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Technical Note

Summary Whilst the use of louvres for the control of solar radiation and daylight has been extensively studied, their impact on airflow through window openings seems to be relatively poorly researched. An experimental study has been carried out to investigate the airflow characteristics through a system of modulated louvres. The pressure flow characteristics across a full-scale louvre system were measured. Airflow models were developed for different louvre inclinations using quadratic relationships of the form $\Delta P = AQ^2 + BQ$ and compared to the power law expression of the form $\Delta P = aQ^n$. The changes to airflow at various angles of louvre inclination for a range of pressure differences were also evaluated.

Airflow through modulated louvre systems

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1 Introduction

Generally the power law has been widely used to describe the relationship between the pressure drop and the volumetric flow rate through different ranges of apertures in buildings (e.g. cracks, slits and gaps around windows and doors etc.)(1–3). The power law takes the form

$$\Delta P = aQ^n \tag{1}$$

where ΔP is the pressure drop in Pa and Q is the volume flow rate in $\mathrm{m^3\,s^{-1}}$, while a and n are constants.

Under the umbrella of power law applications, some authors in the field (e.g. Dick(4)) have suggested as far back as the early 1950s that the flow rate is almost proportional to the square root of the pressure drop; i.e.

$$Q = \alpha(\Delta P)^{1/2} \tag{2}$$

α being a constant proportional to the effective leakage area of the aperture. This relationship is called the square law for convenience.

However, it has been pointed out that the power law equations expressed above are not dimensionally homogeneous since they do not obey Reynolds law of similitude(5), and that the square law approximation is not strictly true for all types of cracks and their different geometries and pressure differentials(6).

A quadratic relationship of the type

$$\Delta P = AQ^2 + BQ \tag{3}$$

has been found to best fit the data obtained from the pressurisation testing of different types of cracks(7) with evidence that the quadratic equation is dimensionally homogeneous and that it had some theoretical validity, based upon the basic flow equation for laminar flow through infinite parallel plates(8). The results of Baker *et al.*(7), combined with previous data and earlier suggestions(9,10), led Baker *et al.* to conclude that the quadratic relationship

$$\Delta P = AQ^2 + BQ$$

could be used as a practical fit to pressurisation data for a range of crack types.

The theoretical foundation upon which the validity of the quadratic relationship is based, as derived from the parallel plate theory of laminar flow, culminates in the equation

$$\Delta P = \frac{C\rho}{2d^2L^2}Q^2 + \frac{12\mu z}{Ld^3}Q \tag{4}$$

where ΔP is the total pressure drop, allowing for edge effects, due to skin friction along the dimension z in the direction of flow (Pa); d is the gap thickness between the plates (m); L is the breadth of the plates (m); μ is the dynamic viscosity (Pas); ρ is the fluid density ($\mathrm{kg\,m^{-3}}$) and C is a dimensionless constant.

It is clear from comparison with equation 3 that

$$A = \frac{C\rho}{2d^2L^2} \tag{5}$$

and

$$B = \frac{12\mu z}{Ld^3} \tag{6}$$

The hypothesis is now put forward that a louvre system could be considered as a series of parallel cracks, either horizontal or inclined and that an expression, quadratic in nature, might be used to describe the air flow characteristics of such a louvre system.

Let the initial position of two parallel louvres be 0°, say (i.e. perfectly horizontal) as shown in Figure 1 (top) and let the louvres be turned through angle θ to the new position as in Figure 1 (bottom). If the breadth of each louvre blade is L and the gap thickness between them is d, then it can be observed that as the louvres are turned through any angle, say θ, both the effective breadth in the direction of flow L_θ and the effective gap thickness d_θ decrease.

From the interplay of the angles, it can be seen that

$$d_\theta = d\cos\theta \tag{7}$$

and

$$L_\theta = L\cos\theta \tag{8}$$

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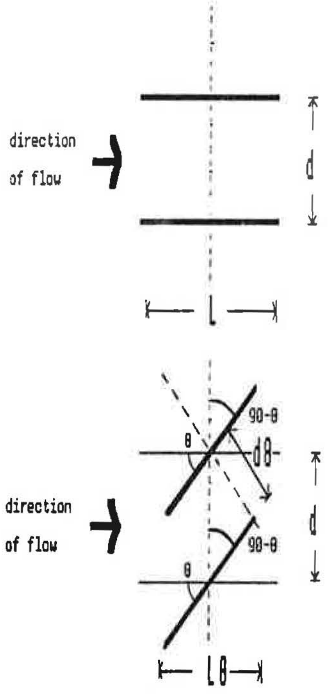

Figure 1 Decrease in aperture with changes in louvre inclination

Using as a model the parallel plate theory (equation 4) the total pressure drop across the louvres at angle θ, ΔP_θ, may be postulated to be

$$\Delta P = A_\theta Q^2 + B_\theta Q \tag{9}$$

where

$$A_\theta = \frac{\rho C}{2d_\theta^2 L_\theta^2} \tag{10}$$

$$B_\theta = \frac{12\mu z}{L_\theta d_\theta^3} \tag{11}$$

Substituting for L_θ and d_θ in equations 10 and 11 would give

$$A_\theta = \frac{\rho C}{2L^2 d^2} \frac{1}{\cos^4\theta} \tag{12}$$

and

$$B_\theta = \frac{12\mu z}{Ld^3} \frac{1}{\cos^4\theta} \tag{13}$$

For horizontal louvres ($\theta = 0°$)

$$A_0 = \frac{\rho C}{2d^2 L^2} \tag{14}$$

and

$$B_0 = \frac{12\mu z}{Ld^3} \tag{15}$$

(renaming A as A_0 and B as B_0, say) and $\Delta P_0 = A_0 Q^2 + B_0 Q$, as in equation 3. It follows therefore that if the parallel plate theory could be applied to the louvres then

$$A_\theta = A_0 \frac{1}{\cos^4\theta} \tag{16}$$

and

$$B_\theta = B_0 \frac{1}{\cos^4\theta} \tag{17}$$

The pressure drop across the louvres, ΔP_θ, would be

$$\Delta P_\theta = \Delta P_0 \frac{1}{\cos^4\theta} \tag{18}$$

showing that the pressure drop is a function of the vertical angle of the louvres, along with other parameters which are embodied in the constants A_0 and B_0. However, this relationship, though theoretically consistent, can only be true if the friction along the dimension z in the direction of flow is assumed constant for all louvre inclinations. Also, equation 18 is valid only for a given value of Q used to calculate both ΔP_θ and ΔP_0.

In order to investigate the airflow characteristics through a system of modulated louvres an experimental study with the aid of a pressurisation test facility was carried out in the Sheffield University Building Science Research Laboratory. The main objective of the experiment was the investigation of the flow characteristics of air through a louvre system. The secondary aim was to give, through the measurement system, a fundamental understanding of the impact of optimising the inclination of the slats of a modulated louvre system on airflow.

2 Experimental instrumentation

The main apparatus required for the experiment was a pressurisation chamber, digital micromanometers, a volume flowmeter, fans, an orifice plate and pressure tappings. The pressure chamber was made of glued and taped plywood, finished with polyurethane varnish. It had a small drilled opening on top to enable the insertion of a pressure tapping and was mounted on wheels for easy motion, although provision was made to stabilise it in position when necessary. Two digital micromanometers were used. One had a dual range of 0 to 1.999 Pa and 0 to 19.99 Pa to measure the pressure difference across the louvres. The other, with a range of 0 to 1.999 mm H_2O, measured the pressure drop across the orifice plate. The manufacturer's quoted accuracy was ±1 on the last digit of the display. Both micromanometers incorporated self-calibrating devices to ensure compensation for zero-drift, making them sufficiently accurate to measure small pressure differences. A sensitive hot wire flowmeter was used to validate the calibration of an orifice plate constructed to BS 1042[11,12]. Four fans, connected in series, were used for the depressurisation. Each fan has a diameter of 480 mm with blades of 14° pitch capable of 1440 rpm. Each fan was fitted with a fan speed control to enable speed alterations.

The need to obtain and measure a high volumetric flow rate which would induce a measurable drop across the louvre system necessitated the use of an orifice plate of 38.1 mm diameter. The orifice plate was made and calibrated in accordance with BS 1042 sections 1.1 and 2.1 respectively[11,12]. Details of the calibration may be found in Yakubu[13]. The equation of the calibration curve was

$$Q = 0.00282(\Delta P)^{0.467} \tag{19}$$

where Q is given in $m^3 s^{-1}$ and ΔP is in mm H_2O. The curve was an excellent fit to the calibration data, as shown by the r^2 value of 0.9953, and as was observed by examining the residuals of the least squares fit. The calibration was then checked for accuracy over a limited range of flows 100–600 l min^{-1} (0.0001–0.01 $m^3 s^{-1}$) by making simultaneous measurements of the orifice plate and a factory calibrated precision hot-wire flowmeter connected in series. The flows measured agreed to within 3% and hence the calibration was certified satisfactory within reasonable limits and was therefore suitable for use in the experiment.

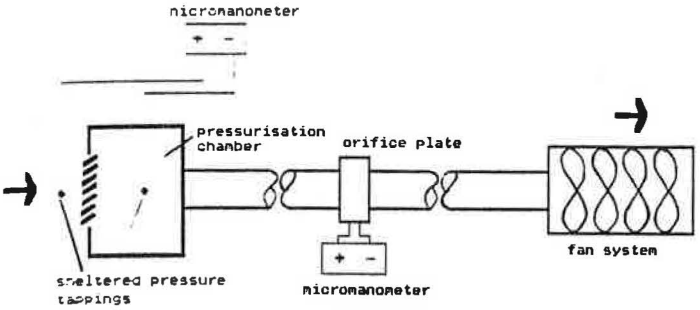

Figure 2 Experimental set-up

3 Experimental procedure

The schematic layout of the experimental arrangement is shown in Figure 2. A louvre system of thin plywood slats was constructed and fitted as a detachable unit onto the front of the pressure chamber. There were five louvres in all, each measuring 450 mm long by 100 mm wide and 5 mm in thickness (full size dimension) and all were fitted so as to allow adjustment of the louvres to align with pre-determined vertical angles clearly marked on the side board. When horizontal and parallel the gap between each louvre was 95 mm. The pressure chamber was then stabilised in position and connected via a 150 mm diameter tubing to the orifice plate, which itself was then connected to the fan system. The pressure tapping, which was connected to the manometer, was enclosed in a small multi-porous cylinder with a hemispherical base and was centrally positioned in the pressure chamber. The pressure tappings of the orifice plate, which was located downstream of the test system, were connected to the 1.999 mm H_2O micromanometer.

All connections in the set-up were so made as to meet adequate considerations for the dynamic nature of the flow, especially with respect to streamline points along the piping to prevent sharp diameter differentials. Also, all the joints were sealed with draught-proof materials to prevent or minimise leakage or infiltration.

4 Measurement principle

The main principle of the experiment was to depressurise the chamber by adjusting the circuit controls of the fan system. As a result of the decreased pressure, air flowed into the chamber through the louvres which were pre-set at a particular vertical angle θ. The volume flow readings and pressure drop readings were recorded from the orifice plate and the micromanometers respectively when the readings had stabilised.

5 Results

The experimental results are shown in Table 1. Least squares fits for both power law and quadratic relationships were tested on the data obtained from the experiment. The following points of interest were highlighted:

(*a*) The data were found to have good least squares fits for both the power law and the quadratic relationships.

(*b*) The r^2 value for the power law least squares fits ranged from 0.5868 for 0° to 0.7996 for 75°, showing that the power law least squares fits gradually improved with increase in louvre inclination (Table 2).

Table 2 Comparison of power law ($\Delta P = aQ^n$) and quadratic ($\Delta P = AQ^2 + BQ$) fits to the experimental data

Louvre angle (°)	Power law relationship			Quadratic relationship		
	a	n	r^2	r^2	A	B
0	3.101	1.11	0.5868	0.9993	177.708	−0.6135
15	3.934	1.12	0.6686	0.9993	186.404	−0.3952
30	5.286	1.14	0.7456	0.9997	193.316	0.0783
45	1.152	1.20	0.7482	0.9996	349.907	−0.0723
60	3.786	1.28	0.7571	0.9997	844.194	−0.5273
75	3.278	1.43	0.7996	0.9992	4442.31	−13.57

Table 1 Experimental results of air flow Q(m^3 s^{-1}) and pressure drop ΔP(Pa) across inclined louvres angle θ

$\theta = 0°$		$\theta = 15°$		$\theta = 30°$		$\theta = 45°$		$\theta = 60°$		$\theta = 75°$	
Q	ΔP	Q	ΔP	Q	ΔP	Q	ΔP	Q	ΔP	Q	ΔP
0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000	0.0000	0.000
0.0048	0.002	0.0053	0.004	0.0048	0.005	0.0048	0.008	0.0047	0.013	0.0049	0.076
0.0063	0.004	0.0065	0.006	0.0062	0.009	0.0064	0.013	0.0062	0.027	0.0065	0.135
0.0098	0.012	0.0102	0.017	0.0099	0.019	0.0101	0.035	0.0099	0.076	0.0104	0.382
0.0124	0.021	0.0124	0.026	0.0125	0.030	0.0125	0.055	0.0125	0.127	0.0125	0.551
0.0133	0.024	0.0133	0.028	0.0133	0.036	0.0133	0.062	0.0133	0.144	0.0133	0.622
0.0142	0.027	0.0142	0.030	0.0142	0.040	0.0142	0.065	0.0142	0.153	0.0142	0.655
0.0173	0.042	0.0172	0.048	0.0173	0.058	0.0173	0.105	0.0171	0.244	0.0173	1.072
0.0187	0.048	0.0186	0.055	0.0186	0.069	0.0185	0.119	0.0185	0.281	0.0182	1.188
0.0213	0.067	0.0214	0.074	0.0212	0.088	0.0214	0.160	0.0212	0.370	0.0213	1.670
0.0224	0.073	0.0222	0.084	0.0221	0.099	0.0221	0.168	0.0220	0.405	0.0219	1.810
0.0248	0.096	0.0248	0.105	0.0249	0.120	0.0247	0.216	0.0245	0.490	0.0248	2.450
0.0258	0.104	0.0258	0.116	0.0258	0.131	0.0258	0.245	0.0256	0.535	0.0255	2.570

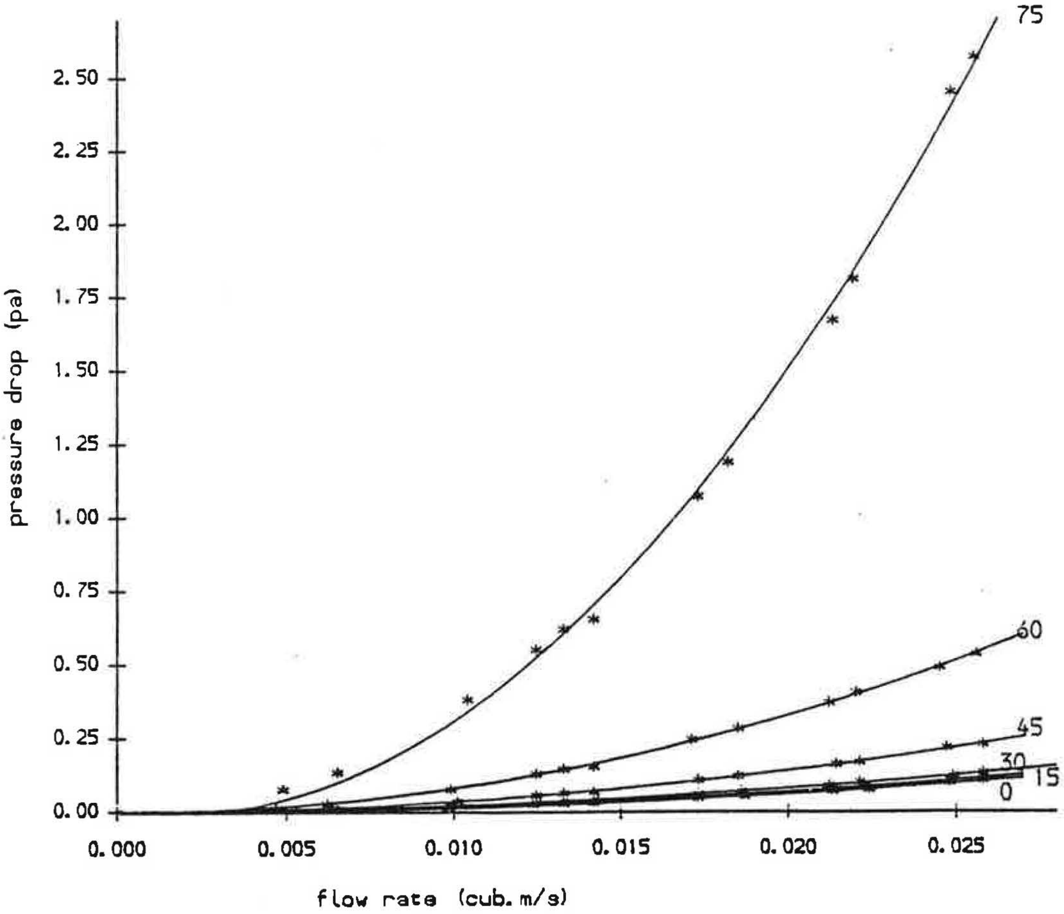

Figure 3 Pressure drop v flowrate for different louvre angles (°)

(*c*) The quadratic fits were much better than those of the power law, with r^2 values exceeding 0.999 for all angles of louvre inclination (Table 2). By examining the correlation coefficients for both relationships it is evident that the quadratic least squares fit was better in all of the cases. Figure 3 shows the curves of the quadratic fits to the data for louvre angles of 0° through 75°.

(*d*) An analysis of measured values of ΔP_θ and ΔP_0 for which the air flow Q in Table 1 was identical for all values of $\theta(Q = 0.0133$ and $0.0142\ \mathrm{m^3\,s^{-1}})$ enabled the validity of equation 18 to be tested. The predicted dependence on $\cos^4\theta$ was not substantiated by this analysis, indicating a more complex relationship between ΔP_θ and ΔP_0 than is suggested by simple parallel plate flow theory.

(*e*) It can be observed from the results that there is no significant decrease in airflow for louvre angles up to 45°, at which angle the decrease in flow is just over 30%. In precise terms, the average reductions were found to be 4.8% for 15°, 13.1% for 30°, 34.2% for 45°, 56.5% for 60° and 72.9% for 75°. This indicates that the decrease to air flow begins to increase significantly from a 60° louvre angle at which the flow is reduced by over 50%. At 75° louvre inclination the reduction can be expected to be about 70%.

6 Conclusions

Models relating airflow to pressure drop across a wooden louvre system with respect to the angles of inclination of the slats have been developed.

(*a*) A quadratic expression of the form

$$\Delta P = AQ^2 + BQ$$

was found to describe the relationship between the pressure drop and the airflow rate through the louvre system better than the power law and is recommended for use as a practical fit to pressurisation data.

(*b*) Although a quadratic expression gives a good fit to the experimental data it has been established that the simple parallel plate theory for laminar flow is *not* applicable to airflow through louvres. This is highlighted by finding (*d*) in the Results section and by the occurrence of negative values of B in Table 1.

(*c*) The relationship between the pressure differential, air flow and the louvre angle was examined. It was also established that for $0° < \theta < 45°$, there is no appreciable resistance to air flow across the louvre system.

Limitations of the experiment

The air flow measurements were restricted to smooth wooden louvres with dimensions of 100 mm in breadth and 5 mm in thickness with a gap of 95 mm between the louvres when they are perfectly horizontal (i.e. 0°). For any other geometry the various regression coefficients derived in this paper would be expected to be different.

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