Humidity Control in School Facilities

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Consulting engineers who design school facilities are challenged with controlling space humidity while also providing continuous ventilation as required by ASHRAE Standard 62-1999, now part of most major building codes.

What would appear to be a simple design process is complicated by various logistical and operational factors. Schools, by nature, have a high occupant density which results in large outdoor air quantities being handled by the heating, ventilating and air conditioning (HVAC) system. The vast majority of schools, particularly those located in hot and humid climates, incorporate packaged cooling equipment, often incapable of effectively managing space humidity when delivering a high percentage of outdoor air. Maintenance departments at many schools are understaffed, which can limit equipment options available.

School facilities are constructed on a tight budget, and capital allocations for mechanical equipment must compete with more visual items such as architectural details, computer labs and maximizing the number of classrooms.

For these reasons, it should not be surprising that the U.S. Government's General Accounting Office reported that 20% of the schools surveyed suffer from poor indoor air quality (IAQ) (GAO 1995, 1996). More than one third (36%) of the schools surveyed considered the HVAC systems "less than adequate".

Schools Need Humidity Control

In an attempt to accommodate the ventilation requirements of ASHRAE Standard 62 at the lowest possible project first cost, many school facilities have been designed with HVAC systems that cannot effectively manage space humidity.

This is unfortunate since it is highly beneficial to control humidity, especially in school facilities. A significant body of research exists (Figure 1) to support this position. Humidity control has been linked to comfort, mold growth, and the incidence of respiratory illness, all factors impacting performance and learning ability (Wargocki 2000b). Asthma, the most common cause of absenteeism, accounts for more than 10 million missed school days annually (NIH 1998). The rate of childhood asthma is rapidly increasing, up 74% between 1980 and 1994 (NIH 1998), and has been tied to indoor air quality and mold, both impacted by space humidity (Arundel 1986).

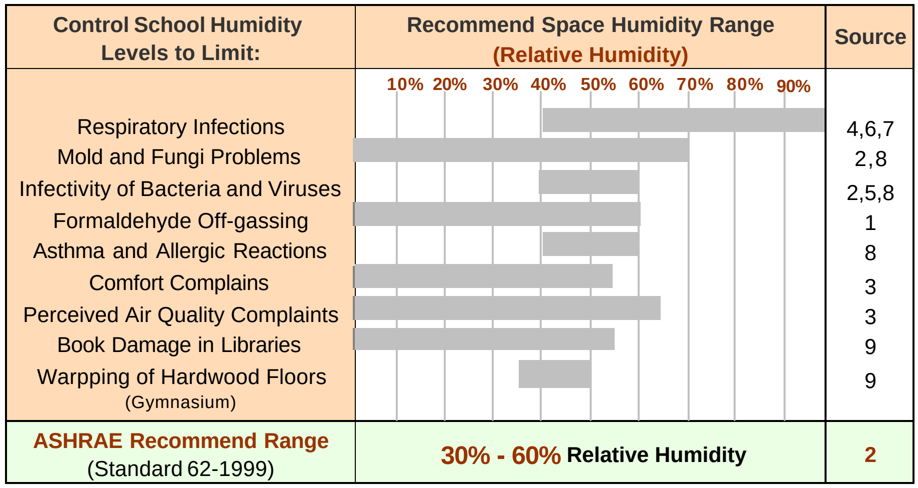

Figure 1: Recommended space humidity levels based on documented research

Physical damage to media centers, books, hardwood floors in gymnasiums, moldy carpeting and ceiling tiles as a result of poor space humidity control has become both commonplace and costly to school facilities (Fischer 1996).

DOE Schools Investigation

A major Department of Energy research investigation studied the impact of humidity control and ventilation on ten schools located in Georgia. Phase 1 of this program produced a document entitled "Causes of Indoor Air Quality Problems in Schools" (Bayer 1999). This report reviewed existing research and concluded with the hypothesis that "most IAQ problems in school facilities can be avoided by providing adequate outdoor air ventilation on a continuous basis (15 cfm/student), controlling the indoor relative humidity between 30% and 60% and providing effective particulate filtration of the outdoor air".

This hypothesis echoes ASHRAE 62 recommendations since Table 2 lists 15 cfm/person of outdoor air for school classrooms and section 5.10 states that indoor "spaces preferably should be maintained between 30% and 60% relative humidity".

In an attempt to test this hypothesis, five schools using conventional cooling systems and five schools incorporating desiccant-based systems, specifically designed to control indoor humidity levels were continuously monitored for temperature, relative humidity and carbon dioxide over a two-year period. Numerous other indoor contaminants also were measured at each school during frequent visits by the research team (Bayer 2001).

This article provides a synopsis of research information needed, yet seldom made available to design engineers. The effectiveness of the systems investigated, the benefits offered by humidity control and the need for increased ventilation is discussed and hopefully articulated in a manner helpful to designers and operators of future school facilities.

Humidity Control and Comfort

The most obvious impact of humidity is comfort. The absolute humidity level (dew point) in our environment impacts perspiration evaporation rate, which helps regulate our body's energy balance, skin moisture levels and thermal sensation. An excellent reference for the interrelationship between human comfort and humidity can be found in Chapter Four of the ASHRAE Humidity Control Design Guide (Harriman 2001).

As the dew point decreases, the rate of evaporation from the skins surface increases as does the associated energy loss. This causes the skin temperature to drop, the body to feel cooler and the desire for a warmer space temperature to achieve comfort. During warm conditions (cooling season), especially at levels of increased activity (not seated at rest), the effect of humidity is most pronounced since perspiration accounts for a much larger percentage of the body's overall energy balance. For these reasons, it is logical that as space dew point levels are reduced, warmer temperatures can be used (higher thermostat settings) to achieve a desired comfort level. Conversely, at elevated dew points a much cooler space temperature will be preferred (cold and clammy) by building occupants.

The Humidity Control Design Guide references a 1998 ASHRAE Journal article (Berglund 1998) that details research supporting this conclusion. Figure 2 presents test data reported by Berglund (shown as green circles) that links humidity levels with a corresponding dry bulb temperature necessary to reach thermal acceptability for 90% of the space occupants (10% dissatisfied). The 90% criteria for acceptability also serve as the basis for the ASHRAE Standard 55 entitled Thermal Environmental Conditions for Human Occupancy.

A careful review of the temperature and humidity database resulting from the DOE schools investigation provided the data points shown in yellow and red in Figure 2. These data points provide excellent agreement with the Berglund data, supporting the suggested relationship between a given humidity content and temperature required to achieve a comfortable space condition. These data also support Burglund's observation that the current ASHRAE comfort zone (shown in gray) would be more accurate if shifted left, by approximately 2.7^{o}F (1.5^{o}C), since none of the schools investigated were controlled above 77^{o}F while two (20%) were controlled below 73^{o}F.

These data suggest that occupant comfort was reached at higher thermostat settings (warmer space temperatures) in the schools where humidity was controlled to a lower level. On average, the schools served by the non-conventional (desiccant systems) were maintained 2^{o}F (1.1^{o}C) warmer (occupant preference) than the schools served by conventional systems. The average space relative humidity was 12 percentage points lower in the humidity controlled schools. The findings are particularly interesting since the occupants independently changed the only control point available to them, the space thermostat, in order to reach comfortable conditions.

Reaching occupant comfort at a higher space temperature, made possible by improved humidity control, can result in significant energy savings. Modeling was completed for a representative school facility using the DOE 2.1 program for the three different cities and three different ventilation rates to project the difference in total cooling cost. As shown in Figure 3, energy savings ranging between 18% and 23% were predicted for schools that were designed to provide the 15 cubic feet of air per minute (CFM) per student of outdoor air required by ASHRAE 62.

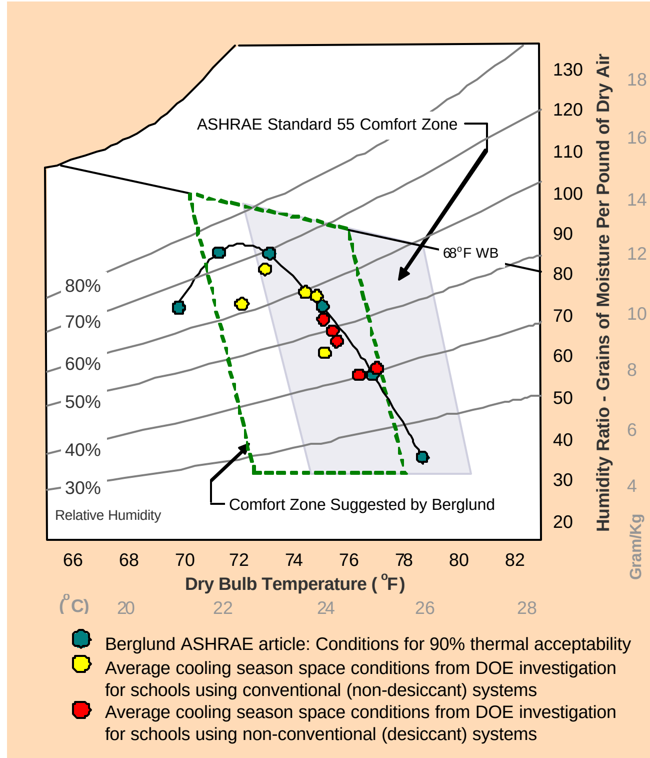

Figure 2: Berglund 90% thermal acceptability data vs. average space conditions measured in the DOE schools investigation

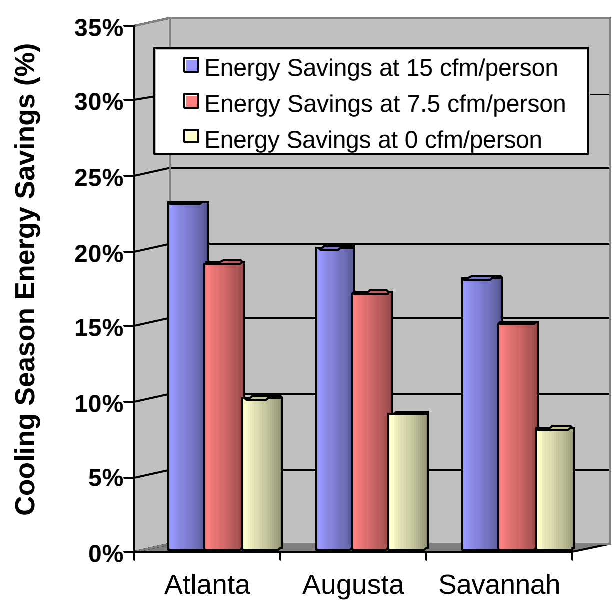

Figure 3: DOE2.1 modeling results estimating the energy savings associated with a 2^{o}F rise in the space temperature set point

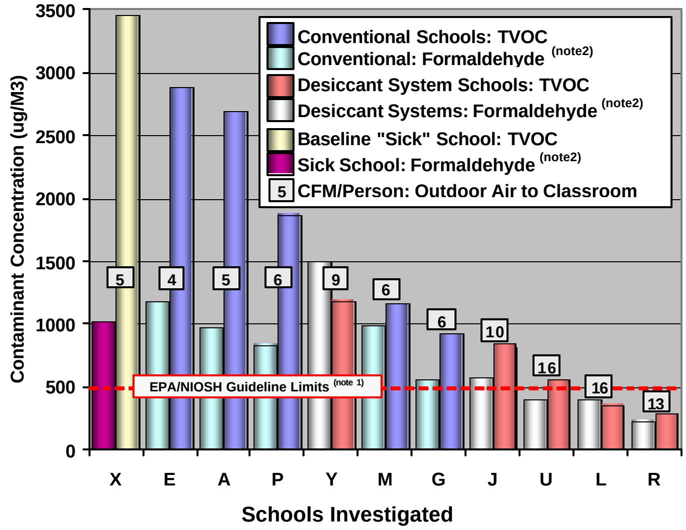

Figure 4: Indoor contaminant levels measured at schools investigated
Note 1: Current EPA/NIOSH guidelines for TVOC and formaldehyde
Note 2: Formaldehyde data/guideline shown as 25 times actual value

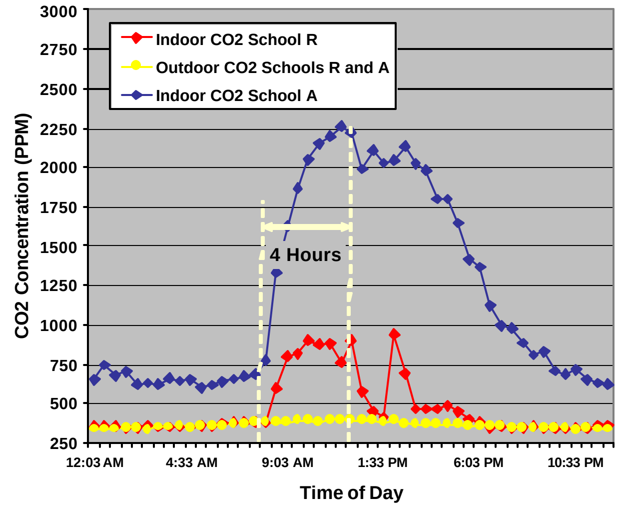

Figure 5: Shows the indoor carbon dioxide concentrations (CO2) measured for two representative schools investigated

Humidity Control and Ventilation Are Directly Linked

An important finding of the DOE research investigation was that none of the schools designed with conventional systems were operated to provide the outdoor air quantities required by ASHRAE 62 and the building codes. The average outdoor air quantity delivered ranged only between four and six cfm/person, compared to the 15 cfm/person required (Figure 4). When qualifying schools for this study, it was reported that all schools participating were designed in accordance with ASHRAE Standard 62. Reasons for this significant shortfall in ventilation rate were identified. In each case, the compromise in the ventilation air quantity resulted from a need to mitigate potential humidity control problems.

Some of the schools were designed with conventional packaged equipment "over-sized" to accommodate loads associated with the higher outdoor air ventilation rates. Since this design approach could not control humidity or maintain a comfortable environment, field modifications were made to the system controls (i.e. fans operated only when the compressor is on) or damper setting to reduce outdoor air quantities.

In other cases, design engineers misinterpreted section 6.1.3.4 of ASHRAE 62 entitled "Intermittent or Variable Occupancy". This section allows the ventilation rate to be reduced to "not less than one half the maximum" requirement of 15 cfm/person if "peak occupancy of less than three hours duration" exists. The DOE investigation found that, with few exceptions, school classrooms were occupied well beyond the three hour criteria. With thousands of portable trailers being used in the Atlanta area alone, few classrooms go unutilized.

Proper Ventilation is Important to School Facilities

Figure 4 presents data emphasizing the need for the minimum ventilation rate recommended by Standard 62. The average concentration of Total Volatile Organic Compounds (TVOC) measured in the school classrooms are compared with the average ventilation rate measured in each space. Note that the TVOC guideline limit of 500 micrograms/cubic meter recommended by the EPA (2002) and others was avoided only when about 15 cfm/person was provided. Also note that some of the schools with reduced ventilation experienced very high TVOC levels, approaching concentrations measured within a known "sick" school (Downing 1993).

The formaldehyde data presented in Figure 4 is of particular interest since formaldehyde has recently been classified as a suspected carcinogen (ACGIH, 1999, NIOSH 2002). As a result, the NIOSH recommended exposure limit (REL) for indoor environments has been reduced to .016 PPM (20 ug/M3). The formaldehyde levels measured in the schools investigated, as with the TVOC data, showed that the 15 cfm/person recommended by ASHRAE was required to maintain contaminant levels below the recognized guideline limits. Table C-2 of ASHRAE 62-1999 has not yet reflected this current scientific data for formaldehyde. Once considered, it should provide strong support for maintaining, if not increasing the ventilation rates currently referenced by Table 2 of the 1999 version of ASHRAE Standard 62.

Figure 5 compares CO2 data from two sample schools, labeled A (conventional system with 4 cfm/person) and R (non-conventional at 13 cfm/person). Both schools were occupied for four continuous hours each morning, exempting it from the "intermittent occupancy" classification. The ASHRAE Standard 62 committee has been clear in this interpretation (Bache, 1995). The Figure 5 data provides strong support to ASHRAE 62 recommendations by contrasting the ventilation effectiveness at the two different rates. As shown, the CO2 concentration (a surrogate for airborne contaminants) reaches much higher levels at the reduced ventilation rate and, as importantly, drops very slowly after the children leave for lunch. In sharp contrast, at the higher ventilation rate, the level of contaminants within the space quickly approaches that in the outdoor air soon after the room is unoccupied.

Ventilation Rates May Enhance the Learning Process

Numerous sources have linked increased ventilation rates to environmental satisfaction, comfort, and productivity. Three independent experimental studies have concluded that improving air quality through increased ventilation rates also improves the performance of a typical office worker when typing, completing arithmetical calculations or proof reading (Wargocki et al.). The research found that for each 10%

decrease in IAQ dissatisfaction, productivity will increase by 1.1%. The study predicts that at five cfm/person 30% of the occupants would be dissatisfied but at 15 cfm/person, only 12.5% would be dissatisfied in what was defined as a low-polluting building. Therefore, the research suggests that productivity or, in the case of a school, the learning process, would be improved by approximately 2% by simply increasing the ventilation rate from five to 15 cfm/student.

Downing (1993) investigated a school having serious indoor air quality problems. Based on the findings of this investigation, it was recommended that no less than 15 cfm/student be provided to the classrooms. Numerous teachers reported significant increases in comfort at the increased ventilation rates. For experimental reasons, (unpublished) the ventilation rate was temporarily reduced from 15 cfm/student to 10 cfm/student within the school. The occupants reported that the space was no longer acceptable. The school has since operated at 15 cfm/person level without incident.

School Humidity Control with Packaged Equipment

Of the five schools investigated that utilized conventional packaged equipment alone, three (60%) were found to be at least "borderline" sick schools by the researchers completing the DOE investigation. This conclusion was based on occupant perception as well as the level of indoor contaminants measured over time (Figure 4). Decreased ventilation rates in response to the performance limitations of conventional packaged cooling equipment when handling high outdoor air percentages, contributed to the poor air quality.

There are many reasons why conventional packaged cooling equipment cannot facilitate high percentages of outdoor air, especially in humid environments. Technical papers discussing the performance limitations of packaged cooling equipment with regard to humidity control have been presented by Henderson (1996), Khattar (1995) and others. An analysis of the sensible and latent heat loads associated with a typical classroom containing 29 students and a teacher, designed to meet ASHRAE 62 recommendations can be helpful to explain why these performance limitations exist.

Figure 6 segments the cooling load in a typical classroom, reflecting several common mistakes made by system designers and their modeling programs. The analysis uses the ASHRAE peak dry bulb design condition of 93°F (33.9°C) dry bulb and 107 grains of moisture (15.3 gm/Kg) for Atlanta. It also uses load data for adults seated at rest to compute the sensible and latent contribution of the students. Lighting sensible load is estimated at three watts/square foot and the infiltration ignores the doors being opened for extended periods as the students enter and leave the facility. This approach results in a sensible heat ratio (SHR) of 62%.

In contrast, the Figure 7 analysis more appropriately uses the ASHRAE dew point design data for calculating the outdoor loads, 82°F (22.8°C) and 133 grains of moisture (19 gm/Kg). It reflects the loads associated with children at a moderate activity level, lighting at 1.5 watts/square foot as called for by ASHRAE Standard 90.1 and the infiltration that occurs as children enter and leave the facility. This more accurate load assessment estimates a sensible heat ratio of only 40%.

Catalogued performance data typical for packaged cooling equipment handling the loads presented in Figure 7 shows a sensible heat ratio (SHR) of approximately 0.67. This means that 67% of the cooling capacity delivered will be in the

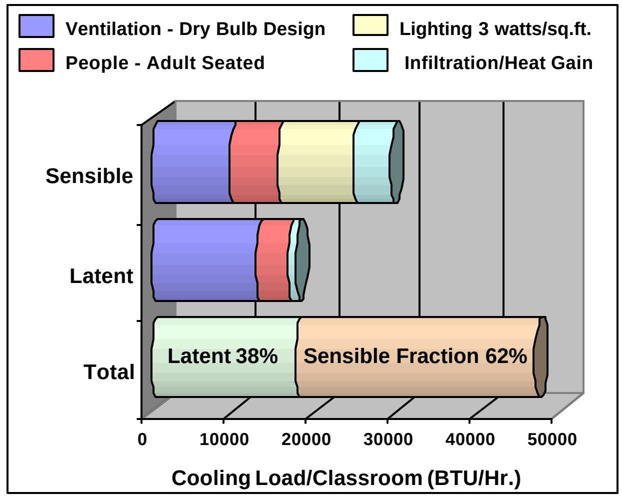

Figure 6: Sensible and latent loads for a typical classroom located in Atlanta, Georgia, calculated incorrectly

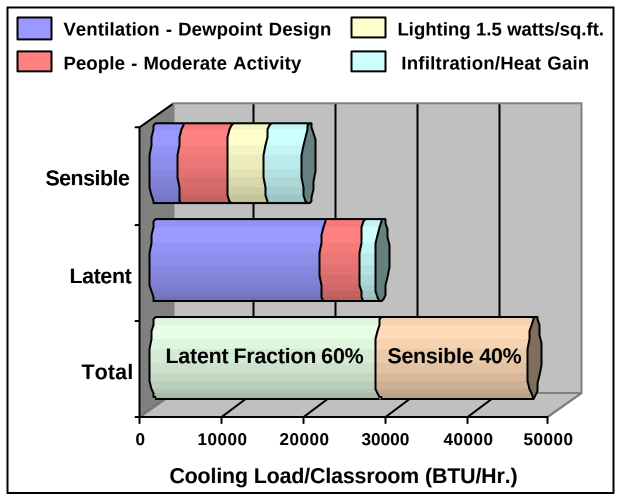

Figure 7: Sensible and latent loads for a typical classroom located in Atlanta, Georgia, calculated more accurately

form of sensible cooling (temperature) with the remaining capacity being latent (humidity). Since the application requires a SHR of only 40%, the use of packaged equipment would result in short compressor cycle times and extended periods where humid outdoor air is delivered, unconditioned, to the occupied space. The inability to control humidity is further exacerbated by moisture re-evaporating from the evaporator coil back into the space as the compressor cycles off and the system fan continues to run to deliver the outdoor air (Henderson 1996).

If a conventional four ton packaged unit is selected to handle the loads presented by Figure 7, the occupied space relative humidity will remain above approximately 65% to 70% at peak load conditions. At part load conditions, the humidity level maintained within the space may often be higher as more unconditioned outdoor air is delivered to the space.

Schools are unoccupied for extended periods of time, often all summer long, with minimal internal sensible loads. Extended high humidity levels must also be avoided during these times to avoid microbial infestation, especially in media centers, a common problem in hot and humid climates.

Research Findings: Conventional Systems

The five conventional schools investigated as part of the DOE research project maintained the indoor relative humidity at elevated but acceptable levels, averaging 58% within the space during the occupied periods. Acceptable humidity levels were achieved at the expense of the ventilation effectiveness, reducing the outdoor air delivered to an average of only 5.4 cfm/student. However, when unoccupied, the space humidity often exceeded 70% relative humidity for extended periods of time, despite the limited ventilation rate.

Figure 8 presents a sample of actual humidity data measured in a representative classroom of School G, served by a conventional HVAC system providing five cfm/student of outdoor air during the second week in September. Also shown is modeled data for ventilation rates of eight and 15 cfm/student, obtained by using the Indoor Humidity Assessment Tool (IHAT) developed by the EPA as part of its Tools for Schools program. Good agreement between the model (not shown) and the actual data obtained at the five cfm/student rate was observed. Good agreement was also observed between the actual data shown for 15 cfm/student (Figure 11) and that projected by the IHAT model in Figure 8. Based on these observations, the IHAT program appears to be an effective tool for estimating humidity levels within school facilities using conventional HVAC systems, including those incorporating energy recovery ventilators.

Increasing the outdoor air ventilation rate from five to only eight cfm/student, as shown in Figure 8, challenges the ability of the conventional systems to maintain the space relative humidity below the ASHRAE recommended 60% level. At the required 15 cfm/student, the space exceeds 70% relative humidity routinely and, at these levels, both comfort and potential microbial problems may be encountered (Crow 1994). These data clearly demonstrate why all of the conventional schools investigated were designed and/or operated with only six cfm/student of outdoor air or less.

During the summer months, when school facilities are typically unoccupied and the outdoor air humidity content is the highest, space humidity levels exceeding 80% were observed in the conventional schools (see Figure 9). To avoid humidity problems, all the schools investigated found the need to operate the HVAC system during the summer months. This highlights the need for a separate, unoccupied operating mode where the ventilation air quantity is minimized and the school is controlled to maintain humidity rather than temperature, especially in hot and humid climates.

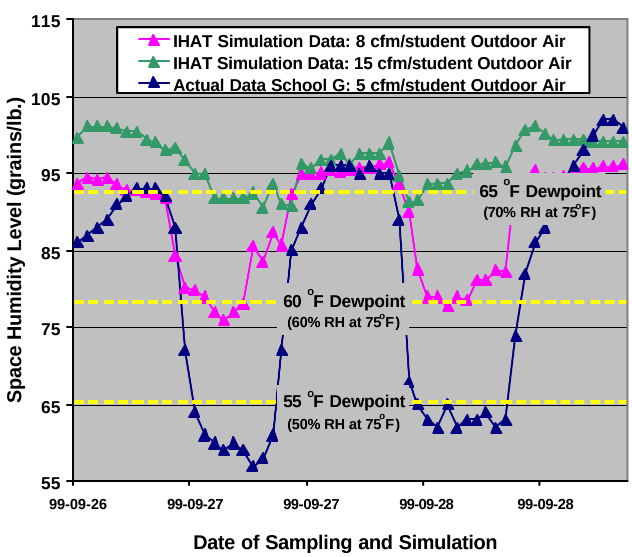

Figure 8: Actual space humidity data from school G at 5 cfm/student

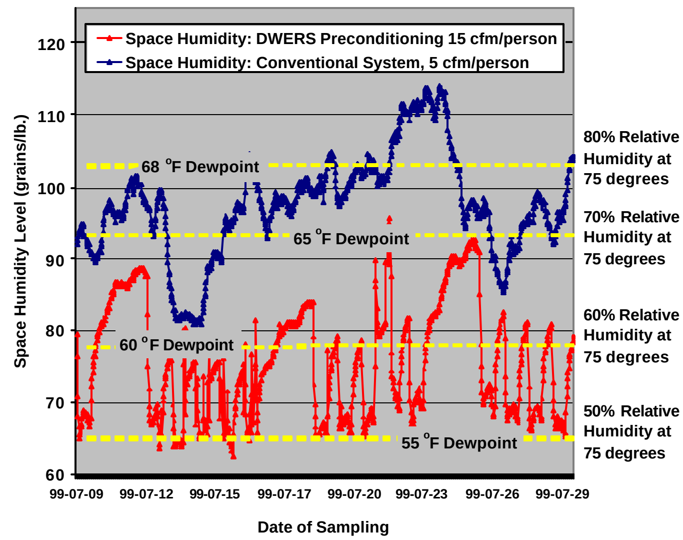

Figure 9: Summer space humidity levels, conventional vs. DWERS

Microbial Observations

Normal microbial levels were observed at the schools investigated. As previously discussed, reducing the outdoor air quantities delivered by conventional schools helped prevent extended periods of elevated humidity. These findings support the ASHRAE 62 recommendations regarding humidity control. Had the ventilation rates not been compromised, the outcome may well have been different. For example, one of the conventional schools investigated was identical (site adapt) to a school previously investigated by Downing (1993) where serious microbial problems were reported. With the exception of site location within the same district, the only significant difference between the two schools was age. The problematic school had experienced several summers with higher than average humidity while the newer school studied as part of the DOE investigation has benefited from an extended period of drought that has persisted since its construction.

Increased Absenteeism

Eight of the schools investigated provided records of absenteeism, covering a period from November 1998 through November 1999. Data was provided for four conventional schools and four schools with humidity controls systems. The conventional schools experienced absenteeism that averaged nine percent higher than those served by the desiccant systems.

Research Findings: Desiccant Preconditioning Systems

The non-conventional systems investigated as part of the DOE research program utilized desiccant based systems to recover energy from air exhausted from the schools facilities and to "decouple" the outdoor air and space latent loads from down-sized conventional HVAC units serving each classroom. This dedicated outdoor system approach (DOAS) allows the space humidity to be controlled in an energy efficient manner.

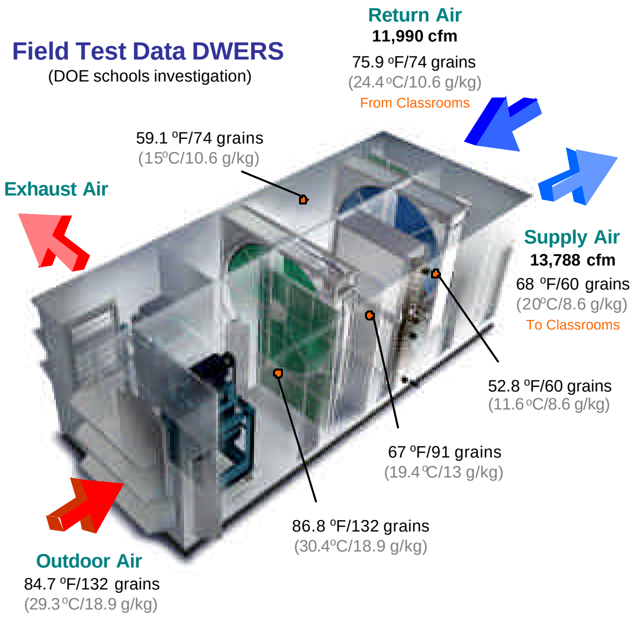

Figure 10: Field measured performance for DWERS at school L

Improved Ventilation Effectiveness

Of the 10 schools investigated, the best air quality existed in the schools labeled R, L and U, all served by a DOAS. Increased ventilation rates significantly improved IAQ, both qualitatively (perception) and quantitatively (measured), and a reduction in absenteeism was observed.

The DOAS configuration used by these three schools was the Dual Wheel Energy Recovery System (DWERS), as shown in Figure 10, with both the outdoor air and the exhaust air ductwork connected directly to the individual classrooms. The DWERS combines a total energy wheel, sensible only wheel and a cooling coil to produce a very energy efficient DOAS.

Detailed descriptions of the DWERS investigated are provided by Fischer (1996). Mumma (2001) found the DWERS to be the most effective DOAS system investigated and concluded that a "DOAS may be the only reliable method for meeting Standard 62-1999" recommendations.

Improved Humidity Control

Figure 11 provides a sample of actual humidity data from the DOE investigation to highlight the performance difference between the conventional systems and those utilizing the DOAS approach. Each school served by the desiccant based DOAS could be operated to control space humidity at the level desired while continuously delivering approximately 15 cfm/student of outdoor air, as required by ASHRAE 62 and the major building codes. If operated at these conditions the conventional systems were found to allow the space relative humidity to exceed 70% a large percentage of the time.

Accommodates an Unoccupied Mode

Figure 9 compares the space humidity at Schools R and G during the last three weeks of July. While the conventional system exceeded 70% relative humidity throughout most of this period, the school served by the DOAS met its 50% relative humidity set point during the day and 60% night setback condition, except for the weekends when the system was cycled off. A preferable unoccupied mode would be to control the space humidity during the weekends as well.

Single Source for High Efficiency Filtration

Most of the DOAS systems investigated used backward curve fans and could therefore accommodate high efficiency filtration. Improved filtration efficiency is beneficial to school facilities. It can help prohibit high quantities of mold spores and other particles from entering the ductwork, coil drain pans and classroom areas. With high efficiency filtration in one central location, replacing filters is quickly and easily accomplished. Cleaning the outdoor air was found to greatly extend the usable life of the low efficiency filters located within the individual room heating/cooling units.

Reduce/Eliminates Condensation in Parallel System

Since the DOAS removes most of the latent (moisture) load from the individual room cooling units, problems often associated with condensate management are avoided. The incidence of musty odors, plugged drain pans and water leaks are greatly reduced by the DOAS approach.

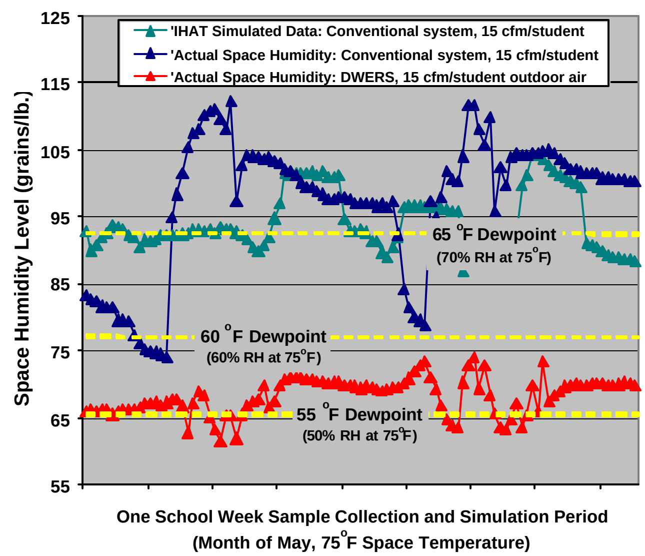

Figure 11: Actual humidity data for DWERS and conventional vs. IHAT simulation for the conventional systems all at 15 cfm/student

Economics: Dedicated Outdoor Air System

Designers of the three schools found to have the best IAQ (R,L and U) reported that the DOAS approach provided them with a cost effective way of meeting ASHRAE 62 and building code requirements. In addition, the annual cost of operating a typical school facility is approximately $15,000 to $20,000 less than a conventional system designed to meet ASHRAE 62 recommendations (Fischer 1996).

The conditions shown in Figure 10, represent actual field data collected for DOE at school L. The system provided 82 tons of total cooling with 56 tons of latent capacity (.32 SHR), using only 42 tons of cooling input. A traditional cooling system requires more than 100 tons to reach similar conditions.

Since schools are owner-occupied, have a life that often exceeds 30 years, pay no taxes and have access to low cost capital (municipal bonds), life cycle analyses of the DOAS systems investigated are particularly attractive.

Conclusions and Recommendations

The results obtained from the DOE schools investigation provide strong support for providing the outdoor air ventilation rates (15 cfm/student) and maintaining the space humidity levels (30% to 60% RH) recommended by ASHRAE Standard 62-1999, supporting the hypothesis that most IAQ problems would be avoided when these recommendations are followed. Other conclusions and recommendations include the following:

- The 15 cfm/student recommended by ASHRAE 62 was found to be the minimum ventilation rate necessary to maintain the levels of important airborne contaminants (formaldehyde, total volatile organic compounds, etc.) below recognized guidelines set by EPA, NIOSH, ACGIH and CDC.
- None of the schools served by conventional systems were found to be in compliance with the local building codes or ASHRAE 62, averaging only 5.4 cfm/student. Three of the five conventional schools investigated (60%) were found to be borderline sick schools by the researchers, despite the fact that the participating school districts selected from their best, least problematic schools to be investigated.
- The low ventilation rates associated with the conventional systems were necessitated by the inability to maintain space humidity at acceptable, comfortable levels while delivering higher quantities of outdoor air.
- Humidity levels in schools should be carefully controlled since they impact comfort, perceived indoor air quality, illness, allergies, microbial activity, and other factors that impact the learning process and absenteeism.
- Lowering the space humidity (dew point) allows for occupant comfort at elevated space temperatures. Raising the space temperature in a school classroom by only 2°F can reduce the cost of running the cooling system by as much as 22% when ventilated at the 15 cfm/student rate.
- Latent loads within the school facilities investigated were often underestimated. ASHRAE Dewpoint design data, increased student activity level, evaporator coil re-evaporation and moisture infiltration through frequent door opening need to be reflected in load calculations. Careful load estimates, equipment sizing and overall system selection is essential for proper humidity control.
- Desiccant based dedicated outdoor air systems proved an effective way to operate school facilities in accordance with ASHRAE Standard 62 requirements. Schools served by the DOAS could be ventilated at the 15 cfm/student rate while maintaining the space humidity as desired, during both occupied and unoccupied periods.
- The schools provided with increased ventilation and humidity control had improved comfort and perceived indoor air quality. Average absenteeism was determined to be nine percent lower for these schools.
- The desiccant based systems investigated proved efficient and cost effective, providing support for section 6.3.6.1 of ASHRAE Standard 90.1, requiring the use of total energy recovery components in systems handling more than 5,000 cfm and delivering more than 70% outdoor air.
- School HVAC systems need an unoccupied mode designed to control the space dew point at elevated space temperatures. Schools investigated operated the HVAC system year round in order to avoid humidity problems.
- Conventional HVAC equipment using forward-curve fans, require rigorous filtration maintenance since excess static pressure can significantly reduce ventilation rates.
- School facilities managers and their staff need to understand the importance of IAQ, humidity control, the operation and the energy savings potential of their HVAC systems so that routine maintenance and proper system operation is given the appropriate priority.

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