specified in ASHRAE 62-1999, add a substantial load to already taxed systems. In a typical school classroom with 20 occupants, ASHRAE 62 specifies that 15 cfm per occupant (300 cfm total) of fresh air be supplied. On a hot, humid day, ventilation air can account for 50% of the cooling load. Ventilation may be through natural means—open windows or leaks—or through mechanical means. In either case, the demands on the cooling system are great when there is a large difference between the desired temperature and humidity conditions of the indoor space and the actual conditions of the outside air.[1]

Fresh ventilation air is needed to maintain a healthy environment inside the conditioned space, so it should not be treated as something that can be cut back in the interest of energy efficiency. Ventilation air must be dealt with just as any other component of cooling load. However, as with other cooling loads, there are ways to mitigate the effect of ventilation air. Preconditioning ventilation air is the most common method for mitigating its thermal effects. This can be done in several ways by exchanging heat and/or moisture with the accompanying exhaust air stream either centrally for an entire building, or locally at individual rooms.

This paper reports efforts of an ongoing project to characterize the potential benefits to a classroom environment from several applied technologies. A classroom at a middle school in Oak Ridge, Tennessee, was retrofitted with a ground-coupled, water-source heat pump incorporating a ventilation-air-to-exhaust-air enthalpy exchange wheel. The system and associated air conditions are presently monitored through a BACnet protocol building control system. In the near future, online, real-time control will be enabled so that control algorithms based on analysis of system operation can be incorporated and easily updated. The project builds on previous laboratory work studying the effectiveness of incorporating an enthalpy recovery wheel with a 2-ton water-source heat pump.

Ground-coupled water-source heat pumps have been shown to be very effective devices for heating and cooling buildings. The inherent tendency of the ground to maintain moderate temperatures throughout the extremes of the winter and summer makes it an effective heat sink for heat pump equipment. Compared with air-source heat pumps, ground-source units maintain capacity and efficiency during extreme-temperature days in both the heating and cooling seasons. In the summer, this characteristic gives them superior latent heat removal capabilities, making them better equipped to handle large dehumidification loads.

The ground-coupled water-source heat pump addresses one aspect of mitigating the extremes of summertime cooling—the high sink temperature of hot air, and the enthalpy wheel addresses another—the excessive load of hot and humid ventilation air. These two technologies coupled together can potentially be used together to both expand the cooling and dehumidification abilities of classroom cooling systems, and to do so without great expense in energy.

In order to characterize the effects of the ground-coupled water-source heat pump and the enthalpy recovery wheel, a real-time Internet-based monitoring system was installed to collect data and to serve as a base for future implementation of a real-time control system. It was installed to monitor both the retrofit room and a similar baseline room. This system was chosen to give access and experience to the school district facilities staff for possible future development. The system is used to gage the relative effectiveness of the new geothermal system, compared with the existing baseline system, for energy efficiency and air quality. Temperature and humidity are monitored for outdoor air, indoor return air, indoor supply air, and semi-conditioned air (retrofit room only), as is power and a variety of system temperatures for each unit.

The carbon dioxide (CO_2) content of the indoor conditioned air is monitored as a way of tracking the need for ventilation air. Ambient outside air contains approximately 0.04% CO_2 (~400 ppm). An indoor level under 1000 ppm is considered acceptable. Above 1000 ppm, the level of CO_2 may begin to cause sleepiness and otherwise be an indicator that the indoor air is stale. Though there is debate in the industry, there is good indication that quality of air in a building can be tied to measures of CO_2 and humidity. A study in part of the effectiveness of monitoring CO_2 can be found in Bayer, et al.[2] As mentioned, CO_2 is an indicator of freshness; humidity, in turn, can be used as an indirect measure of the level of airborne contaminants.

The moisture level of indoor conditioned air affects both the comfort and the health of occupants. Air that is too dry [relative humidity (RH) below ~30%] causes dryness of the skin and a rapid drying of the mucus membranes that has been linked to an increase in the susceptibility to colds. Overly dry air is principally a problem in the heating season in more northern regions. Overly humid air (RH greater than ~70%) decreases the effectiveness of the body's sweat-based evaporative cooling system and may lead to problems such as heat stroke or heat exhaustion. When humidity in a building is either too low or too high, the comfort of the occupants is compromised, leading in many cases to shorter attention spans, lower productivity, and increased irritability.

In addition to the tangible comfort problems associated with extreme humidity levels, many airborne contaminants—bacteria, viruses, fungi, and mites—are more abundant at humidity extremes.[3] Many types of airborne bacteria and viruses increase in abundance in air with RH conditions of below 30% and above 70% and show a marked decrease at around 50% RH. In addition, dust mites are not abundant below 50% RH and proliferate rapidly above 50% RH. Fungi and mildew generally do not appear in air below 80% RH but flourish in the 90–95% range. All of these airborne pathogens are believed to cause a wide range of adverse reactions in people, although the details of the biological mechanisms are not necessarily entirely understood. Considering these factors, it is generally recommended that winter humidity levels be maintained above 30% and that summer levels be held below 70%.

EXAMPLE OF FRESH AIR COOLING LOAD

With some simple assumptions, the degree to which fresh air adds to the air-conditioning requirements of a school classroom is easily illustrated. A classroom filled with 20 people will require 300 cfm of fresh air according to ASHRAE 62-1999. If the desired indoor conditions are 80°F and 53% RH, while the outside air conditions (the source of the fresh air) are 95°F and 85%RH, then the respective air enthalpies are 32Btu/lb (indoor) and 57.5Btu/lb (outdoor). The fresh air at these conditions, coming into the classroom at 300 cfm, adds a load of approximately 31,000 Btu/h to the classroom air conditioning requirements. At the same time, an equivalent amount of cooling is effectively being supplied to the atmosphere. Similar, but reverse, problems occur during the heating season when cold fresh air must be heated to the desired indoor condition. The cooling season problems, however, are particularly acute for several reasons: First, the hottest point of the day occurs during the time when the building typically is occupied—the middle of the afternoon, and second, the efficiency and cooling capacity of air-source equipment decreases as outdoor temperature increases. Both of these problems are mitigated to a degree with the use of a ground-source heat pump where the summer earth temperature is relatively unaffected by the daily air temperature. However, the heat load contained in the ventilation air must still be accounted for.

Table 1 gives the respective air conditions of a typical classroom and a hot summer day. The hot day applies to the hypothetical case at the beginning of this section, where the added demand on cooling equipment was ~31,000 Btu/h for an assumed 20-person classroom. What is less evident is the proportion of that load contributed by moisture. Under the conditions cited, 23 lb/h of evaporated moisture are introduced to the conditioned space through the fresh ventilation air. At 970 Btu/lb·m of condensation energy for water, the moisture load from fresh air is 22,800 Btu/h, or ~74% of the entire fresh air load. Single-coil air-conditioning systems are generally not equipped to handle such proportions. In this case, an enthalpy recovery system for fresh air not only can provide for substantial energy savings, but also can greatly extend the range of fresh air conditions under which the cooling equipment can maintain the desired indoor air-state.

LABORATORY RESULTS

A two-ton water-source air conditioner was placed in an environmental chamber, which simulated classroom conditions, and was connected to a constant-temperature, constant-flow-rate water supply to simulate ground conditions. Ventilation air was brought in from a second environmental chamber (simulating outside air) through an enthalpy recovery system and on to the air-mixing box of the air conditioner. The system was tested with and without operation of the enthalpy wheel. The setup is shown in Figure 1.

The air conditioner was first tested without ventilation air to verify factory ratings per Air-Conditioning and Refrigeration Institute (ARI) test standard 330-93.[4] With ARI indoor air conditions (80°F DB / 67°F WB) and an entering water temperature of 77°F, the air conditioner produced 32,800 Btu /h of cooling capacity with a COP of 3.4 and a condensation rate of 9.3 lb/h (SHR = 0.72).5

For tests incorporating ventilation, air was introduced at 300 cfm at several conditions. Figure 2 shows the moisture content in a 300-cfm air stream as a function of temperature and relative humidity. Results of testing are shown in Table 2 for outdoor air states at 80°F and 90°F, both at 90% RH. Captured moisture rates indicate the amount of moisture originally contained in the ventilation air stream that is prevented from entering the conditioned space. Note that exhausted moisture is constant, as it is only dependent on the inside room air state. Moisture captured by the enthalpy wheel is entrained in the exhaust air stream and exhausted to the outside. At high-temperature/-humidity outdoor conditions, the effectiveness of the enthalpy exchange system increases.

CLASSROOM FIELD TEST

A nominal 4-ton water-source heat pump with an integrated enthalpy wheel exchange system was installed in middle school classroom. A water/glycol heat exchange fluid is pumped through two parallel

Table 1. Air characteristics inside and outside a summertime classroom

Hot summer day—ventilation air–muggy	**Desired room conditions:**	**Notes:**
Temperature: 95°F Relative humidity: 80% Humidity ratio:0.027	Temperature: 80°F Relative humidity => 40-60% Humidity ratio: 0.0085–0.013	Dehumidification => necessary Without dehumidification: Absolute humidity => 0.027 Relative humidity => 100%

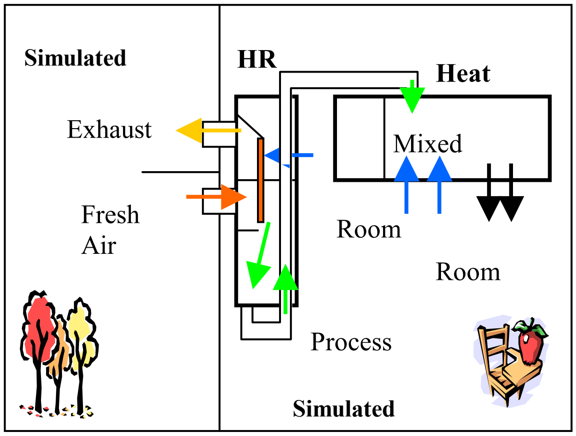

Figure 1. Schematic of laboratory test setup

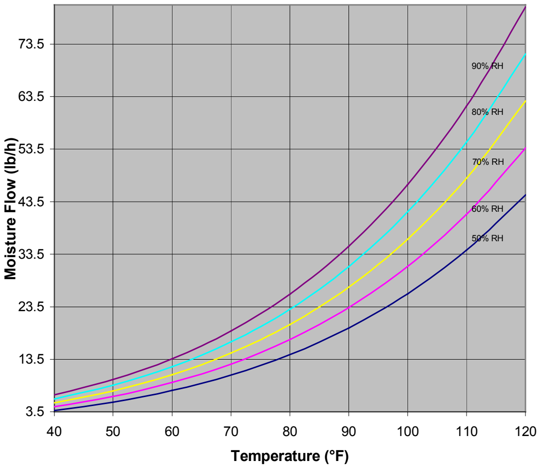

Figure 2. Moisture flow vs. temperature and relative humidity for a 300-cfm air flow

Table 2. Selected results from enthalpy capture tests.

Outdoor conditions	Fresh air moisture rate	Moisture captured by HRU	Moisture exhausted*	Moisture remainder
°F / % RH	lb·m/h	lb·m/h	lb·m/h	lb·m/h
80 / 90	28.6	6.2	14.1	8.3
90 / 90	37.1	9.9	14.1	13.1

*At ARI conditions—80°F / 53%RH.

vertical closed wells bored in the earth just outside the classroom. Figure 3 is a picture of the tops of the wells just after installation. This system replaces a water-source heat pump of similar size that was fed from a central water loop that provided warm boiler water in the heating season and cooling tower water in the cooling season. The new geothermal classroom and a similar baseline neighboring classroom were instrumented to monitor performance.

Ventilation air in the baseline classroom is allowed to enter the return air plenum of the heat pump through a dampered duct leading to the outside. Air is drawn in by the aspirating effect created when the circulating fan is turned on. In the new retrofitted room, ventilation air is brought in and exhaust air is sent out with dedicated fans that direct both air streams through the enthalpy wheel. Both fans are independently controllable and multi-speed.

At the time of this writing, the monitoring system was undergoing final installation and testing.

Figure 3. Geothermal wells

The goals of monitoring are to characterize performance of the geothermal system compared with the baseline system, primarily from the standpoints of energy efficiency and ability to meet demand. In the process, close attention will be paid to ventilation air-flow rates in both classrooms, as they greatly affect the overall load on the classroom cooling equipment. To this end, it is expected that monitoring of CO_2 levels in each room will play an important role. By following the CO_2 level, system operators can adjust ventilation flow rates accordingly. Although ASHRAE 62 recommends 15 cfm per person of fresh air, there is no easy way to know how much fresh air naturally leaks into the room. In the case of substantial natural migration of outside air into the classroom, it may be overkill to mechanically force in 15 cfm of additional fresh air. It is in no way detrimental to have excess fresh air, but it may cause unnecessary burdening of the cooling system.

From watching CO_2 concentration within the classroom, a good correlation can be made as to how much fresh air is actually needed to keep the indoor air within an acceptable range. Figure 4 is a selected daily profile of CO_2 concentration in the retrofit classroom on December 17, 2001. This profile was taken with the mechanical ventilation system operating and providing approximately 200 cfm of fresh air. There is an average of approximately 12 people in the classroom throughout the day from around 7:30 A.M. through 2:45 P.M., with a short break during a 45-minute lunch. In this case, CO_2 levels remain safely under 1000 ppm, and it is conceivable that fresh air rates could be throttled back. However, a single day does not provide sufficient data to draw this conclusion.

The summertime cooling season will introduce a new concern that was addressed earlier, the introduction of large amounts of moisture in the ventilation air stream. Large amounts of fresh air will keep the conditioned-space CO_2 level low but may cause humidity levels to be excessive. The goal of monitoring is to develop an algorithm for determining the most reasonable level of ventilation air-flow that maintains a healthy indoor environment without overburdening the cooling/dehumidification system.

It is anticipated that data collected during the cooling season will give good insight into the intricacies of the relationship between ventilation air flow rate, “freshness” of the indoor environment, and cooling equipment performance and energy efficiency. Data analysis will also provide a means for accurately comparing the retrofit system with forced ventilation with the baseline system with aspirated ventilation. There are already early indications that the baseline room maintains higher levels of CO_2 throughout the day. It is hoped that this field study will provide useful information to the school district on ways both to improve the classroom environment and to reduce overall energy consumption.

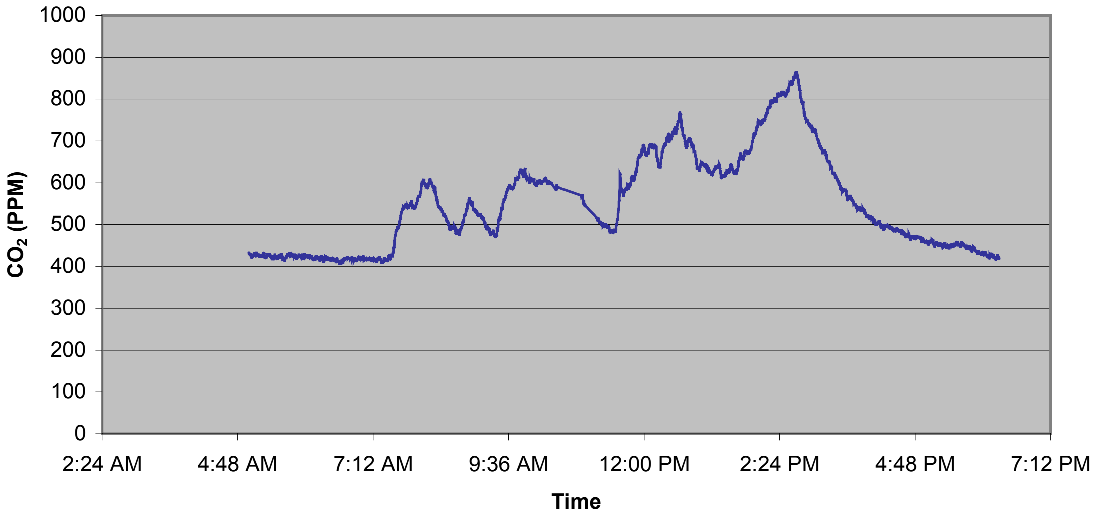

Figure 4. Classroom Carbon Dioxide Level
December 17, 2001--retrofit room

REFERENCES

1. American Society of Heating, Refrigerating and Air-conditioning Engineers, *Ventilation for Acceptable Indoor Air Quality*, ASHRAE Standard 62-1999, Atlanta, 1999.
2. C. W. Bayer et al. *Active Humidity Control and Continuous Ventilation for Improved Air Quality in Schools*, *ASHRAE Transactions*.
3. E. M. Sterling, A. Arundel, and T. D. Sterling 1985. “Criteria for Human Exposure to Humidity in Occupied Buildings,” *ASHRAE Transactions*, 91, Part 1B, 611–22.
4. Air-Conditioning and Refrigeration Institute 1993. ARI-330-1993, Arlington, Virginia.
5. Domitrovic et al. 2001. “Fresh Air Moisture Control with a Water Source Heat Pump and Enthalpy Recovery System,” *ASHRAE Transactions*, June.