AIVC
1928

2444

J. agric. Engng Res. (1984) **30**, 57–63

2444

Interpretation of Tracer Gas Experiments in Ventilation Research

E. M. BARBER*; J. R. OGILVIE†

Many studies to quantify departure from complete mixing in ventilated airspaces have involved the use of tracer gas techniques. The results of tracer experiments do not, in themselves, have any physical significance, but must be interpreted within the context of a valid mixing model. The model most often used in ventilation research accounts for incomplete mixing in terms of a mixing factor, K, usually defined as the ratio of the effective ventilation rate to the actual, or theoretical, ventilation rate. Values of $K > 1$ are interpreted to indicate stagnant regions while values of $K < 1$ are attributed to short-circuiting of supply air to the exhaust outlet. A two-parameter mixing model, first developed for aqueous mixing systems, separates the effects of short-circuiting and stagnant zones, and has been tested for slot-ventilated airspaces. In this paper, a more complicated mixing model was considered in which the airspace was treated as a network of well-mixed regions connected in series or in parallel, with backmixing between adjacent zones. Tracer gas experiments were simulated using a GASP IV computer model to test the response of such an airspace to a step change in tracer concentration in the supply air. Simulated data were compared to experimental data from a tracer study in a scale-model slot-ventilated airspace. This work has shown that mixing factors > 1 may be due to a series arrangement of flow regions between the supply and exhaust openings, while mixing factors < 1 may be caused by the existence of secondary flow zones. The inability of conventional tracer gas techniques to distinguish positively between alternative causes of incomplete mixing limits the usefulness of tracer techniques for diagnosis of ventilation problems.

1. Introduction

Tracer gas experiments are a well-known method for estimating air exchange rates in ventilated airspaces.[1] When the actual ventilation rate is known or can be measured, rate-of-decay tracer gas experiments also can be used to quantify the extent to which mixing is incomplete.[2,3] The results of tracer gas experiments do not, in themselves, have any physical significance, but must be interpreted within the context of a valid mixing model.

2. Mixing models

2.1. *The K-model*

The traditional single-parameter mixing model for an airspace which is assumed to behave as a single mixed flow region is given by

$$(C-C_i)/(C_0-C_i) = \exp(-KQt/V).$$

The parameter K is estimated in rate-of-decay experiments as the negative slope of the plot of $\log_e(Cr)$ versus the dimensionless air exchange number, Qt/V. The concentration of tracer gas, C, is measured within the airspace or at the outlet during the period following a step change in tracer concentration in the supply air. Values of $K > 1$ are attributed to the presence of stagnant zones

---

*Department of Agricultural Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 0W0
†School of Engineering, University of Guelph, Guelph, Ontario, Canada N1G 2W1

Received 5 December 1983; accepted in revised form 7 April 1984
Paper presented at AG ENG 84, Cambridge, U.K., 1-5 April 1984

0021-8634/84/050057+07 $03.00/0

NOTATION

C	concentration of tracer within a well-mixed zone, m^3/m^3
C_e	concentration of tracer in the exhaust airstream, m^3/m^3
C_i	concentration of tracer in the air, m^3/m^3
C_0	concentration of tracer in the mixing zone at time zero, m^3/m^3
Cr	concentration ratio $(C-C_i)/(C_0-C_i)$
j_{xy}	mixing coefficient
K	experimentally-determined mixing factor
m	portion of an airspace which is well mixed
n	portion of supply air entering well mixed zone
Q	airflow rate, m^3/s
t	time, s
V	volume of airspace, m^3

while values of $K < 1$ are presumed due to short-circuiting of supply air directly to the outlet. This simple model does not distinguish between the counteracting effects of stagnant zones and short-circuiting when both occur simultaneously. An example of the interpretation of tracer data by the K-model for the particular case of livestock buildings is provided by the published work of Kaul *et al.*[4]

2.2. *The n,m-model*

A two-parameter mixing model, previously validated for aqueous mixing systems,[5] was described and tested for a slot-ventilated airspace.[6] In this model, a portion of the airspace, m, is assumed to be well mixed while the portion, $1-m$, is stagnant. A fraction, n, of the supply air enters the well-mixed zone while a portion, $1-n$, is short-circuited to the outlet. The model is written as

$$(C_e-C_i)/(C_0-C_i) = n[\exp(-nQt/mV)].$$

Following a step change in tracer concentration in the supply air, the tracer concentration is measured at the outlet. Plotting the $\log_e(Cr)$ versus Qt/V, $\log_e(n)$ is the intercept on the logarithmic axis and the slope of the curve is $-n/m$ (equivalent to K in the K-model).

Experiments to test the validity of the n,m-model were conducted in a one-fifth scale physical model of a swine grower–finisher barn. The inside dimensions of the physical model were 2 × 2·4 × 0·64 m. A removable baffle was used to create a floor-level obstruction 0·25 m high and perpendicular to the primary airflow. Electric heater cable was attached to the floor of the model. The scale model was placed in a temperature-controlled chamber and ventilated with chilled air from within the chamber. Supply air entered the model through an adjustable, continuous slot inlet along the top of one 2 m long wall. Air was exhausted from the model through one of two 75 m diameter ports. One port was located in the centre of the wall below the inlet, while the other port was located in the wall opposite the inlet.

The ventilation rate, inlet jet velocity, and temperature difference between inside and supply air were varied to yield values for a Corrected Archimedes No. (Ar_c) varying between 3 and 130. The Ar_c has been described by Randall and Battams,[7] and is considered to be a good indicator of the direction of a cold air jet entering a warmer room through a slot inlet. For low values of Ar_c, the jet is expected to remain horizontal and attached to the ceiling while for high values of Ar_c, the jet will fall to the floor immediately upon entering the airspace.

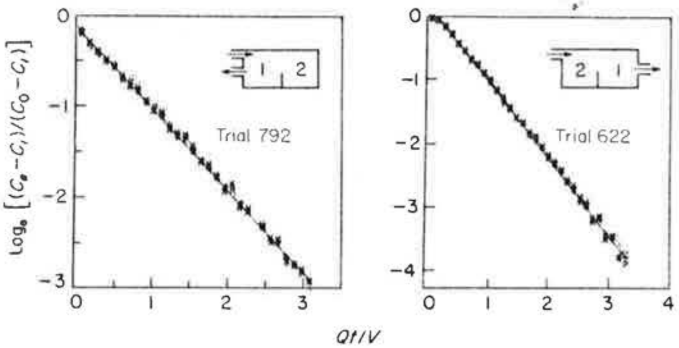

Fig. 1. Examples of experimental results from scale-model study (Trial 792, $K = 0{\cdot}83$; $n = 0{\cdot}87$, $m = 1{\cdot}04$; Trial 622, $K = 1{\cdot}10$; $n = 1{\cdot}16$, $m = 1{\cdot}05$)

Tracer data were obtained in rate-of-decay experiments for a sample collected at the outlet, and for a composite sample collected from within the airspace.[6] The results of 136 trials were reported and analyzed to test the validity of the *n,m*-model for ventilated airspaces. A number of reasons were given for rejecting this model for the experimental slot-ventilated airspace. These reasons included non-zero intercepts for plots of $\log_e (Cr)$ versus Qt/V for sample locations within the airspace, predicted values for n greater than unity, predicted values for m greater than unity and an inability to explain the effects of the floor-level obstruction on incomplete mixing within the airspace.

The results of two trials are summarized in *Fig. 1* to illustrate a major shortcoming of both the *K*-model and the *n,m*-model. Considering Trial 792, the *K*-model predicts a significant amount of short-circuiting ($K = 0{\cdot}83$). The *n,m*-model similarly predicts short-circuiting ($n = 0{\cdot}87$) but the predicted value for the proportion of the airspace which is well mixed ($m = 1{\cdot}04$) is not consistent with the physical constraint that m cannot be greater than unity. Considering Trial 622, where all experimental parameters except outlet location were the same as for Trial 792, the *K*-model now predicts a significant stagnant zone ($K = 1{\cdot}10$). It is far from clear why the change in outlet location alone would have had such a drastic effect on the air distribution pattern and hence on the extent of stagnant regions. The *n,m*-model offers no explanation for the results of this trial ($n = 1{\cdot}16$, $m = 1{\cdot}05$) since neither n nor m can be greater than unity. The delayed decay in tracer concentration at the outlet location is similary not explained by the *n,m*-model. Similar data collected in the same trial for the inner chamber sampling location indicated that the shape of the curve was not caused by errors in defining zero time.

3. Multi-compartment mixing model

An assumption of fundamental importance to the development of the one- and two-parameter mixing models is that the airspace behaves as a single mixed tank. If there is a second zone, that zone is assumed to be completely stagnant and hence thermodynamically isolated from the main flow region. However, flow visualization studies in scale-model and full-scale models have indicated the existence of multiple flow regions, especially where the enclosed airspace is distinctly rectangular.[8,9]

To reflect this complicated flow regime, a four-compartment model of the ventilated airspace is outlined in *Fig. 2*. In this model, the airspace is presumed to behave as a network of mixed tanks (i.e. flow regions) connected in series and/or in parallel with a defined amount of backmixing between adjacent flow regions. Supply air at a flow rate Q, and containing a tracer concentration C_i, enters the airspace where the flow splits into three streams: (1) a portion, n_1, enters zone 1, the primary flow region located closest to the outlet; (2) a portion, n_2, enters zone 2, the primary flow region located remote from the outlet and (3) the remaining portion, $1 - n_1 - n_2$, is short-circuited directly to the outlet without mixing with air in any of the flow zones. To each of the two primary zones is attached a

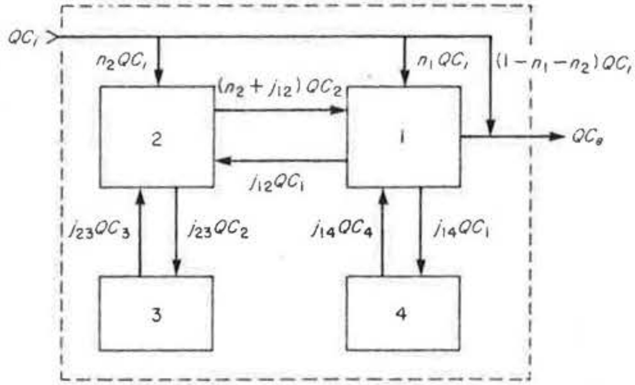

Fig. 2. Airflow and tracer transport in four-compartment model

secondary flow zone. To simplify the analysis, airflow between the two secondary zones is assumed not to occur. In the physical sense, this might be true if the secondary zones existed primarily in the outer corners of the airspace. Airflow between any other pair of zones, x and y, occurs at the rate $j_{xy}(Q)$, where the coefficient j_{xy} may assume any non-negative real value if x and y are limited to the zones as defined.

All four zones are considered within themselves to be well mixed. A mass balance on the tracer, C, yields one equation for each zone:

$$
\begin{aligned}
V_1(\mathrm{d}C_1/\mathrm{d}t) &= n_1Q(C_i - C_1) + n_2Q(C_2 - C_1) + j_{12}Q(C_2 - C_1) + j_{14}Q(C_4 - C_1),\\
V_2(\mathrm{d}C_2/\mathrm{d}t) &= n_2Q(C_i - C_2) + j_{12}Q(C_1 - C_2) + j_{23}Q(C_3 - C_2),\\
V_3(\mathrm{d}C_3/\mathrm{d}t) &= j_{23}Q(C_2 - C_3),\\
V_4(\mathrm{d}C_4/\mathrm{d}t) &= j_{14}Q(C_1 - C_4).
\end{aligned}
$$

The response of the multi-compartment model, measured in terms of the transient tracer concentration in each zone to a step change in tracer concentration in the supply air was simulated using a GASP IV computer program.[10] Results were obtained for different values of the model parameters as plots of the $\log_e(Cr)$ versus Qt/V. Best-fit linear regressions were performed for zone 1 (i.e. for the outlet tracer concentration) and for a composite inner chamber sample location. To be consistent with the terminology used for the models previously described, the negative slope of these curves is designated as K and the intercept of the curve for the outlet location is designated as $\log_e(n)$.

3.1. *Effect of backmixing between primary zones*

Assume that the secondary zones, 3 and 4, do not exist and that the other two zones are of equal size. Further assume that no air is short-circuited directly to the outlet and that all the incoming air enters only one of the two zones. Such might be the situation in a wide airspace with an inlet on only one side. In one possible arrangement, termed the series arrangement, the inlet and outlet are on opposite sides of the airspace and so are separated by two flow regions in series. In this case $n_2 = 1$ and $n_1 = 0$. In the opposite arrangement termed the parallel arrangement the inlet and outlet are on the same wall and $n_2 = 0$ and $n_1 = 1$.

The results of computer simulations for j_{12} between 0 and 10 are collected for comparison in *Fig. 3*. For both inlet–outlet arrangements, the case of a single completely-mixed tank is approached for $j_{12} = 10$. That is, the slope of the curves approaches unity and the curves have an intercept of zero. As the extent of backmixing decreases the plot for the zone with the outlet begins to assume a distinct curvature. For small curvatures the effect of decreased backmixing is manifested as a decrease in the slope of the curve and the occurrence of non-zero intercepts. Thus non-zero intercepts for the inner chamber sample location that could not be explained in terms of the *n,m*-model[6] could be due to the existence of two or more separate flow regions.

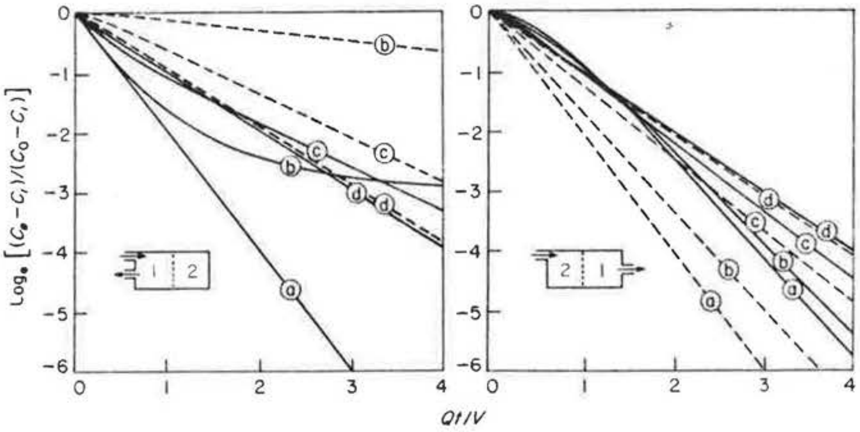

Fig. 3. Effect of backmixing in two-compartment airspace (——, zone 1 response; – – –, zone 2 response; a, $j_{12} = 0$; b, $j_{12} = 0{\cdot}1$; c, $j_{12} = 1{\cdot}0$; d, $j_{12} = 10{\cdot}0$)

As backmixing approaches zero in the parallel arrangement, the case of the two-parameter *n,m*-model is achieved wherein zone 2 is perfectly stagnant and the well-mixed zone has an apparent ventilation rate which is higher than the theoretical rate for a single well-mixed airspace. Since short-circuiting was presumed to be zero, the response measured at the outlet would be identical to that of zone 1. This analysis indicated that, in the parallel arrangement, values for $n < 1$, and for $K < 1$, could originate without any short-circuiting.

As backmixing approaches zero in the series arrangement, the condition of two completely mixed tanks-in-series is approached. For small departures from complete mixing, the plot for zone 1 (and for the outlet) has an intercept greater than zero or values for $n > 1$. For Trial 622 (reported in *Fig. 1*), the value for $n > 1$ that could not be explained by the *n,m*-model could be due to a tanks-in-series flow. Similarly, the K value greater than unity could possibly be due to tanks-in-series flow rather than due to stagnant zones as suggested by the *n,m*-model and the K-model.

3.2. *Effect of secondary zones*

A four-compartment model was simulated where the secondary zones, 3 and 4, each occupied 10% of the airspace, and where zones 1 and 2 each occupied 40% of the airspace volume. The extent of backmixing between the two primary zones (i.e. j_{12}) was simulated at 1, 2, 5 and 25 times Q, the rate of supply air intake. The rate of mixing between the primary and secondary zones was simulated at 0·4, 1·0 and 5·0 times Q.

Results of the simulations are shown in *Fig. 4*. Values for K and n were determined from the plots of $\log_e(Cr)$ versus Qt/V for zone 1 (i.e. the outlet). In the series arrangement ($n = 1$), both K and n are always greater than unity for high levels of backmixing between the secondary and primary zones, but become less than unity for low levels of backmixing. In the parallel arrangement, K and n are both greater than unity for any values of backmixing. In both arrangements, the effect of the secondary zones is always to decrease both the slope and intercept.

3.3. *Effect of supply air path*

In *Fig. 4*, K and n values for the series arrangement were always higher than K and n values for the parallel arrangement when levels of backmixing were the same in each arrangement. However, experimental results indicated that this was not always so for the experimental airspace.

In the models considered so far, all the supply air was assumed to enter just one zone within the airspace. To investigate the effect of a potion of the supply air entering each of the two primary zones, a series of simulations were performed where the parameters n_1 and n_2 were both varied between the two extremes of 0 and 1. No short-circuiting of supply air to the outlet was allowed.

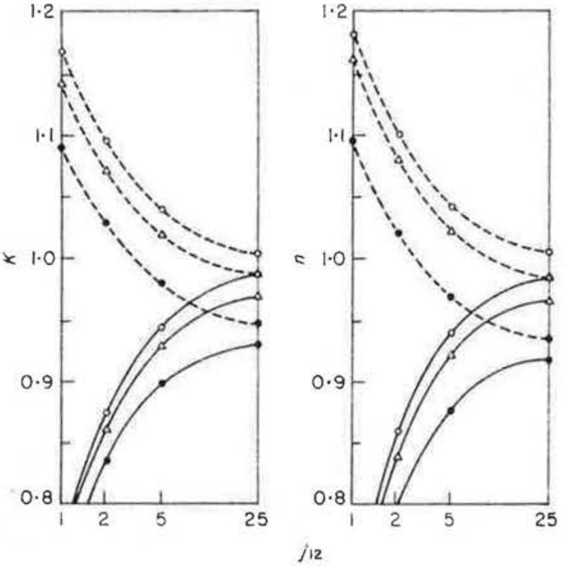

Fig. 4. Response of four-compartment model to inter-zone mixing (---, series arrangement; —— parallel arrangement; ●, $j_{23} = j_{14} = 0{\cdot}4$; △, $j_{23} = j_{14} = 1{\cdot}0$; ○, $j_{23} = j_{14} = 5{\cdot}0$)

Table 1

Values of K as affected by path of supply air

Portion of supply air entering zone remote from the inlet	*Series arrangement*			*Parallel arrangement*		
	zone 1 volume/zone 2 volume					
	0·5	*1·0*	*2·0*	*0·5*	*1·0*	*2·0*
0·0	1·04	1·05	1·04	0·98	0·95	0·92
0·2	1·03	1·03	1·02	0·99	0·97	0·94
0·4	1·02	1·01	0·99	1·00	0·99	0·97
0·6	1·00	0·99	0·97	1·02	1·01	0·99
0·8	0·99	0·97	0·94	1·03	1·03	1·02
1·0	0·98	0·95	0·92	1·04	1·05	1·04

Values for K for the outlet sample location from the simulations are summarized in Table 1. These data show that as the proportion of air which enters the far zone increases, K values for the two inlet–outlet arrangements become more alike and eventually K for the parallel arrangement can exceed K for the series arrangement. In the experimental airspace, some values for $K > 1$ were recorded for the parallel arrangement, but only for low Ar_c. Under these conditions, the supply air jet momentum is high; hence, the jet will penetrate far into the airspace. If the jet does not penetrate to the far wall, at least two flow regions will be established and at least some supply air can be expected to enter into the far zone directly. As shown in Table 1, values for $K > 1$ are possible with such a flow pattern. Temperature profiles were recorded within the airspace for all trials.[11] These data verified that the airspace temperature was lower in the far zone than in the near zone for just those cases where Ar_c was low, further supporting the hypothesis that supply air was entering the far zone. In all other cases, the near zone was cooler than the far zone indicating more supply air was entering the near zone than the far zone.

4. Conclusions

1. Rate-of-decay tracer gas experiments based on only one or two sample locations provide a quantitative test for incomplete mixing, but the reaons for incomplete mixing cannot be discerned from such tests.

2. The reasons most often cited for incomplete mixing in ventilated airspaces are short-circuiting of supply air to the exhaust outlet and the presence of stagnant zones. However, non-uniformity of mixing resulting from a tanks-in-series flow regime and/or the existence of secondary flow zones is at least as likely to be the cause of incomplete mixing in wide airspaces ventilated with a slot inlet along one wall.

3. Tracer techniques are potentially more useful as a laboratory research tool than as a diagnostic tool for invetigation of *in situ* ventilation problems. The lack of suitable tests to positively distinguish between alternative causes of incomplete mixing limits the usefulness of tracer techniques for diagnosis of ventilation problems.

4. In rate-of-decay experiments conducted to estimate ventilation rates, as much consideration must be given to flow geometry as to the intensity of mixing. Even if mixing is very good within separate flow regions, the existence of two or more flow regions will result in unreliable estimates of the total ventilation rate unless multiple sample locations are used.

REFERENCES

[1] **Hitchin, E. R.; Wilson, C. B.** *A review of experimental techniques for the investigation of natural ventilation in buildings.* Bldg Sci., 1967 **2** 59–82

[2] **Barber, E. M.; Ogilvie, J. R.** *Incomplete mixing in ventilated airspaces. Part 1. Theoretical considerations.* Can. agric. Engr, 1982 **24** 25–29

[3] **Grimsrud, D. T.; Sherman, M. H.; Janssen, J. E.; Pearman, N. N.; Harrje, D. T.** *An intercomparison of tracer gases used for air infilatration measurements.* Trans. ASHRAE, 1980 **86** (1) 258–266

[4] **Kaul, P.; Maltry, W.; Muller, H. J.; Winter, V.** *Scientific-technical principles for the control of the environment in livestock houses and stores.* Transl. 430. Br. Soc. Res. agric. Engng, NIAE, Silsoe, 1975

[5] **Clouthier, L.; Cholette, A.** *Effect of various parameters on the level of mixing in continuous flow systems.* Can. J. chem. Engng 1968 **46** 82–88

[6] **Barber, E. M.; Ogilvie, J. R.** *Incomplete mixing in ventilated airspaces. Part 2. Scale model study.* Can. agric. Engr, 1984 (in press)

[7] **Randall, J. M.; Battams, V. A.** *Stability criteria for airflow patterns in livestock buildings.* J. agric. Engng Res., 1979 **24** (4) 361–374

[8] **Baturin, V. V.** *Fundamentals of industrial ventilation* (3rd edn) (O. M. Blunn, transl. to English from Russian). Toronto: Pergamon Press of Canada, 1972

[9] **Randall, J. M.** *The prediction of airflow patterns in livestock buildings.* J. agric. Engng Res., 1975 **20** 199–215

[10] **Pritsker, A. A. B.** *The GASP IV Simulation Language.* Toronto: John Wiley and Sons, 1974

[11] **Barber, E. M.** *Scale model study of incomplete mixing in a ventilated airspace.* Ph.D. Dissertation, University of Guelph, Guelph, Ontario, Canada, 1981 (unpubl.)