The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

Modelling Fluctuating Air Flows Through Building Cracks

S Sharples, R G Palmer

Building Science Research Unit, School of Architectural Studies, The University of Sheffield S10 2UJ, United Kingdom

Synopsis

The paper summarises an approach to determining the equations governing the air flow through simple cracks subject to fluctuating pressures. To this end, an experimental arrangement has been developed that enables the laboratory simulation of fluctuating driving pressure signals. A standard straight crack was subjected to this signal, which fluctuates in both magnitude and frequency.

An air control system permits a high level of fluctuating pressure control. Pressure fluctuations are imposed on a $1m^2$ section of wall with a centrally mounted crack and the overall volumetric air flow rate, pressure distribution and flow direction are monitored. In addition to the experimental testing, computational fluid dynamics (CFD) analyses were carried out for the crack type and specific flow condition. An analysis was made of initial physical test results and a comparison made between these findings and the preliminary CFD models developed.

A background to the work is given and the methods used in simulating the necessary conditions for fluctuating crack flow measurement and the preliminary results of the physical testing and CFD analyses are presented.

1. Introduction

The work presented in the paper augments research in this field which includes that of Baker et al. [1987], Sahin et al. [1988], Mokhtarzadeh-Dehghan et al. [1992] and Riberon et al. [1990]. Work by Baker et al. into non-fluctuating pressures suggested that the power law equation for crack flow,

$$\Delta P = \alpha \cdot Q^{\beta},$$

developed by Etheridge should be replaced by a quadratic form,

$\Delta P = A \cdot Q + B \cdot Q^2$. They found that the relationship

$$\frac{1}{C_d^2} = k.\frac{k}{D_h}.\frac{1}{\mathrm{Re}_h} + C$$

satisfactorily described the crack flow for a wide range of $z/\mathrm{Re}_h.D_h$ values but that it was inadequate at higher values. As an alternative, the theoretical quadratic model of crack flow of the form:

$$\Delta P = \frac{12\mu z}{Ld^3}Q + \frac{\rho C}{2d^2L^2}Q^2$$

was suggested for non-fluctuating flow. Research by Riberon et al. into the effect of wind pressure on air movements in buildings challenged the acceptance of traditional natural ventilation design codes which use a non-fluctuating pressure/flow model. Effects were studied using a numerical model including air compressibility and a wind tunnel model, using pollutant concentration as the indicator. Theoretical solutions were compared with field data from the BOUIN test house. Numerical studies on a 2-room house revealed that transitory wind fluctuations cannot be ignored but that air compressibility can. Tests on CO_2 concentration showed a 35% difference between analyses with constant wind pressure and those with temporal wind fluctuations. However, numerical studies on a 1-room house with a single opening showed that compressibility is a factor. Similar studies on a 7-floor building indicated that taking into account wind fluctuations considerably modifies the instantaneous flow rates. The work concludes by stating the necessity of considering temporal wind fluctuations.

Work by Rao and Haghighat into wind induced fluctuating airflow in buildings similarly challenged acceptance of steady-state, non-fluctuating airflow models. They proposed a new model; employing spectral analysis and statistical linearisation to model the pulsating flow. This splits fluctuating flow into 2 categories - *eddy flow*, which represents additional air exchange through openings due to penetration of eddies, and *pulsating flow,* which is the result of bulk flow (pressure induced) across the opening. Their results showed that coherence between wind pressure and flow is low at high fluctuation frequencies, but that this is not critical as most power densities of the wind pressure occur at low frequencies. Work presented here addresses these low frequency fluctuations. In general airflow through openings can be summarised as follows, with the areas addressed by this work given in italics:

Table 1 Summary of Airflow Through Openings

Causes	*1. Wind Induced Pressure*			2.Thermal buoyancy	3.Mech. systems
Types	Steady-state	***Fluctuating***			
Generators	Mean pressure differences	***Temporal variations in wind-induced pressures***			
Types		***a) Pulsating flow***	b) eddies		
Due to:		***Wind fluctuation and compressibility of air***	turbulence in air stream		

2. Method

The approach to developing an appropriate equation for fluctuating airflow is founded on the pulsating airflow model developed by Haghighat et al. who suggested summing up all the airflows caused by pressures of single sine-wave frequencies. Flow due to compressibility of air is introduced as the third element of the airflow system. This is developed into the modified fluctuating airflow model which includes an eddy-flow component. The aim was to develop a satisfactory CFD model of fluctuating flow through the crack which could be used to model divers pressure fluctuations and hence develop a fluctuating crack flow equation. However, physical validation of CFD simulations of fluctuating crack flow was considered a prerequisite to the development of an appropriate model.

2.1 Physical Testing

To find the airflow at various fluctuating pressures a test rig was developed (see Fig 1). The principal supplementary components to the steady-state system summarised by Baker et al. are the 4 variable speed fans. These permit a more extensive range of pressures to be applied to the crack surface. Also a damper was introduced to control volumetric airflow. The damper was a variable air volume regulator unit (LTG Lufttechnische VRE/SS/250) controlled by a servo drive damper motor (CMR DM10). The maximum rotation angle of the elliptical damper blade was 60°, supplying a volumetric air flow proportional to the percentage opening of the damper at higher pressures. The servo motor was driven by a compact PCB board which had an overload protection fitted to halt the servo motor without the use of end limit switches. This allowed input signals to be applied safely to the flow control unit. Two relays were utilised on the PCB board for the overall driving signal, served by a function generator. This provided a sinusoidal signal to drive the damper.

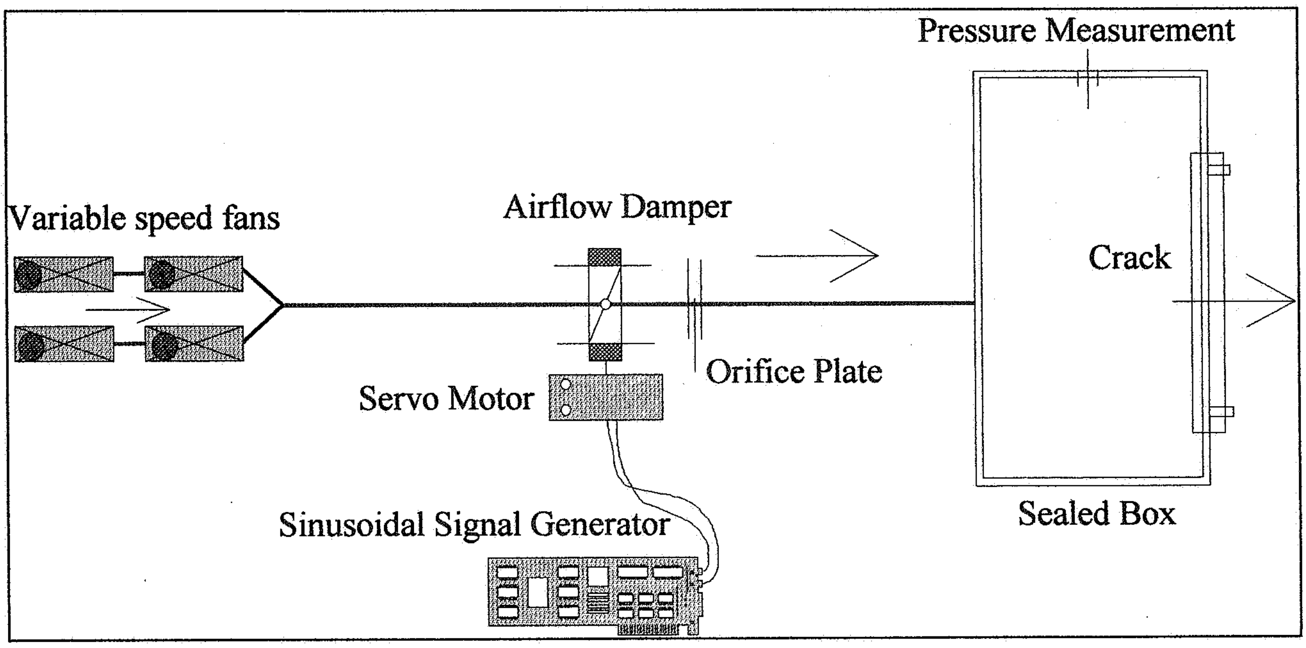

Fig 1 Schematic of Test Rig

The variable speed fans were ran at different power settings and the resultant pressure fluctuations were monitored at 0.1 second intervals for an initial driving signal of 0.66Hz. Fig 2 shows the resultant pressure fluctuations on the face of the wall section at various fan settings (Series 2-6 indicating progressively lower fan power) and records the consistency in pressure patterns. The flow through the crack was calculated from pressure readings from the orifice plate.

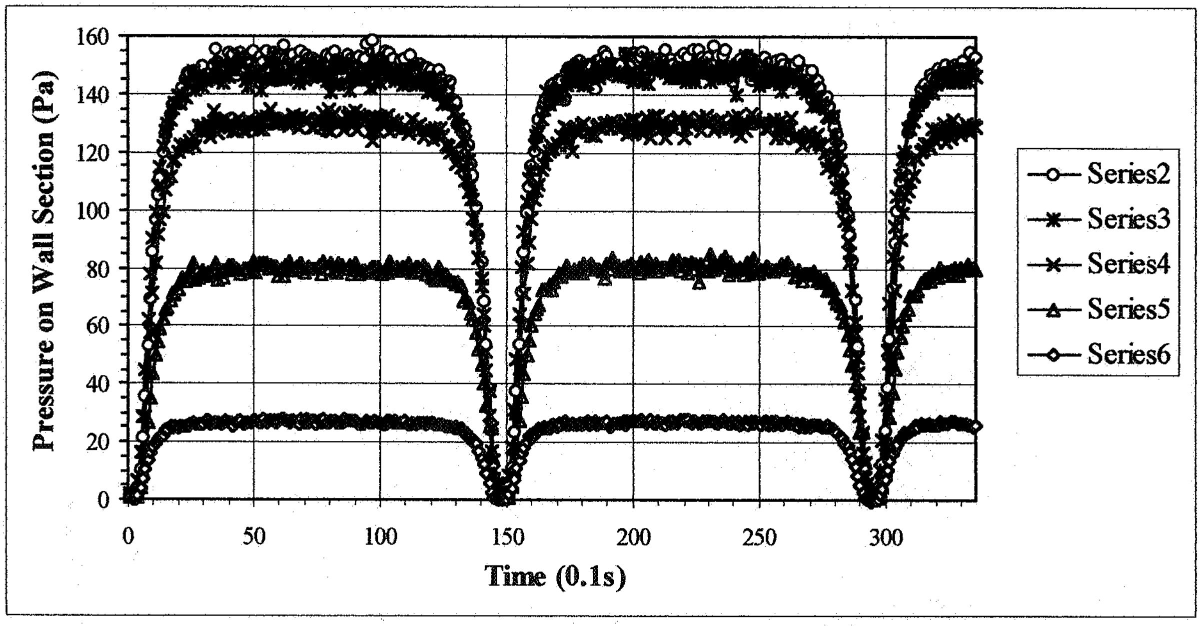

Fig.2 Resultant Pressure Fluctuations on Wall Section

2.2 CFD Modelling

A commercially available finite volume CFD code was used, FLOVENT. This had the capability to model airflow as laminar or turbulent and offered a k-ε solution. The FLOVENT solution method utilised in the analyses of the flow behaviour was fully validated both physically and mathematically before any fluctuating crack flow simulations were made [Tinker and Palmer.1994]. A three-dimensional model was developed in FLOVENT, using simple Cartesian co-ordinates and analyses executed in rectangular cuboid solution domains, where variables were solved using a Gauss-Seidel iteration For convergence to occur, maximum acceptable errors were defined that were realistically attainable and for final modelling these errors were characterised as very small proportions of the overall value of the variable in question. For example, the admissible termination residual for velocities, for which the error is found in the momentum equations, was designated as 1% of the sum of all momentum inflows. However, when overall values were very small the figure of 1% was eased due to the difficulties in achieving the minute values required.
Because temperatures anywhere in the rig were not significantly above the external conditions, density was kept constant throughout the space at $1.19 kgm^{-3}$, which allowed for a RH value of approximately 50% at STP. Also, the variations in air conditions experienced in the rig were relatively small and the specific heat of air in the CFD model was kept constant, at $1.005x10^{3} Jkg^{-1}K^{-1}$, which again was consistent with air at STP. Under the same conditions the laminar dynamic viscosity was set constant to $1.84x10^{-5} kgm^{-1}s^{-1}$.
To expedite the solutions, after an acceptable resolution of each flow case had been found, overall flow boundary conditions were slightly adjusted and a new simulation was made based on antecedent results, i.e. values at individual grid cells were pre-set to existing values from the previous model. Although the initial variable values at each cell only superficially affected the final solution, they had a considerable influence on the rate of convergence of

the model. Overall mesh sizes were limited by the computational power and data capacity of the hardware to 10-15k grid cells, depending on the type of solution. Analyses using a k-ε model requires greater capacity due to the larger number of parameters in the solution and so all preliminary grid definitions were kept as small as possible whilst providing an appropriate soluble model. All key surfaces were identified and grid lines defined along them. Up to 20 cells were defined for the fourth dimension, time, which allowed the fluctuating flows to be modelled.

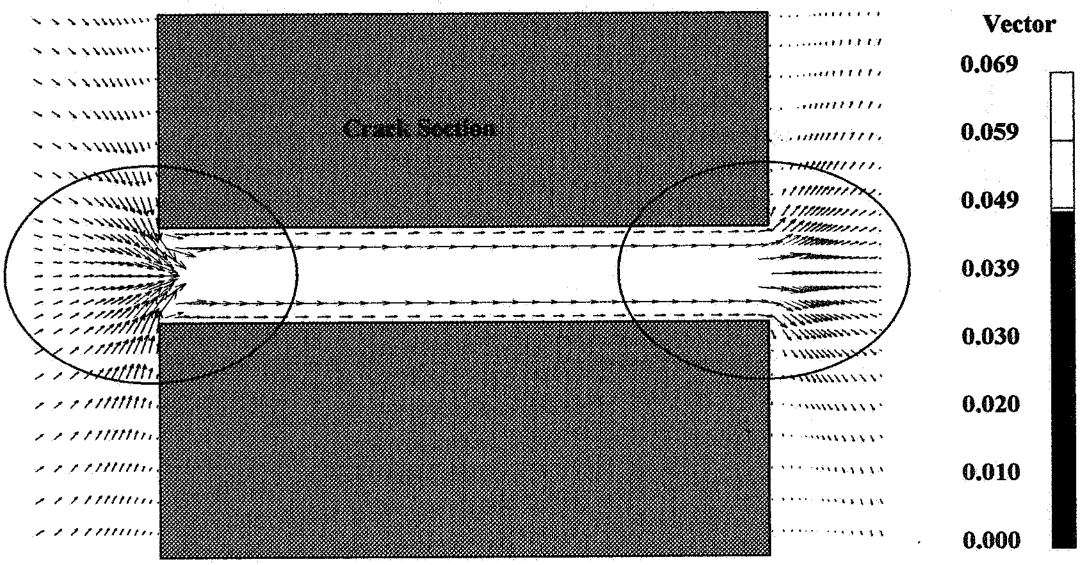

Fig 3 Section of a CFD Simulation of Wall Showing Crack Flow

An appropriate crack model was developed from a comparison of simulation results using various flow boundary parameters with physical tests. This would then enable simulations of models with sinusoidal pressure fluctuations. Fig 3 shows the CFD simulation of the straight crack and shows the airflow pattern at the inlet and outlet from the crack which proved to be an important indicator of appropriate solutions. Fig.4 shows different predicted volumetric flow rates and air distribution patterns for different pressure differentials applied across the same crack. The static pressure was varied according to measurements taken from the test rig and volumetric flow was then calculated from average outlet velocities and crack size.

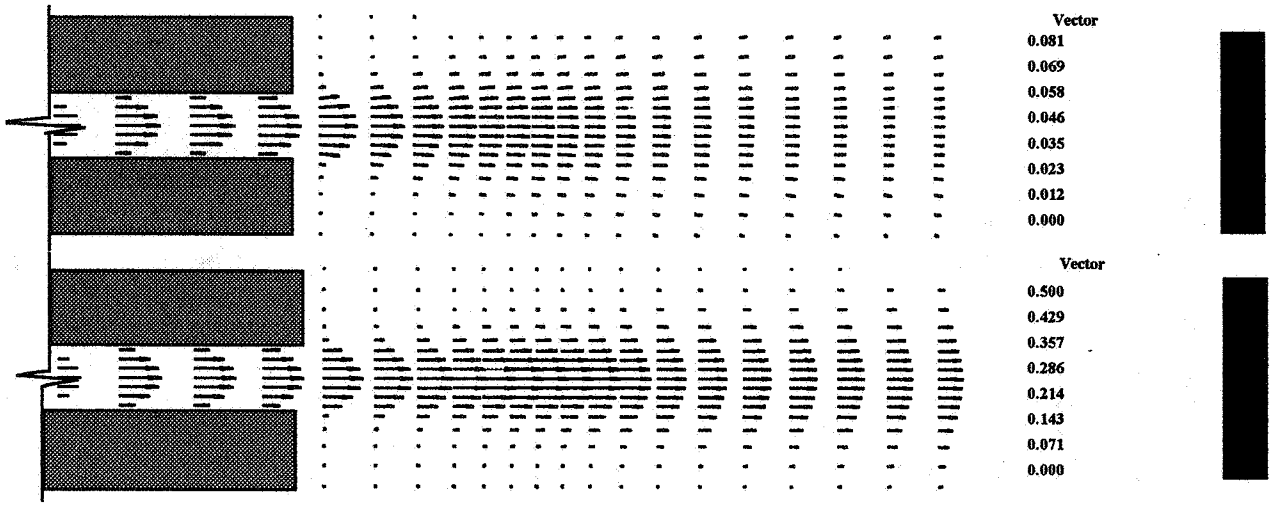

Fig.4 Outlet Conditions for Straight Crack - 20Pa and 140Pa Pressure Differentials

3. Results

For the preliminary test case, measurement of the pressure drop across the crack revealed a fluctuating pressure signal shown in Fig.5, varying from 0Pa to approximately 130Pa. A simultaneous measurement of the pressure differential across the orifice plate indicated flow through the crack succeeded the pressure fluctuation by approximately 0.4 seconds for this test apparatus. The hysteresis is illustrated in Fig.6 which shows a graph of the pressure differential across the crack versus the volumetric airflow through the crack.

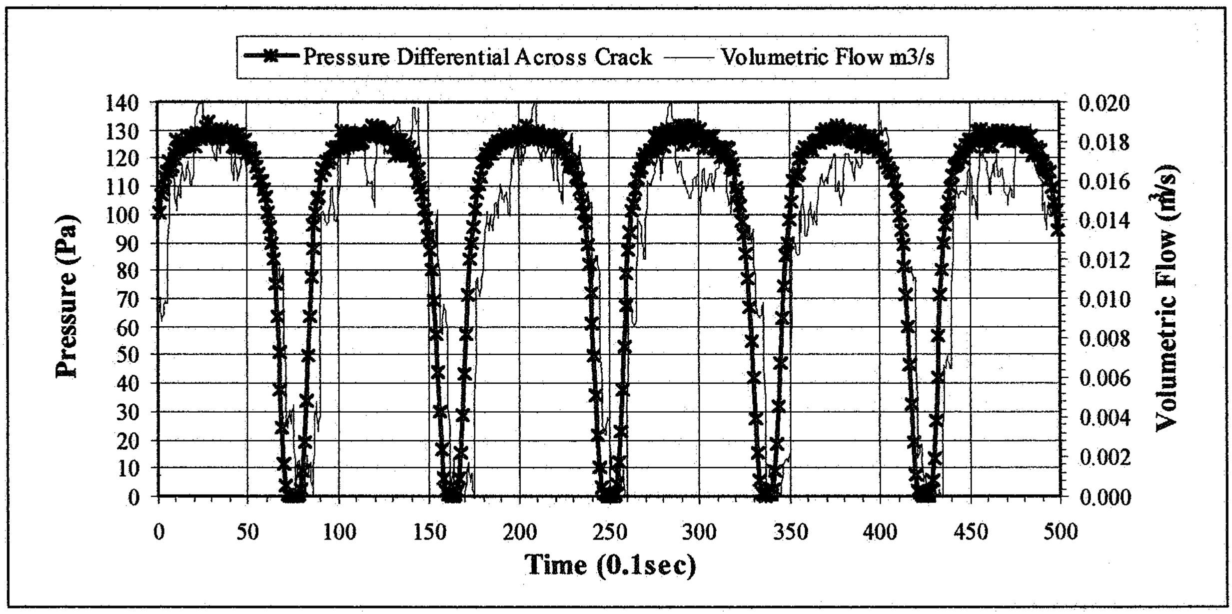

Fig.5 Pressure Differential Across Crack and Volumetric Flow Rate Through Crack vs Time

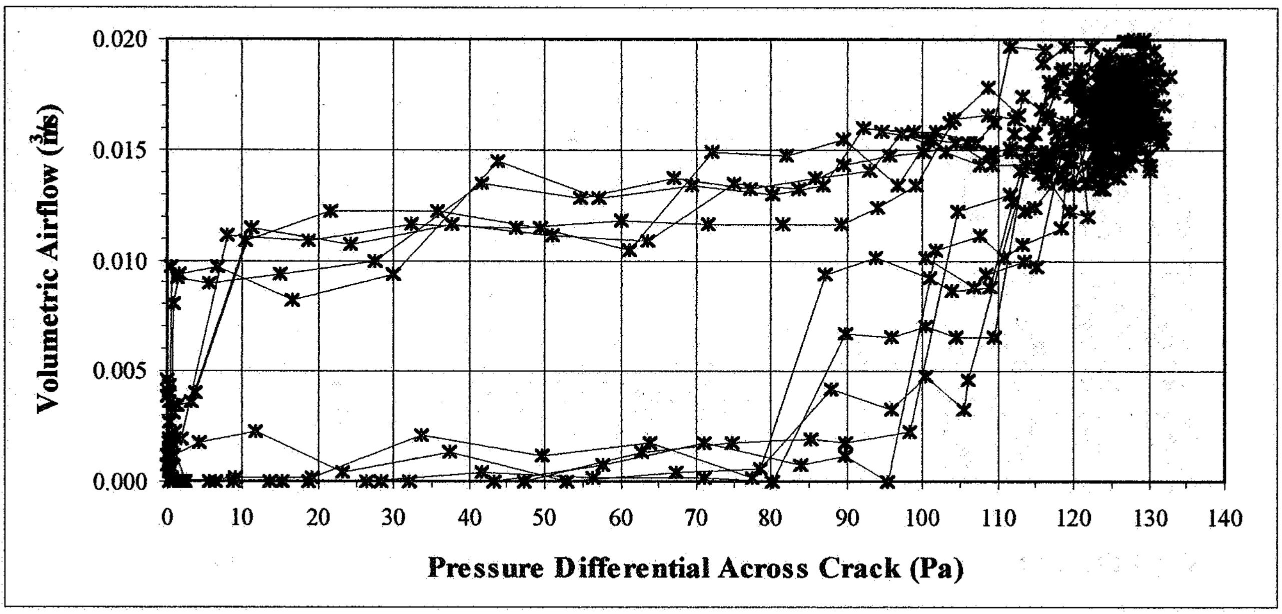

Fig.6 Pressure Differential Across Crack vs Volumetric Flow Rate

With the hysteresis effect removed, a comparison of experimentally found volumetric airflow against applied pressure differential is made for the fluctuating flow experimental results and the steady-state theoretical model and steady-state experimental results. This is shown in Fig.7.

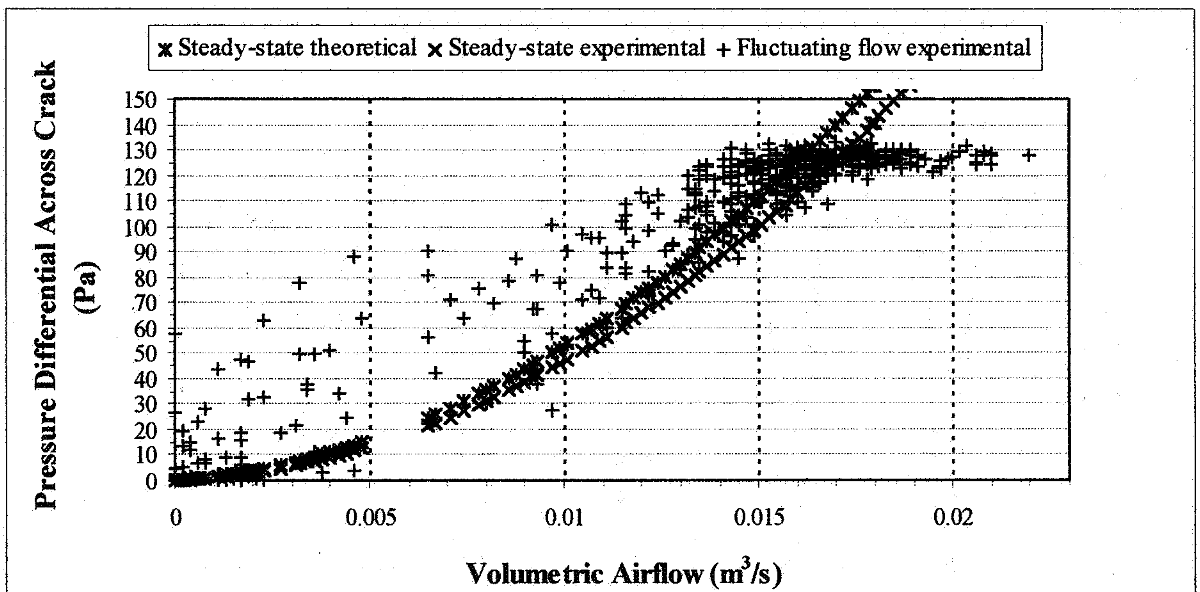

Fig 7 Volumetric Airflow Through Crack vs Applied Pressure Differential for Steady-state Theoretical and Experimental and for Fluctuating Experimental

The results indicate that, for lower pressures, volumetric airflow is lower in the fluctuating flow tests than it is for steady-state cases. However, the flow catches up with pressure fluctuations at the higher end of the pressure range and for no increase in applied pressure across the crack there continues to be an increase in volumetric flow. Initial CFD simulations show that appropriate crack flow modelling requires careful definition of the overall pressure on the face of the wall section. This was most correctly modelled using a static pressure inside the box. The pressure on the outside should be defined as ambient and a head loss of one dynamic head assumed. Defining volumetric inflow and outflow rates tended to over-estimate flow through the crack by in effect forcing air through without consideration of resistance of the crack itself. Initial fluctuating flow simulations show a correlation with experimental results for instantaneous maximum and minimum pressure differentials, but transient flow has proved more difficult to model. Further simulations are being carried out to prepare a model that can confidently model sinusoidal pressure fluctuations.

4. Conclusions

A methodology has been presented as an approach to evaluating air flow through simple cracks subject to fluctuating pressures. Initial results indicate that fluctuating pressures of varying frequency and magnitude can be simulated using this approach and that the resultant volumetric flows can be quantified. Similarly, comparative studies of results from the test rig have led to the formation of a reliable CFD model which can form the basis for further pressure simulations and ultimately sinusoidal fluctuations.

The results show the existence of considerable hysteresis in flow due to fluctuating pressure differentials and that quantification of this and overall volumetric flow should provide the basis for adjusting steady state crack flow equations for fluctuating flow.

References:

ETHERIDGE D.W. "Crack flow equations and scale effect" Bldg Envir. 12. 1977.

BAKER P.H., SHARPLES S., WARD I.C. "Air flow through cracks" Building and Environment, 1987.

SAHIN B., CLARK C., REYNOLDS A.J., WAKELIN R. "Ventilation generated by a fluctuating pressure differential" Effective Ventilation, 9th AIVC Conference, 1988.

MOKHTARZADEH-DEHGHAN M.R., WARD-SMITH A.J., WALKER R.N. "A study of laminar air flow through cracks by numerical solution of the differential equations" Int.Journ. Numerical Methods in Fluids, 1992.

RIBERON J., BIENFAIT D., BARNAUD G., VILLAIN J. "Effect of wind pressure on air movements in buildings" Ventilation System Performance, 11th AIVC Conference, 1990.

RAO J., HAGHIGHAT F. "Wind induced fluctuating airflow in buildings" Air movement and ventilation control within buildings, 12th AIVC Conference, 1991.

HAGHIGHAT F., RAO J., RIBERON J. "Modelling fluctuating airflow through large openings" Ventilation for energy efficiency and optimum air quality, 13th AIVC Conference, 1992.

TINKER.J.A and PALMER.R.G. "Measurement and computational modelling of thermal pollution due to PC's and VDU's". BEPAC 94, 1994.