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A Four Zone Ventilation Test Facility

C E Brouns, J R Waters

Coventry University, School of the Built Environment,
Priory Street, Coventry CV1 5FB, UK

ABSTRACT

This paper describes a laboratory model for the testing and validation of tracer gas measurement techniques. Previous attempts at experimental validation have often been limited to two zones, or a particular measurement strategy, or a particular range of flows.

The model consists of four zones, each of $1m^3$ internal volume. The zones are connected so that all possible inter-zone flow paths exist. The flow down each path is driven by a pump and monitored by a flow meter. A control panel enables any combination of inter-zone flows to be set, within the capacity of the pumps. By the application of scaling, one can also represent real buildings in which the zones are not of equal volume.

The model may be used to validate tracer gas measurement techniques for the extraction of inter-zone flows and for the determination of Ventilation Effectiveness parameters. In principle, the model can be used with any tracer gas injection strategy and any tracer gas measuring method. Examples are given of the use of the model in exploring these parameters.

INTRODUCTION

The multi-zone theory is a well established method for modelling ventilation and airflows in all types of buildings. The model may be used to predict contaminant concentrations and to determine inter-zone flows from suitable measurements.

There are a large number of publications detailing the measurement of ventilation rates and inter-zonal airflows by tracer gas experiments. However, only a small number of these publications specifically describe validation measurements, where a comparison has been made between the flows obtained from tracer gas measurements, and those measured independently, by some type of flow meter.

Some early validation work was attempted by Afonso and Maldonado [1] who carried-out a series of four tests in a two zone model of a building, with a connecting door between the two zones. For each test, the opening of the door was varied, from fully closed to fully opened. A comparison between the measured and the calculated results led to the conclusion that the model can predict the effective volumes with a standard deviation of about 2 %, and that the airflow rates between the zones and the outside is feasible. Irwin and Edwards [2] attempted to validate a multiple tracer gas technique for the determination of airflows between three interconnected cells. The air movements between the three cells were induced by means of ducted low speed fans, in combination with the air supply feeding the chambers. The air velocities in the supply ductwork were measured using a pitot tube and inclined-tube manometer, whilst the air velocities between cells were measured using a hot wire anemometer probe. Three series of measurements were carried-out, with different flow patterns for each series, making a total of twelve experiments. Errors between calculated and measured airflow rates were approximately $\pm 20\%$, and that the effect of these errors on the air change rate for each chamber was approximately $\pm 10\%$. A closer inspection of their results shows that the errors in individual flows can be very large, with a maximum of 100 %. Although the measurement method was validated with independent measurements of the inter-zone flows, only a small number of three zone models with well determined flow patterns were tested, and the experimental procedure was confined to one particular injection strategy. Riffat [3] validated a two zone model in the laboratory by measuring air flows between two small chambers using two tracer systems, and an independent flow device. Two experiments were carried-out, each with different values of air flow rates. Riffat found that the errors between calculated and measured (using the flowmeter) air flow rates were +9% and -5% for experiments 1 and 2 respectively. This is similar to the level of accuracy obtained by Afonso et al. [4]. In a further two zone validation study, Riffat [5] examined a number of analysis procedures, and compared them on the basis of the errors in the individual flows. He showed that the scatter in the errors may be very large, that is, the errors in the calculated flow rates range between -8% and +33%. Enai, Shaw and Reardon [6] also used a two zone laboratory model to test a multiple tracer gas technique for measuring inter-zonal airflows in buildings. Three tracer gases were used, two injected into the rooms under decay mode, and the third gas was released into one of the rooms at a constant rate. By suitable choice of injection strategy and careful selection of data, they found that good agreement was obtained only when the inter-zone flow rates were of similar magnitude. O'Neill and Crawford [7] used a three zone experimental facility to validate their own single tracer gas method. The experiments were based on the single pulse injection strategy where the tracer gas was injected into each zone in turn, and allowed to decay. The results showed that all but one of the inter-zone flows were identified to within 10 % of their independently measured value, and the effective volumes were found to within 3 %. However, these findings apply to one specific three zone model with a single flow pattern where all possible inter-zone flows appear to exist, one specific injection strategy and one specific analysis procedure. Mattson [8] carried-out an experiment for airflow determination by quadratic programming. This study concentrated on a seven room model of a building with mechanical air supply and exhaust, and dampers for re-circulated air. The flow rates were extracted from measurements performed with constant tracer gas injection during about one hour in each zone of the model. The flow rates were also measured independently using orifice plates and inclined-tube manometers. A comparison between the airflows estimated from the tracer gas measurements and those obtained from the orifice plates showed a maximum difference of 15 % in the results. This study is based on one single seven zone model, and uses only one injection strategy and one analysis procedure. Furthermore, because many of the inter-zone flows were zero, constraints could be applied to the solution, such that the model had a relatively small number of unknowns. Heidt, Rabenstein and Schepers [9] used a two zone laboratory model in which the flows between zones were induced by means of pumps, such that any flow patterns could be established and measured, and monitored independently by means of flow meters. They found that the accuracy of the inter-zone flows found from tracer gas measurements depended on the injection strategy and on the time scale of the experiment. This study is based on a specific two zone model, and a single flow pattern in which the sum of the flows into or out of one zone is equal to that of the other zone. More recently, Kvisgaard and Schmidt [10] examined inter-zonal airflow measurements, as a tool for solving pollution problems. Although not primarily a validation study, some of this work relates to the validation of a constant concentration method of measurement, in a two cell test house. The flow patterns selected in this case, were very nearly redundant, that is, the ratio of the sum of the flows into both zones over their respective volumes were nearly equal. Also, a symmetry effect could be observed in each zone, i.e. the flows from the outside to the inside of each zone and vice-versa were approximately the same.

Most of the experimental validation work to date, relates to specific cases, and is limited to the authors' particular requirements. That is, there appears to be no continuity, and little cross-referencing. None of the validation studies are complete, because they are restricted to the authors' own needs. Nearly all are limited to either two or three zone cases, and a restricted range of flow patterns.

There is, therefore, a need for a systematic experimental study of the extraction of inter-zone flows from tracer gas measurements, with the objective of validating any measurement and analysis method. For such validation to be complete, a range of different flow patterns must be tested in carefully controlled conditions. This is difficult to achieve in a full scale building, and points to the need for a multi-zone laboratory model in which the conditions can be accurately monitored.

DESIGN OF THE MULTI-ZONE LABORATORY MODEL

Requirements of the laboratory model

Several requirements have to be considered in the design of the multi-zone laboratory model. These are:-

(i) The choice of the number of zones to be included in the model.
This is based on the need to offer as much flexibility as possible in the flow patterns, while providing a system which is reasonably easy to handle. A two zone model is not adequate, as it does not cater for re-circulation flows with complex eigenvalues, and limits the range of possible tracer gas experiments. A three zone model allows for a re-circulation with complex eigenvalues to take place. On the other hand, only two of the three zones can generate complex eigenvalues. Again, this restricts the range of flow patterns that can be tested. A four zone model also allows for a re-circulation with complex eigenvalues to arise. It is a property of the eigenvalues that they always occur in conjugate pairs. Therefore, in the case of a four zone model, either two or four zones can generate complex eigenvalues. Hence, all the necessary flow effects are included and can be tested. The need to incorporate more than four zones in the model is thus unnecessary, as it would not supply more information, and would also be more difficult to handle. A four zone model gives twenty possible inter-zonal flows and sixteen independent flows.

(ii) The scaling factor.
Since the solution depends on the ratios of the flows to the volumes, it is simpler to design each zone in the model with an equal volume. Previous experience of model studies by Budek [11], suggests that enclosures of relatively small volumes are adequate. With that in mind, and considering the space available in our laboratory, each zone was designed with an internal volume of 1 m^3.

Because all zones are fully mixed, boundary layer effects are insignificant, and therefore it is not necessary to match the Reynolds number. The only relevant scaling parameter is the time constant, τ_c. It is known from simulation studies, for example Heidt et al. [12] and Sutcliffe [13], that a minimum of two time constants of data are needed in the analysis procedure. The experiments must therefore span over at least two time constants. On the other hand, if the time constant relative to the sampling time interval of the tracer gas measuring equipment is short, then the number of data points available for the analysis procedure may be too small. Also, the time constant must be sufficiently long with respect to the operation of the tracer gas injection system. This led to selecting a time constant of the order of magnitude of 30 minutes for the system. With $V=1\ m^3$, this gives a fresh air flow rate of 2 m^3/hour into each zone. The flow patterns of greatest interest occur when the inter-zone flows are within a certain range on either side of the fresh air flow rate, typically from one tenth to ten times the fresh air flow rate. Below one tenth, the zones are effectively behaving independently. Above 10 times, the system is approaching a fully mixed state, when the single zone theory is sufficient. This gives a range of 0.2 to 20 m^3/hour, corresponding to flows between 3 to 300 l/min.

Generation of inter-zonal flows and their measurement.

Air flows between two zones can be generated either by means of miniature fans, or by means of air pumps. The choice is influenced by the method of flow measurement. The different options considered were:-

i) Flow meters of the rotameter type which give a direct reading of the volumetric flow rates in the pipes.
ii) Orifice plates which measure the pressure differential, and which in turn must be converted into volumetric air flows.
iii) Hot wire anemometers, which give readings of the velocity of the air in the pipes. Again, these readings have to be converted into volumetric flow rates.
iv) Mass flow transducers which give a direct measure of the mass flow rates in the pipes. However, this type of transducer is very expensive. As the model requires the independent measurement of twenty flows, the total cost of twenty mass flow transducers was found to be prohibitive. This option could therefore not be considered.

A comparison between the miniature fans and the air pumps for the different methods of measurement is as follows:-

i) Miniature fans create small pressure differentials, and require large diameter pipes which produce large dead volumes.
ii) Air pumps create high pressure differentials, and therefore can be used with small diameter pipes which in turn produce small dead volumes.

Both orifice plates and hot wire anemometers require that the pipe be of a sufficient length to ensure, in the measuring section, a distribution of velocities corresponding to a fully stable flow regime. The settling length required when using either an orifice plate or a hot wire anemometer, may be up to twenty times the diameter of the pipe in which the measurements are to be taken. Where miniature fans are used, pipes with an internal diameter of approximately 60 mm would be required, therefore, the length of the pipes must be at least 1.20 m for each flow path. As the model includes 20 independent flow paths, it was thought that the total amount of pipework required would be excessive with respect to the space available. Where air pumps are used, pipes with an internal diameter of about 6 mm can be used, therefore, the length of pipes must be at least 0.12 m. This option is more practical, but the diameter of the pipes would be too small for the reliable operation of either an orifice plate, or a hot wire anemometer. On the other hand, rotameters can be used with small diameter pipes and have the advantage that they are direct reading. This is a considerable advantage when flow patterns need to be set-up. From these considerations, it was decided to select a combination of small diaphragm air pumps and rotameters equipped with flow control valves.

The rotameters are calibrated for ambient temperature and pressure at their outlet. The accuracy claimed by the manufacturer ranges from ± 1.25 % of the full scale deflection (FSD) for high flow rates, to ± 2.5 % of the full scale deflection for low flow rates. The flows given by the flow meters are used for comparison with the flows obtained from tracer gas experiments, and so it was necessary to check the manufacturer's claim. To this end, a calibration rig was designed, using a simple water displacement method, as shown in figure 1.

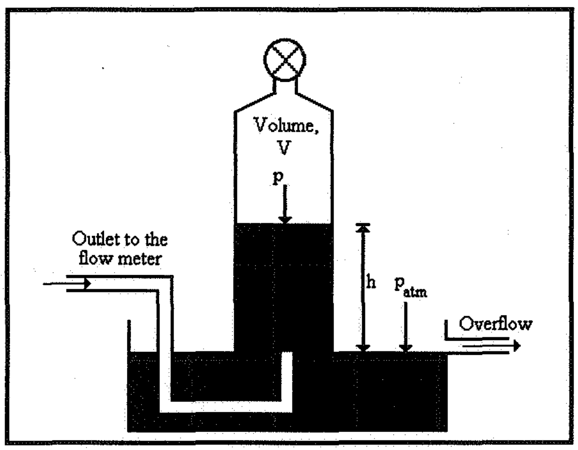

Figure 1 - Schematic diagram of the flow meters calibration rig.

The outlet of the flow meter is placed so as to remain at atmospheric pressure. The air is allowed to flow through the tube into the calibration rig, thus displacing the water. The time, t, taken to collect a certain mass of water, M, is recorded, and is converted into a flow rate, F. Corrections are applied for the prevailing temperature, pressure and for any head of water remaining in the collecting vessel.

The calibration showed that the rotameters were all within the manufacturer's tolerances, provided the float was rotating freely.

The problem now consists in designing the system so that the pressure in each zone remains close to atmospheric and is not affected by the pressure changes in the inter-zonal flow paths. Firstly, each pump draws air from a zone, thus inducing a pressure rise in the flow path. Then, the air passes through the control valve which has the effect of reducing the pressure in the system. Finally, the air passes through the flow meter and into the next zone where the pressure drops back down to atmospheric. This is consistent with the calibration of the flow meters, as this is carried-out with their exhaust side at atmospheric pressure. Manometers check that each zone remains at atmospheric pressure. This also ensures that unwanted leakage between each zone and the outside is minimised. A schematic diagram of a typical flow path between two zones is given in figure 2. A bleed was inserted between the exhaust to the pump and the flow valve, to improve control over the pumps, and prevent the overloading of their motor.

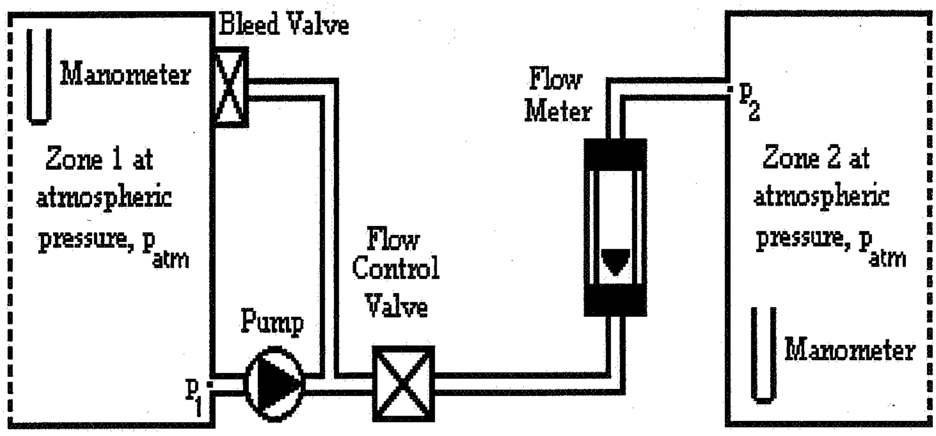

Figure 2 - Schematic diagram of a typical flow path between two zones.

An 18 mm thick marine grade plywood was used to build each zone which was then coated internally using a flexible and continuous chlorinated rubber paint. The joints between the panels were sealed using a latex solution, and a coat of varnish was applied on the outside surface of each zone. Each zone has a built in double glazed window which allows an easy access into the zones, and a light which could prove useful should smoke tests be performed. A tracer gas injection point and a sampling point are also provided for each zone. The sampling points are situated at the centre of each zone. Small oscillatory fans ensure that the air in each zone is fully mixed. Extensive leakage tests were carried-out for each zone to ensure that they were well sealed.

VALIDATION MEASUREMENTS

In principle, the rig can be used to test any type of tracer gas method and analysis technique. A series of validation experiments have been carried-out using a single tracer gas and the six channel detection rig previously described by Waters et al. [14]. This programme was designed to explore the effect on errors in the solution for the inter-zone flows due to:-

i) changing the inter-zone flow pattern.
ii) increasing number of zones.
iii) seeding strategy.
iv) the selection of portions of the data set to be included in the analysis routine.
v) the method of analysis.

Schedule of measurements

Tracer gas measurements were first carried out on two, then three, and four zone models. A full description of the flow patterns that were tested for each models, along with the injection strategy used, is as follows:

i) Two zone models.

A schematic diagram of the two zone model is given in figure 3, and table 1 gives a detailed account of the different flow patterns that were tested.

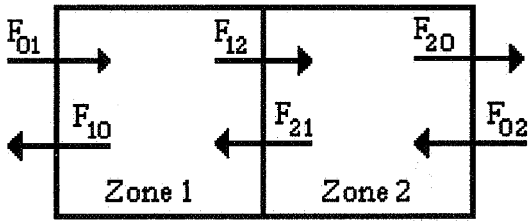

Figure 3 - Schematic diagram of the two zone model.

Table 1 - Description of the flow patterns selected for the two zone model.

Test No 2z..	Ventilation flow rate (l/min)						Comments
	F_{01}	F_{02}	F_{10}	F_{12}	F_{20}	F_{21}	
01, 02, 03	20	20	10	10	30	0	Special case, i.e. $F_{01}=F_{02}$
04, 05	30	10	20	10	20	0	Special case, i.e. $F_{10}=F_{20}$
06, 07	30	15	15	15	30	0	Special case, i.e. $S_1=S_2$
08, 09	30	0	10	20	20	0	General case
10	20	10	15	5	15	0	General case
11, 12	30	15	20	20	25	10	General case

In all these cases, tracer decay experiments were carried-out. For all experiments, the tracer gas was injected into zone 1, with the exception of experiment 2z03, for which the tracer gas was injected into zone 2.

ii) Three zone models.

A schematic diagram of the three zone model is given in figure 4, and table 2 gives a detailed description of the different flow patterns that were tested.

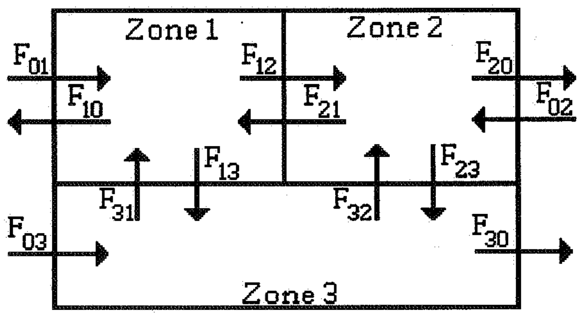

Figure 4 - Schematic diagram of the three zone model.

Table 2 - Description of the flow patterns selected for the three zone model.

Test 3z..	Ventilation Flow Rates, F_{ij} (l/min)								
	F_{01}	F_{02}	F_{03}	F_{10}	F_{12}	F_{13}	F_{20}	F_{21}	F_{23}
01 - 14	25	25	25	25	15	0	20	0	20
15 - 17	25	20	15	20	15	0	20	0	15
18 - 19	20	15	10	15	10	5	10	5	15
20	25	0	15	10	20	0	15	0	15
21	25	15	20	15	10	5	20	5	10

Test 3z..	F_{ij} (l/min)			Comments
	F_{30}	F_{31}	F_{32}	
01 - 14	30	15	0	Special case, i.e. $F_{01}=F_{02}=F_{03}$
15 - 17	20	10	0	Special case, i.e. $F_{10}=F_{20}=F_{30}$
18 - 19	20	5	5	Special case, i.e. $S_1=S_2=S_3$
20	15	5	10	Special case, i.e. $S_1=S_2=S_3$
21	25	0	10	General case

The seeding strategies used, were as follows:-

- Tracer decay experiments were carried-out for tests 3z01, 3z02, 3z03, 3z13, 3z15, 3z18, 3z19, 3z20 and 3z21. In these cases, the tracer gas was injected into zone 1.
- Tracer decay experiments were carried-out for tests 3z04, 3z05 and 3z16. In these cases, the tracer gas was injected into zone 2.
- Tracer decay experiments were carried-out for tests 3z06, 3z07 and 3z17. In these cases, the tracer gas was injected into zone 3.

- Multiple step-up experiments were carried-out for tests 3z08, 3z09, 3z10 and 3z11. Although the duration of each tracer gas injection was of 30 minutes in all cases, the order in which the zones were injected varied. For experiments 3z08 and 3z09, the tracer gas was first injected into zone 1, then zone 2, and finally zone 3. For experiment 3z10, the injection started in zone 3 followed by zone 1 and finally zone 2. For experiment 3z11, the first injection took place in zone 2, followed by zone 3, and finally zone 1.

- A step-up experiment followed by a tracer decay was carried-out for test 3z12. The tracer gas was injected into zone 1 for 60 minutes before being allowed to decay.

- A multiple pulse experiment was carried-out for test 3z14. The tracer gas was injected at intervals of 40 minutes into zone 1, 2 and 3 successively.

iii) Four zone models.

A schematic diagram of the four zone model is given in figure 5, and table 3 gives a detailed description of the different flow patterns that were tested.

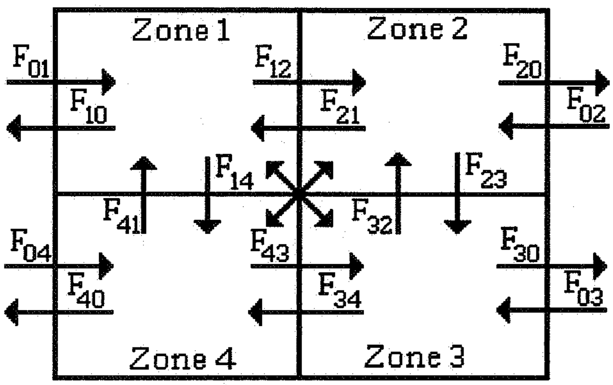

Figure 5 - Schematic diagram of the four zone model.

Table 3 - Description of the flow patterns selected for the four zone model.

Test 4z..	Ventilation Flow Rates, F_{ij} (l/min)											
	F_{01}	F_{02}	F_{03}	F_{04}	F_{10}	F_{12}	F_{13}	F_{14}	F_{20}	F_{21}	F_{23}	F_{24}
01 - 02	15	15	15	15	10	15	0	0	20	5	10	0
03 - 05	18	8	15	7	12	15	0	0	12	4	12	0
06	20	15	10	8	10	15	0	10	10	10	15	0

Test 4z..	Ventilation Flow Rates, F_{ij} (l/min)								Comments
	F_{30}	F_{31}	F_{32}	F_{34}	F_{40}	F_{41}	F_{42}	F_{43}	
01 - 02	10	0	5	15	20	5	0	5	$F_{01}=F_{02}=F_{03}=F_{04}$
03 - 05	12	0	5	15	12	5	0	5	$F_{10}=F_{20}=F_{30}=F_{40}$
06	13	0	5	17	20	5	0	10	$S_1=S_2=S_3=S_4$

The seeding strategies used, were as follows:-

- Tracer decay experiments were carried-out for tests 4z01, 4z03 and 4z06. In these cases, the tracer gas was injected into zone 1.
- A tracer decay experiment was carried-out for test 4z02, in which the tracer gas was injected into zone 2.

- A multiple pulse experiment was carried-out for test 4z04, in which the tracer gas was injected successively into zone 1, 2, 3 and 4, at intervals of 30 minutes.

- A multiple step-up experiment was carried-out for test 4z05, in which the tracer gas was injected into zone 1, 2, 3 and 4 successively, for a duration of 30 minutes in each zone.

Prior to carrying out any experiments, the flows were carefully set to ensure that the pressures throughout the system were equalised, thus indicating that the flow pattern was well balanced. The analysis procedure requires a minimum of two time constant of data thus, the duration of each experiment was determined accordingly. Also, the quantity of tracer gas injected into the zones for each experiment was determined as a function of the maximum possible concentration allowed by the measuring equipment, that is, 200 vpb of SF_6 in air, to avoid saturation.

EXAMPLE RESULTS

Inter-zone flows were derived from the measured tracer gas concentrations by several types of batch processed least squares technique. Details are described by Brouns [15]. The most convenient global criterion for comparing the derived flows with those recorded by the rotameters, was found to be a percentage RMS error, defined by:

$$RMS = \frac{\left[\frac{(F_{ij(rot)} - F_{ij(der)})^2}{n}\right]^{\frac{1}{2}}}{\sum F_{ij(rot)}} \times 100\%$$

where n is the total number of inter-zone flows.

Figure 6 shows the percentage RMS error and standard deviation for all the two zone tests against the method of solution.

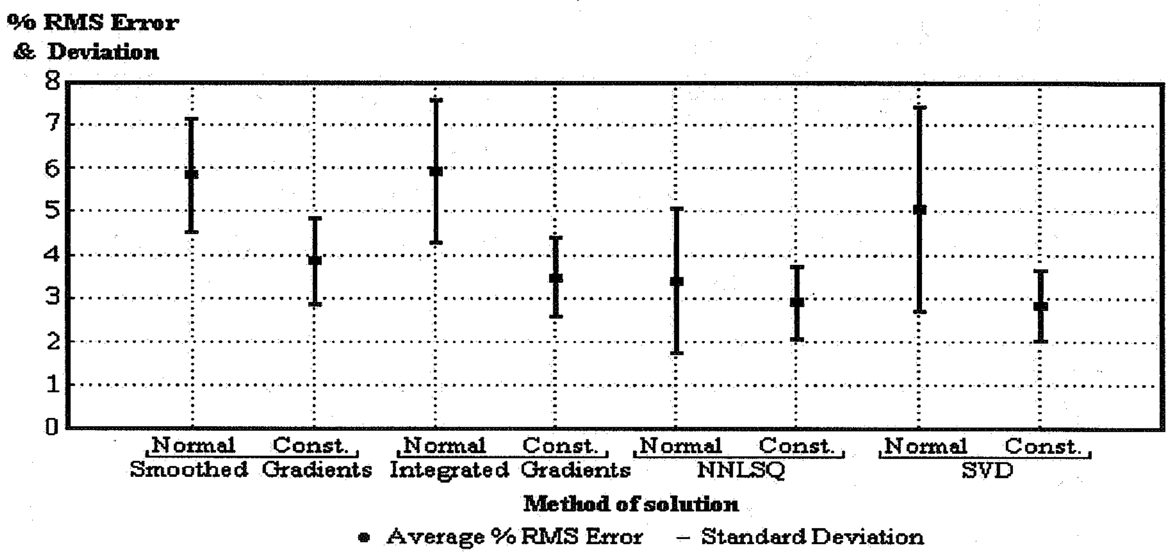

Figure 6 - % RMS Error and Standard Deviation versus Method of Solution (two zone tests).

Figure 7 shows similar results for the overall air change rate (ACR); the first solution is obtained from the steady portion of the decay curve (i.e. from the dominant eigenvalue), whereas the remainder are found from summing the internal/external flows.

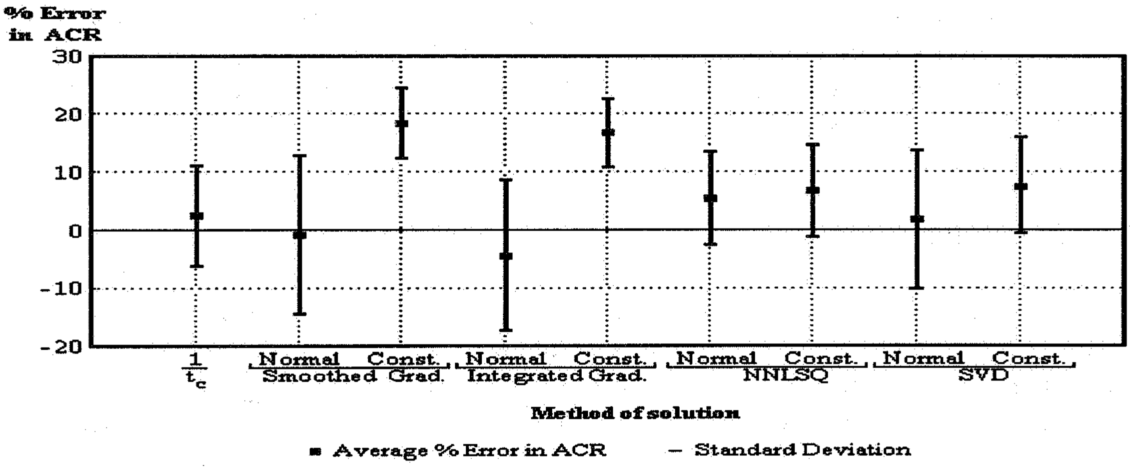

Figure 7 - % Error in ACR estimated from measured data sets (two zone tests).

Figures 8, 9 and 10, 11 extend these results to three and four zone cases respectively.

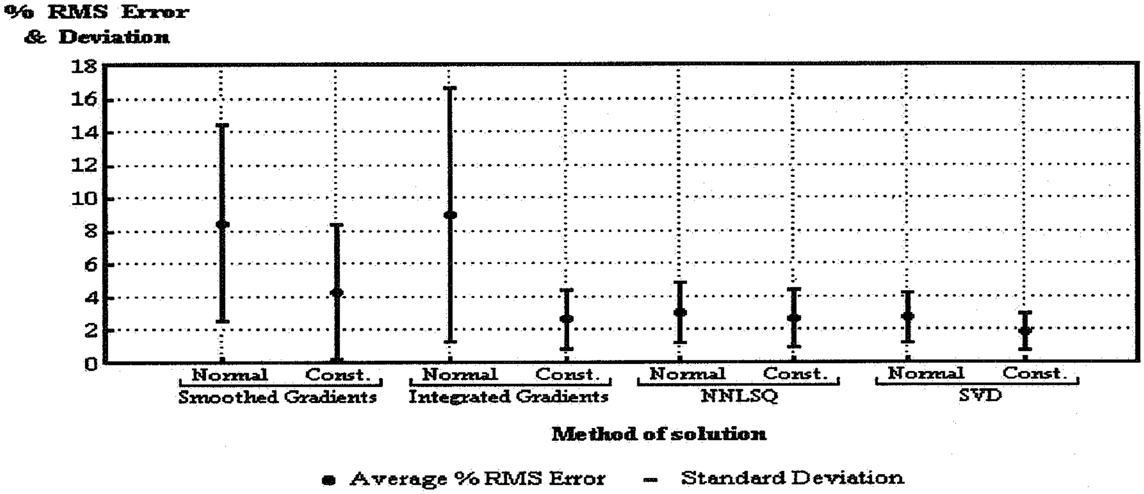

Figure 8 - % RMS Error and Standard Deviation versus Method of Solution (three zone tests).

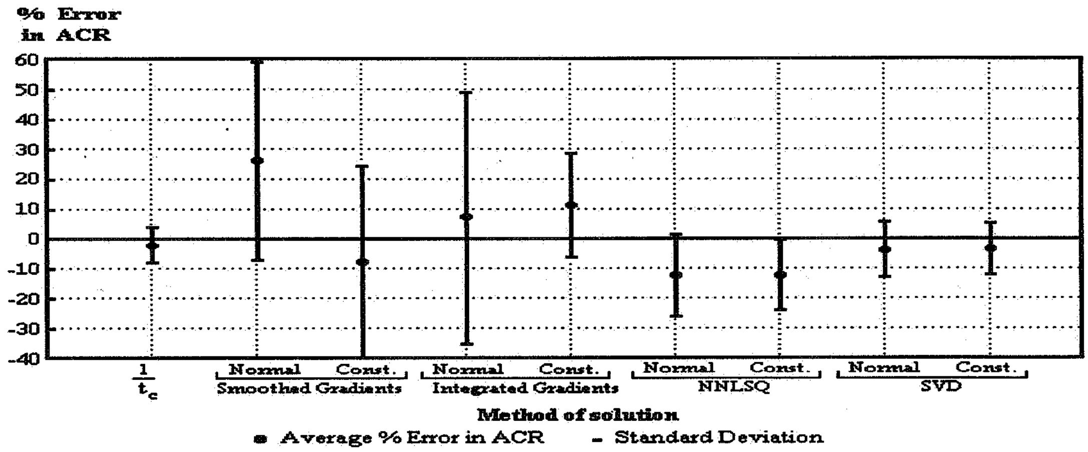

Figure 9 - % Error in ACR estimated from measured data sets (three zone tests).

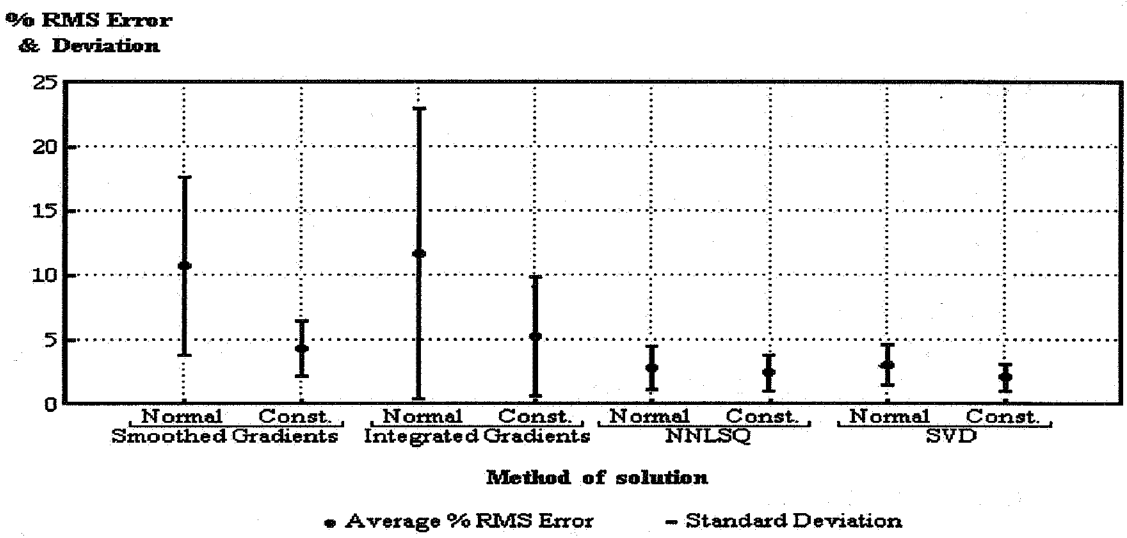

Figure 10 - % RMS Error and Standard Deviation versus Method of Solution (four zone tests).

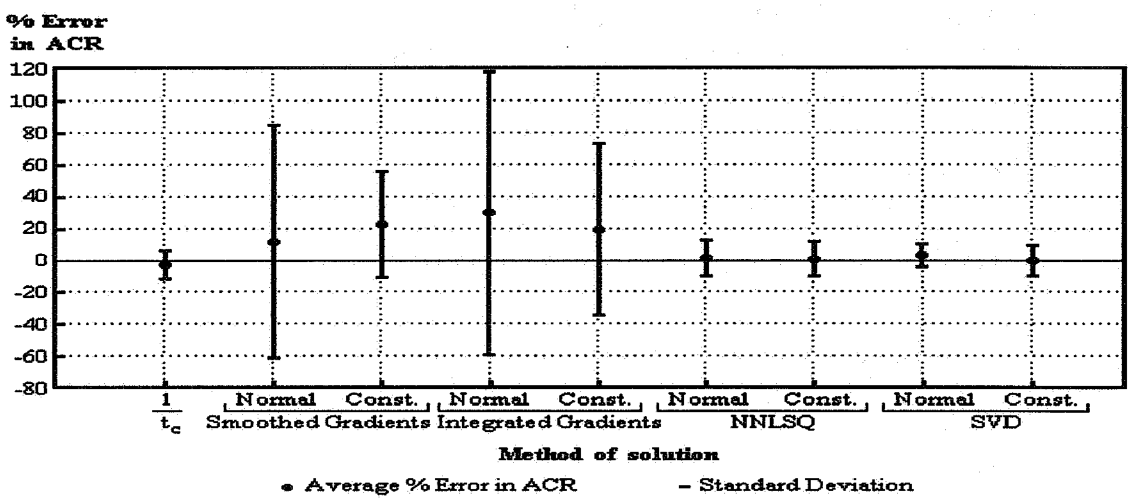

Figure 11 - % Error in ACR estimated from measured data sets (four zone tests).

Two main conclusions can be drawn from these results. These are:-

i) The inter-zone flows are reliably determined provided a non-negative least squares (NNLSQ) or singular value decomposition (SVD) solution technique is used, with constraints where there are known flows. Other techniques are not as reliable.

ii) The overall air change rate is found most reliably from the steady state decay curve, that is when the dominant eigenvalue is controlling the rate of decay.

These conclusions become more clearly defined as the number of zones increases. The facility has been used for other validation studies, details of which are given by Brouns [15].

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