Energy Savings and Indoor Air Quality

Demand Controlled Ventilation by Means of CO_2 Sensors

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CONTENTS

Demand Controlled Ventilation, Energy Savings and IAQ

1 Demand Control of Indoor Air Quality

Indoor air pollution is primarily due to the presence of humans, and includes water vapour, CO_2 and other gases due to respiration and bodily odours, as well as dust brought in by clothing and footwear or becomes whirled up from floors, carpets etc. In addition, large amounts of vapours and particles from materials may be released -particularly in so-called modern buildings. Work-related processes in industry and various other activity may contribute less common pollutants. However, such non-human contributions to indoor climate may to a large extent be reduced by applying existing knowledge and protective measures - and a willingness to make a priority of people's health and environment, e.g., by choosing appropriate building materials. Consequently, under most circumstances the load of people in each separate room will be the decisive factor for the quality of local indoor climate suffered by any individual.

Years of research and experience have sufficed to show that the concentration of CO_2 is a useful and relevant indicator of total indoor air quality, being directly indicative of people's presence through CO_2 from respiration. Fresh air contains 370-400 ppm (part-per-million) of CO_2, while each exhalation of air from humans carries ca 3 % of CO_2. In several countries, health authorities have set standards for indoor air of 800 - 1,000 ppm of CO_2, as upper limits that should not be exceeded.

Suppose 1 l of air is exhaled ten times a minute by a moderately active person, resulting in 0.3 l of pure CO_2 per minute. In a 10 m^2 (100 sq feet) room without ventilation, occupied by a single individual, the air would be close to the limiting concentration of CO_2 after half an hour. (This estimate may be conservative). Worse: In a typical classroom with 20 - 25 students, the air would reach 1,000 ppm of CO_2 after less than 10 minutes unless actively ventilated. Indoor air quality in occupied rooms thus becomes reduced very rapidly, much earlier than our senses are normally able to tell us.

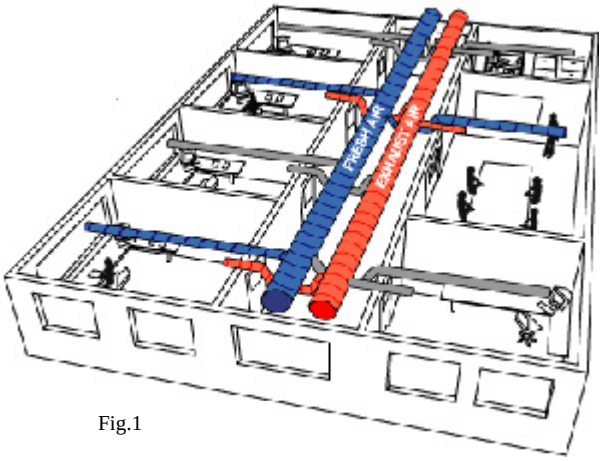


Fig.1

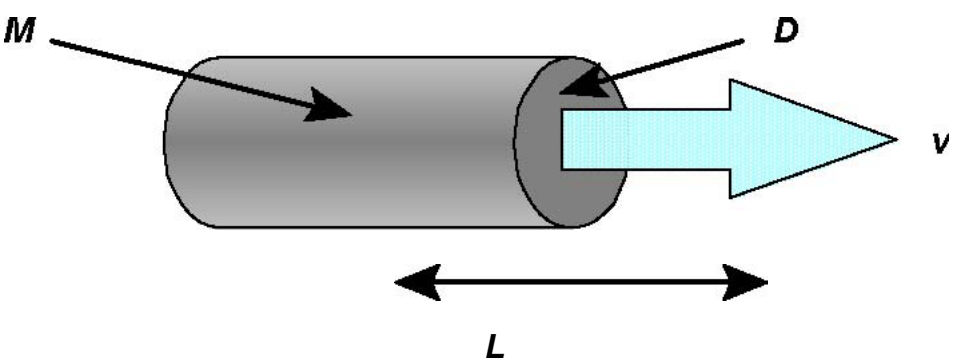
In demand controlled ventilation (DCV) each room is served by a CO_2 gas sensor, which allows ventilation to be activated before air quality in any room is reduced beyond administratively set limits. Ventilation may then be reduced or turned off wherever air quality standards are satisfied. In this manner, the capacity of the ventilation system essentially becomes moved around the building on local demands, depending on which rooms are occupied at any time. An animated demonstration found on *www.demand-controlled-ventilation.info* provides a working example of DCV, an excerpt of which is shown in Figure 1. Such functions may easily be automated by communicating sensor signals to a central command unit with computer-based decision routines. Quality indoor air may thus be secured wherever people are present.

The concept of DCV, and most technologies needed to make it a technical reality, have been around for quite a while, as has the motivation for improved indoor climate: Research has shown that close on half of short time absence from work in the US may be related to factors in the indoor air. Yet DCV has not caught on primarily due to the lack of suitable CO_2 sensors. CO_2 is comparatively easy to measure with various methods, chiefly chemical, electrochemical and infrared. The limiting problem has been to do it reliably, reproducibly and cost-effectively, so that CO_2 sensor calibrations are not lost after a few months' time. That problem has now been solved by recent developments in infrared CO_2 gas sampling. Those new, digital IR CO_2 gas sensors remove any existing obstacles for the introduction of DCV on a large scale, in old and new buildings alike. As will be seen below, DCV may also be economically quite rewarding in saving large amounts of energy in buildings.

2 Energy Factors in Ventilation

When ventilation is only activated where required, energy is saved for heating/cooling of ventilated air as well as for operating the ventilation system itself. This contrasts with conventional systems where ventilation most often is continuously ON - possibly with night reductions -and without reference to people's presence or otherwise. A simple model will show how the energy savings potential under DCV may be estimated:

(Figure 2)



Suppose ventilation air moves through a duct system with cross sectional area ***D***. Any length of duct equal to ***L*** = *1 m* thus contains a volume of air ***M = DL*** moving at velocity ***v***, as illustrated in Figure 2. This volume of air contains two kinds of energy: Thermal energy E_T proportional to the volume of air ***M*** being heated or cooled, and mechanical energy of motion given by the laws of kinematics as $E_v = \frac{1}{2}Mv^2$, valid for any moving mass (well known also from breaking lengths of motor cars increasing four times when speed doubles). This "package" of energy is driven through the ducts by the ventilation fans, whose task it is to provide each such "package" with its individual velocity ***v***.

Since the "package" has a length of ***L***= *1 m* and velocity ***v*** *m/s*, for every second ***v*** such "packages" of air will be supplied into the duct system, each "package" carrying an amount of energy $E_T + E_v$. In a certain time span of duration ***t***, therefore, a number of "energy packages" given by ***n = vt*** will be delivered.

From this follows the energy budget of ventilated air during time ***t***:

- Thermal energy equal to $\boldsymbol{nE_T}$, which as might be expected is proportional to the total volume of air $\boldsymbol{nM = Mvt}$ that passes through the ducts during time ***t***. 30 % reduction of ventilated air thus saves 30 % of thermal energy.

- Mechanical energy $\boldsymbol{nE = ½Mv^3t}$ (by insertion for ***n*** and $\boldsymbol{E_v}$, respectively), which ***v*** consequently *increases in proportion to the cube of air velocity* in the ducts. In any given ventilation system, the air velocity varies with air demand - double the supply of air requires doubling the velocity -, in which case the energy requirement of the ventilation fans would increase by a factor of eight: $(2)^3 = 8$. Conversely, if the demand of air is halved, the required mechanical energy delivered by the fans would be reduced by a corresponding factor of 8.

For example, 30 % reduction of ventilated air would lower the mechanical energy demand to $(0.7)^3 = 0.34$ or 34 % of the original, thus saving 66 % of the former fan energy, against the same air reduction saving only 30 % of thermal energy. With less ventilated air, therefore, mechanical energy is reduced far more than is the associated thermal energy, due its cubic dependence on air velocity inside the ventilation ducts. Here lies the more significant - and largely neglected - savings potential that makes DCV unique for the economy of operating buildings in which the occupancy of individual rooms may vary strongly and/or randomly with time.

3 Calculated Energy Savings

On the basis of such analyses as above, one is able to calculate the amount of energy that can be saved by DCV. The most important parameter to determine is the so-called *simultaneity factor S*, which indicates what fraction of rooms in a building is occupied at any time. *S* may be found empirically for individual buildings or for buildings of different kinds; normal values for *S* are in the range 0.4 -0.9 with $S = 0.6$ as a typical value for office complexes. *S* thereby provides a measure of how much the air demand may be reduced in DCV, consequently, *S* and the ventilated air velocity ***v*** are linearly connected. From this follows that the thermal energy demands reduce in proportion to *S*, while mechanical energy requirements on the ventilation fans varies with the cube of *S*.

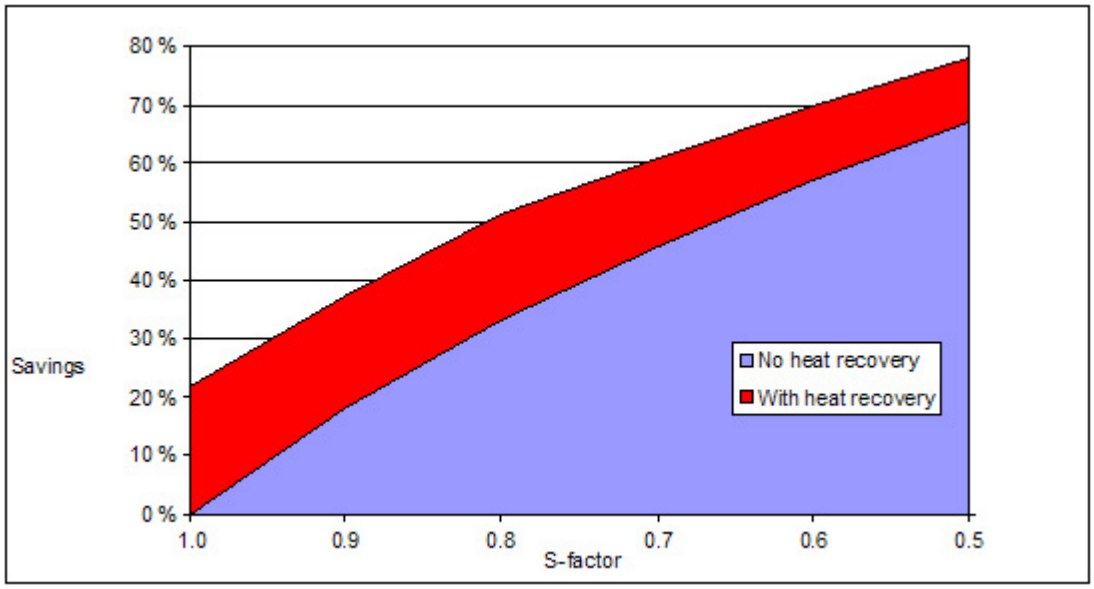
Consider a building that for a start has an energy budget $E_0 = A + B$ for heat and ventilation, where *A* is the thermal energy demand and *B* is the fan energy. Without heat recovery, the thermal energy typically is somewhat larger than the mechanical fan energy, e.g., $A = 0.55E_0$ and $B = 0.45E_0$. Introduction of effective heat recovery of 65 - 70 % may reduce the thermal energy by a factor $F = 0.6$, while the mechanical fan energy remains unchanged. This would save 40 % of thermal energy, amounting to 22 % of the initial energy E_0. Thereafter the larger share of energy would fall on the fans, with $A = 0.33E_0$ while $B = 0.45E_0$ as before, in which case the fan energy would constitute almost 58 % of the reduced total. DCV without ($F = 1$) or with ($F = 0.6$) heat recovery thus may reduce the total energy *E* needed for heat and ventilation as calculated below:

-Reduced energy demand with DCV: $E = FAS + BS^3$
-Total energy savings using DCV: $\Delta E = E_0 - E$

The following table shows the percent wise energy savings $\Delta E/E_0$, with and without heat recovery, in relation to the initial energy demand E_0.

Energy savings with DCV:

S-factor	Without heat recovery		With heat recovery	
	A = 0.55E0	*B = 0.45E0S**3***	*A = 0.33E0*	*B = 0.45E0S**3***
1.0	0 %		22 %	
0.9	18 %		37 %	
0.8	33 %		51 %	
0.7	46 %		61 %	
0.6	57 %		70 %	
0.5	67 %		78 %	



The table suggests what energy savings can be realized with full DCV. With or without heat recovery, savings may easily reach more than half the original energy budget for heat and ventilation. More exact calculations would require detailed information about the distribution of energy use in a particular building. Yet the table provides a relevant picture of the energy savings potential that can be realized with DCV. Most probably the calculations are conservative in favour of DCV. With modern heat recovery being already installed in a building, the fan energy may amount to as much as 70 % of the remaining heat and ventilation budget, which would amplify the energy savings factor in DCV.

Most importantly, the calculations demonstrate that DCV is a much more powerful and economical energy savings measure than conventional heat recovery. Heat exchange most often reduces the energy budget by somewhat more than 20 %, while DCV cuts the energy demands two or three times more even without additional heat recovery. Those savings result from a lowered ventilated air volume, which in particular reduces the mechanical fan energy very strongly due to its cubic dependence on air velocity. Such large reductions are only possible when ventilation and air quality are checked and controlled locally in a building. The inevitable conclusion appears to be that DCV offers superior paybacks on energy saving investments when

compared with heat recovery -even without assigning any value at all to an improved and controlled indoor air quality.

It is important to note that those advantages do not apply to heated buildings only; the savings may actually be even larger when the ventilated air needs to be cooled. This is because it normally costs more to cool a volume of air than to heat it by the same degree due to more complex machinery for cooling. Moreover, in a heated system the input air is used to cool the fans that drive the air thus heating the ventilated air, which would be counterproductive in a cooling system. Even more substantial cooling costs may result from heat due to room illumination, computers and other machinery that is "free" heat in cold periods but needs to be removed by expending even more energy to cool in hot periods. Indeed, in modern buildings lights and office equipment often contribute so much heat that the need is to cool even in wintertime. Thus HVAC costs can easily be at a maximum in summer. However, with clever coordination of air quality and temperature, DCV could reduce such excess costs and energy waste by large margins.

When seen in a broader perspective that includes economy as well as health and indoor environment, there may be reason to request a turn-around of the present prevailing practice, to start with DCV as the standard energy savings measure with energy recovery as an eventual add-on. In addition DCV secures a healthy and well-controlled indoor air quality, which is gotten essentially for free - being paid for by the reduced energy bill.

4 Dimensions of Ventilation Ducts

With less air demand one might think that the dimensions of the ventilation ducts might be reduced likewise, thus saving somewhat also on the hardware installations. However, such is not necessarily the case. Suppose that one seeks to reduce the air demand by a factor S as in the examples above. That could be achieved by reducing the cross sectional area D of the ventilation ducts in the same ratio S as for the air volume, keeping the air velocity unchanged. The same velocity would then supply a reduced air mass, which would reduce the fan energy in the same proportion S as for the thermal energy - and not by S^3 as when keeping the ducts unchanged. The larger contribution to energy savings would then be lost.

This discussion also throws some extra light on the question of high pressure versus low-pressure ventilation systems. With narrow ducts, the fans have to work against higher pressures to force the same amount of air through the system. Harder work means more energy, and so the teaching has been that low-pressure systems with wider ducts are more economical. When seen in the present perspective, however, one realizes that it is not a question of air pressure but of air velocity: Doubling the duct cross section halves the air velocity and reduces the fan energy by a factor of eight even before introducing DCV.

If anything, this suggests that one might rather consider the use of wider duct dimensions as a consequence of introducing DCV, to further decrease the air velocity and save even more fan energy. The question of which duct dimensions are more economical, therefore, can only be answered from close analyses of each particular case, supported by considerations of acceptable payback times for the total investments in DCV.

5 Choice of Fan Systems

DCV requires synchronous frequency steering of the fan engines in order to have accurate control of fan speed and delivered air volume. These cost more than conventional equipment. Theoretically one might save investments in DCV by choosing fans with lower air capacity. On the other hand, operators will often emphasize the need for fans to be able to handle an occasional absolute maximum demand in excess of what DCV suggests. However, in upgrading old systems, existing fans can be equipped with frequency steering at reasonable cost. The same old ventilation fans that were unable to supply a sufficient volume of air under the old CAV regime, may then be entirely up to the mark in delivering the reduced DCV air volumes into that same old duct system. DCV, therefore, appears as the ideal upgrade alternative on outmoded ventilation systems whose capacity is not dimensioned after modern standards.

Optimizing expenses relative to fan power, duct dimensions and ventilated air volume (from the ppm-settings to trigger ventilation) against savings on energy cost may be made by means of advanced model simulations on computer, as is now being taken up by some HVAC companies. Ventilation ducts comprise a complex, hydrodynamic flow system with nonlinear responses. The total picture may be quite complex, and may have been to some extent neglected in everyday HVAC. Introduction of DCV will necessitate a change in this. A more basic, detailed and professional approach is required in order to secure those advantages that are now technically at hand, i.e., for energy savings as well as for obtaining healthy and controlled indoor air quality for people to live and work in.

6 Systems and Buildings

In conventional ventilation system where air supply has been controlled from other parameters than CO_2, it has become usual to apply so-called VAV-*(Variable Air Volume)* regulators to set the airflow into and out of a room quite in detail. These are the "balanced" systems; what goes in must go out, one consequence being that windows cannot be opened since that disturbs the "balance". It has also been customarily assumed that at least 10 - 20 % of full ventilation must flow into any room at any time, to remove pollution from materials etc, and to avoid the air being perceived as "old" in rooms that have been vacant for a while. To the extent that CO_2 sensors have been used, these have customarily been placed in the outlet ducts. Upgrading a VAV-based system into DCV is in most cases rather straightforward.

At least two VAVs are required for each room, they are expensive, and with economical CO_2 sensors now being made available the VAVs could be limiting the economy of new DCV systems. However, simpler and more flexible solutions become possible in DCV. VAV regulators may for instance be replaced by inexpensive ON/OFF dampers, so that ventilation is fully ON until the air quality has reached a set level; dampers then close until fresh air would again be required. And CO_2 sensors would have to be situated inside the room and not in the ventilation ducts (expensive), in order to know when ventilation is required. This has several practical consequences.

Opening of windows to let free, fresh air into a room from the outside has been a problem in conventional, "balanced" ventilation systems. Not only does the open window destroy the input-output balance of air through that particular room, the room also becomes a low pressure point in the system with excess air ventilated into it precisely when not required. Air circulation and supply in other parts of the building may then be seriously disturbed, too. Permanently closed windows

can only reduce the indoor air quality, and have become a nuisance in modern buildings. In a DCV system, on the other hand, open windows have no negative consequences either inside or outside of the room: The CO_2 sensors simply close the input and outlet ducts when the air is good, and the remainder of the building is not affected. The possibility of opening windows again, just like the old days, further reduces the need for ventilated air and saves even more money. DCV thus offers advanced flexibility on a systems level as well as for the individual occupant.

Night reduction of ventilation might disappear in practice as well as in concept: DCV would automatically limit ventilation in accordance with the reduced, nightly simultaneity factor *S*, yet the lone office worker burning her oil at late hours would still enjoy the full benefit of freshly ventilated air. Nor would special night reductions need to be implemented for sleeping rooms, like in hotels, hospitals etc; metabolism and thus CO_2 production is reduced in sleep and DCV would take care of the reduced ventilation requirements. Indeed, with active and dynamic DCV no difference needs to be made between day and night, ventilation will be at any time adjusted to suit instantaneous demands while optimizing also the energy savings.

The practice of maintaining a minimum ventilation of 10 - 20 % of full blast even in rooms that are not in use may also be changed. Unoccupied rooms will be identified by central control as not developing any CO_2. Routines may then be worked out that serve to briefly ventilate such quarters, too, at regular intervals, but not all those rooms at the same time to keep instantaneous air velocities down and save on maximum power demands. As a result, all rooms will have been freshly aired at any entrant time. In addition, energy would be saved because heat is not continuously vented out as before.

And, of course, use better building materials. A frightening example is the seniors' complex in Europe that we were recently concerned with -but, alas, too late. The consultants had made their reports, the plans were ready and the owners were about to start building when we entered, suggesting that they use DCV instead of the planned constant air volume (CAV) ventilation. Consultants were entirely embarrassed, and the owners did not know what to believe. After a short but intense exchange of technical arguments, the consultants finally won the day with the owners when to their satisfaction they discovered that, *because* of the (low) quality buildings materials that they had themselves recommended, the official building codes required a certain level of ventilation that upon calculations proved to be exactly five times what would have been necessary based on occupation. Now that is five times the air volume and five times the thermal energy, which is bad enough. *But it is onehundredandtwentyfive -125 times the fan energy!!* Not one cared; the consultants, the owners and the regulations all had had their priorities accepted and confirmed. And no one was any wiser.

One was left wondering what excesses in high quality, low emission materials could have been justified in exchange of the enormous savings on running cost that DCV would have allowed. The lesson may well be that, by introducing DCV into the planning of buildings from start, it might actually be found to pay off quite handsomely to use high quality, low emission materials in order to have whatever extra construction cost that would imply, doubly rewarded by savings in running expenses. One consequence of DCV, therefore, could be to precipitate a change from high emission/high ventilation into a low emission/low ventilation strategy when buildings materials and ventilation are seen in connection. Or, if one prefers, a change from low-quality/high-energy/high-budget to high-quality/low-energy/low-budget buildings. Such choices are now free to be made.

7 Arguments and Counter-Arguments

Arguments have been laid against the suggested ON/OFF control of room ventilation, in that fan adjustment and control takes place by means of pressure sensors inside the ducts. Opening and closing of dampers would then - it is claimed - create pressure pulses that propagate around the ducts to disturb the pressure regulation of fan operation. ON/OFF dampers therefore are said to be impossible to use in a DCV system, so that VAV regulators would yet be necessary.

However, those are simple technical problems that can readily be solved. For example, ON/OFF dampers are far from instantaneous, and such soft pressure changes as will occur can easily be accommodated by a suitably prepared control system. Alternatively, the fans may be operated on demands expressed not through duct air pressures, but rather in accordance with the total room volume that is to be ventilated at any time. Due to the omnipresence of CO_2 sensors, all necessary information exists about the distribution of rooms in need of ventilation, their sizes and their air quality. Such inputs suffice to let a suitable computer program control all facets of ventilation including fan drive.

Today's practice of pressure steering the fans, "balanced" ventilation using VAV regulators etc is based on yesterday's ventilation technology, and is not necessarily suited for the new options that are offered by DCV. To the extent these do not exist, the new regime - DCV - will develop its own methodologies and technologies. It would, therefore, be totally misunderstood to let conservatism and conventional thinking block the emergence of what could be the greatest advance in ventilation, indoor air quality and energy savings for a generation.

8 Alternative DCV Solutions

DCV can be introduced on any levels of complexity of building ventilation. The most economical solution will be, of course, to have DCV included from early in the planning stage. All relevant technical decisions like building materials, fan power, duct dimensions and choice of dampers and sensors etc can then be seen in context, to arrive at a balance between initial investments, operational cost and indoor air quality. It also needs to be decided how the CO_2 sensors will be used to control the ventilation dampers, either locally for each room or from a central control unit using modern automation technology including communication and other hardware for optimized overall performance.

The simplest approach is to vent outside air directly into each room separately, by means of a small fan in the wall and an outlet damper. The CO_2 sensor in the room would then essentially make decisions for ventilating that particular room independently of all other rooms, on the basis of preset levels for ventilation ON and OFF. The ON level needs to be higher than the OFF level, e.g. by 100 ppm or more, to avoid the fan and dampers switching ON/OFF all the time. No ventilation ducts would have to be installed in the building, and only cabling inside each room - from sensor to dampers and fan -would be required. For upgrading old and existing buildings without functional ventilation systems, this may be an economical approach that would also provide full local functionality.

Similar results can be had for the more numerous buildings with CAV ventilation driven by a central fan. With CO_2 sensor and dampers installed, each room would then be able to individually receive air from the existing duct system, on local demand based on preset ppmlevels in the local

sensor. In order to adapt to such variable individual demands, the central fan would need frequency steering, e.g., by means of pressure sensors to gauge the changing duct pressures as ducts open and close for local air supplies independently of the central control. Existing VAV systems could be upgraded by such measures, too.

Maximum flexibility will be achieved with a centrally controlled system that operates on the basis of signals from all CO_2 sensors. All information about room location, volumes and air quality status will then be available for the central control unit to regulate the air demand at any instant. Automated, programmable strategies can then be applied to keep total energy demands inside certain limits even at peak hours while still preserving satisfactory IAQ.

9 Sensor Requirements

Sensors for Demand Controlled Ventilation need to be reliable and accurate: Too low readings might reduce the indoor air quality, while too high readings would lead to systematic excess ventilation and waste of energy. In both cases, serious consequences would result for the operation of DCV in relation to given technical, economical and IAQ standards. Optimization of DCV can only be achieved on the basis of CO_2 measurements that are accurate, stable and reliable over time. This has not been the case with several brands of CO_2 sensors that may habitually err by several hundred ppm up or down. Such equipment would be unsuited for ventilation control based on exact criteria.

In particular, loss of calibration even on short time scales has been a problem not only with electrochemical sensors, but also for IR sensors in general. Recalibration of each individual sensor may then be required, perhaps several times a year at a cost of up to half a sensor each time. In addition to operational down time this would increase the system's total cost of ownership dramatically. Variable, unstable and unreliable calibration, in addition to the traditional high pricing of IR sensors, thus belong among the prime obstacles that have made DCV remain dormant for so long.

However, this may change with the development of new and innovative IR sensor technologies (see, e.g., *http://www.comag-ir.com*). CO_2 sensors are now being made that essentially maintain their calibration indefinitely. With superior stability, sensitivity, programmability and user economy in addition, such sensors satisfy all technical and economical requirements that allow DCV to be implemented on a broad scale. The sensors are based on advanced IR technology processed by digital electronics, with output signals communicated on digital serial bus formats (e.g., BACNet) or else converted to standard analog formats such as 4 -20 mA or 0 -4 (10) V. With each measurement being completed by asingle IR pulse of sub-second duration, repeated at any sequence in time, each sensor may easily be made to service two or more rooms thus further improving the DCV economy. Such sensors are ideally suited to work with central computerized buildings control, to optimize local demands on ventilation and indoor air quality while effectively realizing major overall energy savings and operational cost on HVAC.

Above: SmartScan CO2/temp/humidity Dataloggerkit

10 Safety Factors

In combination with ON/OFF dampers, DCV offers additional options in emergency situations such as when a fire alarm has been given. Ventilation through rooms on fire would be turned OFF (all dampers "Closed"); however, fire gases might be vented out through separate channels to avoid flashover ignition. Adjacent rooms and corridors may then be pressurized (input dampers "Open", output dampers "Closed") to reduce leakage of fire gases out of the fire zone. By means of such measures, the spreading of fire might be delayed or contained while evacuation routes would be made more secure.

Such strategies have become even more powerful with the recent development of infrared CO (carbon monoxide) gas sensors that have sensitivities of a few ppm of CO gas (see *http://www.comag-ir.com*). This enables reliable fire alarms to be made that will react (alarm levels 45 -100 ppm of CO) at a smoldering stage of the fire, even before smoking flames are developed. As soon as a fire alarm has been given, CO sensors outside of the fire zone may then serve as detectors of poisonous CO gas, to further secure or redirect the evacuation routes.

Moreover, CO and CO_2 detection may easily be combined into one and the same gas sensor at little extra cost, which improves the economy of including such safety factors into DCV-operated buildings. Similarly, multi-gas sensors for several relevant gases could be used to include other safety aspects of complex buildings and quarters such as hospitals, hotels, office towers, offshore platforms, passenger ferries, cruise vessels etc.

11 Conclusions

Demand Controlled Ventilation has been seen to offer new technical and administrative tools for the operation of complex buildings. In particular, the energy budget for heat and ventilation may typically be halved by careful design, thus considerably lowering the running expenses. Equally important, however, are the improvements in indoor air quality that follow as a free bonus of DCV, since air quality is measured and controlled against set standards wherever and whenever people are present - for energy saving reasons. Health personnel concerned about bad indoor climate for the workforce need not any longer argue against the perceived high cost of securing good IAQ; talk instead to the company economist about DCV and his bottom line.

The simple model presented in this paper allows the benefits of DCV to be easily understood from a physical point of view. With just a little information about how a building is being used and populated at various times, the operator can now make his own calculations of expected savings when introducing DCV. Most often, the payback time of extra investments is of the order of six to eighteen months. Indeed, DCV pays off so well that energy companies would be well adviced to cover all extra cost of installing DCV with customers on long term contracts in particular, given that the customer accepts to pay his usual electricity bill for, say, the next three years. After that, the customer takes over the DCV installation at no cost, and reduces his HVAC expenses by typically 50 %. In the meantime, the energy company has been making good money by selling the saved energy on the spot market. Through such approaches, DCV may made into a major strategy for overall energy savings on a national level, with substantial savings resulting from win-win relations at all levels and for all involved.