ON-DEMAND VENTILATION CONTROL: A NEW APPROACH TO DEMAND-CONTROLLED VENTILATION

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ABSTRACT

In this paper a new strategy for controlling ventilation systems is described. The strategy provides fresh air at a flow rate proportional to an estimate of the rate at which occupants generate carbon dioxide. Thus, the ventilation rate is nearly proportional to the occupant density even under transient conditions. Properties of the new strategy are described, and the performance is compared to a concentration regulating strategy in a simulation. The new strategy is shown to respond faster to a change in the occupant density and to keep the concentration at or below a threshold.

INTRODUCTION

Demand-controlled ventilation (DCV) is a method for controlling ventilation systems so that ventilation above a baseline level is provided only when it is needed. Demand is usually defined either as contaminant concentration, or as occupant density. Measuring the concentrations of critical contaminants is often difficult and expensive, so demand is usually defined as occupant density. In many buildings, occupant density changes substantially with time and is difficult to measure, so demand-controlled ventilation is often implemented as a carbon dioxide concentration control strategy such as in (1,2) because under equilibrium conditions the carbon dioxide concentration is proportional to the occupant density. The problem with most carbon dioxide-based demand-controlled ventilation strategies is that carbon dioxide concentration is a lagging indicator of occupant density. Under certain conditions the response time of the concentration regulator is dependent on the response time of the ventilation system. In some cases, it may take more than one hour for a concentration regulator to respond to a change in the number of occupants. In other cases, a concentration regulator may not respond at all to a change in the number of occupants.

In this paper, a new strategy for ventilating buildings and other types of occupied enclosures is described. This new strategy provides ventilation air in proportion to an estimate of the rate at which occupants generate carbon dioxide, because the rate at which occupants generate carbon dioxide is a non-lagging indicator of occupant density. The effect is that the ventilation rate tracks the occupant density closely. In other words, the strategy provides ventilation on-demand, so it is referred to as On-Demand Ventilation Control (ODVC).

The next section describes the model used to estimate the rate at which occupant generate carbon dioxide. Then the behavior of the ODVC strategy is described and methods for estimating the rate at which occupant generate carbon dioxide are described. Simulations of a single-zone system demonstrate the improvement in performance over a concentration-regulating DCV strategy.

MODELING

The model used in the ODVC strategy is a perfect-mixing model which is based on conservation of mass for air and a gas species. This type of model can be found in many texts (e.g., (3)). The model is based on the following assumptions:

1. The mass of the air is constant.
2. The concentration distribution is spatially uniform.
3. The gas species is transported by bulk air motion rather than by diffusion.

Under these assumptions, the following linear, time-varying differential equation describes the accumulation dynamics of a zone.

$$M\dot{\omega} = f(\omega_i - \omega) + r \tag{1}$$

where M is the mass of the zone, ω is the zone mass concentration, the dot notation refers to differentiation with respect to time, f is the supply air flow mass flow rate, ω_i is the supply air mass concentration, and r is the source strength. For a detailed derivation of this model see (4).

CONTROL STRATEGY

Figure 1 shows a block diagram of the ODVC strategy.

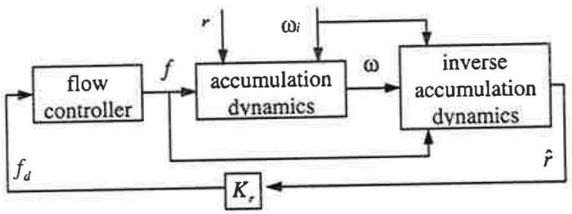

Figure 1 Block diagram of ODVC strategy.

The system is a flow-controller in which the setpoint for the flow loop is proportional to the estimated strength of the carbon dioxide source, denoted as $\hat{r}$ in Figure 1.

Some properties of the ideal ODVC are described next. For the ideal ODVC strategy, the fresh air flow rate is proportional to the actual rate at which carbon dioxide is generated

$$f(t) = K_r r(t) \tag{2}$$

If ω_i and r are constant, then it can be shown that the steady state value of ω in the ideal ODVC is

$$\omega_{ss} = \frac{1}{K_r} + \omega_i \tag{3}$$

If a concentration error is defined as

$$e = \frac{1}{K_r} + \omega_i - \omega \tag{4}$$

then it can be shown that

$$\dot{e} = -\frac{K_r r}{M} e \tag{5}$$

The concentration error definition means that the inverse of the controller gain plus the supply concentration can be interpreted as a concentration setpoint. Equation 5 implies that the ideal ODVC will not allow the concentration to overshoot this setpoint. In other words, the ideal ODVC strategy may be interpreted as a concentration-limiting feedback strategy where the concentration limit is ω_{ss}.

The analysis above is for an ideal control law in which the source strength is known or can be measured. In practice, the strength of the carbon dioxide source cannot be measured directly; it must be estimated from concentration and flow measurements. Estimating the strength of the source involves inverting the dynamics of the mixing process. There are two problems associated with this inverse problem. One is that inverting the dynamics amplifies high-frequency noise. Therefore, there is a tradeoff between the bandwidth of the inverse filter and the effect of noise on the estimate of the source strength. A second problem is that the process parameters may not be well-known. See (4) for details on estimating r and a process parameter such as M simultaneously.

There are numerous algorithms that could be used to estimate r. A simple method is to start with an analog low-pass filter of r, then discretize the analog filter to get a digital implementation. If the filter is first-order, then the analog filter dynamics are described by the following equation

$$\tau\dot{\hat{r}} = r - \hat{r} \tag{6}$$

Substituting Equation 1 into Equation 6 and discretizing the continuous-time equations for digital implementation completes the filter design. One problem with this filter is that large and abrupt changes in r will produce large errors that persist for a length of time that depends on the filter gain. In order to reduce the effect of these transients, the filter gain must be increased. However, increasing the gain increases the sensitivity to noise.

This problem can be solved by detecting large and abrupt changes in r, temporarily increasing the gain, then reducing it. A filter to do this is described in (6). A minimum-variance estimator is used to estimate r and the statistics generated by the minimum-variance estimator are used to construct hypothesis tests about whether or not an abrupt change in r has occurred. Using this method, abrupt changes are detected quickly, r is accurately estimated, and sensitivity to noise is minimized.

SIMULATIONS

In this section the performance of the ODVC strategy is compared to the performance of a DCV strategy with a simulation of a space intended to represent a conference room or classroom. In both simulations, it is assumed that the flow control dynamics are instantaneous. The control law for the DCV strategy used in the simulation is

$$f(n) = K_p(\omega_d - \omega(i)) + TK_i\sum_{i=0}^{n}\omega_d - \omega(i) \tag{7}$$

which is a PI controller normalized by the concentration difference to yield linearized dynamics. The proportional and integral gains are chosen according to the following equations to place the poles of the linearized, continuous-time dynamics at $s = -\lambda$

$$K_p = 2M\lambda \tag{8}$$

$$K_i = M\lambda^2 \tag{9}$$

For both the ODVC and the DCV strategies, the fresh air flow rate is never allowed to drop below a quantity denoted by f_{min}. Integration is suspended when $f = f_{min}$ to prevent windup.

Stationary, uncorrelated, pseudo-random gaussian sequences with standard deviations of 3 ppm were added to the concentrations to simulate measurement noise. The same sequences were used to simulate both strategies. The following parameters were used in the simulation: $f_{min} = 0.035$ kg/sec (62.6 cfm), $K_r = 1012$ kg/kg, $M = 150$ kg, $T = 30$ sec, $\lambda = 1/300$ rad/sec, $\omega_d = 1.52 \times 10^{-3}$ kg/kg (1000 ppm), $\omega_i = 5.32 \times 10^{-4}$ kg/kg (350 ppm), The values of K_r and ω_i used in the simulation imply that the ODVC should prevent the concentration from exceeding 1000 ppm.

Figure 2 shows the source strength and estimated source strength as a function of time. On average, a single sedentary occupant generates 10^{-5} kg/sec (0.3 standard liters per minute) of carbon dioxide. Therefore, when the room is occupied, there are between 5 and 22 occupants. One can see that except for a few transients, the estimated source strength is very close to the actual source strength. In most cases, the abrupt changes in r were detected in two time steps (one minute).

Figure 3 shows the fresh air flow rates for the two strategies. Except for a brief moment just before 90 minutes of simulated time, the DCV strategy does not increase the ventilation rate above the minimum level until 170 minutes of simulated time. In contrast, the ODVC strategy increases the ventilation rate just two minutes after the first set of occupants enters. The delay before the DCV strategy raises the fresh air flow rate above the minimum is the amount of time that it takes the concentration to accumulate to the setpoint. Since the process may have a time constant of more than one hour, this delay may be long. Under certain conditions, it may be indefinitely long. When the source strength and outdoor air concentrations are constant, the steady-state concentration is

$$\omega_{ss} = \omega_i + \frac{r}{f_{min}} \tag{10}$$

Therefore, if the source strength is sufficiently low or if the minimum fresh air flow rate is sufficiently high, the DCV strategy will never raise the fresh air flow rate above the minimum level. In other words, under these conditions the DCV strategy will not respond to the demand.

Figure 4 shows the carbon-dioxide concentrations for the two strategies. Under nearly all conditions, the ODVC strategy results in a lower concentration than the DCV strategy. During the transients in which the number of occupants increases, the DCV strategy does not maintain the concentration below the setpoint. In contrast, the ODVC strategy maintains the concentration below the setpoint after these transients. The highest concentration allowed by the ODVC strategy in this simulation exceeds ω_{ss} by only 3 ppm, which is the standard deviation of the measurement noise.

CONCLUSIONS

A new demand-controlled ventilation strategy is described. This strategy provides fresh air at a rate proportional to an estimate of the rate at which occupants generate carbon dioxide. Therefore, the ventilation rate is proportional to the occupant density even under transient conditions. Under ideal conditions, this strategy has the property that the carbon dioxide concentration is never allowed to exceed a limit that is a function of the controller gain. Comparison with a carbon dioxide regulating strategy demonstrates the improved dynamic performance.

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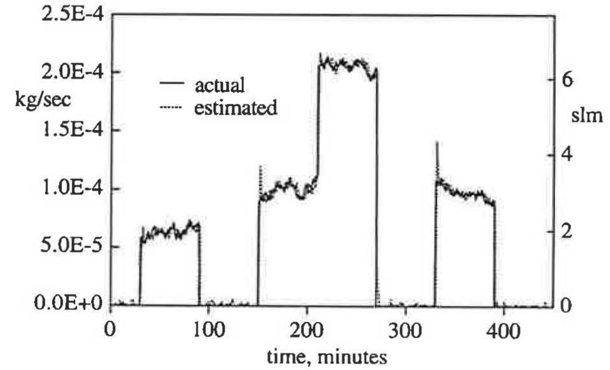

Figure 2 Source strength estimation.

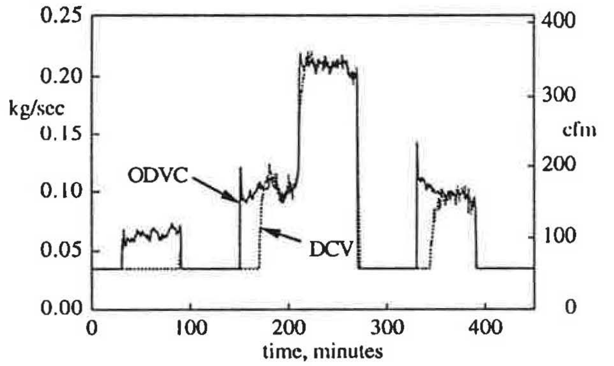

Figure 3 Flow rate comparison.

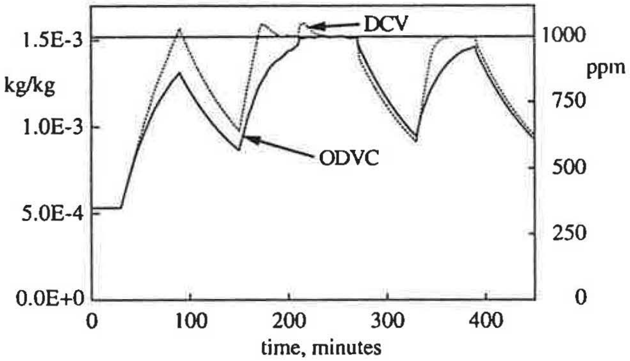

Figure 4 Carbon dioxide concentrations.

An Experimental Study on the Air Distribution and Thermal Performance of the Air Circulation Wall

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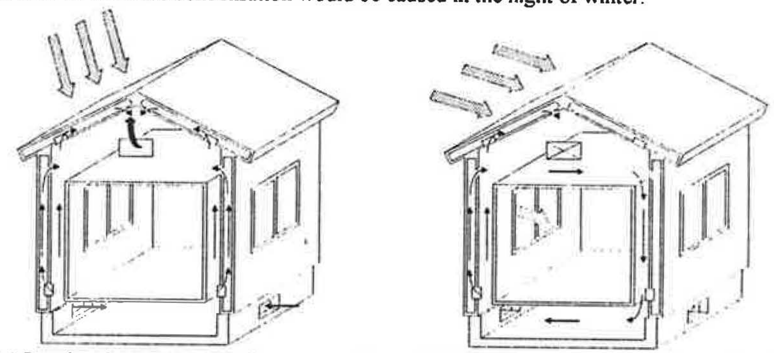
ABSTRACT

The air circulation wall is a triple envelope and double air layer system of outside walls and roofs. Its midst envelope is a thermal insulation board and divides the wall into two air layers. Since its outer air layer works like as a solar collector, this system increases indoor air temperature in winter under closed air circulation. In summer, its open air circulation exhausts hot air to the outdoor. Many Japanese wooden houses with this air circulation system have been constructed. However, many problems are remained for its optimum designing such as the precise prediction of thermal characteristics in the layers, etc. This paper investigates the air distribution and thermal performance of the air circulation system through real-size model experiments.

INTRODUCTION

A solar house equipped with this system has characteristic air circulation through spaces by means of natural ventilation caused by stack effects. If the air circulation layers suck outdoor air through lower opening and exhaust warm air through higher opening in daytime of summer, cold draft or moisture condensation would be caused in the night of winter.



(a) Daytime in summer (ventilator opened)　(b) Daytime in winter (ventilator closed)

Figure 1 Air flow distribution of the air circulation wall