# ESTIMATING THE IMPACT OF INCOMPLETE TRACER GAS MIXING ON INFILTRATION RATE MEASUREMENTS

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## ABSTRACT

The mixing of a tracer gas with zonal air was compared between two zones in an unoccupied test building in both the horizontal and vertical direction. A constant injection of sulphur hexafluoride ($SF_6$) tracer gas was released into each zone separately and its concentration was measured at different positions within the zone. Variations in concentration were observed for different horizontal positions in the southern zone indicating incomplete mixing. The impact of incomplete mixing on the accuracy of subsequent infiltration measurements was determined and compared to the case where good mixing was achieved. Absence of direct solar radiation was identified as the predominant cause of incomplete tracer gas mixing observed in our experiments.

## KEYWORDS

Tracer Gas, Mixing, Ventilation, Infiltration.

## 1 INTRODUCTION

The removal of unwanted moisture and pollutants from indoor air is an important issue. Natural ventilation, termed infiltration, plays a vital role in the removal of these contaminants, which has led to numerous techniques being developed that measure the air infiltration rate of a building. Common amongst most infiltration rate measurement techniques is the use of a tracer gas such as carbon dioxide, nitrous oxide or sulphur hexafluoride ($SF_6$) which is used in the experiments presented in this paper, to name a few.

Tracer gases can be used in various ways to determine the infiltration rate of a room or building but all methods rely on the same conservation laws to infer the air infiltration rate. Specifically, it is assumed the air flow into and out of a zone obeys the following mass flow balance equation (Sandberg et al, 1989; Sherman, 1990; Sherman et al, 2014):

$$V\dot{C} + QC = Q_T \tag{1}$$

Where $V$ is the volume of the zone, $C$ is the instantaneous tracer gas concentration, $Q$ is the ventilation rate of the zone, and $Q_T$ is the injection rate of the tracer gas into the zone. Using modern mass flow controllers, it is straight forward to accurately know $Q_T$, whereas $C$ can be measured down to low levels from different sampling points within the zone using a calibrated gas analyser.

Tracer gas concentration can only be sampled at discreet locations within a zone leading to the assumption that the tracer gas is homogeneously mixed with both the air already present in the zone and the air that is entering the zone (Sherman et al., 2014). However, it has been shown that tracer gases do not always perfectly mix within a zone such that infiltration rate measurements can be influenced by tracer gas sampling positions (Barber et al, 1984; Lunden et a., 2012; Maldonado et al, 1983; Van Buggenhout et al, 2009).

A common solution to incomplete tracer gas mixing is to incorporate a fan into the setup to artificially mix the air and ensure concentration homogeneity of the tracer gas (Chao, 1994; Lunden et al, 2012). However, mixing the air by means of a device such as a fan can introduce errors in the infiltration measurement if the device is driving ventilation as reported by Shao et al, 1994.

We examined the horizontal and vertical mixing of a tracer gas released inside a test building without the use of an artificial mixing device. The influence of solar radiation on the mixing process was investigated and an estimated error associated with incomplete mixing for this scenario was obtained.

## 2 EXPERIMENTAL PROCEDURE

Figure 1(a) shows the floor plan of the unoccupied test house used to conduct the tracer gas mixing experiments. Only the northern (sun-facing) zone, labelled Zone 1, and the south-facing zone, labelled Zone 2, were used. Separate experiments were conducted in the two zones to determine the tracer gas mixing for different vertical heights and for different horizontal positions across each zone. The airtightness of each zone was controlled through removable ports in the walls, ceiling and floor of each zone while the zone door was kept closed during experimentation. No artificial mixing devices were used and the test building was unoccupied while the experiment was running. Wind, sun and outside temperature data was collected via an external weather station located next to the test building.

To prevent cross contamination of tracer gas between zones, experiments conducted in the two zones illustrated in Figure 1(b) were carried out at different times. Similarly, horizontal and vertical mixing experiments were also conducted separately.

The zone was initially dosed with enough $SF_6$ to ensure the overall concentration within it was several times above background levels. The flow of $SF_6$ into the zone was then reduced to a constant rate to try to maintain a constant concentration. A mass flow controller allowed us to accurately measure the injection rate. Tracer gas concentrations were measured at each sampling point by removing a small sample of air from a given location and passing it through an Innova 1412 Photoacoustic Field Gas Analyser. Once the concentration of the tracer gas at that sampling point was ascertained, the air sample was released back into the zone. Samples were taken at each sampling point every 10-15 minutes over a couple of days.

For vertical mixing tests, sampling tubes measured $SF_6$ concentration at the centre of the zone at three different heights; 55 mm, 1065 mm and 2065 mm from the floor. Figure 1(b) illustrates the locations of the sampling points for the horizontal mixing tests. Each sampling point in the horizontal tests was 1600 mm above the floor of the zone.

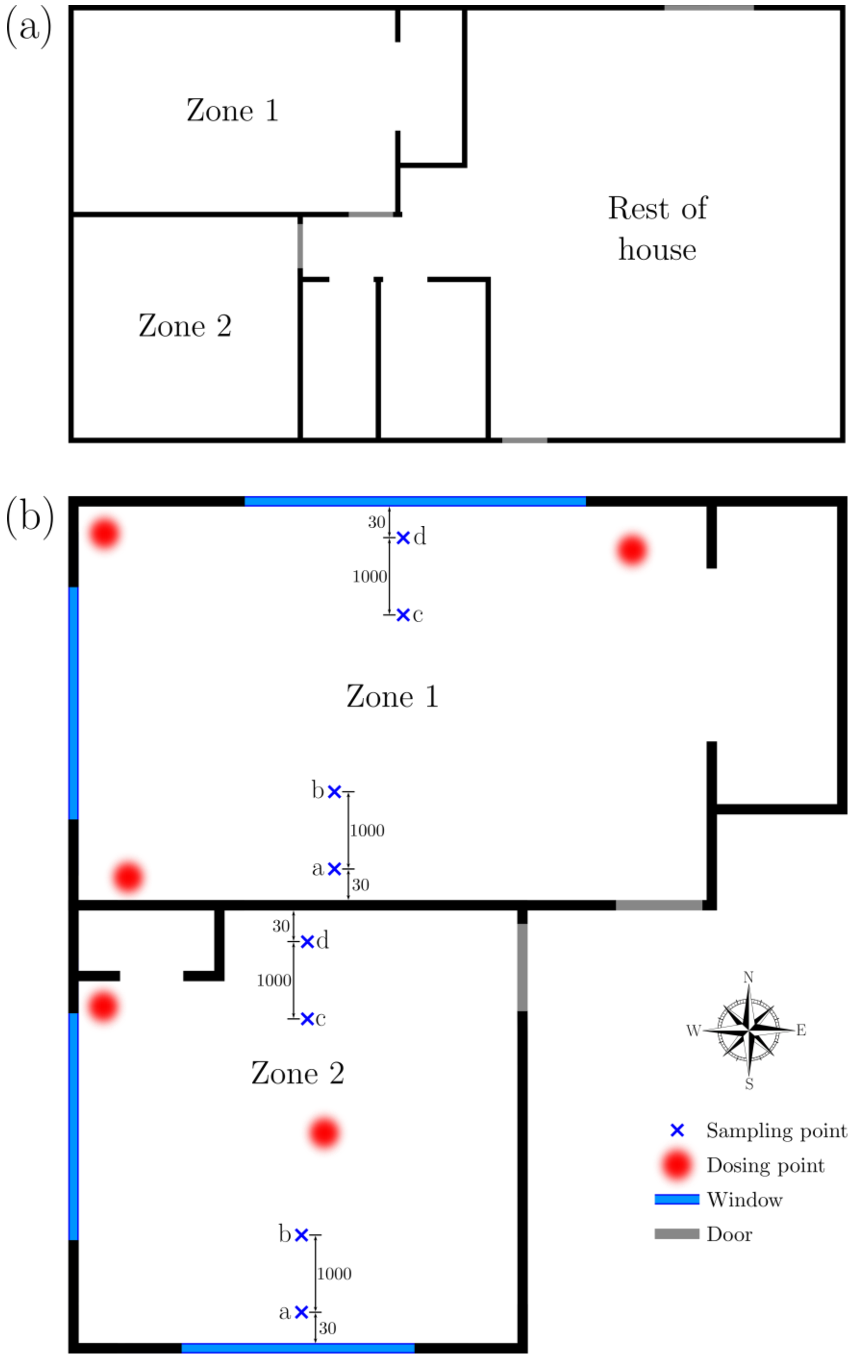


Figure 1: (a) Floor plan of the entire test house; (b) Locations of the sampling and dosing points in Zones 1 and 2 for horizontal mixing experiment. All sampling points were at a height of 1600 mm from the floor. Distances indicated in the figure are in units of mm.

# 3 RESULTS

## 3.1 Vertical Mixing

Figure 2 shows the difference in tracer gas concentration between three different heights above the zone floor for the two zones of interest together with the relevant environmental data. We observed negligible variation between tracer gas concentrations at different heights for the two zones. The airtightness of each zone was approximately 1 ACH at 50 Pa with major changes in infiltration rate being wind-driven. For the majority of the two experiments, wind speed was less than 4 $ms^{-1}$ with no discernible impact on the vertical mixing of the tracer gas.

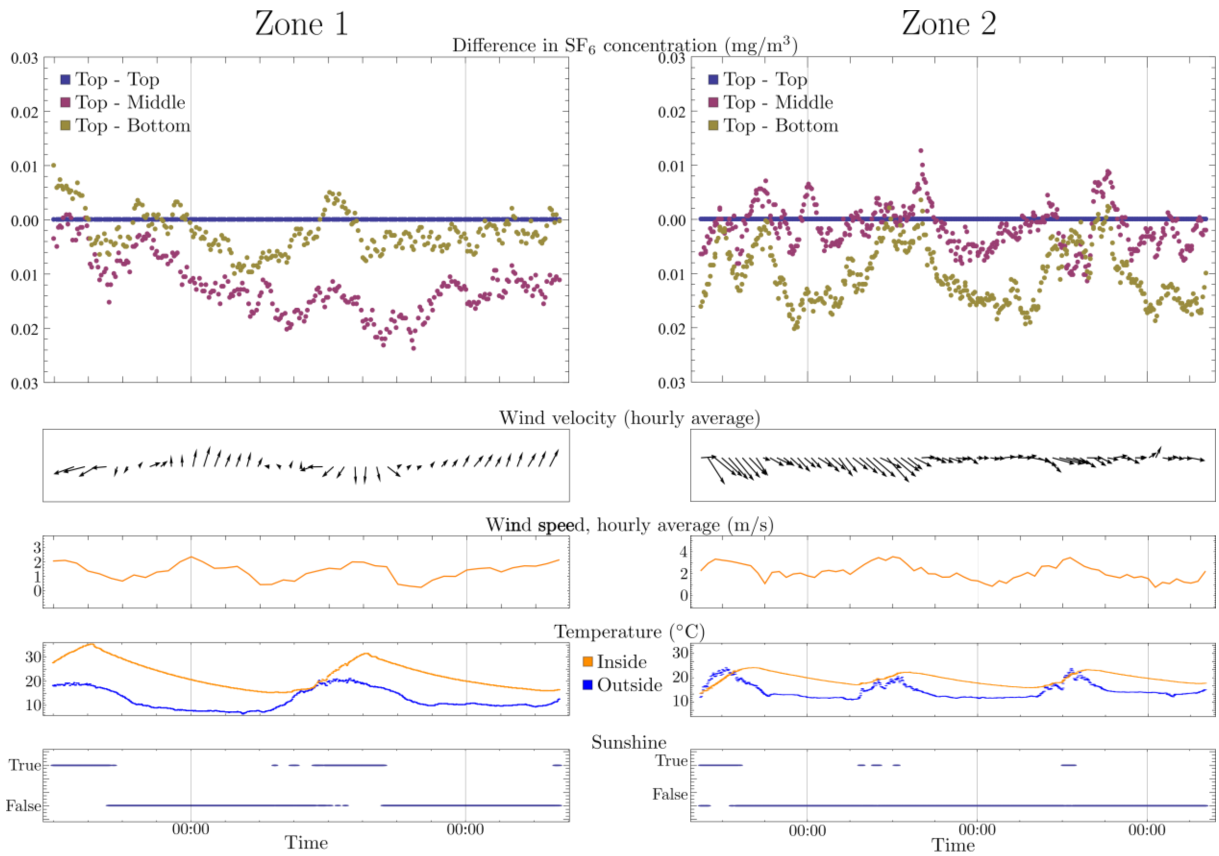


Figure 2: Results of vertical mixing experiment for Zones 1 and 2. Three sample points were used; 2065 mm (top), 1065 mm (middle) and 55 mm (bottom) above the zone floor. The two uppermost plots show the difference in $SF_6$ concentration between the top sample point and the middle and bottom sample points.

## 3.2 Horizontal Mixing

Figure 3 shows the difference in tracer gas concentration between four different locations of equal height in each of the two zones together with the relevant environmental data. Zone 1 shows no discernible variation between tracer gas concentrations at the different sampling locations suggesting good mixing in that zone.

A discrepancy between gas concentrations at different sampling points in Zone 2 indicated incomplete mixing within that zone. This feature appears more prominently at certain times of the day when tracer gas concentrations are greater at the southernmost sampling points than at the northern most sampling points in the room.

The airtightness of Zones 1 and 2 during the horizontal mixing experiments was approximately 8 ACH at 50 Pa. This was achieved by opening ports in the walls and ceiling of the zone as described in Section 2.

Both zones were measured over periods that had similar wind velocities and sunshine hours. However, we do note that the ambient air temperature inside the zone was on average warmer in Zone 1 than in Zone 2. This discrepancy was expected since Zone 1 is north (sun)-facing whereas Zone 2 faces away from the sun.

The infiltration rate of a given zone can be determined from Equation 1. Using this expression and the concentration data for horizontal mixing in Figure 3 we were able to estimate the error associated with an infiltration measurement under the current conditions. We did this by first determining the infiltration rate based on the concentration data from each sampling point individually averaged over 24 hours. We considered the true infiltration rate to be the mean of the four values (one for each sampling point) with an error given by the standard deviation.

Incomplete mixing in Zone 2 in the horizontal plane was found to give an uncertainty in the infiltration measurement of approximately 4%. This is in comparison to the same experiment in Zone 1 that displayed good tracer gas mixing, where we found the infiltration rate uncertainty to be approximately 1%.

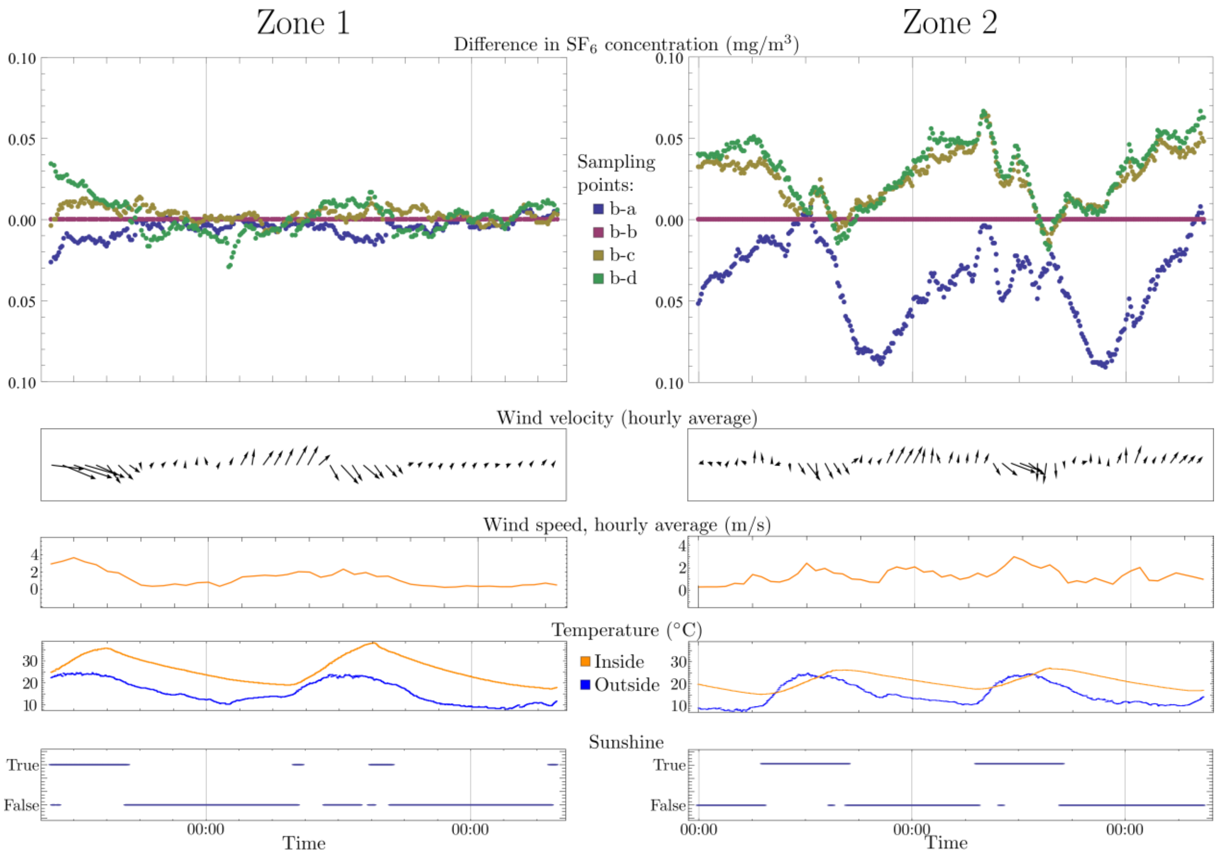


Figure 3: Results of horizontal mixing experiment for Zones 1 and 2. Four sampling points were used in each zone as illustrated in Figure 1(b). A consistent $SF_6$ concentration across all sampling points in Zone 1 indicates good mixing in the horizontal plane within that zone. Variation in tracer gas concentration at different sampling points in Zone 2 suggests incomplete mixing within that zone.

## 4 DISCUSSION

The tracer gas appeared to mix reasonably well in the vertical plane for both the north (Zone 1) and south (Zone 2) facing zones regardless of external environmental conditions. The same conclusions can also be drawn for horizontal mixing in the north-facing zone. However, horizontal mixing in the south-facing zone appears to suffer from stratification at certain times of the day. This stratification leads to a greater uncertainty when determining the infiltration rate and as such is a problem that deserves consideration.

The collective mixing effects of diffusion, convection, direct solar radiation convection, and air movement through infiltration all contribute to mixing of a tracer gas within a zone. The two zones we considered were of roughly equal air tightness and tested under similar environmental conditions. From this we conclude that direct solar radiation was the limiting mechanism for mixing. In the south-facing zone, where we observed incomplete tracer gas mixing, there was no direct solar radiation into the zone which is in contrast to the north-facing zone.

Convections within a zone can be driven by temperature gradients caused by solar radiation. Air within a zone can absorb heat when in contact with direct solar radiation through say a window. Buoyancy forces cause the warm air to rise due to the stack effect (Straube et al, 1995) creating a convective process as cold air moves to fill the void left by the warm air. This convective process increases mixing of the tracer gas with the air present in the zone. The absence of direct solar radiation in Zone 2 meant the occurrence of this process was minimal, leading to incomplete mixing.

We have assumed here that the stack effect is the dominant source of natural mixing within the zone. However, it should be noted that a less airtight house or one that is more susceptible to wind-driven ventilation (e.g. in an area of greater wind speeds) may have enough natural ventilation to adequately mix all the air within the zone and hence not exhibit the same behaviour we observed here.

The magnitude of infiltration rate errors resulting from incomplete mixing are due partly to the geography of the zone being measured and the ventilation within it. Van Buggenhout et al., 2009 observed an error of 86% between the measured and the actual ventilation rate for a mechanically-ventilated test zone with openings at each end. Tracer gas concentration differences of up to 44% have been observed within a single zone of a three-storey test house (Maldonado et al, 1983). Both of these experiments were performed under different conditions to the experiments presented here and therefore do not allow for direct comparison of errors. However, they do show that incomplete tracer gas mixing is not a feature specific to just our test building.

## 5 CONCLUSIONS

Lack of direct solar radiation can lead to incomplete mixing of a tracer gas within a zone when no artificial mixing apparatus is used. We showed that for the test house used in our experiments this incomplete mixing caused an increase in the uncertainty of our infiltration measurements from approximately 1% in a sun-facing zone to 4% in a non-sun-facing zone in the horizontal plane. Tracer gas concentrations in the vertical plane were observed to display good mixing in both zones.

## 6 ACKNOWLEDGEMENTS

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