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Air Flow Through Smooth and Rough Cracks

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Synopsis

A series of laboratory experiments are described which investigated the effect of surface roughness on the air flow characteristics of simple, straight-through, no-bend cracks with smooth and rough internal surfaces. The crack thicknesses used in the study were 1.0, 1.5 and 2.0mm. The crack lengths, in the direction of flow, were 50.8mm and 76.2mm. For the rough cracks the roughness was simulated with two different grades of commercially available emery-cloth (grade 60 and 100). The experimental results were satisfactorily fitted to a quadratic relationship between Δp and Q of the form $\Delta p = AQ + BQ^2$ for both the smooth and rough crack data. The effect of roughness on the reduction of air flowing through a crack is also discussed.

1.0 INTRODUCTION

1.1 Background

The amount of air flowing in and out of an enclosure is greatly influenced by the size and distribution of the cracks contained within or around the surfaces which form the boundaries of the enclosure. It is desirable to know the flow characteristics of cracks so that, from a knowledge of the pressure drop across a crack, it is possible to calculate the air flowing through that crack. Much work to establish crack flow equations has been carried out in the last twenty years [Hopkins and Hansford (1974), Etheridge (1977), Baker *et al.* (1987), Fleury *et al.* (1990)]. However, most of the fundamental experimental studies associated with this area of research have tended to use idealised cracks made from smooth surface materials such as Perspex or steel. This arrangement may be a reasonable approximation for air flowing through the cracks found, for example, around window or door frames. In reality many building cracks are formed at the junctions of constructional elements such as concrete blocks or brickwork. Such elements may contain appreciable surface roughness, and it of interest to understand how degrees of roughness can influence the fundamental crack flow equations. The classic work by Nikuradse (1933), on pipes whose internal surfaces were coated with sand, dealt with a geometry where the separation between the surfaces was large compared to the size of the roughness elements. An excellent review of this and other relevant work is given by Kronvall (1980). Gardner and Tyrrell (1986) investigated what happened to the Nikuradse equations as the separation between rough plane surfaces was reduced. Their crack separations tended to be much larger than those investigated in this study. Gardner and Tyrrell observed that as the roughness elements came close enough together to overlap then an upper limit on the friction factor was achieved. For even smaller separations the friction factor started to fall.

1.2 Crack flow equations

The results from many experimental and theoretical studies suggest that the practical relationships for describing the flow of air through a crack may be categorised in one of two ways:

$$Q = kL(\Delta p)^n \tag{1}$$

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

where Q = air flow through crack, m^3s^{-1}
k = flow coefficient, $m^3s^{-1}m^{-1}Pa^{-1}$
L = length of crack, m
Δp = pressure drop across crack, Pa
n = flow exponent
A,B = flow coefficients

Both the power-law (equation 1) and the quadratic form (equation 2) of the crack flow equation are widely used. The quadratic form has a stronger theoretical basis and is, unlike the power law, dimensionally homogeneous in that it obeys Reynolds law of similitude. In practice, for the range of pressure drops and air flows typically encountered across building cracks either equation will usually give good agreement with measured data - see, for example, Liddament (1987). One objective of this study was to see if this assertion held for flow through rough cracks. Therefore, all the measured data from the smooth and rough cracks were curve fitted to both power and quadratic forms of the crack flow equation.

2.0 EXPERIMENTAL METHOD

2.1 Equipment

For the laboratory experiments a well sealed wooden box with a volume of 1 m^3 was constructed. The front plate of the box accommodated a model crack with a crack length of 0.5m. The crack itself was assembled using two steel plates which could be set to simulate various crack thicknesses. Two sets of different steel plates breadths (length in flow direction) of 50.8 and 76.2 mm were tested. The steel plates are adjusted for each set of measurement to create crack thickness of 1.0, 1.5 and 2.0 mm.
Figure 1 shows the set-up of the depressurisation technique used for the smooth and rough crack measurements. A fan was used to draw air through the rig to maintain the desired pressure drop across the crack in the front plate of the box. Baker *et al.*(1987) found during their investigation that a shielding "box" used for protection against external pressure fluctuations in the laboratory e.g. doors closing was not necessary. Flow rates below 0.00167 m^3s^{-1} were measured with a commercially available laminar flow device. Flow rates above 0.00167 m^3s^{-1} were measured using an orifice plate constructed and calibrated according to BS 1042 (1964). The pressure drop across the crack was set by adjusting the bleed valve of the fan system. Flow measurements were taken at several pressure drops in the range 0 to 50 Pa when the readings on the manometers had become steady at each set point. To ensure that only the flow through the crack was considered in the analysis the crack was sealed over and a leakage test of the 1m^3 box was performed. The flow through the leakage of the box was then subtracted from the overall flow in order to obtain the flow through the crack only.
The steel plates were altered to simulate different kinds of roughnesses. The roughnesses were simulated by attaching emery cloth to the upper and lower surfaces of the cracks. The emery cloths corresponded to grades of 60 and 100, with the 60 grade being the rougher of the two. The average peak heights of the grains for each of these grades were measured using a microscope. The results are shown in Table 1.
The thickness of the crack was defined as shown in Figure 2. The grains on the emery cloth block off some of the open area, thus the effective leakage area gets smaller the rougher the crack is. This way of defining the crack thickness set-up was chosen to make it possible to

compare the flows through the same crack with and without the roughness being present. The ambient conditions in the laboratory, dry and wet bulb temperature and the barometric pressure, were measured to enable the calculation of air density, air viscosity and kinematic viscosity.

Table 1 Peak heights of emery cloth grains

Grade of emery cloth	Average peak height (mm)
60	0.613
100	0.375

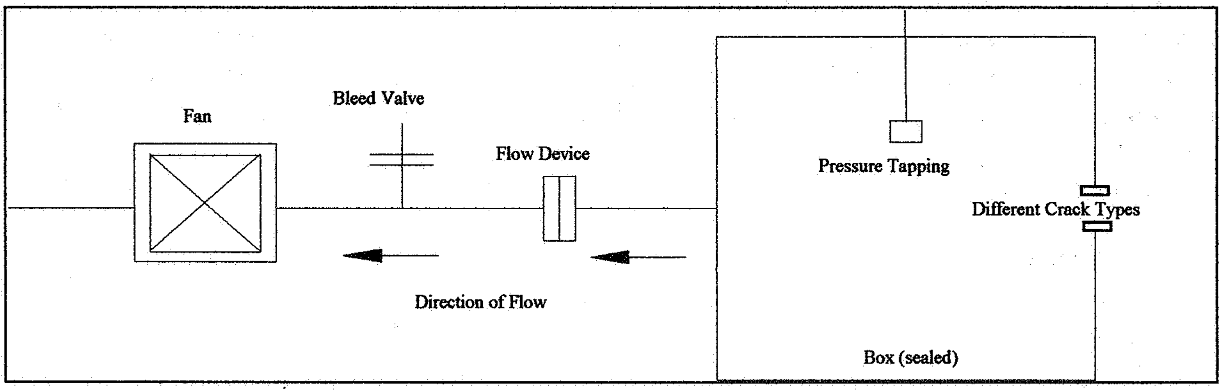

Figure 1 The Experimental Measurement Rig

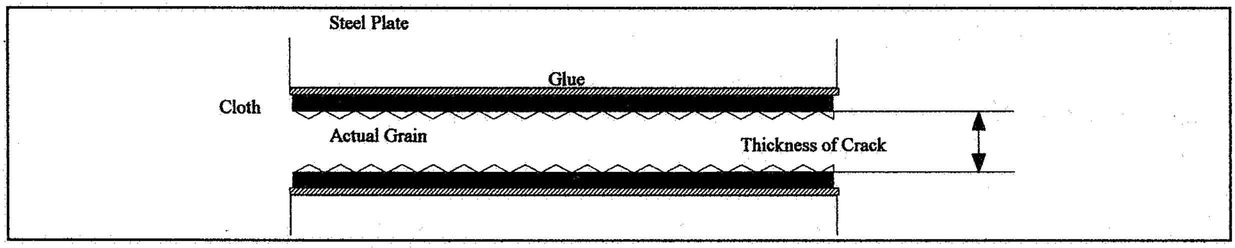

Figure 2 Measurement of the Rough Crack Thickness

3.0 RESULTS

3.1 Crack designation

Each crack used in the measurement programme had a designation code made up as:

Smooth or Rough -Crack length / crack thickness / grade of roughness

For example, a smooth 50.8mm long, 2.0mm thick crack would have the designation S50/2 while the same crack with the 60 grade emery cloth applied would be R50/2/60.

3.2 Smooth crack results

All the experimental measurements of air flow Q and pressure difference Δp were curve fitted to both the quadratic and power law forms of the crack flow equation. Table 2 gives the results of these fits and the r^2 correlation coefficient. It must be stressed that all the statistical results presented in the tables below are only strictly valid for the ranges of Q and Δp measured during the experiments. Both fits obviously provide excellent regression curves through the experimental data. The quadratic fit is seen to be consistently slightly better than the power law and was, therefore, the chosen approach for further analysis.

Table 2 Quadratic and power fits to the smooth crack data

Crack designation	Quadratic fit r^2	Power law fit r^2
S50/2.0	0.9999	0.9999
S50/1.5	0.9991	0.9974
S50/1.0	0.9946	0.9905
S76/2.0	0.9999	0.9984
S76/1.5	0.9991	0.9943

The regression coefficients for the quadratic fit are given in Table 3.

Table 3 Coefficients for regression fit $\Delta p = AQ + BQ^2$ for smooth crack data

Crack designation	A	B
S50/2.0	1117	703067
S50/1.5	3562	1578596
S50/1.0	14534	7986388
S76/2.0	2726	1113949
S76/1.5	7109	2430740

3.3 Rough crack results

The rough crack results were plotted graphically and these plots indicated that the relationship between Q and Δp could be described by a quadratic or power law curve fit. The correlations resulting from these curve fits are given in Table 4.

Table 4 Quadratic and power fits to the rough crack data

Crack Designation	Quadratic fit r^2	Power law fit r^2
R50/2.0/60	0.9995	0.9979
R50/1.5/60	0.9859	0.9749
R50/1.0/60	0.9184	0.9097
R50/2.0/100	0.9994	0.9947
R50/1.5/100	0.9992	0.9942
R50/1.0/100	0.9514	0.9362
R76/2.0/60	0.9988	0.9911
R76/1.5/60	0.9863	0.9767
R76/2.0/100	0.9999	0.9992
R76/1.5/100	0.9991	0.9937

As with the smooth crack data, both regressions give excellent fits to the data, with the quadratic equation again giving the slightly better r^2 value in each case. The regression coefficients for the quadratic fit are shown in Table 5.

Table 5 Coefficients for regression fit $\Delta p = AQ + BQ^2$ for rough crack data

Crack Designation	A	B
R50/2.0/60	4476	3780333
R50/1.5/60	11679	19122030
R50/1.0/60	30037	189480200
R50/2.0/100	2583	1456533
R50/1.5/100	4280	2252611
R50/1.0/100	33825	92263960
R76/2.0/60	7090	3887698
R76/1.5/60	20614	31179210
R76/2.0/100	6802	2197209
R76/1.5/100	12991	5420307

3.4 Comparison of smooth and rough crack results

The effect of the roughness on the air flow through the cracks is best understood by plotting the Q-Δp relationships for the smooth, 'rough 60' and 'rough 100' data for each individual crack, and these plots are shown in Figures 3 to 7. The actual reduction in the air flow as the crack becomes rougher may be expressed as :

flow reduction $= [(Q_{smooth} - Q_{rough}) / Q_{smooth}] \times 100\%$

The flow reductions at Δp values of 10 and 50 Pa are shown in Table 6

Table 6 Reduction in flow due to roughness

Crack type	Flow reduction 60 grade, 10Pa	Flow reduction 60 grade, 50Pa	Flow reduction 100 grade, 10Pa	Flow reduction 100 grade, 50Pa
50/2.0	63%	59%	38%	33%
50/1.5	72%	70%	17%	16%
50/1.0	69%	75%	64%	67%
76/2.0	53%	50%	46%	38%
76/1.5	69%	70%	54%	50%

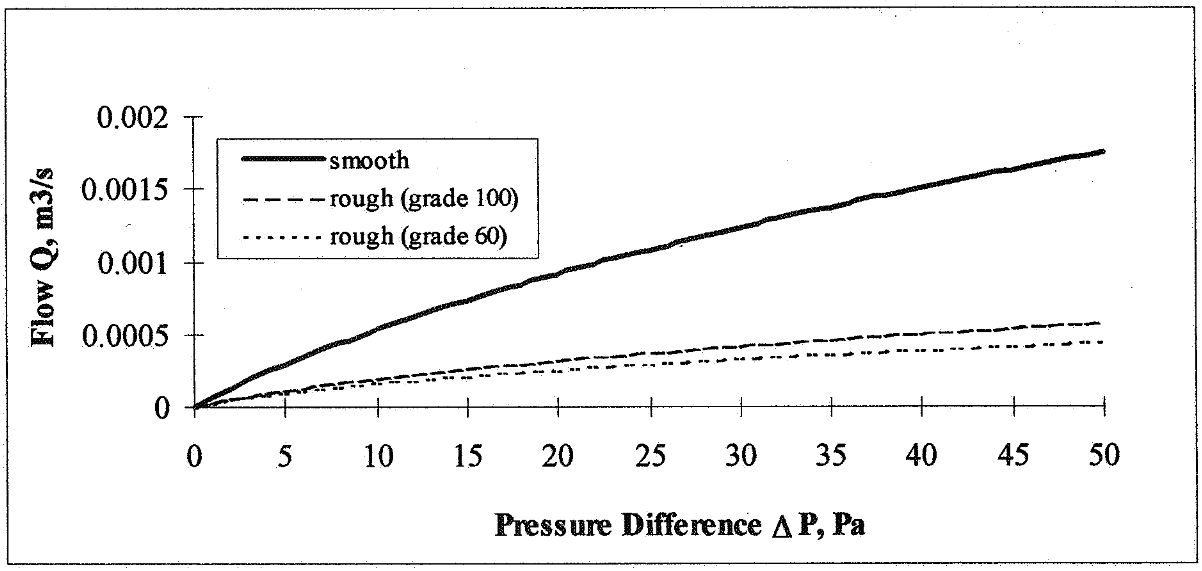

Figure 3. Smooth and Rough Flows for 50.8 x 1 mm Crack

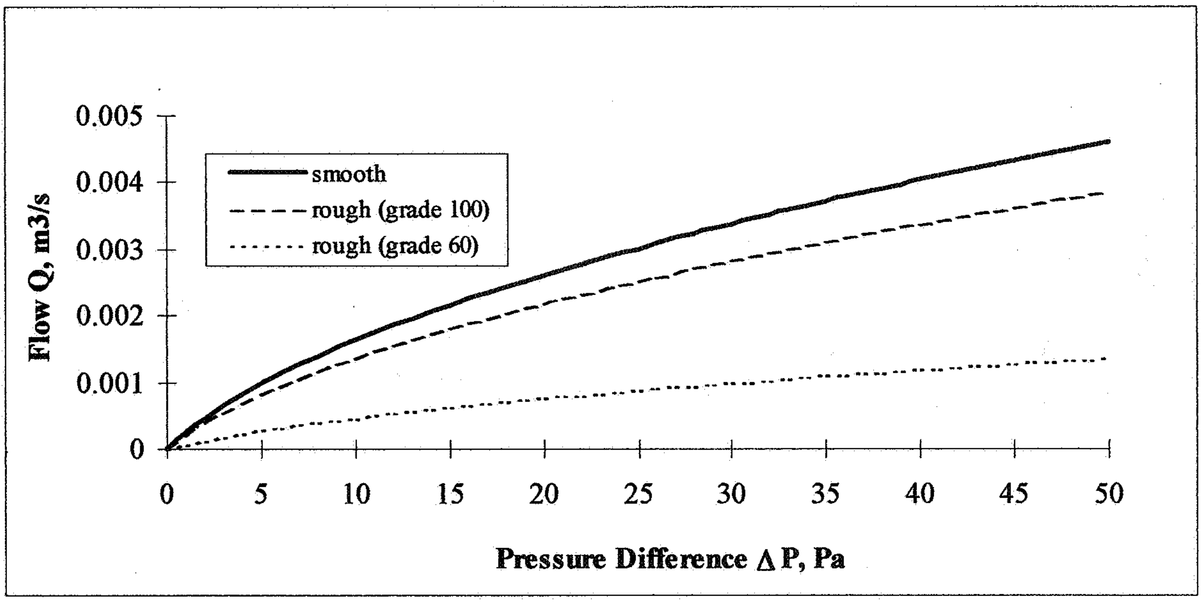

Figure 4. Smooth and Rough Flows for 50.8 x 1.5 mm Crack

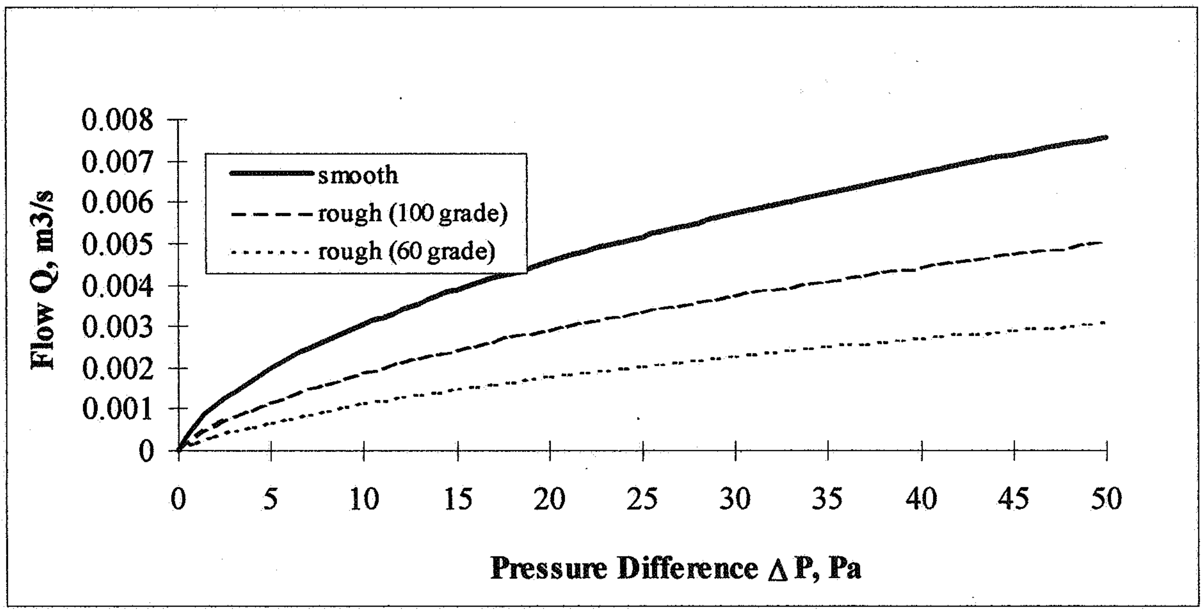

Figure 5. Smooth and Rough Flows for 50.8 x 2 mm Crack

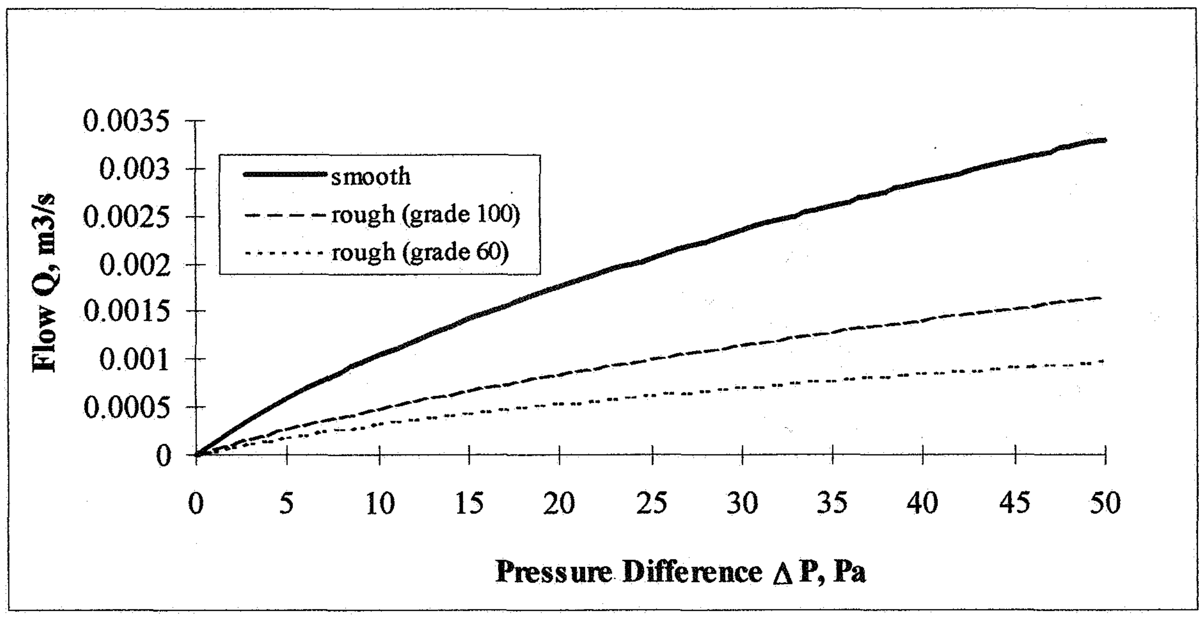

Figure 6. Smooth and Rough Flows for 76.2 x 1.5 mm Crack

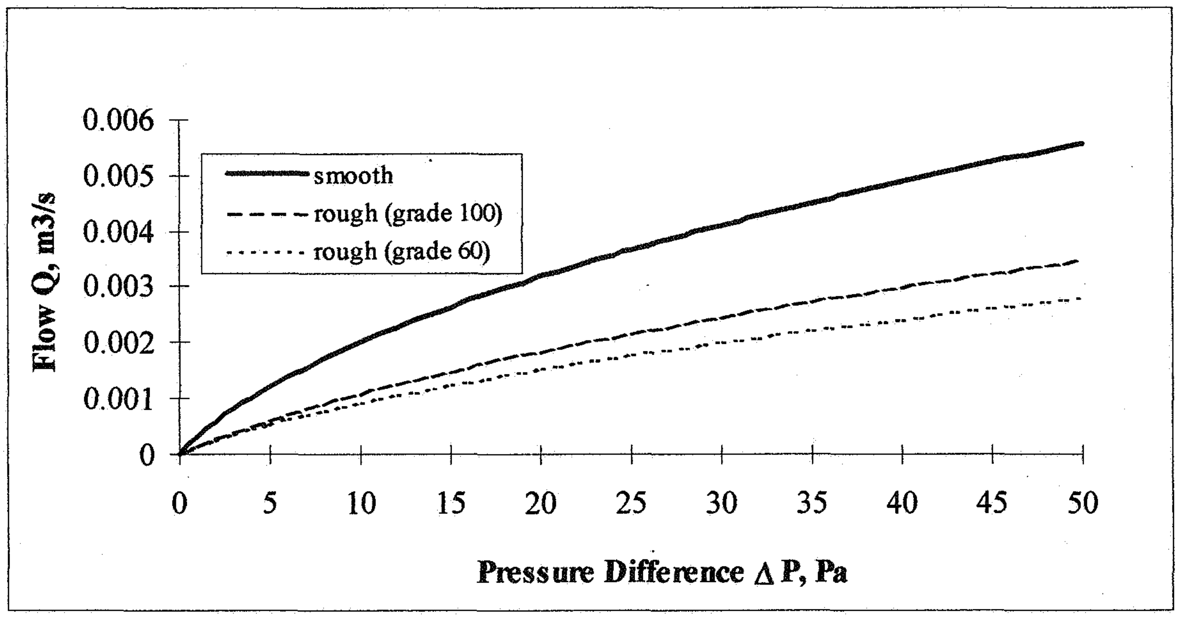

Figure 7. Smooth and Rough Flows for 50.8 x 2 mm Crack

4.0 DISCUSSION

Adding roughness to a crack can lead to a substantial reduction in the flow through that crack. Table 6 indicates that, for each crack, this reduction is fairly constant over the range of Δp used in this study. This suggests that if the roughness of a crack's surface can be established then a constant may be applied to the smooth crack flow equation to obtain an estimate of the air flow through the rough crack. Table 6 also displays a very small flow reduction for the 50/1.5 crack with the 100 grade roughness. This may be an experimental mistake, although all measurements were repeated several times for all of the experiments. Another explanation is that the flow conditions for this configuration may be in the regime where the friction factor λ, as a function of the Reynolds number, is close to its minimum value. The work of Nikuradse on flow through pipes coated with uniform sand roughnesses, as described in Kronvall (1980), suggested that λ displays a minimum value at Re values around 2.5×10^3. It may be that an analogous situation exists for flow through rough cracks, but this study has not been extensive enough to allow this suggestion to be validated.

5.0 CONCLUSIONS

An investigation of the effect of crack surface roughness on air flow has been described. The main conclusions to be drawn are:

- crack flows through both smooth and rough cracks are well described by power law and quadratic forms of the crack flow equation, with the quadratic being slightly better
- the addition of even a small degree of roughness can greatly reduce the flow through a crack, compared to the smooth equivalent, for the same pressure difference
- the percentage flow reduction, for a given crack, over the range of pressure differences used in this study appears to have a fairly constant value
- it is tentatively suggested that there may be some configurations of flow and crack geometry and roughness which display a minimum in the friction factor.

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