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Single-sided Ventilation: A Comparison of the Measured Air Change Rates with Tracer Gas and with the Heat Balance Approach

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SINGLE SIDED VENTILATION: A COMPARISON OF MEASURED AIR CHANGE RATES WITH TRACER GAS AND WITH THE HEAT BALANCE APPROACH

SYNOPSIS

In the frame of the European PASCOOL project, several experiments regarding single sided ventilation were carried out at BBRI in the outdoor PASSYS test cell. The test room of 30 m3 has a vertical window of about 1 m^2. During a first measurement period, an open cold box, which allows one to control the vertical wind speed, was placed in front of this window. During a second measurement period, the window was directly exposed to "real wind". The air change rates were evaluated by using two different methods: a tracer gas technique and the heat balance approach. The heat balance approach is very attractive in this test cell because the heat flow through the cell envelope can be accurately determined thanks to the Pseudo-Adiabatic-Shell. The tracer gas measurement is made difficult because a clear air flow pattern appears and accordingly, the concentration in the room is not homogenous. An error analysis has been applied on both methods. The agreement between both methods is very good and the heat balance approach proved to be more accurate than the tracer gas technique. A correlation model was derived from the first measurement period.

LIST OF SYMBOLS

m_{SF6} = mass of SF6 contained in the test room (mg)
S_{SF6} = SF6 injection rate (mg/s)
Q_{in} = air flow rate leaving the test room (m3/s)
Q_{out} = air flow rate entering the test room (m3/s)
C_{SF6}^{in} = SF6 concentration of the air flow entering the test room (mg/m3)
C_{SF6}^{out} = SF6 concentration of the air flow leaving the test room (mg/m3)
T_{in} = temperature of the air entering the test room (K)
T_{out} = temperature of the air leaving the test room (K)
q_{sun} = global vertical solar radiation through the opening (W)
Q = heat contained in the air and in the materials present in the test room (J)
q_{PAS} = heat flow entering the test room through the PAS (W)
$q_{Heating}$ = heating power provided by electrical convectors in the test room (W)
q_{wall} = heat flow entering the test room through the reference wall (W)
$q_{ventilation}$ = heat flow leaving the test room due to ventilation (W)
ρ_{out} = density of the air leaving the cell (kg/m3)
c_p = specific heat of the air (J/kg)
ΔT = mean temperature in the test room minus outside temperature (K)
$V_{coldbox}$ = air velocity in the cold box
$Q_{thermal}$ = air flow rate through the large opening due to ΔT
Cd = coefficient of discharge
W = width of the opening (m)
H = height of the opening (m)
g = 9.81 (m/s2)
$\overline{T}$ = mean temperature of the air flows in the opening

1. INTRODUCTION

The estimation of air change rates in the case of single sided ventilation received the last years attention in several research projects. This paper presents experiments carried out in one of the outdoor PASSYS test cells on the BBRI site. Two separate approaches were used to evaluate the air change rates in a continuous way: on the one hand, tracer gas measurements, on the other hand, the heat balance of the test room. The objective of this experiment was to obtain information on the air flow through large openings. Both measurement approaches were compared and an estimation of the confidence interval integrated to the analysis. An attempt was made to correlate the measured air flow rates with the wind velocity and the temperature difference between inside and outside. This kind of model could be very useful for air flow simulation tools since, at the present time, they do not take into account the effect of the wind. In this paper we mainly focus on the comparison between the tracer gas measurements and the heat balance approach. After a description of the experimental set-up both methods are explained in detail, major sources of uncertainty, inherent in each method, are discussed. Results are then given and interpreted.

2. EXPERIMENTAL SET-UP

The outdoor PASSYS test cell is represented on figure 1. The south component is exchangeable. A "reference wall" was used during this experiment. It is made up of three layers: wood (12mm), PS30 (100mm) and wood (12mm) and has a vertical window of about 1 m^2.

The PASSYS test cell has its own instrumentation (for the measurement of air and surface temperature, solar irradiance, wind velocity and direction, heat fluxes, heating power,...). It is fully described in reference 1. In addition to those basic measurements, a specific instrumentation was employed for the needs of our experiments. It will be described hereafter in the sections devoted to the measurement methods.

During a first measurement period an open cold box, which allows one to control the vertical wind velocity, was placed in front of this window in order to obtain a kind of reference experiment for which the wind conditions are more or less controlled. The wind velocity in the cold box varied between 1 and 2 m/s. The opening was directly exposed to "real wind" during a second measurement period. During both periods, the test room was heated by electrical convectors.

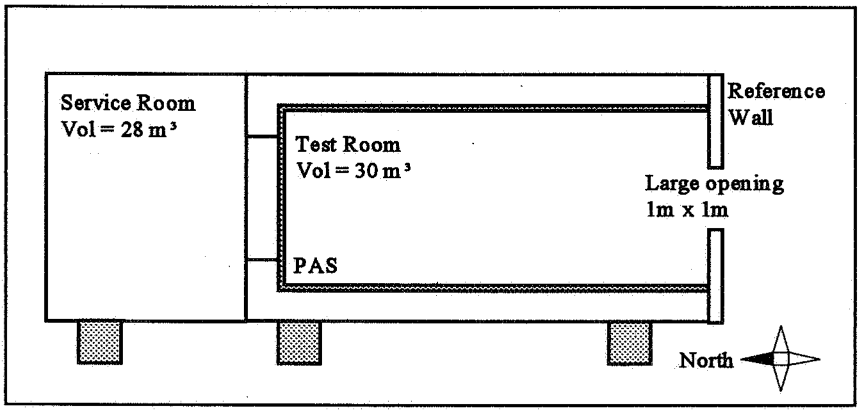

Figure 1: The PASSYS test cell - sectional view

3. TRACER GAS METHOD

3.1 INTRODUCTION

The single sided ventilation is driven by two "motors": the wind and the natural convection. In our experiments, the natural convection is mainly due to temperature difference between inside and outside.

The major difficulty encountered for measuring air flow rates is that a clear air flow pattern appears in the room. As the test room was continuously heated, the outside temperature is lower than the inside temperature. That implies that the cold air comes from the outside through the lower part of the window and runs down on the floor. Accordingly, the tracer gas concentration in the room is not at all homogenous. This makes it impossible to use classical tracer gas techniques for which a "perfect mixing" is required. When the effect of the wind is dominant such techniques could however be used because no clear air flow pattern appears and the concentration in the room can reasonably be considered as homogenous.

3.2 SPECIFIC SET-UP

We employed the Brüel&Kjaer tracer gas equipment (types 1302, 1303 and 7620). Sulphur hexafluoride was used as tracer gas. Eight injection points were placed in the test room. They were all connected to the same nozzle by tubes of the same length. Doing this, it was expected that the injection rate would be the same at each point. But it emerges from the analysis of the concentration measurements that sulphur hexafluoride was only injected at lower points. This is probably due to the static pressure resulting of the gas column in the climbing part of the tubes going to the higher points. Figure 2 shows the measurement locations as well as the injection locations. In order to eliminate inaccuracies due to very local fluctuations in gas concentrations, we used 4 sampling points connected together at each measurement location. They are distributed in a small zone of typically 20x20x20 cm3. A temperature sensor was placed at each sampling zone. The time step between two concentration measurements is about 15 minutes. Other measurements are scanned every minutes.

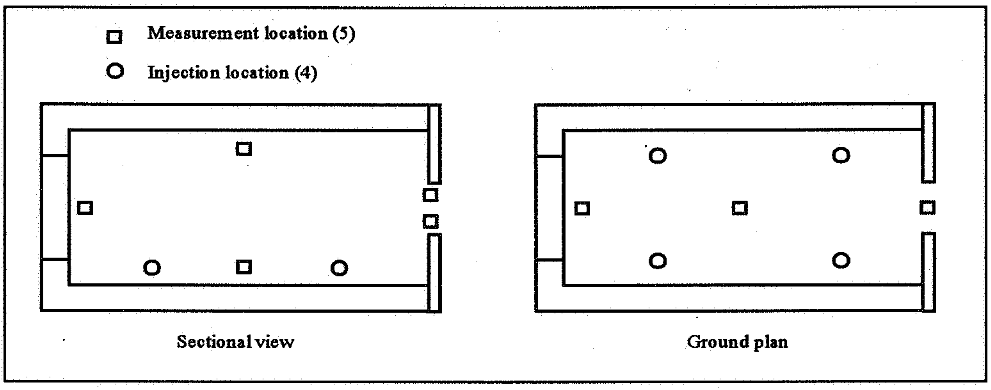

Figure 2: Measurement and injection locations

3.3 EQUATIONS

The mass balance equations of the room for the tracer gas and the air are:

$$\frac{dm_{SF6}}{dt} = S_{SF6} + Q_{in}.C_{SF6}^{in} - Q_{out}.C_{SF6}^{out} \qquad \text{[mg/s]} \qquad (1)$$

$$\frac{dm}{dt} = Q_{in}.\rho_{in} - Q_{out}.\rho_{out} \qquad \text{[kg/s]} \qquad (2)$$

Assuming that the mass of air in the cell remains constant, equations 1 and 2 yield:

$$\frac{dm_{SF6}}{dt} = S_{SF6} + Q_{out}.(C_{SF6}^{in}.\frac{T_{in}}{T_{out}} - C_{SF6}^{out}) \qquad \text{[mg/s]} \qquad (3)$$

$$\frac{Q_{in}}{T_{in}} = \frac{Q_{out}}{T_{out}} \qquad \text{[m3/s.K]} \qquad (4)$$

We can derive the air flow rates (Q_{out}, Q_{in}) from equations 3, 4. The temperature difference between inside and outside is of about 5 Kelvin and accordingly, Q_{in} and Q_{out} do not differ from more than 2%.

3.4 EVALUATION OF THE DIFFERENT TERMS

The next paragraphs explain how the terms of equation 3 are derived from the measurements.

During all the experiment the temperature in the test room was kept higher than the outside temperature. This implies that the air flows in the large opening have always kept the same direction: the lower flow was entering the room and the upper flow was leaving the room. Therefore, the concentration of the air leaving/entering the room is measured at the sampling zone located in the upper/lower part of the opening. Doing that, we implicitly assume that the SF6 concentration of the air leaving/entering the test room is constant in the upper/lower part of the opening. As a matter of fact, the reality is different since the concentration in the room is not homogeneous. The value that we should use is an average (weighted by the air velocity) of the SF6 concentrations in the upper/lower part of the opening and we measure an average of SF6 concentrations at 4 points distributed in the sampling zone of the upper/lower part of the opening. Accordingly, a large uncertainty will be taken on those concentrations for the confidence band calculation.

The SF6 injection rate is measured by the B&K tracer gas system.

The mass of SF6 contained in the test room is obtained from the average of the concentrations measured at the 5 different sampling zone. It is a quite rough approximation but a sensitivity analysis showed that it does not affect strongly the calculated air flow rate.

3.5 ASSUMPTIONS REGARDING MEASUREMENT UNCERTAINTIES

The following table shows errors on the different measured values due to the measurement equipment (thermocouples, gas analyser,..). They are given by the manufacturers.

Amount of gas injected	2%
Temperature	0.2 K
Concentrations	2.5%

Table 1: Tracer gas method - measurement errors

Besides this first uncertainty, we have to take into account the fact that the values we measure are not the values we use in equations 3 and 4. The representativity of the different terms derived from the measurements must be estimated. The next table shows the assumptions chosen for errors of representativity.

m_{SF6}	Mass of SF6 in the room	40%
C^{in}_{SF6}, C^{out}_{SF6}	Concentrations in the opening	20%

Table 2: Tracer gas method - representativity errors

4. HEAT BALANCE APPROACH

4.1 INTRODUCTION

The energy balance equation of the test room allows one to calculate the losses or gains due to the ventilation. Knowing the temperatures of the air entering and leaving the room, the air flow rate can be derived.

4.2 SPECIFIC SET-UP

It was possible to use the heat balance approach because the PASSYS test cell in which the experiments were carried out is equipped with the Pseudo-Adiabatic-Shell (PAS). The PAS allows to evaluate the heat flux leaving the cell through all the walls except the south one. It consists of a second shell (130 mm) which can be heated at its outside surface by heating foils and which is added inside the cell envelope. The position of the PAS in the test cell can be seen on the figure 1. The heating foils are controlled (on/off regulation) in order to maintain the temperature difference between inner and outer surfaces of the PAS as small as possible. Doing this, the losses through the envelope are reduced to a minimum.

4.3 EQUATIONS

The heat balance equation of the test room is:

$$\frac{dQ}{dt} = q_{PAS} + q_{Heating} + q_{wall} - q_{ventilation} + q_{sun} \qquad [W] \qquad (5)$$

The heat flow is related to the air flow as:

$$q_{ventilation} = \rho_{out}.c_p.Q_{out}.(T_{out} - T_{in}) \qquad [W] \qquad (6)$$

Equation 6 yields Q_{out} and Q_{in} can be calculated from equation 4.

4.4 EVALUATION OF THE DIFFERENT TERMS

The heat flow through the cell envelope is derived from the external and internal average surface temperatures of the PAS. The RC-scheme modelling the PAS was identified with MRQT software on calibration experiment data.

The electrical heating power is directly measured (PASSYS instrumentation).

The heat flux through the reference wall was measured at two different places by fluxmeters. The total heat flow is estimated as the average of both measurements multiplied by the surface of the wall.

The variation of the energy contained in the air and in the materials present in the room is evaluated from the variation of the average air temperature of the room (7 measurements).

The materials are assumed to have the same temperature than the air. The sensitivity analysis shows that this approximation does not put a large uncertainty on the air flow rate.

The solar irradiance is directly measured.

Two thermocouples were placed in the large opening at the centre of the tracer gas sampling zones shown on the figure 2 in order to measure the temperatures of the air entering or leaving the room. The remark given for concentration measurements in the opening is still valid: the temperature of the air entering/leaving the cell is not constant. This is taken into account in the error calculation.

4.5 ASSUMPTIONS REGARDING MEASUREMENT UNCERTAINTIES

As for the tracer gas measurements, the difference is made, in the following tables, between measurement and representativity errors.

Electrical heating power	1%
Temperature	0.2 K
Heat flux	5%

Table 3: Heat balance approach - measurement errors

q_{PAS}	Heat flow through the PAS	20%
q_{WALL}	Heat flow through the reference wall	20%
T_{in}, T_{out}	Temperatures in the opening	10%
	Mean temperature of the test room	0.5 K

Table 4: Heat balance approach - representativity errors

The error chosen on the temperatures (heat balance approach) in the opening is smaller than the one chosen on the concentrations (tracer gas approach) in the opening. Indeed, the temperatures were measured every minutes and then averaged whereas the concentrations were measured every 15 minutes. Moreover, the temperature is more homogenous than the tracer gas concentration in the room.

5. EXPERIMENTAL RESULTS

5.1 EXPERIMENT WITH COLD BOX

5.1.1 AIR FLOW RATES AND CONFIDENCE BANDS

Figure 3 compares results obtained from both methods. The 95% confidence bands are represented.

As one can seen, the agreement between both method is very good, the confidence band overlaps during the whole measurement period. The heat balance approach appears to give a less fluctuating and more accurate air flow rate than the tracer gas measurements. A sensitivity analysis has shown that the main source of error for both methods is the uncertainty on the measurements taken in the large opening (temperature or concentration). Therefore, the confidence interval is mainly defined by the error of representativity: 10% on the temperatures in the opening and 20% on the concentrations in the openings.

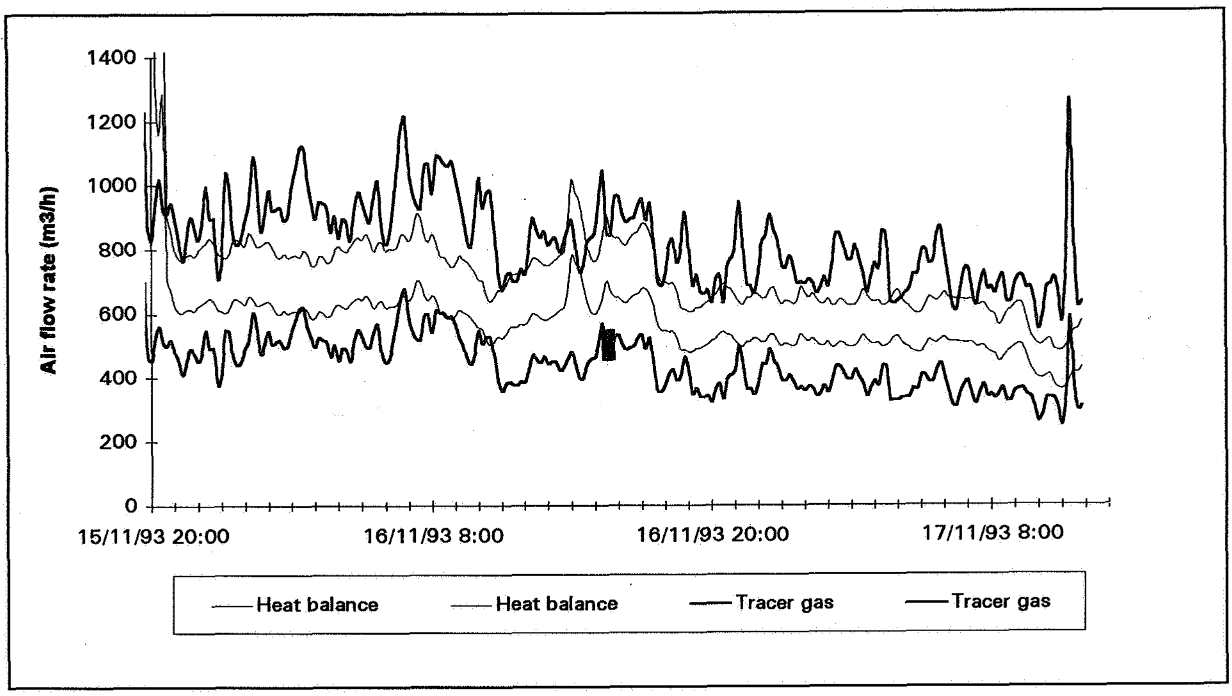

Figure 3: Period with cold box - Comparison of the air flow rates calculated from tracer gas and heat balance methods

5.1.2 CORRELATION MODEL

The results from the heat balance approach being more accurate, they were used to derive empirical model. The following correlation model was found:

$$Q_{out} = (153 \pm 8).\sqrt{\Delta T} + (195 \pm 6).V_{coldbox} \qquad [\text{m3/h}] \qquad (7)$$

The correlation coefficient is 0.78.

Using the classical simplified equation for the gravitational flow, we can give an evaluation of the coefficient of discharge.

Theory gives (see reference 2) :

$$Q_{thermal} = \frac{1}{3} \cdot Cd \cdot W \cdot H^{\frac{3}{2}} \cdot \sqrt{\frac{g}{T} \Delta T} \qquad [\text{m3/s}] \qquad (8)$$

Equation (8) gives in the studied case :

$$Q_{thermal} = Cd \cdot 257 \cdot \sqrt{\Delta T} \qquad [\text{m3/h}] \qquad (9)$$

Comparing the thermal part of the correlation model (7) and equation (9) yields:

$$Cd = 0.60 \pm 0.03$$

The confidence interval given comes from the statistical analysis performed. It gives an indication of how the model represents the measurements, but it does not take into account the measurement error. Since the error made on the air flow rate calculated by the heat balance approach is on average 12 %, in first approximation the error made on the discharge coefficient is of the same order.

5.2 EXPERIMENT WITHOUT COLD BOX

5.2.1 AIR FLOW RATES AND CONFIDENCE BANDS

Figure 3 compares results obtained from both methods. The 95% confidence bands are represented.

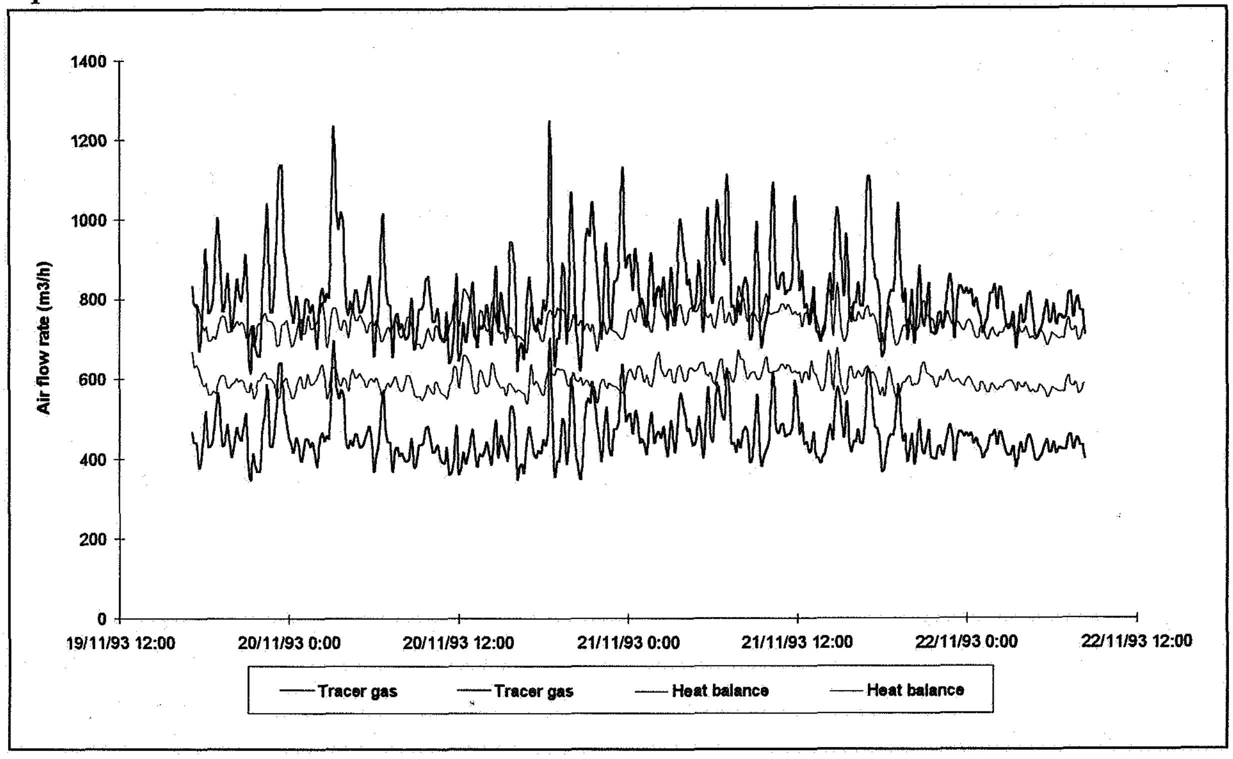

Figure 4: Period without cold box -Comparison of the air flow rates calculated from tracer gas and heat balance methods

The same remarks than for the first experiment can be made. The air flow rate obtained from the tracer gas measurements fluctuate even more. This was expected since the "artificial wind" provided by the cold box is obviously more stable (direction and speed) than the "real wind" to which the large opening was exposed during this second experiment.

5.2.2 CORRELATION MODEL

The temperature difference and the wind conditions, which are the parameters of the model, did not vary enough to derive a satisfactory empirical model.

5.3 IMPROVEMENT OF THE SET-UP

BBRI will set-up new experiment of the same type in a near future. The points of attention will be to put more measurement points in the opening and to make the temperature difference between the inside and the outside vary widely.

6. CONCLUSIONS

6.1 MEASUREMENT METHODS

Two different methods were used to analyse the single sided ventilation experiments: the heat balance approach and the tracer gas approach. Both methods have shown a good agreement.

The heat balance approach proved to be more accurate. For both methods the evaluation of the air flow rate through the large opening requires the measurement of physical characteristics of the air leaving the cell and of the air entering the cell. This is either the temperature (heat balance approach) or the tracer gas concentration (tracer gas approach). These measurements are achieved by placing devices in the opening. Therefore we have to know in which part of the opening the air will leave the cell and in which part of the opening the air will enter the cell. This is only possible for experiments for which the thermal part is clearly dominant. Indeed, in this case, there is only one neutral plane in the middle of the opening. If the wind effects are dominant, the direction of the air flow in the opening can change rapidly and several neutral planes can appear. In such a situation it is impossible to measure the physical characteristics of the air entering and the air leaving the cell. The heat balance approach allows however to calculate the heat flow through the large opening in every cases. A tracer gas measurement is still possible if the assumption of perfect mixing is fulfilled. That will be the case if the wind are largely dominant. If the thermal effect is not negligible, an air flow pattern will appear in the room and the gas concentration will not be homogenous. For the cold box experiment, the thermal effect is not dominant but the wind is stable and does not affect the positions of the air flows in the opening. In the second experiment, the thermal effect is largely dominant. The accuracy of both method can probably be improved by a better set-up.

6.2 RESULTS

The accuracy of the analysis by tracer gas is about 30 %. The accuracy of the analysis by heat balance is about 12 %. The analysis of the cold box experiment allows us to propose a model for a wind parallel to the plane of the opening. The analysis of the second experiment does not give a satisfactory model. This is mainly due to the fact that the temperature difference and the wind velocity do not vary enough. The results are however valuable. They should be used with other results from other team to derive a correlation model.

ACKNOWLEDGEMENTS

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