Failing Grade for Many Schools

Report Card on Humidity Control

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Consulting engineers who design school facilities are challenged with controlling space humidity while also providing continuous ventilation as required by ANSI/ASHRAE Standard 62-1999, *Ventilation for Acceptable Indoor Air Quality,* now part of the 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 that results in large outdoor air quantities being handled by the HVAC system. The vast majority of schools, particularly those located in hot and humid climates, use packaged cooling equipment. These units are incapable of effectively managing space humidity when delivering a high percentage of outdoor air.

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

For these reasons, it should not be surprising that a federal General Accounting Office survey reported that 20% of schools suffer from poor indoor air quality (IAQ).[1] 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 to support this position. Inadequate humidity control has been linked to discomfort, mold growth, and the incidence of respiratory illness, all factors impacting performance and learning ability.[16] Asthma, the most common cause of absenteeism, accounts for more than 10 million missed school days annually.[17] The rate of childhood asthma is rapidly increasing, up 74% between 1980 and 1994,[17] and has been tied to indoor air quality and mold, both impacted by space humidity.[18]

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.[14]

DOE Schools Investigation

A major U.S. Department of Energy (DOE) investigation studied the impact of humidity control and ventilation on 10 schools in Georgia. Phase 1 of this program produced the document, "Causes of Indoor Air Quality Problems in Schools."[2] 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 [7 L/s per student]), controlling the indoor relative humidity between 30% and

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60% and providing effective particulate filtration of the outdoor air."

This hypothesis echoes Standard 62 recommendations since Table 2 lists 15 cfm/person (7 L/s per student) 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 using desiccant-based systems, specifically designed to control indoor humidity levels, were continuously monitored for temperature, relative humidity and carbon dioxide during a two-year period. Many other indoor contaminants also were measured at each school during frequent visits by the research team.[3]

This article provides a synopsis of needed research information, which is 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) impacts perspiration evaporation rate, which helps regulate the 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 ASHRAE's *Humidity Control Design Guide for Commercial and Institutional Buildings*.[4]

As the dew point decreases, the rate of evaporation from the skin's 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 larger percentage of the body's overall energy balance. For

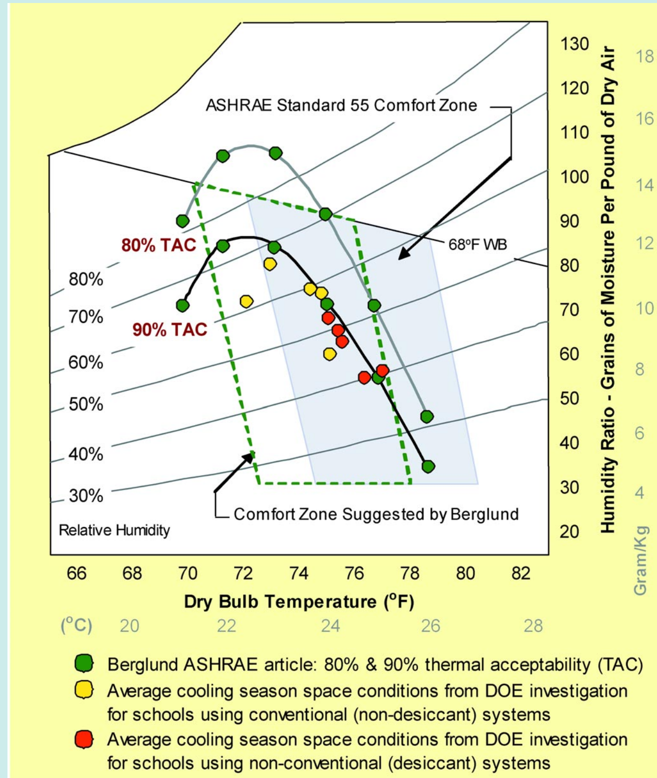

Figure 1: Berglund thermal acceptability data vs. average space conditions measured in the DOE schools investigation.

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 cooler space temperature will be preferred (cold and clammy) by building occupants.

The *Humidity Control Design Guide* references a 1998 ASHRAE Journal article[5] that details research supporting this conclusion. *Figure 1* 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 both 80% and 90% of the adapted space occupants (20% and 10% dissatisfied) during the cooling season. An 80% criterion for overall thermal acceptability serves as the basis for ANSI/ASHRAE Standard 55, *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 1*. These data points provide excellent agreement with the Berglund 90% data, supporting the suggested relationship between a given humidity content and temperature required to achieve a comfortable space condition. These data also support Berglund's observation that

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the current ASHRAE comfort zone (shown in gray) would be more accurate if shifted left, by approximately 2.7°F (1.5°C), since none of the schools investigated were controlled above 77°F (25°C) while two (20%) were controlled below 73°F (23°C).

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°F (1.1°C) warmer (occupant preference) than the schools served by conventional systems. The average space relative humidity was 12% 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. The data also suggest occupants will select thermostat settings to reach 90% thermal acceptability if given the option.

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 three different cities and three different ventilation rates to project the difference in total cooling cost. Energy savings ranging between 18% and 23% were predicted for schools that were designed to provide the 15 cfm/student (7 L/s per student) of outdoor air required by Standard 62. These energy savings help offset any increase in project first cost or operating cost associated with the equipment required to better control space humidity.

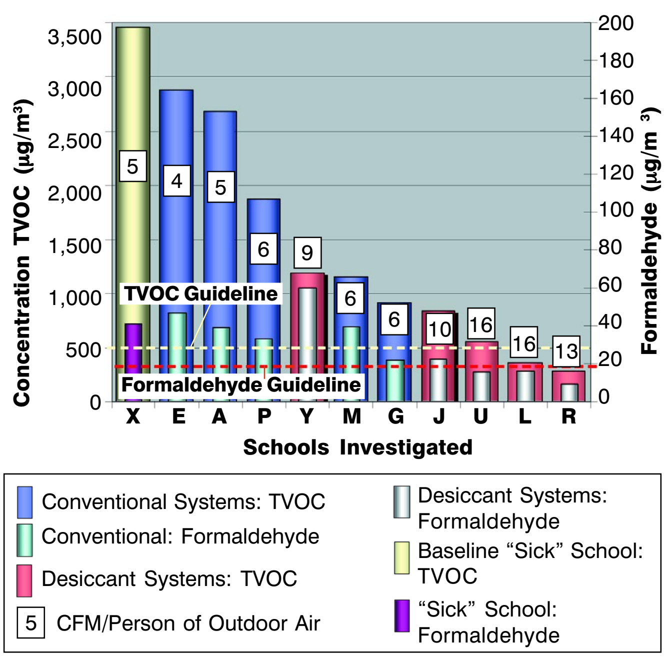

Figure 2: Indoor contaminant levels and ventilation rates measured at schools investigated.

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 Standard 62-2001 and the building codes. The average outdoor air quantity delivered ranged only between 4 and 6 cfm/person (2 to 3 L/s per person), compared to the 15 cfm/person (7 L/s per person) required (*Figure 2*). When qualifying schools for this study, it was reported that all schools participating were designed in accordance with Standard 62. Reasons for this shortfall in ventilation rate were identified. In each case, the compromise in ventilation air quantity resulted from a need to mitigate potential humidity control problems.

Some of the schools were designed with conventional packaged equipment "oversized" 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 settings to reduce outdoor air quantities.

In other cases, design engineers misinterpreted Section 6.1.3.4 of Standard 62-2001 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 (7 L/s per 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 unused.

Proper Ventilation Is Important to School Facilities

Figure 2 presents data emphasizing the need for the minimum ventilation rate recommended by Standard 62-2001. The average concentration of total volatile organic compounds (TVOC) measured in the classrooms is compared with the average ventilation rate measured in each space. Note that the TVOC guideline limit of 500 micrograms/m^3, a time weighted average (TWA) during an eight-hour workday and 40-hour workweek, recommended by the EPA[6] and others was avoided only when about 15 cfm/person (7 L/s per person) was provided. Note that some of the schools with reduced ventilation experienced high TVOC levels, approaching concentrations measured within a known "sick" school.[7]

The formaldehyde data presented in *Figure 2* is of interest since formaldehyde has been classified recently as a suspected carcinogen.[8,9] As a result, the National Institute for Occupantional Safety and Health (NIOSH) recommended exposure limit (REL) for workplace environments (TWA) has been reduced to 0.016 ppm, based upon risk evaluations using human or animal health effects data. The formaldehyde levels measured in the schools, as with the TVOC data, showed that the 15 cfm/person (7 L/s per person) recommended by ASHRAE was required to maintain contaminant levels below the recognized guideline limits. Table C-2 of Standard 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 Standard 62-1999.

Figure 3 compares CO_2 data from two sample schools, labeled A (conventional system with 4 cfm/person [2 L/s per person]) and R (non-conventional at 13 cfm/person [6 L/s per person]). Both schools were occupied for four continuous hours each morning, precluding it from using the "intermittent occupancy" classification. The Standard 62 committee has been clear in this interpretation.[10] The *Figure 3* data provides strong support to Standard 62 recommendations by contrasting the ventilation effectiveness at the two different rates. As shown, the CO_2 concentration (a surrogate for human bioeffluents) reaches higher levels at the reduced ventilation rate and, as importantly, drops very slowly after the children leave for lunch. In sharp contrast, higher ventilation rates dilute the level of CO_2 (and by inference, other contaminants within the space) causing the indoor CO_2 concentration to quickly approach the outdoor air concentration soon after the room is unoccupied.

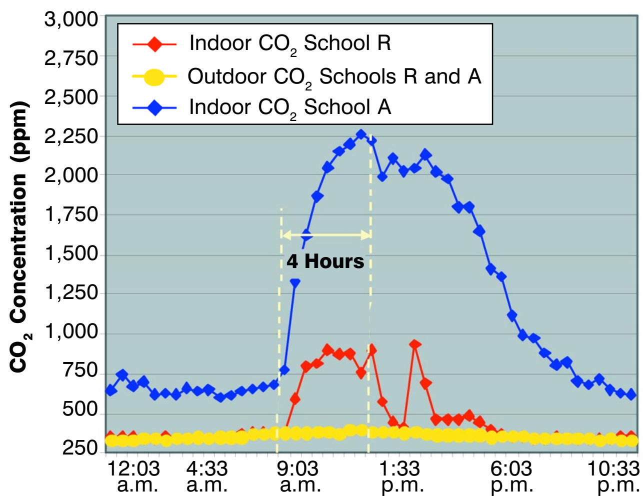

Figure 3: Indoor CO_2 cocentrations for two schools.

School Humidity Control with Packaged Equipment

Of the five schools investigated that used conventional packaged equipment alone, three were at least "borderline" sick schools according to the researchers completing the DOE investigation. This conclusion was based on occupant perception and the level of indoor contaminants measured over time (*Figure 2*). 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,[11] Khattar,[12] and others. An analysis of the sensible and latent heat loads associated with a classroom containing 29 students and a teacher, designed to meet Standard 62 recommendations can be helpful to explain why these performance limitations exist.

Figure 4 segments the cooling load in a typical classroom, reflecting several common errors made by system designers and their modeling programs. The analysis uses the ASHRAE 0.4% peak dry-bulb design condition of 93°F (33.9°C) and 107 grains of moisture (15.3 gm/kg) for Atlanta, and space conditions of 75°F (23.9°C) dry bulb and 50% relative humidity. It uses load data for adults seated at rest to compute the sensible and latent contribution of the students. Lighting sensible load is estimated at 3 W/ft^2 (32.4 W/m^2) 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 5* analysis more appropriately uses the ASHRAE 0.4% dew-point design data for calculating the outdoor loads, 82°F (22.8°C) and 133 grains of moisture (19 gm/kg [16.2 W/m^2]) and the same space conditions. It reflects the loads associated with children at a moderate activity level, lighting at 1.5 W/ft^2 (16.2 W/m^2) as called for by ANSI/ASHRAE/IESNA Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings,* 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%.

Cataloged performance data typical for packaged cooling equipment handling the loads presented in *Figure 5* shows a sensible heat ratio (SHR) of approximately 0.67. This means that 67% of the cooling capacity delivered will be in the form of sensible cooling (temperature) with the remaining capacity being latent (humidity). Since the application requires an 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.[11]

If a conventional 4 ton (14 kW) packaged unit is selected to handle the loads presented by *Figure 5,* 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 often may be higher as more unconditioned outdoor air is delivered to the space (*Figure 6*).

Furthermore, schools are unoccupied for extended periods

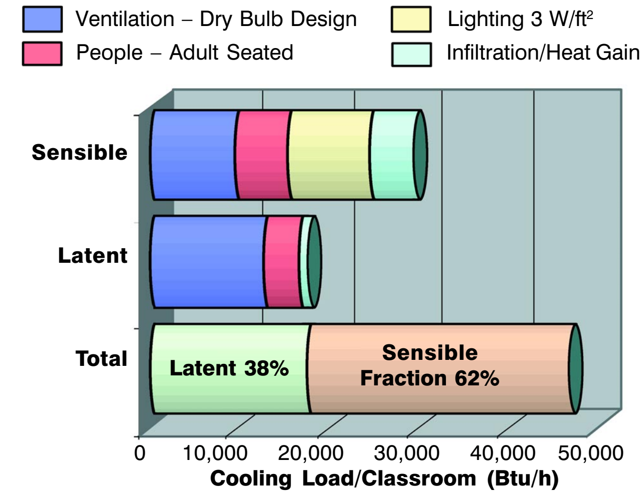

Figure 4: Sensible and latent loads for a typical classroom in Atlanta, inaccurately calculated.

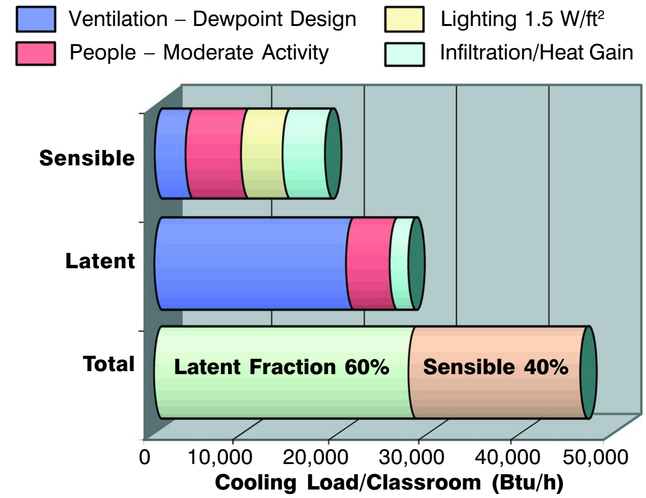

Figure 5: Sensible and latent loads for a typical classroom in Atlanta, more accurately calculated.

of time, often all summer, with minimal internal sensible loads. Extended high humidity levels must be avoided during these times to avoid microbial infestation, especially in media centers.

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 (2.5 L/s per student). However, when unoccupied, the space humidity often exceeded 70% relative humidity for extended periods of time, despite the limited ventilation rate.

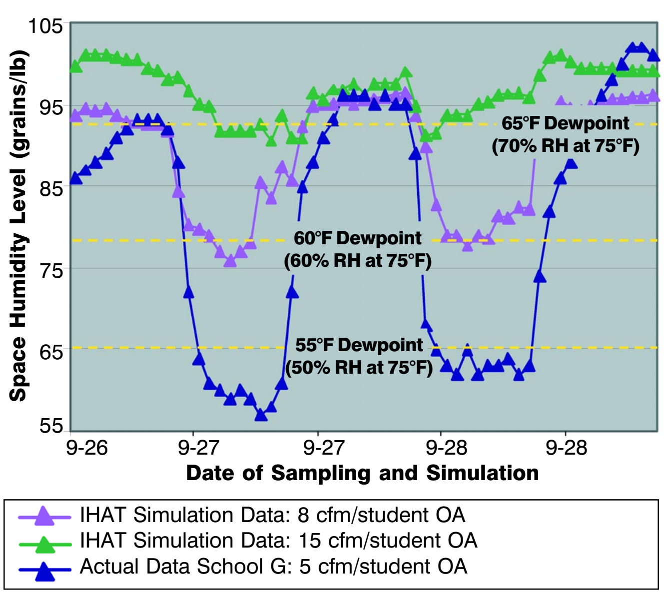

Figure 6: Actual space humidity data from School G at 5 cfm/student and IHAT simulations at 8 and 15 cfm/student of OA.

Figure 6 presents a sample of actual humidity data measured in a representative classroom of School G, served by a conventional HVAC system providing 5 cfm/student (2.4 L/s per student) of outdoor air during the second week in September. Also shown is modeled data for ventilation rates of 8 and 15 cfm/student (3.7 and 7 L/s per student), obtained by using the Indoor Humidity Assessment Tool (IHAT) developed by the EPA's Tools for Schools program. Agreement between the model (not shown) and the actual data obtained at the 5 cfm/student (2.4 L/s per student) rate was observed. Agreement was also observed between the actual data shown for 15 cfm/student (7 L/s per student) (*Figure 9*) 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 using energy recovery ventilators.

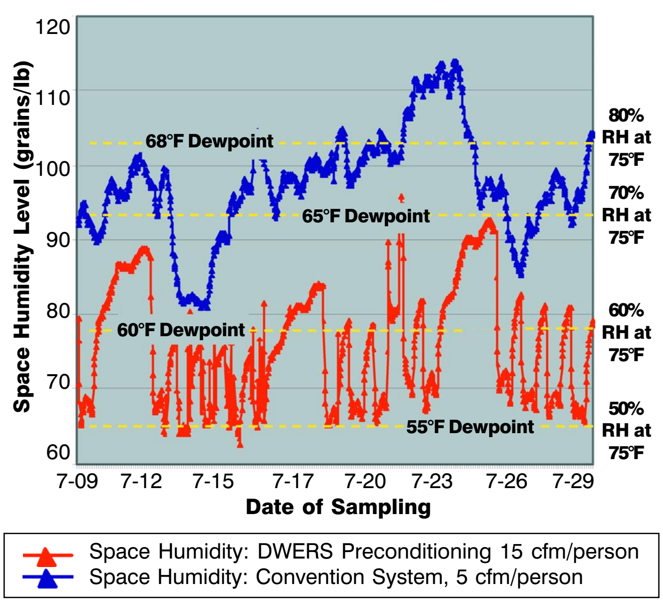

Figure 7: Summer space humidity levels, conventional vs. DWERS.

Increasing the outdoor air ventilation rate from 5 to only 8 cfm/student (2.4 L/s to 3.8 L/s per 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 (7 L/s per student), the space exceeds 70% relative humidity routinely and, at these levels, both comfort and potential microbial problems may be encountered.[13] These data clearly demonstrate why all of the conventional investigated schools were designed and/or operated with only 6 cfm/student (2.8 L/s per person) 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 relative humidity levels exceeding 80% were observed in the conventional schools (*Figure 7*). To avoid humidity problems, all the investigated schools needed 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.

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 Standard 62 recommendations regarding humidity control. Had the ventilation rates not been compromised, the outcome well may have been different. For example, one of the conventional schools investigated was identical (site adapt) to a school previously investigated by Downing[7] 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 in the DOE investigation had 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 9% greater than those served by the desiccant systems.

Research Findings: Desiccant Preconditioning Systems

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

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 schools was the Dual Wheel Energy Recovery System (DWERS), as shown in *Figure 8,* 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 an energy efficient DOAS.

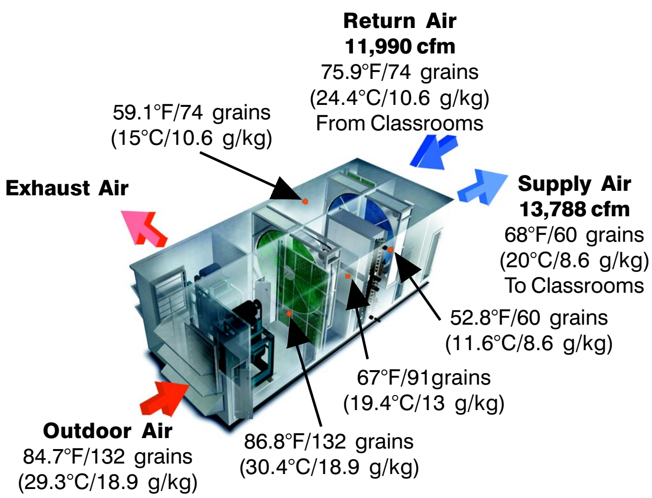

Figure 8: DWERS field measured performance at School L.

Detailed descriptions of the DWERS investigated are provided by Fischer,[14] which also discusses where and when to use single wheel total energy recovery systems. Mumma[15] 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 9 provides a sample of actual humidity data from the DOE investigation to highlight the performance difference between the conventional systems and those using the DOAS approach. Each school served by the desiccant-based DOAS could control space humidity at the level desired while continuously delivering approximately 15 cfm/student (7 L/s per student) of outdoor air, as required by Standard 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% much of the time.

Accommodates an Unoccupied Mode

Figure 7 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 setpoint 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. With high efficiency filtration in one central location, replacing filters is quick and easy. 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, the incidence of musty odors, plugged drain pans and water leaks are greatly reduced by the DOAS approach.

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 Standard 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 Standard 62 recommendations.[14]

The conditions shown in *Figure 8* represent actual field data collected for DOE at School L. The system provided 82 tons (288 kW) of total cooling with 56 tons (197 kW) of latent capacity (0.32 SHR), using only 42 tons (148 kW) of cooling input. A traditional cooling system requires more than 100 tons (351 kW) 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:

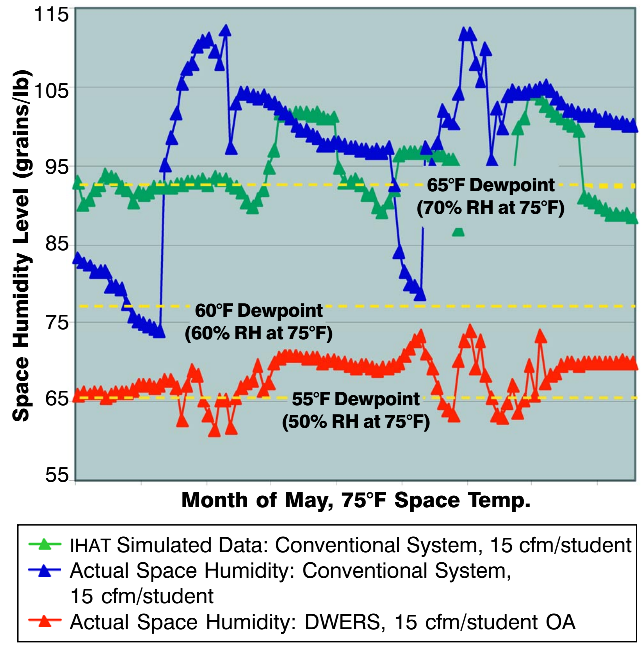

Figure 9: Actual humidity data for DWERS & conventional vs. IHAT simulation for conventional systems at 15 cfm/student.

• The 15 cfm/student (7.5 L/s) recommended by ASHRAE Standard 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 Standard 62, averaging only 5.4 cfm/student (2.5 L/s) of delivered outdoor air. 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 (1°C) can reduce the cost of running the cooling system by as much as 22% when ventilated at the 15 cfm/student (7.5 L/s) rate.

• Latent loads within the school facilities investigated were often underestimated. ASHRAE dew-point 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 (7.5 L/s) 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 energy 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 (2500 L/s) 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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