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Determination of k-factors of HVAC System Components Using Measurements and CFD Modelling

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SYNOPSIS

Indoor air quality, comfort and energy use in buildings are largely dependent on the performance of HVAC systems. However, the pressure loss factors available to the designer show large discrepancies depending on the source of the data. In particular there are very few data regarding the effect on k-factors of interactions between duct components in close proximity. This paper describes measurement and computational fluid dynamics (CFD) modelling of pressure loss in HVAC system components. The results were compared with those data given in the ASHRAE and CIBSE guides.

LIST OF SYMBOLS

A	Area of the duct [m^2]
C	Concentration of tracer-gas [ppm]
ΔP_m	Measured pressure difference across the duct fitting [Pa]
ΔP_s	Actual pressure difference [Pa]
k	k-factor
P_k	Kinetic pressure [Pa]
q	Tracer-gas injection rate [m^3/s]
ρ	Density of air [kg/m^3]
V_1	Air velocity before duct fitting [m/s]
V_2	Air velocity after duct fitting [m/s]
V	Air velocity in the duct [m/s]

1.0. INTRODUCTION

Indoor air quality, thermal comfort and energy use in buildings are largely dependent on the performance of HVAC systems. The pressure loss of ductwork supplying air to various zones can be calculated using computer models which incorporate pressure loss factors (k-factors) for duct fittings based on data given in the CIBSE guide "Reference Data" (1), and ASHRAE handbook "Fundamentals" (2). However, there are significant discrepancies concerning these data which can result in inaccurate sizing of fans used in HVAC systems and wastage of fan energy.

There are differences of up to several hundred percent between values quoted in the CIBSE and ASHRAE guides. In addition, they do not consider the interaction of duct fittings and they do not include many duct fittings used in HVAC systems. Designers are forced to make "intelligent guesses" for some k-factors used in their calculations. There is clearly a need for an expanded and accurate guide for k-factors of HVAC system components.

Data given by the CIBSE and ASHRAE guides have been determined experimentally using traditional instrumentation such as pitot tubes and orifice meters. These measurements can be greatly distorted by the size or geometry of ductwork, obstructions to the airflow or a high level of turbulence. Tracer-gas techniques offer an alternative approach for measuring airflow in ducts and can be used to provide accurate measurement of flow rates over a wide range of velocities without the requirement for a long duct length for the development of fully developed flow. The techniques are easy to use and have been successfully applied to airflow measurements in HVAC systems (3, 4).

The experimental approach for obtaining k-factors requires that ducts and duct fittings are built and assembled for each test; this could be costly if a wide range of fittings is to be tested. Computational fluid dynamics (CFD) can simulate duct flows accurately using the k-ε or Reynolds stress models commonly employed in existing CFD packages (5). Furthermore, the numerical simplicity associated with modelling the components, which have relatively regular shapes and simple boundary conditions, also assists the accurate application of CFD.

This work examines the application of tracer-gas and CFD methods for estimation of k-factors of HVAC system components.

2.0 THEORY

2.1 k-Factors

When a fluid, such as air, flows through a duct containing duct fittings there is inevitably an energy loss due to factors such as friction and turbulence. The energy loss is manifested as a loss of static pressure across the duct component, ΔP_s. The magnitude of the static pressure loss can be shown to be proportional to the kinetic pressure in the duct, P_k. The k-factor (k) is defined such that:

$$\Delta P_s = k\, P_k \quad (1)$$

In order to determine the k-factor for any given fitting both ΔP_s and P_k need to be determined experimentally for a range of flow rates.

In cases where there is a change in area between the two static pressure tappings, the resulting change in kinetic pressure must be accounted for as follows:

$$\Delta P_s = \Delta P_m - 0.5\rho(V_2^2 - V_1^2) \quad (2)$$

2.2 Tracer-Gas Techniques

Throughout the experimental work the constant injection technique was used. In this method tracer gas is released at a constant rate, q. The concentration, C, of tracer gas is then measured downstream of the injection point. The flow velocity, v, can then be calculated using:

$$v = q/CA \quad (3)$$

where A is the area of the duct. The kinetic pressure can then be determined from:

$$P_k = \rho V_2^2/2 \quad (4)$$

where ρ is the density of air. The value of ΔP_s can be determined directly by the use of a manometer. The k-factor for the given component can then be calculated from (1).

2.3 Pitot Tube Technique

A pitot static tube in conjunction with a manometer can also be used to measure the flow velocity, although a traverse is needed in order to achieve an accurate value for the mean flow velocity. The pitot tube measurements were carried out at standard positions following the method described by CIBSE guide (1). The k-factor can then be calculated in the same way as for the tracer-gas technique.

3.0 EXPERIMENTAL

Fig. 1 shows a schematic diagram of the experimental set-up for use of tracer gas techniques. The injection rate of SF_6 was governed by the mass flow controller to be 1 litre per minute during the experiments. The use of a reservoir allowed the flow to be consistent. A sampling tube was placed into the duct to pump a sample from the duct through the gas analyser. The flow rate was controlled and filtered in order to allow the gas analyser to work accurately. An analogue manometer was used to measure the pressure difference between 8 pressure tappings across the double bend. For the pitot tube measurements a simple traverse was used, and a mean value for the flow velocity was calculated using the same values from the static pressure tappings as for the gas analyser method.

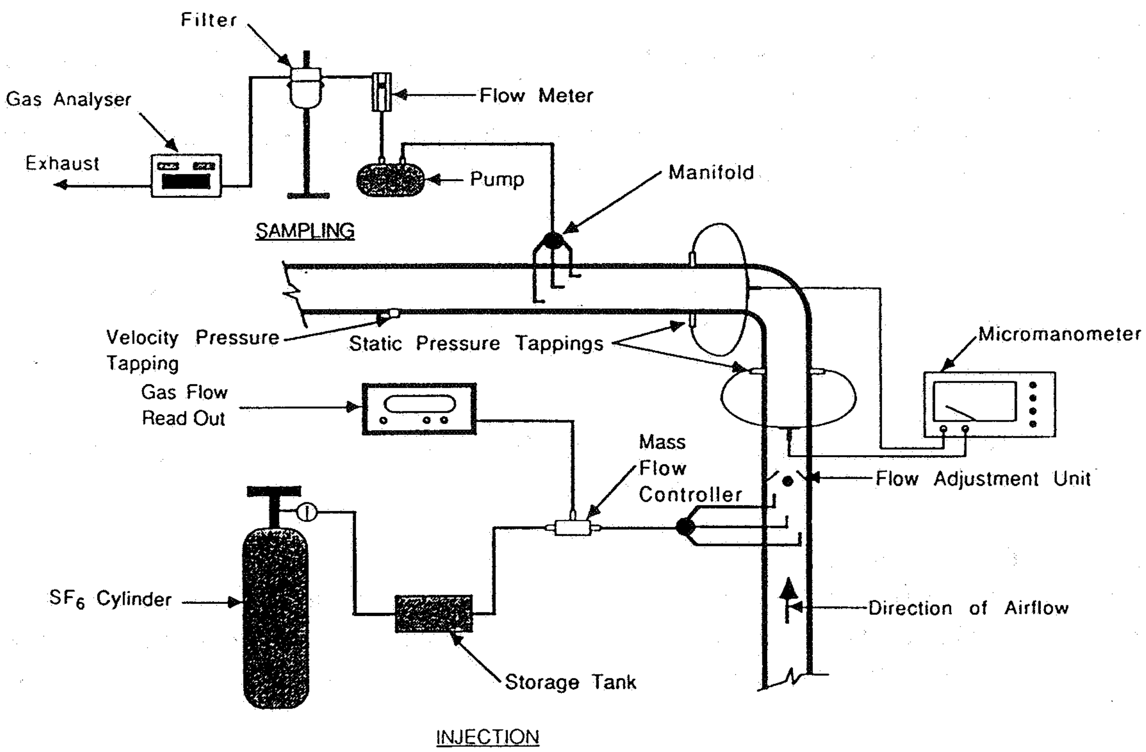

Fig. 1 Instrumentation for the constant-injection tracer-gas technique

4.0 RESULTS AND DISCUSSION

A large number of experiments were carried out to assess the effect of the distance between two 90-degree bends on the overall k-factor. Both the pitot tube and the tracer-gas technique were employed to provide a comparison between the two methods.

Figures 2 shows the relationship between ΔP_s and P_k over a range of duct flow rates for distances between the bends of 1.0m. The results from the pitot tube and the tracer-gas technique are displayed together in each case. In each case the value for ΔP_s is the mean value for the tappings at 25mm, 40mm, 55mm and 70mm from the bend. These points were selected since closer to the bend the flow is separated from the inside wall of the duct causing a lowering of the static pressure, and hence an error in the k-factor calculated. Further away from the bend the effect of friction from the duct would start to become important, and entrance effects might also cause errors if readings were taken closer to the inlet.

It can clearly be seen that the relationship between ΔP_s and P_k is linear, and passes through the origin, as the theory for k-factors suggests. Least squares regression has been

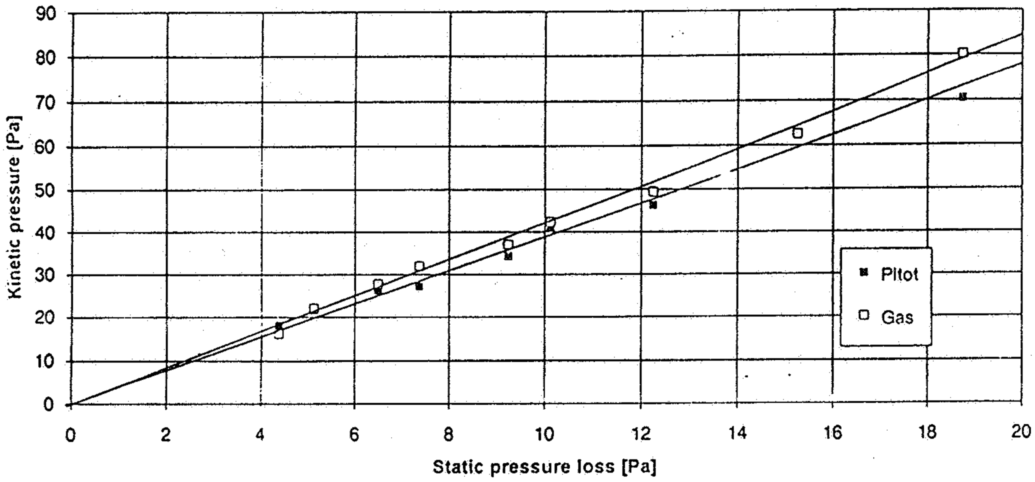

Figure 2. Pressure loss for two 90 degree bends 1.0m apart.

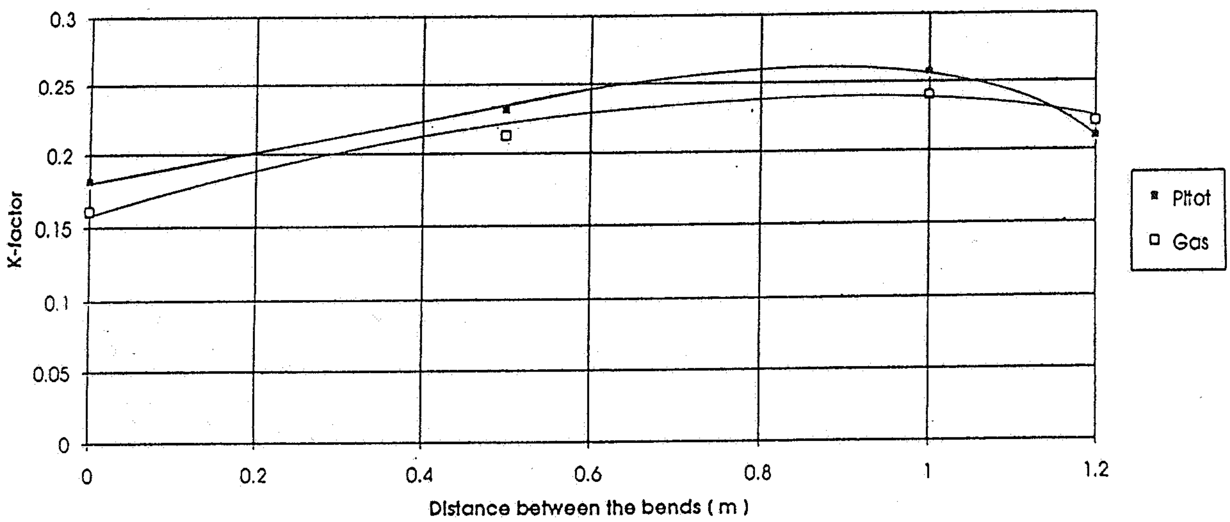

Figure 3. Variation of k-factors with distance between two 90 degree bends.

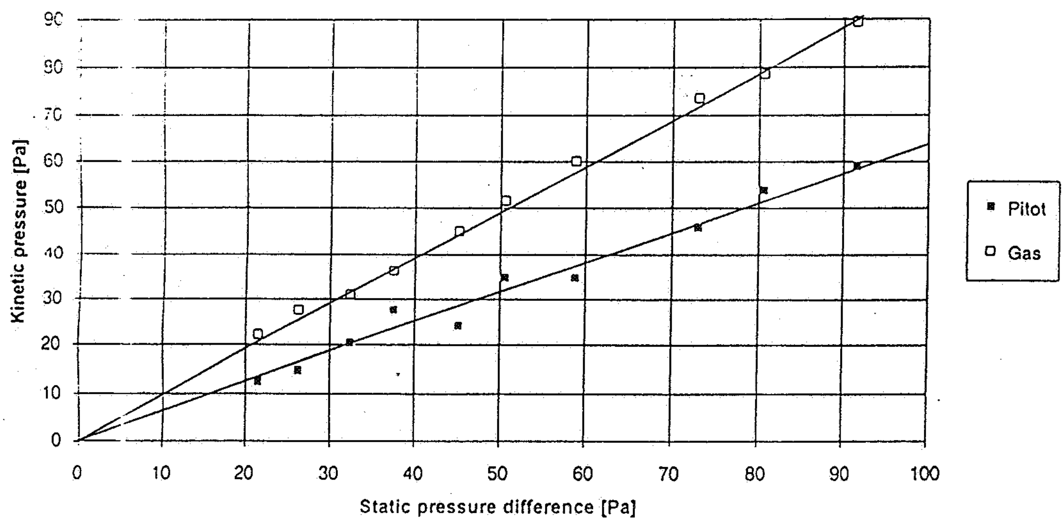

Figure 4. Pressure loss for a contraction followed by an expansion 1.0m apart.

applied to the data for each experiment in order to determine the k-factors. Figure 3 shows a chart of the variation of k-factor with distance between the two bends and Table 1 shows these results in tabular form along with the values quoted in the CIBSE and ASHRAE guides. The product moment rank correlation coefficient, R^2, is also shown as an indication of the closeness of the experimental data to the given straight line.

Figures 4 shows the relationship between ΔP_s and P_k over a range of duct flow rates for a contraction followed by an expansion respectively. In each case the reduction in area was of 50%. As for the 90 degree bends a mean value for the pressure drop was assumed. Although the actual pressure drop needed to be calculated as shown in section 2.1. The same pressure tappings were also used.

Table 1. k-factors from the measurement and ASHRAE and CIBSE guides

Distance apar of bends	Gradient		K-factor				R squared	
	Pitot	Gas	Pitot	Gas	CIBSE	ASHRAE	Pitot	Gas
0	5.507426	6.213388	0.181573	0.160943	0.25	0.24	0.977	0.985
0.5	4.33172	4.70437	0.230855	0.212568	0.23	0.26	0.941	0.96
1	3.886418	4.163717	0.257306	0.24017	0.23	0.26	0.994	0.995
1.2	4.76345	4.535674	0.209932	0.220474	0.23	0.26	0.921	0.987

From the experimental data it can be seen that:

i) The distance between two 90 degree bends does have an effect on the overall k-factor for the bend. This effect is of a parabolic nature. Neither the CIBSE or ASHRAE guides give a different value for the k-factor in this range, except for a full 180 degree bend with no separation, where ASHRAE give a small reduction in the k-factor, and CIBSE a small increase.

ii) The tracer-gas method gives a closer fit to a straight line than the pitot tube technique. It is therefore likely that the tracer gas results are more accurate. This is probably due to the fact that the tracer gas levels can be averaged over a long time period giving more reliable results while the pitot tube measures the velocity at 9 points and these are averaged.

iii) The tracer-gas method give a lower value (between 3.5 to 10% lower) for the k-factor than the pitot tube method. This is most likely due to the error caused from placing the pitot tube into the air flow, thus increasing the air flow rate locally around the pitot tube.

iv) Both the pitot tube and the tracer gas methods show that the k-factor is significantly reduced when there is no separation between the bends. Neither CIBSE or ASHRAE quote such a reduction, CIBSE even quote an increase. The error between the experimental tracer gas results and the value quoted by CIBSE is 36%. This is significantly large, especially considering it is only for a single component. It is true, however, that both the CIBSE and ASHRAE values are quoted for all bend geometries and are therefore an average of the k-factors for a large number of bend sizes. The experimental data presented here is only for a single geometry (that of a bend radius 1.5 times the duct width). Further experimentation would be required to ascertain whether the CIBSE and ASHRAE mean values are sufficiently accurate.

v) For the contraction the CIBSE value takes no account of the reducer angle; the k-factor is therefore at best only an approximation. The ASHRAE value for the particular geometry used in the experiments is similar to that obtained.

vi) Neither CIBSE or ASHRAE provided tables on the interactions between reducer and enlargement components. The best table available is the one used for interactions between two bends.

5.0 COMPUTATIONAL FLUID DYNAMICS SIMULATION

The computations were performed using the commercial flow simulation software FLUENT. The Reynolds stress terms in the averaged Navier-Stokes equations were computed using the standard two-equation k-ε model and in the region of low Reynolds number close to the walls, wall-functions were used instead. Most HVAC ducts have aspect ratios between 1 and 4, in which case, all sides of the duct exert significant influence on the character of the duct flow. It is therefore necessary to treat the simulation as a three-dimensional problem. The duct fittings examined in this CFD study are identical to those used in the experimental study described above. The assumption was made that during the computation, air velocity distribution at the entrance of a duct is uniform (6m/s) and that the flow direction is normal to the inlet cross-section. As the air enters and moves along the duct, the uniform velocity distribution gradually changes into a fully developed profile. The length over which this change is completed is referred to as the entrance length, where the friction and pressure loss are larger than in the fully developed parts of the duct. To avoid the entrance length effect interfering with the effect of the bend, the section of duct upstream of the bend must be long enough to allow the velocity profile to develop fully. An upstream duct length of 20 duct widths was used. A three-dimensional body-fitted co-ordinate (BFC) grid was used to allow accurate representation of the smooth curved bends, the axis of which form an arch with a radius of 0.3m, in the computational domain. Using the Cartesian grid system in such cases would mean that the curved duct walls be approximately modelled by a series of steps, which would cause great distortion of the flow patterns and pressure loss characteristics of the bend. The Navier-Stokes equations were discretised by a finite volume method and solved using the SIMPLE algorithm.

Fig. 5 shows the pressure contours in the double-bends described previously. The separation between the bends are, for the assemblies from top to bottom, 1.2m, 1.0m, 0.5m and 0m, respectively. Each contour line along the duct marks a further amount of pressure fall which is approximately 2 Pa. Clearly, the pressure drop in the vicinity of the bend is far greater than anywhere else in the duct. As can be seen, the pressure contour patterns in the two bends for the 1.2m-separation case are very similar to that of the 1.0m case. As the separation reduces to 0.5m, some of the contour lines in the two bends join together, but other parts of the contour patterns, including that before the upstream bend and that after the downstream bend, remain largely unchanged. This indicates that the pressure loss in the double bend is not affected by the shortening of the separation. As the separation falls to zero, more contour lines join together but the contour pattern before the upstream bend and that after the downstream bend are still relatively unaffected. Obviously, the pressure loss across the four double bends would be rather similar, which is borne out by examination of the detailed pressure loss data in the flow fields. The relative difference between the largest and smallest of the four pressure losses is less than 6%, which agrees quite well with the experimental results for double bends with separations 1.2m, 1.0m and 0.5m. The measured pressure loss of the double bend with 0m separation is, however, much smaller than the other

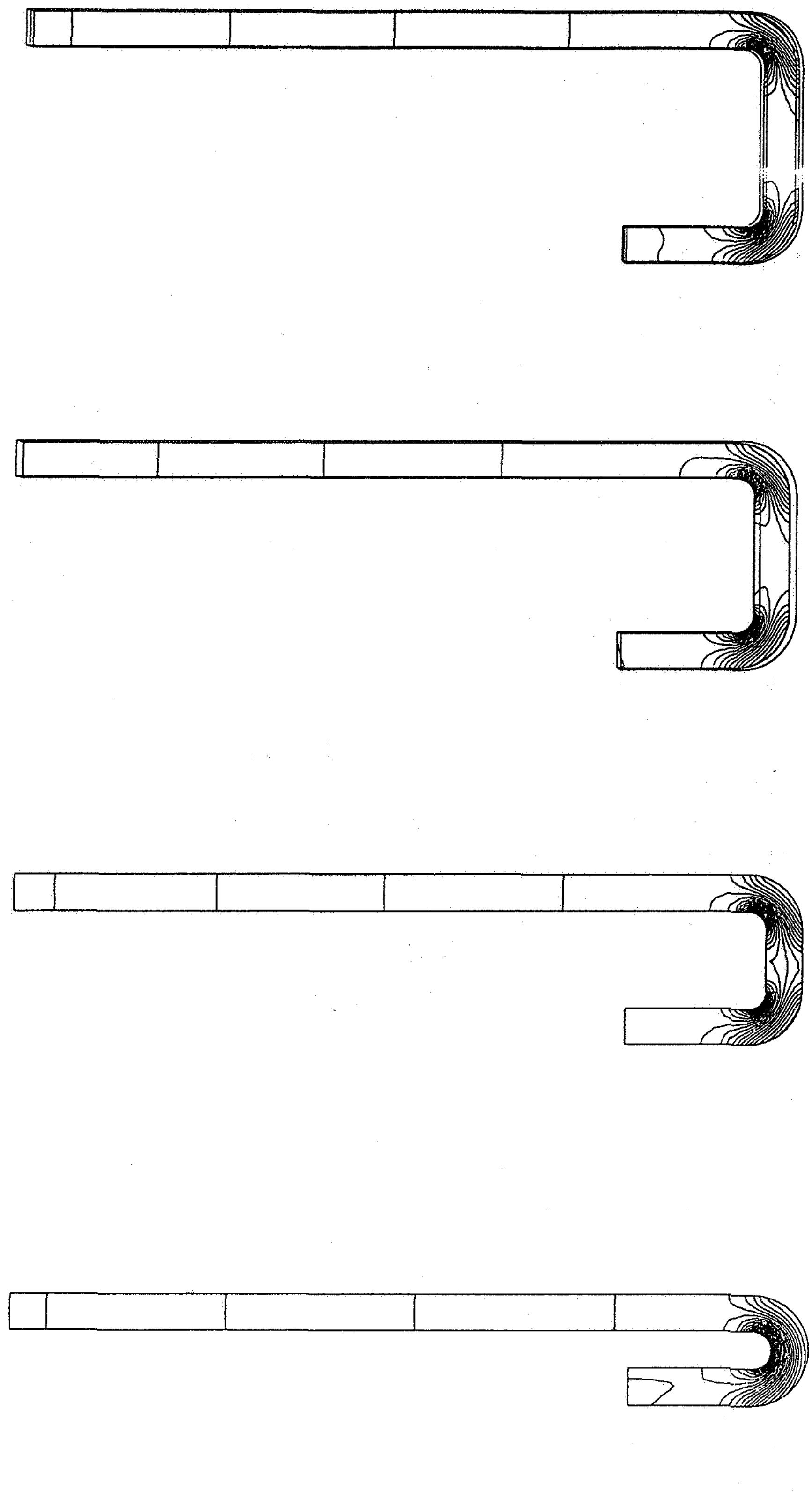

Figure 5. Pressure contour patterns in double-bends

three, with relative difference of about 33% based on the largest pressure loss at 1.0m separation. The trend predicted by CFD is in very good agreement with the CIBSE and ASHRAE data, as shown in the sixth and seventh column of Table 4.1.

6.0 CONCLUSIONS

The experimental data acquired thus far show that there is a relationship between the k-factor and the separation between two 90 degree bends. Furthermore, there is a significant reduction of the k-factor as the distance between the bends becomes small. Although the ASHRAE and CIBSE data do give an allowance for this reduction, it appears that the change is greater than that quoted in the guides. Further work would be required to ascertain whether this is true for all configurations, or just those used in the current experiments.

The experiments with the reducer-enlarger combination have demonstrated that there is considerable interaction between duct components, and that this interaction can have a large effect on the overall k-factor. Neither ASHRAE or CIBSE give data on such effects. The interaction effect between reducers and enlargements is significantly different from that for two 90 degree bends. Further work would be required to determine how individual components are affected by the proximity of other components.

The CFD method has been used to predict k-factors of double bends of various separation distances. Flow fields in duct fittings were simulated by solving the three dimensional Navier-Stokes equations with body-fitted co-ordinate grids, the k-ε model and a finite volume method. It was found that variation of the separation distance between the double bend causes only minor changes (6%) in its k-factor. This result agrees well with the CIBSE and ASHRAE data and, except for one measurement point (zero separation), also agrees well with the experimental data reported above. It should be pointed out however, that the accuracy of CFD and the consistency of the agreement need to be verified by studying interactions of other types of duct fittings.

7.0 REFERENCES

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