Effective Ventilation and Indoor Air Quality at Modular Schoolrooms

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SUMMARY

The use of modular schoolrooms in the U.S. has increased drastically, with the primary reason being a reduced capital expense commitment. The most common HVAC equipment installations for these rooms are sidewall mounted packaged units, and the basic installation generally provides outdoor air using fixed air inlet louvers. Field tests of a representative room with this setup indicate that limited (approximately 3 cfm or 1.5 l/s per person) ventilation air of is provided by this arrangement. The addition of a modulating outdoor air damper for demand controlled ventilation and/or economizer operation can provide more ventilation air to the space but it is an added cost option. Field measurements also showed that units with the modulating dampers can provide ventilation air which matches the requirements of ASHRAE Standard 62-1999.

This paper presents results of a side-by-side comparison of indoor air quality and energy consumption for two rooms, one with outdoor air ventilation matching the basic fixed louver configuration and one with a modulating outdoor air damper with economizer and demand controlled ventilation (DCV) control. The room with the fixed louver ventilation demonstrated poor indoor air quality, as measured by the concentration of CO_2 in the room. For rooms with only the fixed inlet louvers for outdoor air, the use of economizing cooling control and the associated potential for energy savings is not possible.

It already has been documented how improved indoor air quality can improve the learning environment in a schoolroom. Thus, it is to the benefit of the students and school districts to work to provide the best practical indoor air quality environment. The issue is how to get decision makers to recognize life-cycle cost and other long term benefits in evaluating and specifying projects.

INTRODUCTION

The use of modular schoolrooms in the U.S. has increased drastically, with the primary motivation being a reduced capital expense commitment in providing classroom space in areas of rapidly growing student populations. The state of California alone has over 100,000 modular classrooms installed to accommodate a rapidly growing student population and a state mandate to lower class size. The most common HVAC equipment installations for these rooms are sidewall mounted packaged units, and the basic installation provides outdoor air via relatively small fixed air inlet louvers. According to HVAC equipment supplier estimates, over 80% of the HVAC units installed use the fixed outdoor inlet louver configuration.

It already has been documented how improved indoor air quality can improve the learning environment in a schoolroom. For example, Raiford [1] describes recent and ongoing studies concerning the impact of improved indoor air quality on student performance and the overall economic value that has to society. Thus, it is to the benefit of the students and school districts to work to provide the best practical indoor air quality environment. Poor indoor air quality (IAQ) is a real concern in U.S. school systems, and in our increasing litigious society the number of IAQ related lawsuits has steadily increased [2]. The issue is in what manner should the decision making process recognize these long-term benefits, and the potential for overall life-cycle cost savings, when evaluating and specifying HVAC systems for these facilities.

This paper summarizes a field evaluation where CO_2 levels in a room were measured for three different ventilation cases: 1) typical ventilation associated with the standard fixed ventilation louver, 2) fixed ventilation rates that satisfy ASHRAE Standard 62-1999 [3], and 3) variable ventilation provided by a demand controlled ventilation (DCV) scheme. In this paper, the label “DCV On” is given when the ventilation control is with the demand controlled ventilation active. When fixed ventilation is set to match the Standard 62-1999 level, this configuration is termed “DCV Off”.

TEST SITE DESCRIPTION

As part of the ongoing Building Energy Efficiency Program projects sponsored by the California Energy Commission, demand controlled ventilation (DCV) systems were installed at modular schoolrooms at two school districts in California. Each of the four rooms where DCV was installed did not originally have controllable outdoor air dampers, but rather ventilation air was introduced using the factory issue fixed air louvers. As part of the DCV system study, the rooms were retrofitted with controllable ventilation air dampers. Controllable outdoor air dampers would be required for any HVAC system incorporating DCV or economizer cooling.

Each test room was configured with a commercially available ventilation control system that incorporated a combined DCV and economizer cooling control. A separate monitoring system was also installed which collected HVAC and control system performance data. The data were recorded every five minutes and uploaded daily to a central site via a cell phone communications setup.

Each modular structure houses a single classroom, and the rooms at the study test site were located side-by-side (Figure 1). During the 2001-02 school year, sixth grade students occupied these rooms with an enrollment of 32 students per room. The rooms are modular in construction with an internal floor area of 74 m² (12.2 m x 6.1 m). The test school site is located in a medium sized city in northern California near Sacramento.

A representative floor plan of the rooms showing the relative location of the HVAC unit supply and return air vents, the single entry door and the two operable windows is given in Figure 2. From discussions with the teachers in the rooms and from personal observations, the windows are rarely opened. Figure 2 also shows the location of the CO_2 sensors used during the study.

Room temperature control and ventilation is provided by sidewall mounted packaged heat pump units. Return air is brought in through a grill in the external wall of the room connecting to the back of the HVAC unit. Supply air is provided to the room via two outlet diffusers approximately 4 and 8 meters from the unit. Outdoor ventilation air is mixed in with the return air on the suction side of the supply fan.

Room CO_2 levels were measured in each test room at the three locations shown in Figure 2. The sensor used for the DCV controller was mounted at the return air grill on the room wall. During the period of this study, two additional CO_2 sensors connected to portable data loggers were located at opposite ends of the room to help estimate the bulk room CO_2 concentration. A fourth CO_2 sensor measured the outdoor air concentration for both rooms. All CO_2 sensors were of the same manufacturer make and model number, and were set to read in the 0-2000 ppm_v range. Data were recorded on a five minute time interval.

Figure 1 - School Site Test Rooms – Rear View Looking East

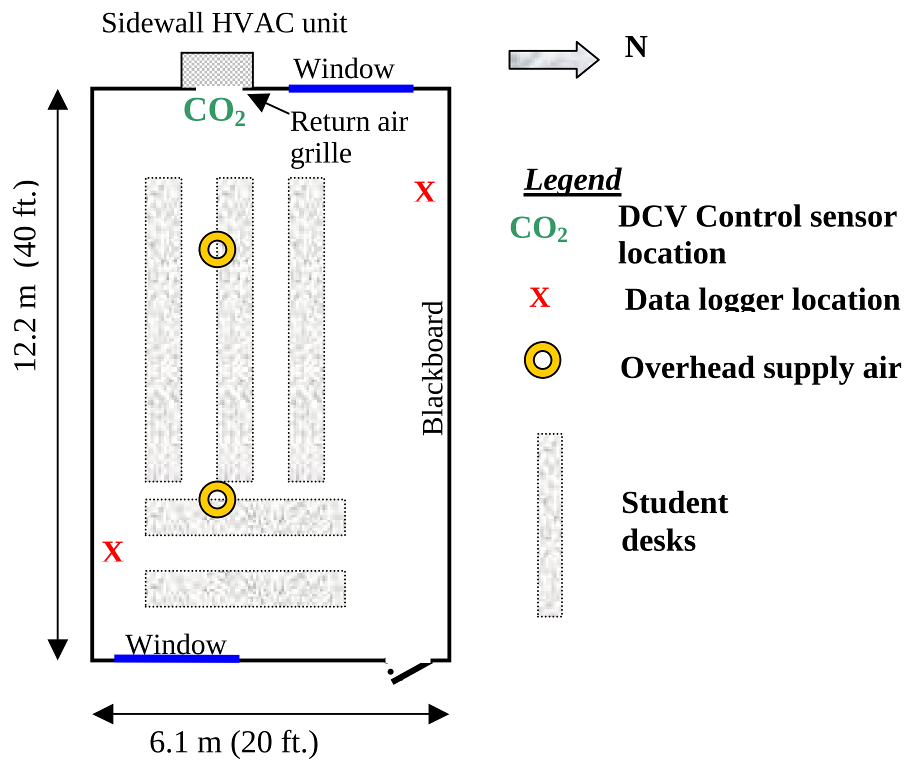

Figure 2 - Test Rooms Floor Plan and CO_2 Sensor Location

The design of the sidewall mounted HVAC unit only provides for a general mixing of the supply and return air streams and does not allow for the possiblility of getting 100% outdoor air flow. Having the capacility of achieving 100% outdoor air supply would be more desireable for economizer cooling and demand controlled ventilation.

TEST SETUP AND VENTILATION AIR MEASUREMENT

The first step in setting up this study was to determine the amount of fresh outdoor air provided by a unit with the standard factory fixed air louvers. Since the two test rooms had already been previously retrofitted with a controllable outdoor air damper, a nearby room with identical configuration was selected for conducting an airflow balance measurement. Flow measurements were made using an airflow hood on the outdoor air inlet, the supply air from the two supply air diffusers and the return air grill in the sidewall of the room. A summary of the airflow balance computed for this room is given in Figure 3.

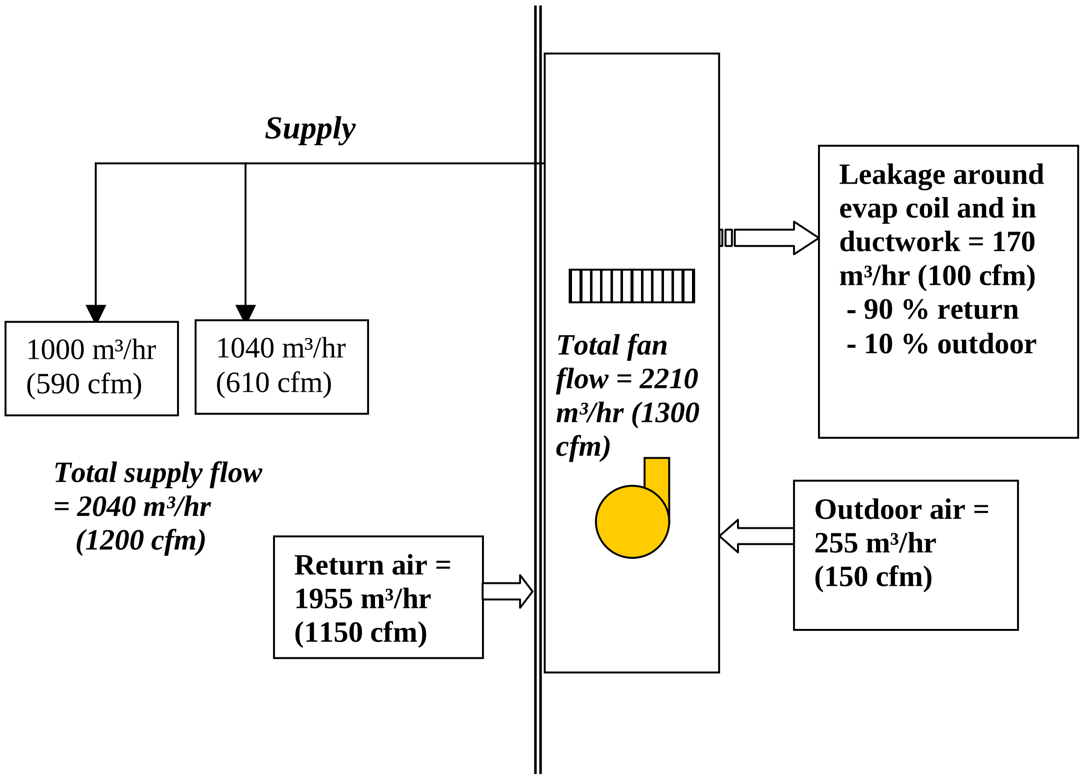

Figure 3 - Airflow Balance for Typical Room without Controllable Damper

From measurements of the total supply air flow to the room, the return air back to the HVAC unit and the outdoor air flow, air leakage in the HVAC unit around the evaporator coil and in the supply air ducting was estimated to be approximately 170 m^3/hr (100 cfm), or about 8% of the total supply flow. For purposes of estimating the net ventilation air into the room, the air leakage was assumed to be proportional between the return and outdoor air flow streams. The resulting flow balance indicates approximately 240 m^3/hr (140 cfm) of ventilation air is provided to the room, or approximately 11.7% of the total supply flow.

Measurements taken at both test rooms with controllable outdoor air dampers indicate that only a maximum outdoor air ventilation of about 55% of the supply air flow is possible, as shown in the plot of outdoor air flow versus damper position given in Figure 4. Total measured supply airflow to the test rooms taken on several different days ranged from 1785 to 2040 m^3/hr (1050 to 1200 cfm). The manufacturer's rating for the sidewall heat pump unit of this size is 1400 cfm. The total supply flow is a little lower probably due to the additional pressure drop of the supply ducting inside the room and duct leakage.

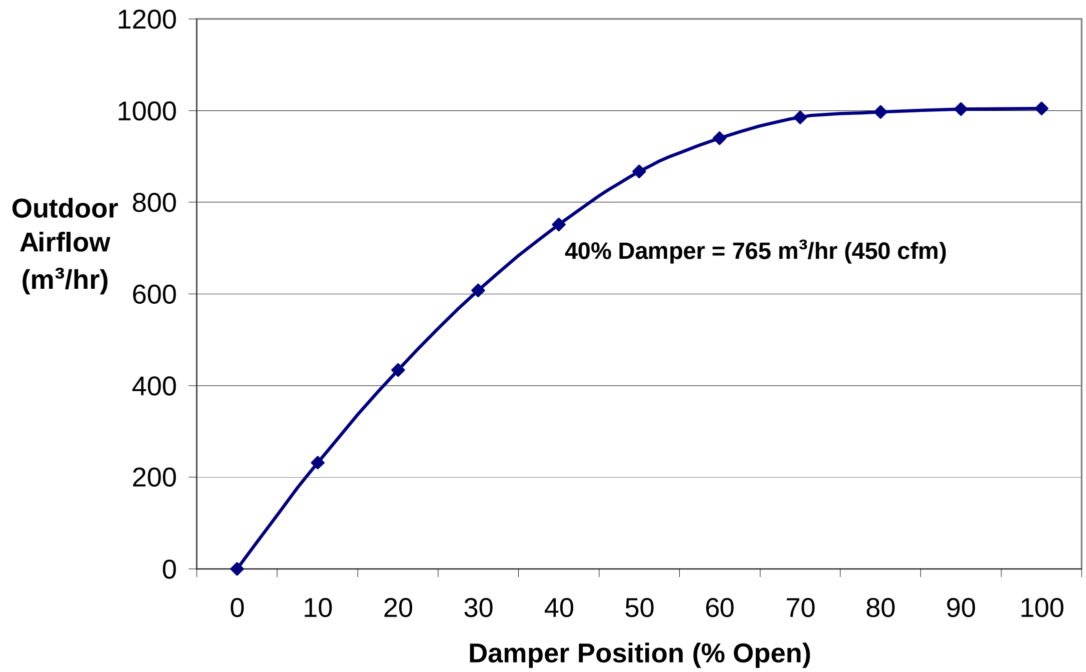

Figure 4 - Modular School Test Room Outdoor Air Ventilation versus Damper Position

During the time period of this study, the damper in one test room was fixed in place to provide the same outdoor air flow and percentage of the supply air flow as measured with the unmodified room with a fixed ventilation air louver configuration. Measurements of the airflow distribution were made using the same equipment and procedures as done with the unmodified room with fixed air ventilation louvers. The outdoor air damper only needed to be barely opened (approximately 10%) in order to match the outdoor ventilation flow. The resulting flow balance is shown in Figure 5.

Measurements made during the test setup indicate around 200-250 m^3/hr (120 to 145 cfm) of ventilation air to the rooms with the standard fixed louver ventilation system. At an average room occupancy of 32 students plus one teacher at this site this translates to around 3-5 cfm per person, well below the levels specified in ASHRAE Standard 62-1999 or the California standards referred to as Title 24 [4].

During the comparison period with the test room set to the low ventilation levels typical of the fixed louver configuration, the neighboring room was set to have the DCV control system active. When the DCV system is on for this testing, the minimum outdoor air damper position is set closed and is modulated open when the CO_2 level exceeds the setpoint, or when economizer cooling mode is called for.

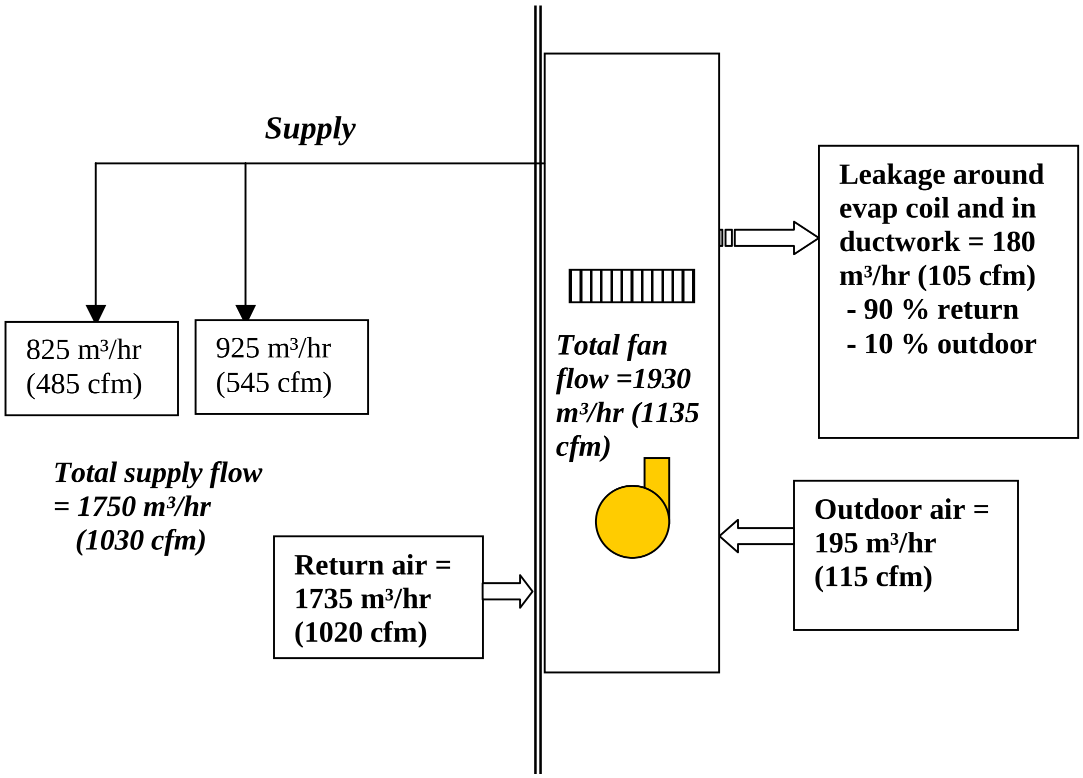

Figure 5 - Airflow Balance for Test Room with Controllable Damper Set to Match Room with Fixed Air Louver

The system modifications were completed on 7 May 2002 and data recording continued until the school year ended on 7 June.

CO_2 LEVEL RESULTS

The average bulk room and return air CO_2 concentrations measured during this test period were calculated during school days between 8 in the morning and 3 in the afternoon. The levels are compared from two different perspectives.

The first comparison was made of the test room configured to match the low fixed ventilation rate during the same time period with the other test room which was configured with the demand control ventilation system active at a CO_2 setpoint at 800 ppm_v. This comparison is given in Table 1.

A second comparison is made using the results from the test room with the ventilation rate set to match the lower flow with the fixed louver configuration compared to the CO_2 values in the same room made during the previous weeks before the test period. This comparison therefore compares the operation of the identical room with the same student population. The CO_2 levels recorded when the room was provided with ventilation flow equal to that with a fixed louver configuration were compared with data taken earlier for periods when the room ventilation control was set to include DCV and economizer control (DCV On) and when economizer only control was operating (DCV Off). When the DCV system is off, the minimum damper position is set at 40%, which provides 450 cfm of fresh airflow (see Figure 4) which translates to approximately 15 cfm per person. The result of this second comparison is given in Table 2.

Table 1 - Comparison of Internal CO_2 Concentrations at Test Room with Ventilation Matching Fixed Louver Configuration to Second Room with DCV Control On

Room, Configuration	Mean Return [CO_2] ppm_v	Mean Bulk Room [CO_2] ppm_v	Supply Air [CO_2] ppm_v	Average Ambient [CO_2] ppm_v
North room, Fixed ventilation	1075	1218	992	401
South room, DCV on	728	790	580	401

Table 2 - Comparison of Internal CO_2 Concentrations at Test Room and the Same Room with DCV System On

Room, Configuration	Mean Return [CO_2] ppm_v	Mean Bulk Room [CO_2] ppm_v	Mean Supply Air [CO_2] ppm_v	Mean Ambient [CO_2] ppm_v
North room, Standard fixed louver ventilation Dates: 7 May – 7 June, 2002	1075	1218	992	401
North room, DCV on Dates 10-15 April, 29 April – 6 May	638	708	525	399
North room, DCV off [15 cfm/person] Dates 13 March – 9 April, 15 – 26 April	687	768	559	396

In both of these comparative analyses, the supply air concentration was computed using a volume balance based on the return and ambient air CO_2 concentrations and the resulting airflows at the current damper position. For the first test case (Table 1), the mean return and bulk room CO_2 concentration above the ambient level in the room with the ventilation equal to the fixed louver configuration are over twice those for the room with the DCV system on.

In the second comparison (Table 2), the standard fixed louver ventilation flow without controllable dampers also resulted in significant higher CO_2 levels in the room. For example, the mean return concentration above the ambient was nearly three times that seen with the same room with the DCV on and about two and one half times higher than the same room with the DCV system off. During the time period for all test comparisons, economizer cooling was active, particularly during the morning hours.

A plot of the transient bulk room CO_2 concentrations in the test room with the ventilation equal to the standard fixed louver configuration also provides insight. This plot, given in Figure 6, shows the CO_2 concentrations between 8 am and 4 pm daily for a representative week during the test period. Note that the bulk room CO_2 concentrations at some times approached or even exceeded the 2000 ppm_v upper limit setting for the CO_2 sensor. For three of the days during this week, the interior concentration remained around 1000 ppm_v up until 4 pm when the system fan is shut off by the programmable thermostat.

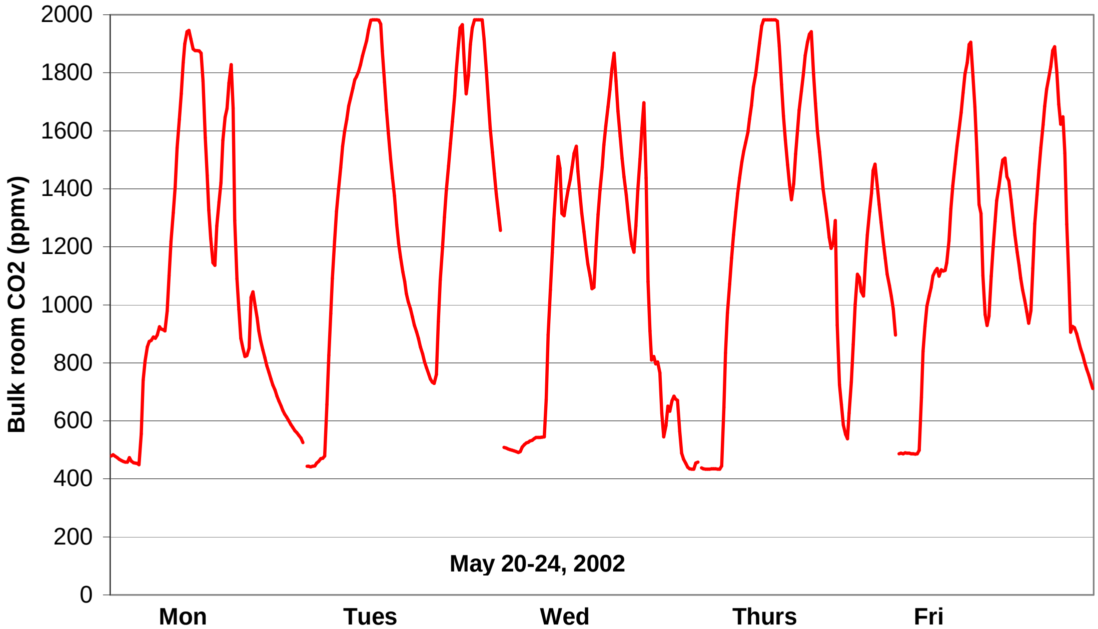

Figure 6 - Bulk Room CO_2 in Test Room for Representative Week

Another way to compare the CO_2 levels is through the use of a histogram showing the frequency of time that the CO_2 levels were within a given concentration range. Figure 7 shows this for the first comparison of the north room (limited fixed ventilation) versus the south room with DCV On during the same time period. The second comparison using data from the north room alone is given in Figure 8. This plot compares the histogram for CO_2 levels in the north room with the limited fixed ventilation and other periods a month or so earlier when the DCV control was active (DCV On) or the ventilation was set to the fixed ASHRAE Standard 62-1999 levels.

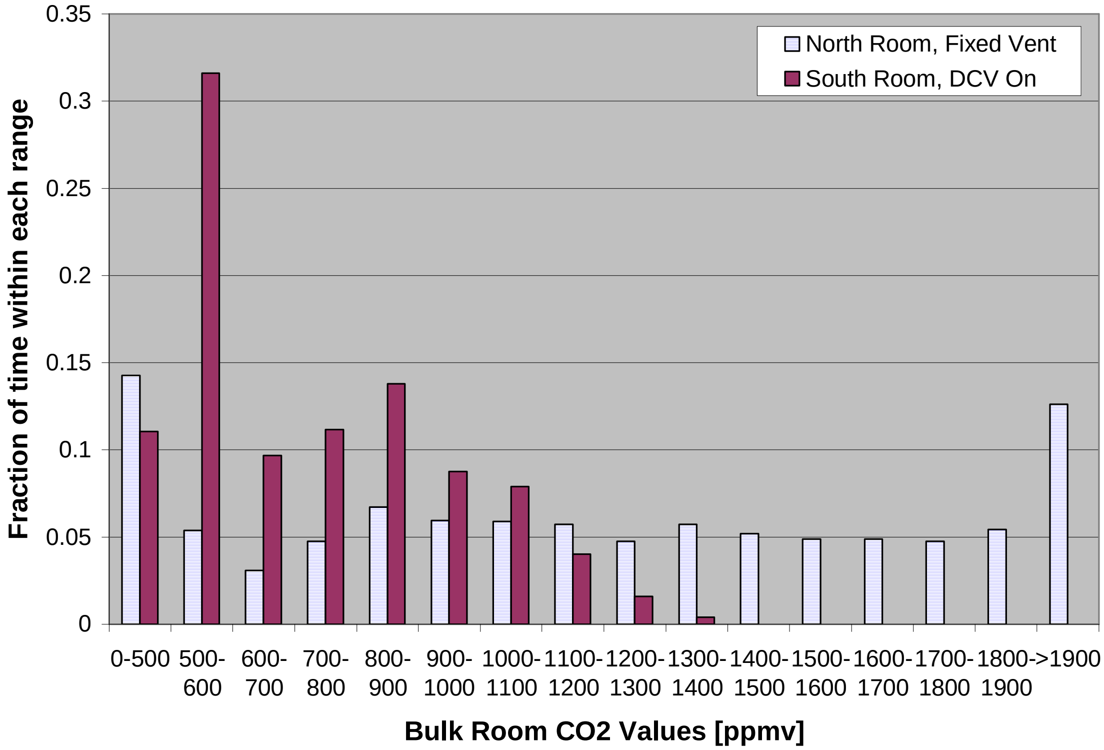

Figure 7 – Frequency of Occurrence of CO_2 Ranges – North Room versus South Room

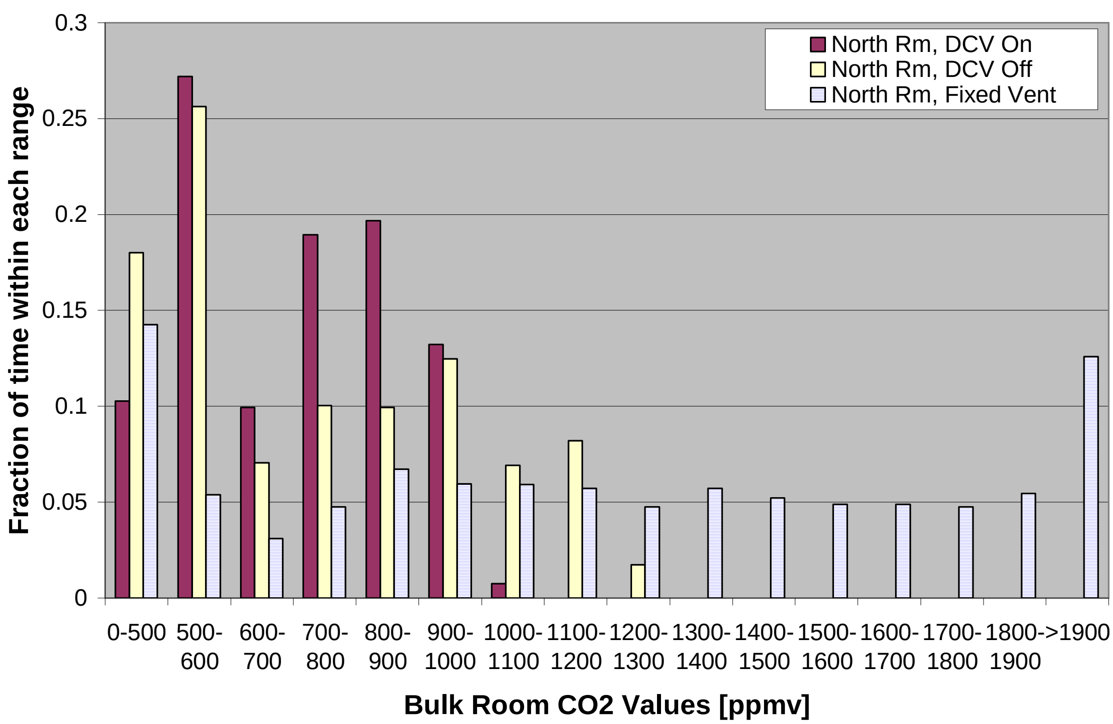

Figure 8 – Frequency of Occurrence of CO_2 Ranges – North Room Only

DISCUSSION AND CONCLUSIONS

A significantly higher CO_2 concentration was measured in the test room with ventilation flow matching that of a room without controllable dampers. This indicates a poorer overall indoor air quality as the result of outdoor air ventilation rates that do not meet minimum standards set by ASHRAE 62-1999.

Thus, it appears that retrofitting systems to include DCV and economizer control, or including them with new installations, may have significant benefits for improving indoor air quality compared to the HVAC package with fixed ventilation louvers at the typical modular schoolroom. Such a retrofit would improve indoor air quality. A separate benefit is the potential for energy cost savings. School districts may be reluctant to retrofit or even require these upgraded systems, however, due to the cost of a retrofit. A retrofit cost would need to include the damper assembly (approximately $250 USD wholesale) as well as the upgraded sensor system, miscellaneous wiring and equipment, and the additional installation labor cost. At current prices in the U.S., this would amount to approximately $900 for each room assuming a single zone, single rooftop unit situation. An additional potential cost to be added to a retrofit situation was noted during the installation at this particular test site. Here, the main internal power wiring of the HVAC unit had to be rerouted in order to make room for the controllable damper assembly. These types of problems are expected for field retrofits and tend to increase the final labor and miscellaneous materials cost for the retrofit.

A final interesting point to note from the Figure 8 comparison is that the measured CO_2 values when the ventilation was fixed at the ASHRAE 62-1999 flow rate tended to be a little higher than when the DCV control was active. This may imply that the metabolic activity levels (hence CO_2 source generation rate) are higher than expected and assumed in the ASHRAE standard.

RECOMMENDATIONS

Based on the results of this field study, it is recommended that school districts reconsider their decisions regarding HVAC equipment for their modular schoolroom installations. The opportunity to make smart decisions is particularly possible with new system installations. However, to do so will require looking beyond the initial cost of buying and installing the system to also include the total life cycle cost of the unit and the intangible benefits of improved indoor air quality.

ACKNOWLEDGMENT

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