#5910

Energy conservation and acceptable indoor air quality in the classroom

Standard 62-1989 *impacts heavily on heating/cooling capacity and energy use in both new and retrofitted schools*

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The Ventilation Rate Procedure, as found in *ASHRAE Standard 62-1989*,[1] increases outdoor air ventilation rates over the previous standard for many applications. Few are likely to be affected more decidedly than the school classroom.

When the standard's estimated maximum occupancy is combined with the ventilation rate, the outdoor air supply to a classroom is 0.75 cfm per ft^2 (3.8 L/s per m^2) of floor space. This rate can be more than half of the total air supply needed for cooling. Moreover, this rate is also the minimum permissible total air flow as well as the outdoor air component.

Thus, variable air volume (VAV) terminals are limited to a 2:1 turndown ratio or less. To avoid overcooling when cooling loads are less than 50% of design, reheat is necessary. In most American climates, preheat will also be required. Consternation over increased energy use and heating and cooling capacity requirements for schools appears to be well-founded.

Classroom model

To analyze this concern, national and state statistical data describing class size and other parameters were examined. In addition, characteristics of general studies classrooms and the HVAC systems that serve them were surveyed in Maryland public elementary and secondary schools.

The surveys revealed that the average class size is close to 25 persons. System operation was commonly reported to have ceased within an hour following classes, but some operated for extended hours to accommodate staff, after-school programs and community meetings during evening hours.

Currently, the predominant type of heating and air-conditioning system in classrooms is not variable air volume, but unit ventilators. Many schools equipped with unit ventilators have no mechanical cooling provision.

Although VAV was chosen for the study model, unit ventilators remain a popular choice. Any evaluation of unit ventilators must recognize that outdoor ventilation rates are at best difficult to balance, with continued reliability of such balancing even more doubtful. Survey responses did not indicate a clear preference between these two system types, but VAV had a slight edge regarding perceived indoor air quality (IAQ).

IAQ complaints reported in order of incidence were: thermal discomfort, 80% of complaints; stuffiness, 70%; and odors, 20%. The cause of thermal discomfort was frequently identified as malfunctioning or mismanaged room terminal controls.

Room and class sizes, occupancy and operational characteristics of elementary and secondary schools were found to be fairly similar. A common model of a classroom representative of both situations proved feasible for the purpose of analyzing HVAC requirements and evaluating the ventilation, the energy consequences of ventilation, and strategies for minimizing energy use while meeting ventilation objectives. Data describing site, physical and occupancy characteristics of the model are given in *Table 1*.

This study is based on a VAV system with either a fixed amount of outdoor air for ventilation or a fixed rate per occupant. One HVAC system serves multiple classrooms (each a temperature controlled zone), and is independent of other systems serving other school areas (i.e., offices, auditorium and gymnasium).

Model analysis

Heating and cooling loads were calculated based on ASHRAE Handbook methods. Energy use was determined for those days throughout the year that classes were in session using the ASHRAE Modified Bin Method Procedure and weather data for Andrews Air Force Base, which is near Washington, D.C. The analysis simulated a fan-powered VAV system with reheat and an auxiliary convection heating system for use during non-operating hours.

In Maryland, designers compare the outdoor ventilation rate requirements of the Building Officials and Code Administrators (BOCA) Mechanical Code to *ASHRAE Standard 62-1989*, which is generally considered state-of-the-art. For the classroom, the standard calls for 15 cfm (8 L/s) of outdoor air per person, which could translate to 0.75 cfm/ft^2 (3.8 L/s per

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m²). The BOCA code currently would permit as low as 8.3 cfm (3.9 L/s) per person or, based on a specified minimum occupant density, 0.42 cfm/ft² (2.1 L/s per m²) of outdoor air.

The ASHRAE standard requires a minimum of 0.1 cfm/ft² (0.5 L/s per m²) outdoor air for corridors versus BOCA's 0.02 cfm/ft² (0.1 L/s per m²). The prudent engineer opts for the ASHRAE path, but with concern over the initial and energy cost implications of such a decision.

The environmental contaminants of interest in the classroom setting can be identified as:

• Odorous bioeffluents emitted by the occupants. Odors may also be emitted from outgassing of particulate contaminants collected on air-conditioning system components.

• Microorganisms. Two identifiable sources are the occupants shedding or aerosolizing (respiration, coughing or sneezing) and air-conditioning components acting as reservoirs or amplifiers of bacteria or fungi dispersed into the room during operation. Unit ventilators with wet coils and condensate pans are next-of-kin to fan coil and water source heat pumps impugned as sources.[2]

Table 1. Classroom Model Characteristics

Site characteristics
- Latitude: 39° North
- Outdoor summer design conditions: 90°F (32°C) DB, 76°F (24.5C) WB
- Outdoor winter design temperature: 14°F (−10°C)
- Indoor summer design conditions: 75°F (24°C), 55%RH
- Indoor winter design conditions: 72°F (22°C), 25%RH
- Indoor unoccupied minimum temperature: 55°F (13°C)

Physical characteristics
- Floor area: 810 ft² (75 m²)
- Ceiling height: 8 ft-10 in. (2.7 m)
- Exterior wall area (1 wall): 270 ft² (25 m²)
- Window glass area: 81 ft² (7.5 m²)
- Orientation: composite of NESW
- Wall and glass U-factors: 0.15, 0.6 Btu/(hr, ft², °F) (0.85, 3.4 W/(m², °C))
- Composite glass and shading factor: 0.41
- Lighting: 2 W/ft² (21.5 W/m²)
- Floor area of adjacent interior corridor (allocated to a classroom): 150 ft² (13.9 m²)

Occupancy characteristics
- Average class enrollment: 25 people
- Normal attendance: 23 people
- Daily class use: 8 am to 2 pm
- Daily HVAC system operation: 7 am to 5 pm
- Total class session days: 182 days per year

• Volatile organic compounds (VOCs). Classroom sources include building materials, art supplies, perfume and cleaning agents.

While ventilation may succeed in diluting emissions, the primary path to good IAQ is source control. This is especially true of VOC emissions. Control of contaminant generation within air-conditioning system components is achieved through maintenance rather than ventilation.

Energy conservation

The major objectives assigned to the classroom HVAC system are: low initial and operating costs; thermal comfort; pathogen and allergen removal; and odor dilution. Further discussion of classroom design criteria is appropriate.

Relative humidities above 60% contribute to thermal discomfort and odor perception. Low humidity in winter is a recognized contributor to school children absenteeism.[3] Yet HVAC systems that provide for humidification are rare.

This consideration is of greater importance in cold climates where the moisture content of the ventilation air is low for long periods. Without humidification, the higher the outdoor ventilation rate, the lower the room humidity is likely to be during cold weather.

Total air exchange is also important. No specific criterion for total air ventilation is imposed on the designer. However, the rate of air circulation can relate to stuffiness complaints. Total circulation coupled with the use of filters in the recirculated air stream can limit the level of airborne, disease-bearing particulates in the breathing environment.[4]

Proposed HVAC concept

An air-conditioning concept tailored to meet these objectives is described in *Figure 1.* This concept (abbreviated as FAFVAV) is essentially a conventional VAV system with fan-powered, series arrangement terminals. Air supply to the room is constant. Air recirculated from the room to the terminal during periods of less-than-full (design) primary air flow is filtered.

In the flow pattern illustrated, the recirculated air exits the room low, carrying airborne particulates. It then passes through a conveniently accessible filter, and is ducted back to the VAV mixing box or returned to the central air handler.

How would the proposed FAFVAV concept compare to conventional VAV (CVAV) and a ventilation-only system (VS), possibly supplementing a water source heat pump installed in the classroom?

Recirculated air is a blend from all spaces returned for reprocessing in the central air unit. If the average carbon dioxide (CO_2) concentration in this recirculated airstream is lower than in the classroom, supplying such recirculated air will produce a lower CO_2 level in that room than would a minimum outdoor air only system or any system that features recirculation internal to the room.

Consequently, with respect to CO_2 (a surrogate for gaseous bioeffluent), either VAV system being compared may perform better than the VS system whenever the total air flow from the system is above the minimum setting of the terminal box. This setting, according to the standard, must equal the outdoor ventilation rate.

Figure 2 illustrates the comparative effectiveness of the three HVAC concepts with respect to airborne microbials. For this analysis, a generation rate of airborne microbials (bacteria and fungi) of 424 colony forming units (CFU) per minute per person was deduced from an assumed 1,000 CFU/m^3 in the room.

Indicated filter efficiencies are based on particle size range predicted for viable particles (0.5 μm to 200 μm).[2,5] At least 60% of microbial removal appears obtainable with filters having ASHRAE dust spot efficiency as low as 25% to 30%; 90% removal capability is likely with 60% or higher efficiency filters.[6] The same efficiency for filtering recirculated air in the central air handling units as in the FAFVAV recirculation path is assumed.

At full-load, both the CVAV and FAF-VAV concepts produce the same total room air exchange (in and out of the room) and particulate control. The VS system has a lower total air exchange and, therefore, inferior particulate control. As the demand for primary supply air reduces in response to thermostat control, the performance of the CVAV terminal will diminish toward that of the VS system.

Reductions in viable particulates within the classroom comparable to FAF-VAV are achievable with other system concepts, such as constant volume, unit ventilators equipped with superior filters, and supplemental filter/fan units.

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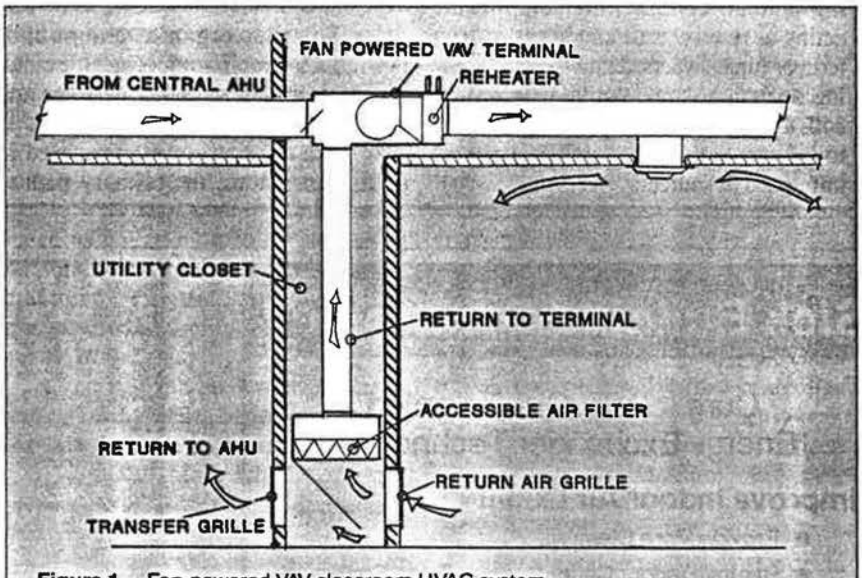

Figure 1. Fan-powered VAV classroom HVAC system.

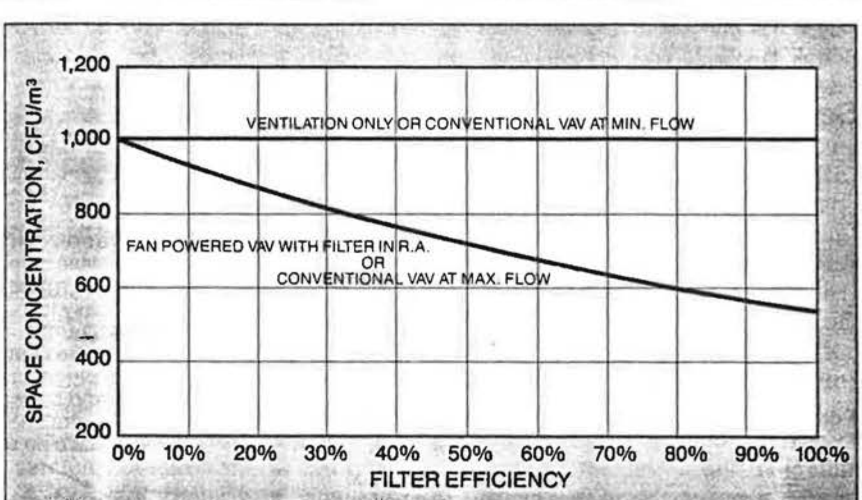

Figure 2. Comparing HVAC systems for classroom microbial contaminants.

Energy conservation

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Energy-saving strategies

The FAFVAV system concept also serves as a basis for evaluating strategies for limiting energy demand and usage.

Estimating classroom occupancy. Table 2 of *Standard 62-1989* lists the estimated maximum occupancy of a classroom at 50 persons per 1,000 ft^2 or 100 m^2. The actual anticipated occupancy may be used if it differs from the listed value. Design outdoor temperatures do not represent extremes for a locality, but reasonable maximums exceeded only a small percentage of the time. Consistent logic should apply to the maximum occupancy in determining the classroom ventilation air supply.

The maximum occupancy chosen for the model is 23 persons, based on an enrollment of 25 less two absentees. The classroom outdoor ventilation requirement is determined to be 345 cfm (163 L/s), not the 607 cfm (287 L/s) that would result from the Table 2 occupancy estimate. Realistic predictions of occupancy can result in lower fan, refrigeration and boiler capacity requirements as well as reduced energy use.

Demand controlled ventilation (DCV). According to Raatschen,[7] "A DCV system is a ventilation system in which the air flow rate is governed by airborne contaminants... A DCV system can consist of a time clock control, and/or a presence control, and/or a sensor control."

Many schools operate the classroom HVAC system one hour prior to and after the class day. Some operate extended hours for school programs and as a service to community organizations, but at a reduced occupancy. Programmed control of the system outdoor air supply and the air economizer cycle can drastically reduce ventilation when the classrooms are sparsely occupied.

Because the percentage of outdoor air to total air for the classroom system can be quite high, energy savings can accrue from reduced preheating, cooling and reheating of air. Programming (manual or time-controlled) should be incorporated into the control system design.

Control of system ventilation air can also be accomplished by sensing the CO_2 concentration either within the classrooms or in the common return airstream where an average concentration is sensed. Such control is most advantageous where occupancy is highly variable or the infiltration rate through classroom windows and doors is high.

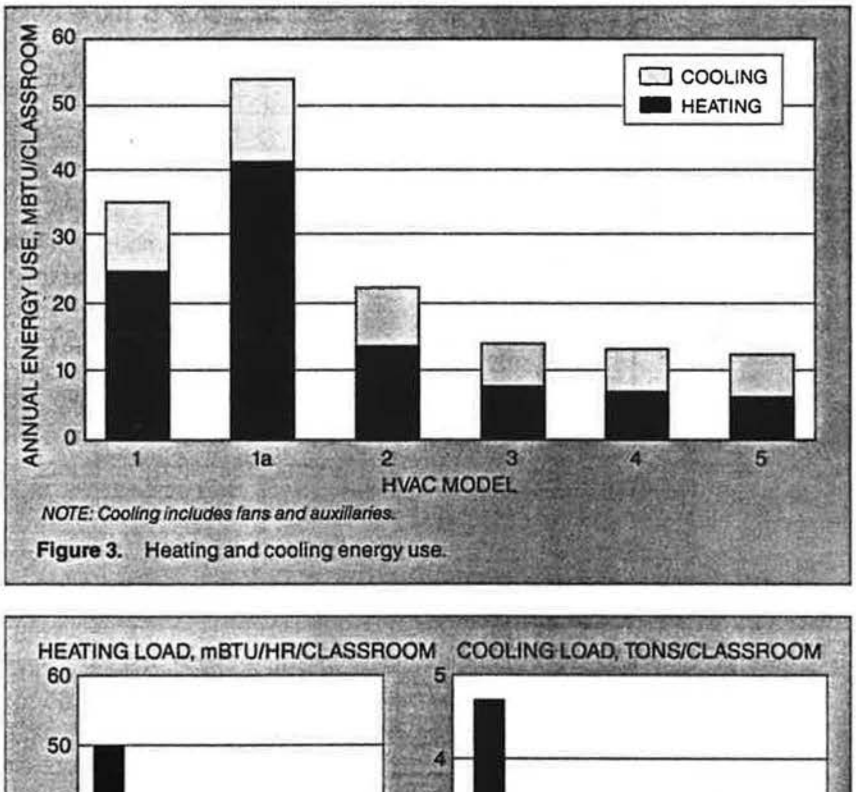
Additional control (no matter how beneficial) carries an additional maintenance burden that the school or school system should accept in advance. CO_2 sensors generally require periodic recalibration.

Figure 3 and *Figure 4* compare the energy use and capacity relating to a single classroom and its corridor area for five strategy models:

- Model 1 with fixed minimum outdoor air flow based on *Standard 62* estimated maximum occupancy during operating hours except as overridden by the economizer cycle. Model 1a extends the operation of Model 1 to 2,100 hours.
- Model 2, similar to Model 1, except based on the actual anticipated occupancy.
- Model 3, similar to Model 2, with ventilation substantially reduced, minimum VAV terminal air flow constraints eliminated and humidification discontinued by automatic programming during the four hours when the classroom is virtually unoccupied.
- Model 4, similar to Model 3, except a CO_2 sensor in the return air regulates the amount of outdoor air during class hours.
- Model 5, similar to Model 3, except the minimum ventilation rate is reduced during occupancy to 10 cfm (5 L/s) per person.

Energy demand and usage are based on hot water heating, chilled water refrigeration, medium pressure air distribution and air economizer control. Power for cooling tower fans, chilled and hot water pumping is included.

Realistic occupancy estimating and varying the total system ventilation as occupancy changes can save about 20 MBtu (21 GJ) per year for each classroom.



NOTE: Cooling includes fans and auxiliaries.

Figure 3. Heating and cooling energy use.

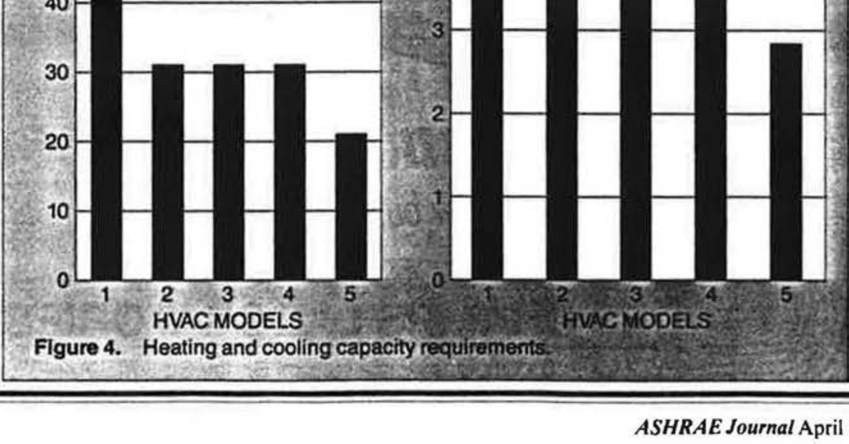


Figure 4. Heating and cooling capacity requirements.

The strategies comply with *Standard 62-1989*, yet energy use would compare favorably with that now required by most building codes.

At $9 per MBtu for energy, $180 annual savings per classroom are projected for new construction as well as retrofitted existing school buildings. In the latter situations, school officials worry whether compliance with *Standard 62-1989* will mandate larger heating and cooling plants.

The capacities of existing refrigeration equipment and boilers may prove to be adequate if appropriate strategies are employed. However, central air handling unit controls and classroom terminals may require upgrading. When occupancy is realistically estimated, the capacities of heating and cooling plants are about one-third less than needed for the occupancy suggested by the standard.

CO_2 sensor control of ventilation demonstrates little advantage over timer programming of classroom activity. Where occupancy is quite variable and difficult to profile into a timer program (as in an auditorium or gymnasium), CO_2 sensor control can be advantageous.

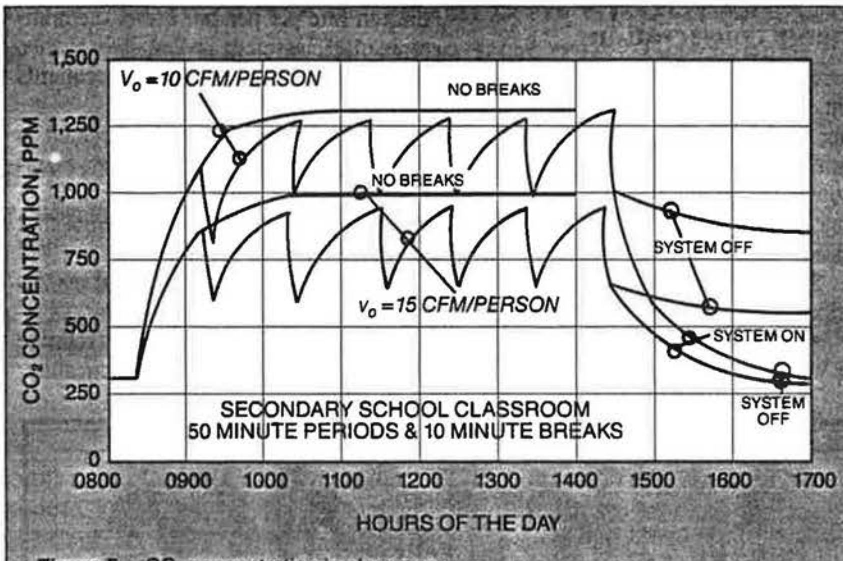


Figure 5. CO_2 concentration in classroom.

Reduced ventilation

Reduction to 10 cfm (5 L/s) per person (analyzed in Model 5) does not comply with the standard. Gunnarsen[8] observed the ready adaptability of persons to human bioeffluents, stating that reduced ventilation is reasonable in rooms "where persons enter an unpolluted room at the same time. . .Classrooms. . .are good examples of this."

A prediction of the CO_2 concentrations during a typical day in a secondary school classroom was calculated. The results for outdoor air rates of 15 cfm and 10 cfm (7 L/s and 5 L/s) per person are plotted in *Figure 5*. Peak CO_2 concentrations of about 1,270 ppm are shown to result from the lower outdoor air rate. The predicted CO_2 concentrations permit an appraisal of both visitor and occupant satisfaction with respect to occupant-produced bioeffluent odor.

Fanger[9] relates 20% visitor dissatisfaction (conversely 80% satisfaction) to a ventilation rate of 15 cfm/olf (7 L/s per olf). An olf is defined as the emission rate of bioeffluents from a standard person (i.e., an adult office worker averaging five baths per week). This emission rate is extended here to apply to an American adolescent.

Fanger's equation predicting the percent of visitors dissatisfied (PD) for a given ventilation rate (q in L/s per olf) is:

$$PD = 395e^{-1.83q^{.25}} \quad (1)$$

The PD for visitors entering at the peak is 26% with the reduced rate versus 20% with 15 cfm (7 L/s) of outdoor air. At the end of breaks, the CO_2 level at the lower ventilation rate is within the standard's yardstick of acceptability. With faith that this prediction is valid for the classroom setting, the lower ventilation rate might be expected to shift the reaction of one of the 23 in the entering class from satisfactory to unsatisfactory perception.

The adaptation of people to human bioeffluent odors, as reported by Gunnarsen and Fanger[10] and Cain,[11] would occur within several minutes. Thus, once class is underway, any benefit of the higher ventilation rate diminishes even further.

By sustaining the total rate of filtered air circulation removing most of the airborne pathogen-carrying particles, the dilution benefit afforded by the higher rate of outdoor ventilation in this regard is negligible. Dilution of each internally produced contaminant is assumed to occur in direct proportion to the rate of ventilation air, free of that contaminant, following the procedure described in Appendix E of the ASHRAE standard.

Consequently, continuous emissions of VOCs from building materials and similar sources are regarded separately and of sufficiently low magnitude by virtue of source control as to be held to a satisfactory level by the ventilation needed for occupant bioeffluent.

Undesirable levels of VOCs or other airborne pollutants resulting in the classroom from accidents, housekeeping procedures or remodelling are mitigated somewhat more effectively by the higher ventilation rate. Such unavoidable episodes are better remedied by specific short-term ventilation strategies, such as manually shifting system controls to supply all out door air, operating return air fans for exhaust, or simply opening windows.

The lower rate of outdoor air ventilation saves energy and initial cost. With an economizer cycle changeover temperature higher than the design supply air, cooling energy savings would be greater than those indicated in *Figure 3*. The lower rate also offers improved classroom relative humidity during the winter.

For the study model, 28% RH can be maintained during design winter conditions in occupied classrooms supplied with 10 cfm (5 L/s) of outdoor air without humidifying. With 15 cfm (7 L/s), only 21% can be held.

A 25% RH minimum during occupancy without humidification is achievable even in areas with colder winters than Maryland with the lower ventilation rate. The value of maintaining minimum relative humidity in the classroom as a preventative for respiratory illness has been well-documented,[4] but remains underappreciated in the quest for good indoor air quality.

Discussion and summary

Design and control strategies offer opportunities for our schools to have good IAQ without burdensome demands on heating and cooling capacities and energy costs. In the course of its standard revision procedure, ASHRAE should reconsider the prescribed ventilation rate for schools as well as the importance of total filtered air circulation for many applications[12] in

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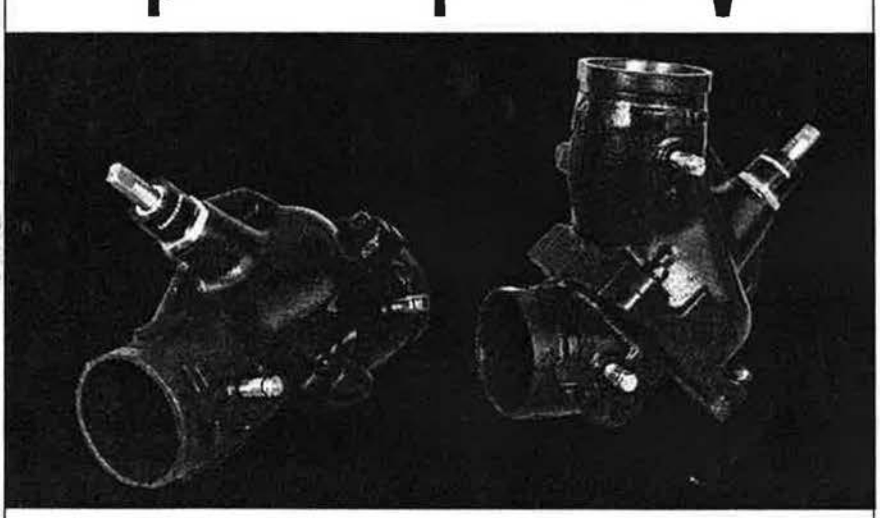
light of the new information forthcoming since *Standard 62-1989* was developed. With roughly one million classrooms in public schools throughout this country alone, the impetus for such consideration indeed exists.

Specific classroom HVAC recommendations resulting from this study are:

- Design to meet *Standard 62-1989*. For VAV systems, maintain a constant ventilation rate per person. Preset the minimum total classroom air flow at that value.
- Estimate the number of occupants realistically.
- Select an HVAC concept (such as the one described) that will produce a continuous high rate of room air exchange.
- Select filters for effective removal of microorganisms from room air.
- Employ demand controlled ventilation (DCV) to save energy.
- Provide for a minimum relative humidity as close to 30% as practicable.
- Consider a reasonable level of maintenance and operation.
- Share with the user a common insight of design provisions and objectives.

An amplified version of this paper, co-authored with A.C. Abend, appears in the *Proceedings of Healthy Buildings—IAQ '91.*[13] ■



References

1. ASHRAE. 1989. *Standard 62-1989, Ventilation for Acceptable Indoor Air Quality*. Atlanta, Georgia.

2. Morey, P. 1988. "Microorganisms in buildings and HVAC systems: A summary of 21 environmental studies." *Proceedings of IAQ '88*. Atlanta, Georgia: ASHRAE.

3. Green, G. 1982. "The positive and negative effects of building humidification." *ASHRAE Transactions*. Atlanta, Georgia. Vol. 88, Pt. 1.

4. Green, G. 1985. "The effect of ventilation and relative humidity upon airborne bacteria in schools." *ASHRAE Transactions*. Atlanta, Georgia. Vol. 91, Pt. 2.

5. Burge, H. 1988. "Environmental allergy, definition, causes, control." *Proceedings of IAQ '88*. Atlanta, Georgia: ASHRAE.

6. ASHRAE. 1988. *Handbook—Equipment*. Atlanta, Georgia. p. 10.5.

7. Raatschen, W. 1990. *Demand Controlled Ventilating System*. State of the Art Review. International Energy Agency. Stockholm, Sweden: The Swedish Council for Building Research.

8. Gunnarsen, L. 1990. "Adaption and ventilation requirements." *Proceedings of Indoor Air '90*. Toronto, Ontario. Vol. 1.

9. Fanger, P. 1988. "The olf and the decipol." *ASHRAE Journal*. Atlanta, Georgia. October.

10. Gunnarsen, L., Fanger, P. 1988. "Adaption to indoor air pollution." *Proceedings of Healthy Buildings '88*. Stockholm, Sweden. Vol. 3.

11. Cain, W. 1974. "Perception of odor intensity and the time-course of olfactory adaption." *ASHRAE Transactions*. Atlanta, Georgia. Vol. 80, Pt. 1.

12. Wheeler, A. 1990. "The influence of HVAC concept selection upon office indoor air quality." *Proceedings of Indoor Air '90*. Toronto, Ontario. Vol. 4.

13. Wheeler, A., Abend, A. 1991. "Meeting the objectives of energy conservation and ventilation for acceptable indoor air quality." *Proceedings of Healthy Buildings—IAQ '91*. Atlanta, Georgia: ASHRAE.