OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

17th AIVC Conference, Gothenburg, Sweden,
17-20 September, 1996

THE EFFECT OF RECIRCULATION ON AIR-CHANGE EFFECTIVENESS

Clifford C. Federspiel

Johnson Controls, Inc.
Milwaukee, WI, USA

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Johnson Controls, Inc.
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Synopsis

The effect of recirculation on the age of air is described. A new effectiveness measure called the relative air-change effectiveness is defined in such a way that the air distribution pattern in a room may be quantitatively characterized even when the age of the supply air is non-zero. This admits the evaluation of air distribution patterns in single-zone systems that recirculate air, and also multizone systems with or without recirculation. It is shown that the relative air-change effectiveness may be calculated either solely from age of air measurements or from age of air measurements and flow rate measurements. Re-evaluation of previously published experimental data demonstrates how knowledge of the relative air-change effectiveness may change conclusions drawn from experiments in working buildings.

1 Introduction

Ventilation performance measures have been developed for quantifying the behavior of ventilation systems and for comparing the behavior of different systems. These measures are either related to how well fresh air is delivered or to how well contaminants are removed. Although these two concepts are closely related, this paper focuses exclusively on the former.

Several different definitions of air delivery performance have been proposed. Most often experimental determination of air delivery performance is conducted with tracer gases. Air delivery performance is determined either from steady-state concentration levels of tracer gas or from a transient tracer gas response. In [1] an air delivery performance measure called the relative ventilation efficiency was defined as a ratio of concentration differences at steady-state. Methods for determining this measure from transient response tests were discussed. In [2] a performance measure called relative air diffusion efficiency was defined as the ratio of the nominal time constant to the mean age of air. In [3] ineffective ventilation was modeled by assuming that some of the supply air bypasses the zone and flows directly to the return duct. A performance measure called the ventilation efficiency was then defined as one minus the bypass factor. In [4] a performance measure called the pollutant control index was defined as a time-averaged tracer gas concentration multiplied by a constant that is a function of the tracer source strength and the size of the space.

In many kinds of heating, ventilating, and air-conditioning (HVAC) systems, the ventilation function is coupled with the heating and cooling function. In order to deliver the required quantity of air to different zones of a building at the required temperature, it is necessary to recirculate and redistribute some of the air that leaves these zones. This poses a problem for evaluating ventilation performance using a measure such as the relative air diffusion efficiency because it was developed under the assumption that "neither is it possible for a molecule either to return upstream once it has entered the room, or to re-enter the room once it has left it" [2].

In this paper, the effect of recirculation on air-change effectiveness calculations is described. First the age of air in the presence of recirculation is presented. Then it is shown how recirculation affects the conventional measure of air-change effectiveness. The theory of air-change effectiveness is extended to include single-zone systems with recirculation and multi-zone systems with or without recirculation by defining a new measure of air-change effectiveness. Implications of this theory for ventilation performance evaluation and control are discussed.

2 Age of Air

Consider the ventilation system depicted in Figure 1 in which a single zone is supplied by air that is a combination of recirculated return air and outdoor air. The fraction of

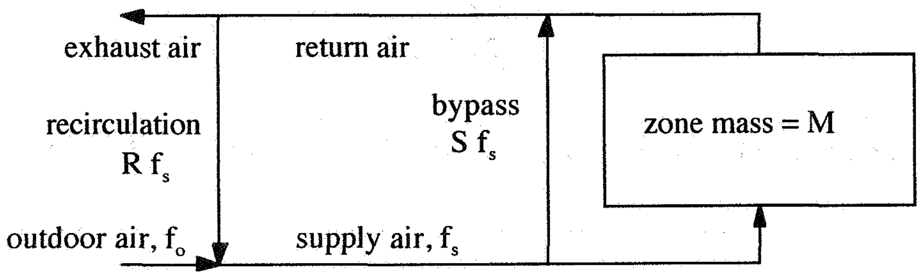

Figure 1: Schematic diagram of a single-zone ventilation system with recirculation and bypass.

recirculated air in the supply air will be denoted as R. Assume for now that the bypass factor, S, is zero. The age of air at a point in the room is the length of time that it takes a massless particle entering the system from outdoors to reach that point. The age of air will be denoted as a. The mean age of air in the room is the volumetric mean of the age of air at all points within the room. It will be denoted as $\bar{a}$.

First the age of air for two abstract systems will be described. Perfect mixing systems are the most commonly considered abstract systems used to analyze the performance of ventilation systems. When the air in the system shown in Figure 1 is perfectly mixed, then the accumulation dynamics of a component of the air (e.g., a tracer gas) can be described by the following equation

$$M\dot{\omega} = f_s(\omega_s - \omega) + r \tag{1}$$

where M is the mass of the air in the zone, ω is the mass concentration of the component in the zone, the dot notation refers to differentiation with respect to time, f_s is the mass flow rate of supply air, ω_s is the mass concentration of the supply air, and r is the rate at which the mass of the component gas is generated within the zone. It can be shown that the accumulation dynamics can also be expressed as

$$M\dot{\omega} = f_o(\omega_o - \omega) + r \tag{2}$$

where f_o is the outdoor air mass flow rate and ω_o is the outdoor air concentration. Since this is a linear, time-invariant, first-order differential equation, the mean age of the air is equal to the nominal turnover time, which is denoted as τ_n

$$\bar{a} = \tau_n = \frac{M}{f_o} \tag{3}$$

For a perfect-mixing system, the mean age of the air is independent of the recirculation fraction.

Another kind of abstract system that is commonly considered when analyzing air-change effectiveness is the system with plug flow and no diffusion (PFND). When f_o and R are constant, the PFND system is a linear, time-invariant transport delay. The zone delay is the time that it takes a particle to cross the zone from the supply to the return. It is equal to the local nominal turnover time of the zone, denoted as T

$$T = \frac{M}{f_s} \tag{4}$$

It can be shown that for a PFND system

$$\bar{a} = \frac{T}{2}\frac{1+R}{1-R} \tag{5}$$

which implies that the age of air depends on the recirculation fraction for a PFND system. Figure 2 demonstrates how recirculation affects the age of the air. The figure shows the

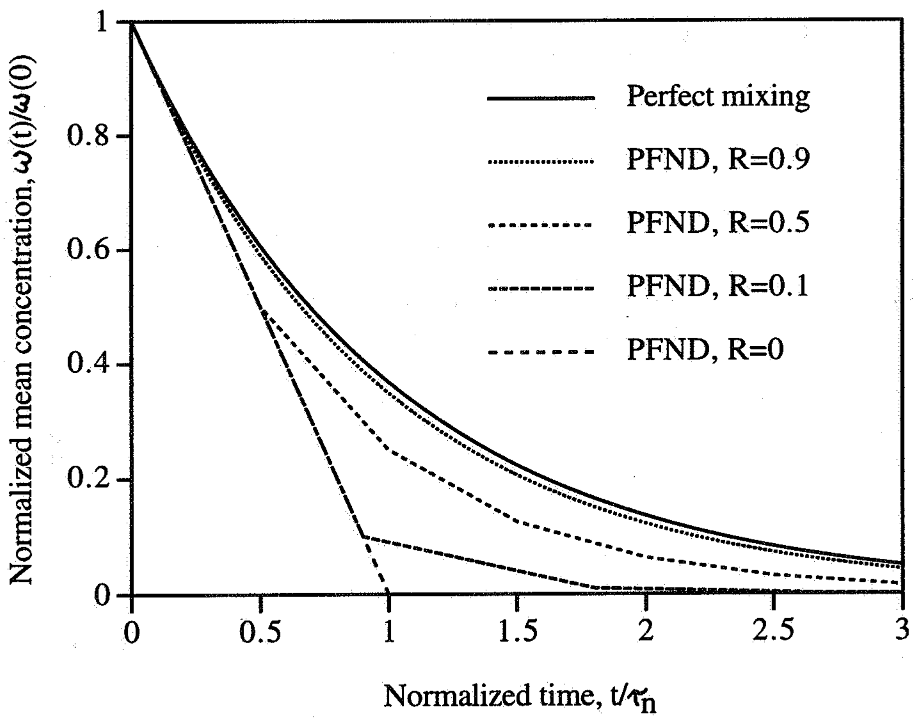

Figure 2: Normalized tracer gas decay for a perfect-mixing system and several PFND systems with different recirculation fractions.

normalized concentration decay curves for a perfect mixing system and several PFND systems with different amounts of recirculation. As the recirculation fraction increases, the decay response moves closer and closer to the response of the perfect-mixing system.

In practice the air will not behave like it does in these abstract systems. Since the age of return air for systems with no recirculation is independent of the air distribution and is equal to T [2, 5], one can show that the age of air in any single-zone system is

$$\bar{a} = \bar{a}_{R=0} + \frac{TR}{1-R} \tag{6}$$

where $\bar{a}_{R=0}$ is the mean age of air that would exist if $R = 0$.

3 Air-Change Effectiveness

For a single-zone system, the absolute air-change effectiveness is defined as the ratio of the nominal turnover time to the mean age of air

$$\varepsilon_a \equiv \frac{\tau_n}{\bar{a}} \tag{7}$$

The absolute air-change effectiveness is the same as the air diffusion effectiveness defined in [2]. The absolute air-change effectiveness can be defined at a point by substituting the age at the point for the mean age. The absolute air-change effectiveness for a perfect-mixing system is 1, and is independent of the recirculation fraction. For a PFND system, the absolute air-change effectiveness is

$$\varepsilon_a = \frac{2}{1+R} \tag{8}$$

In general, the absolute air-change effectiveness is

$$\varepsilon_a = \frac{\tau_n}{\bar{a}_{R=0} + \tau_n R} \tag{9}$$

If there were no recirculation, then the absolute air-change effectiveness would provide a measure of the air distribution in the zone. Therefore, another air-change effectiveness measure, which will be referred to as the relative air-change effectiveness, is defined as the value of the absolute effectiveness that would have been calculated had the recirculation fraction been zero.

$$\varepsilon_r \equiv \frac{T}{\bar{a}_{R=0}} \tag{10}$$

For a single-zone system, it can be shown that

$$\varepsilon_r = \frac{\tau_n - a_s}{\bar{a} - a_s} \tag{11}$$

where a_s is the age of the supply air. Equation 11 demonstrates the similarity between the relative air-change effectiveness defined in this paper and the relative ventilation efficiency defined in [6]. As with the absolute air-change effectiveness, the relative air-change effectiveness can be computed at a point by substituting the age of air at a point for the average age of air in Equation 11. When there is no recirculation, the age of the supply air is zero, so the relative air-change effectiveness becomes the same as the absolute air-change effectiveness. For single-zone PFND systems, the relative air-change effectiveness is equal to two regardless of the recirculation fraction. For perfectly mixed systems it is equal to 1.

It can be shown that for a single-zone system, the relation between $\varepsilon_a, \varepsilon_r$, and R is

$$\varepsilon_a = \frac{\varepsilon_r}{1 - R + \varepsilon_r R} \tag{12}$$

This relation is shown in Figure 3. The figure shows that as the recirculation fraction

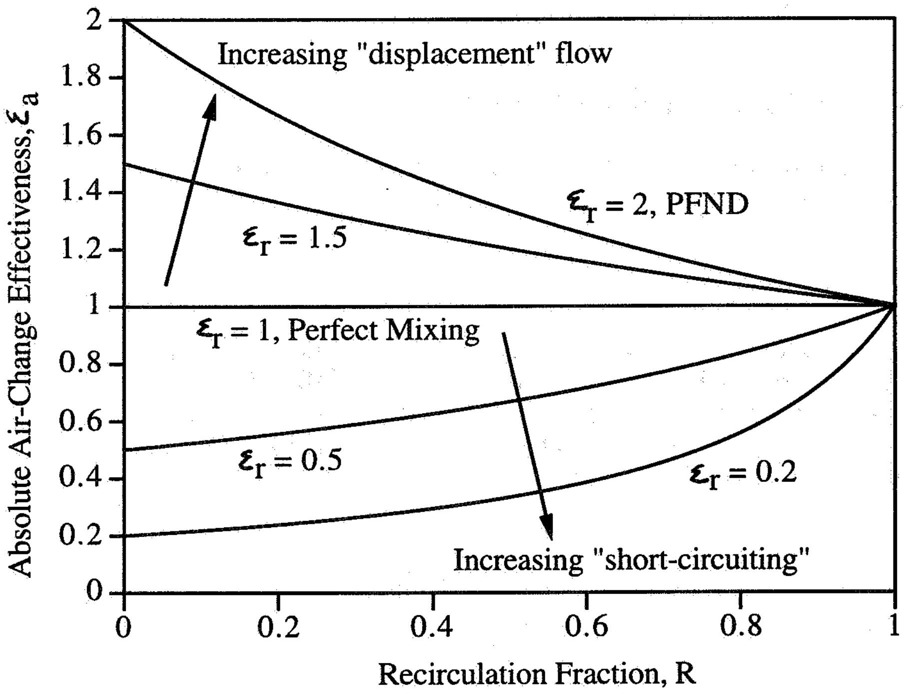

Figure 3: Schematic diagram of a single-zone ventilation system with recirculation and bypass.

approaches 1, ε_a approaches 1 regardless of the value of ε_r. It also shows that by itself, ε_a only provides a qualitative description of the air distribution pattern. If $\varepsilon_a < 1$, then one can say that there is some "short-circuiting," but one cannot say how much without knowing either ε_a and R or just ε_r.

Most buildings contain a number of zones that interact both through recirculation in an air-handling unit and directly through passages such as doorways. The theory described above can be applied to any multizone system in which the flow-weighted average age of the air entering and leaving the zones can be evaluated. For example, in Figure 4, the relative air-change effectiveness of zone 2 could be calculated as

$$\varepsilon_{r_2} = \frac{a_{e_2} - a_{s_2}}{\bar{a}_2 - a_{s_2}} \tag{13}$$

$$a_{s_2} = \frac{f_{s_1} a_{e_1} + f_{s_3} a_{e_3}}{f_{s_1} + f_{s_3}} \tag{14}$$

where a_{e_2} is the age of the air leaving zone 2, a_{e_1} is the age of the air leaving zone 1

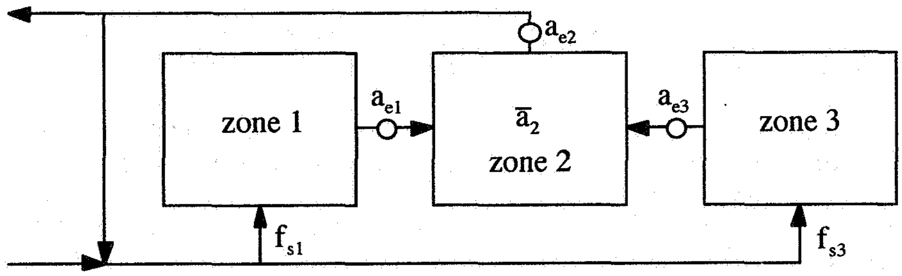

Figure 4: Schematic diagram of a multizone ventilation system with recirculation.

and flowing into zone 2, a_{e_3} is the age of the air leaving zone 3 and flowing into zone 2. Note that the quantity in the numerator of Equation 13 could be computed from flow rate measurements as

$$a_{e_2} - a_{s_2} = \frac{M_2}{f_{s_1} + f_{s_3}} \tag{15}$$

Also note that ε_{r_2} could not be calculated from ε_{a_2} of zone 2 and R even if the age of air at the return grille in zone 2 were used to compute ε_{a_2} because zone 2 is not directly supplied with air by the air-handling unit.

Sometimes ineffective ventilation is modeled by assuming that some of the supply air bypasses the breathing zone and passes directly to the return duct [3, 7]. This can be modeled by assuming that $S > 0$ in Figure 1. It can be shown that for this system

$$\varepsilon_a = \frac{1 - S}{1 - RS} \tag{16}$$

The absolute air-change effectiveness is a measure of how well outdoor air is utilized. In [3], a ventilation performance measure called ventilation efficiency is defined as

$$\eta = 1 - S \tag{17}$$

It can be shown that

$$\varepsilon_r = \eta \tag{18}$$

In other words, for a perfect-mixing system with bypass, the relative air-change effectiveness is the fraction of the supply air that is used to ventilate the zone. In general, the relative air-change effectiveness is a measure of how well supply air is utilized. A problem with the bypass model is that some ventilation systems make more effective use of ventilation air than perfect-mixing systems. When this happens, the bypass factor, S, must be negative. A negative value of S does not have a physical interpretation as does a positive value.

4 Discussion

Many published experiments on air-change effectiveness involve tests on systems that recirculate air. Typically the absolute air-change effectiveness is reported, and the tests are often carried out with large recirculation fractions (e.g., minimum outdoor air conditions). The theory presented above predicts that under these conditions the absolute air-change effectiveness will be close to unity. This prediction is consistent with many published findings such as [8, 9, 10] although some experiments such as those described in [11] have shown that the absolute air-change effectiveness may be significantly less than one even with recirculation.

To demonstrate the significance of the theory presented above, the data reported in [11] are re-evaluated, and relative air-change effectivenesses are calculated. The article describes a tracer gas experiment on a zone in a multizone system which was divorced from the other zones. The HVAC system was operated in the heating mode, so the supply air was warmer than the zone air. Table 1 shows the values of the breathing-zone absolute air-change effectiveness reported in [11] and the relative air-change effectiveness calculated from information supplied in the article. The values of ε_r shown in the table

Table 1: Re-evaluation of the data presented in [11]

configuration	ε_a from [11]	ε_r
H1, ceiling supply & return	0.73	0.31
H2, ceiling supply & return	0.66	0.34
H3, ceiling supply, floor return	0.76	0.56
H4, ceiling supply, floor return	0.73	0.47
H5, "short-circuiting" design	0.57	0.44

were not calculated with Equation 11 even though the age of air at the supply, return, and breathing zone were all reported in the paper. This is because one of the configurations delivered air to a ceiling plenum rather than directly to the zone, and because there was some uncertainty about leakage of air into the return duct. Instead, ε_r was calculated as follows

$$\varepsilon_r = \frac{T}{a_b - a_p - a_s} \tag{19}$$

where T was calculated from the reported nominal ventilation rate, volume of the space (total volume minus the volume of the ceiling plenum) and recirculation fraction (67%), a_b was the age of air in the breathing zone, a_p was the additional age of the supply air induced by supplying the air to the ceiling plenum rather than directly to the room, and a_s was the age of the supply air, which was measured as it left the rooftop air-handling unit. The results reported in [11] indicate that the configuration designed to induce short-circuiting had the lowest absolute air-change effectiveness. However, by calculating ε_r, one can see that the system with ceiling supply and return induced more "short-circuiting" than the system designed to induce it. This is probably because the supply air velocities were higher with the system designed for "short-circuiting," and the higher velocities probably entrained surrounding air and induced more mixing.

Another implication of the theory described in previous sections pertains to the use of experimentally-determined effectiveness parameters in controlling ventilation systems. It is proposed in [12] that values of ε_a determined from an experiment on the system be used to adjust the minimum outdoor air flow rate. This may cause the effective outdoor air flow rate to be too high or too low depending on the conditions of the test and the operational behavior of the system. For example, if the system tested in [11] had been a variable-air-volume (VAV) system, and if the value of ε_a calculated in test H1 were used to adjust the outdoor air flow rate, then if the system were to operate with 100% outdoor air and the adjusted minimum flow rate, the effective outdoor air delivery to the breathing zone would be only 42% of the design value because with 100% outdoor would equal ε_r, which was 0.31 rather than 0.73.

5 Conclusions

1. Recirculation of air in buildings confounds the quantitative description of air distribution patterns when only absolute air-change effectiveness is reported.

2. This paper extends the air-change effectiveness theory to single-zone systems with recirculation and multizone systems with or without recirculation by accounting for the age of the supply air.

References

[1] Sandberg, M., 1981, "What is Ventilation Efficiency?," *Building and Environment*, Vol. 16, No. 2, pp. 123-135.

[2] Sandberg, M. and M. Sjoberg, 1983, "The Use of Moments for Assessing Air Quality in Ventilated Rooms," *Building and Environment*, Vol. 18, pp. 181-197.

[3] Rask, D. R., J. E. Woods, and J. Sun, 1988, "Ventilation Efficiency," Proceedings of *Building Systems: Room Air and Air Contaminant Distribution*, NSF, University of Illinois.

[4] Fisk, W. J., D. Faulkner, and A. T. Hodgson, 1993, "The Pollutant Control Index: A New Method of Characterizing Ventilation in Commercial Buildings," Proceedings of *Indoor Air '93*, Vol. 5, pp. 9-14.

[5] Mantegna, M., 1993, "An Invariant of the Age of Air: Proof and Applications," *Air Infiltration Review*, Vol. 14, No. 2, pp. 14-18.

[6] Kim, I. G. and H. Homma, 1992, "Possibility for Increasing Ventilation Efficiency with Upward Ventilation," *ASHRAE Transactions*, Vol.

[7] Janssen, J. E., 1984, "Ventilation Stratification and Air Mixing," Proceedings of *3rd International Conference on Indoor Air Quality and Climate*, Vol. 5, pp. 43-48.

[8] Fisk, W. J., R. J. Prill, and O. Seppanen, 1988, "Effective Ventilation," Proceedings of *9th AIVC Conference*, Gent, Belgium, September 12-15, pp. 161-182.

[9] Persily, A. K. and W. S. Dols, 1991, "Field Measurements of Ventilation and Air-change Effectiveness in an Office/Library Building," *Indoor Air*, Vol. 3, pp. 229-245.

[10] Persily, A. K., W. S. Dols, and S. J. Nabinger, 1994, "Air Change Effectiveness Measurements in Two Modern Office Buildings," *Indoor Air*, Vol. 4, pp. 40-55.

[11] Offermann, F. J., 1988, "Ventilation Effectiveness and ADPI Measurements of a Forced Air Heating System," *ASHRAE Transactions*, Vol. 94, Part 1, pp. 694-704.

[12] ASHRAE, 1996, "Ventilation for Acceptable Indoor Air Quality," ASHRAE Standard 62R (in review).