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BRIEF COMMUNICATION

PRESSURE LOSS THROUGH RETURN BENDS IN AIR–SOLID FLOWS

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1. INTRODUCTION

Return bends are widely used in pneumatic conveying systems for structural purposes, as parts of expansion joints or as means of bypassing other equipment. Pressure losses in these bends are higher than an equivalent straight pipe, because of the change in the direction of fluid and solids, the impact of solids on the walls of the pipe and the subsequent reacceleration of solid particles.

Studies on the effect of pipe fittings on the conveyed air–solid mixtures are sporadic in the scientific literature. Flows through 90° bends and elbows enjoy the lion's share of studies, because such fittings are most commonly used. Investigations on venturies, orifices and double branches also appear. A small number of data on return bends appear in the paper by Uematu & Morikawa (1961) together with the derived correlation:

$$\zeta_{bs} = 0.828\, m^*, \quad [1]$$

where ζ_{bs} is the additional pressure-loss coefficient due to the solids and m^* is the solids loading.

Usually, in design calculations it is assumed that the pressure drop in a return bend is twice that which is due to a 90° bend. This is a gross approximation because the pressure drop in the 90° bends includes a component due to the reacceleration of solids, and the latter may not be given as a constant multiple of the reacceleration in return bends. In addition, the flow field is different in the return bends, there are more particle collisions with the walls, and the effects of three-dimensional varieties are more pronounced downstream.

The present study was prompted by the demonstrated need for more experimental data on the flow of air–solid mixtures through return bends.

This paper describes the experimental facility used, the method of obtaining the total pressure loss due to the bend, and presents the final correlation of the data. The complete set of data and more details about the experimental facility and the instrumentation used may be found in the thesis by Lai (1985).

2. DESCRIPTION OF THE EXPERIMENTAL FACILITY

Equipment

The experimental facility used is of the vacuum type and is shown in figure 1a. Air enters through the nozzle, N, and solid materials fall from a hopper, H. The flow of solids is controlled precisely with an electromagnetic motor-feeder, F, which assures constant mass flow rate of solids in the pipe. The solid matter falls through a special T-section, which assures uniform flow of both phases. The pipeline after this T-section is made of steel with i.d. 40 mm; a straight length of this line (9.2 m) assures the complete acceleration of solids, before the mixture enters the bend. Actually, the pressure data showed that solids were completely accelerated after about 3.2 m downstream of the T-section (80 pipe diameters).

The bends were manufactured by special order, to ensure uniform internal diameter, constant curvature and roundness. Three bends were used in the course of the experiments; their radii of

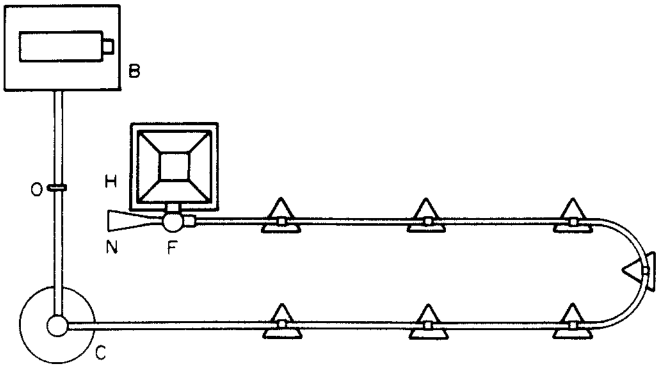

Figure 1a. The experimental facility.

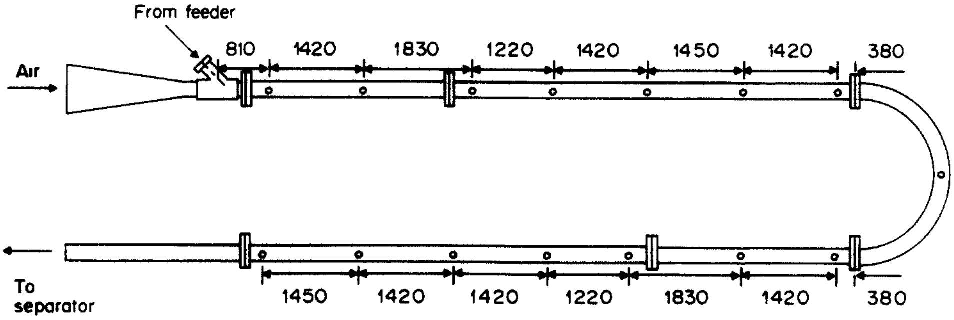

Figure 1b. Positions of the pressure transducers (distance in mm).

curvature were: 0.30, 0.61 and 1.22 m. Downstream the bend, another straight length of pipe conveyed the mixture to a cyclone separator, C, fitted with a filter for the removal of the solids. The air alone then passed through an orifice plate, O, where its rate was measured and subsequently discharged in the laboratory via a 3 hp air blower, B, fitted with a bag filter. The air flow rate was regulated with a gate valve before the blower (not shown). The triangular elements shown in figure 1a around the loop are projections of stands, approx. 1.2 m height. The planes of the U-bends were always horizontal.

Instrumentation

The solids feeder was calibrated with a balance for each one of the solids conveyed, and the calibration curve was checked at the end of the experiments. The air flow rate was measured with an orifice plate fitted according to the ASHRAE standards (1981). Its coefficient of discharge was verified with a pitot tube. Pressure was measured in 14 locations (7 upstream and 7 downstream the bend) with semiconductor absolute pressure transducers. The positions of the transducers are shown in figure 1b. For higher accuracy, each one of the transducers was calibrated in the range of pressures it was used. The transducer calibrations were linear with very high correlation coefficients; the calibrations were checked again at the end of the experiments. The transducers' output was collected in a Monitor Labs logger and then directed to a computer where reduction of the data was accomplished.

The solids conveyed

Five types of solids were conveyed: lucite pellets, wax beads, sand, wheat and corn. The sizes were medium to coarse, but sand had a great number of fine particles. Only wax beads had spherical

Table 1. Properties and dimensions of particles conveyed

	Density (kg/m^3)	Average diameter (mm)	Shape
Lucite	1200	2.5	Prismatic
Wax	800	1.0	Spherical
Sand	2600	0.5	Irregular
Wheat	768	3.0	Ellipsoidal
Corn	720	5.0	Trapezoidal

shape; and sand particles had irregular shape and lucite pellets were prismatic. Minor breaking-up of the solid particles occurred during the experiments, but subsequent analysis of the data did not show any significant effect of breaking in the final results. The properties and dimensions of solid particles are given in table 1.

3. INTERPRETATION AND REDUCTION OF DATA

The transducers attached on the pipe give the whole pressure profile and enable the investigator to distinguish the solids acceleration region, the straight-pipe pressure gradient upstream, the pressure drop in the bend, the recovery region where the solids are reaccelerated and the pressure gradient in the straight pipe downstream the bend. These regions are shown in figure 2a and the profile of actual measurements is shown in figure 2b. The total pressure loss due to the bend ΔP_b is also shown in figure 2a. It is apparent that it consists of the pressure drop inside the bend and that due to the reacceleration of the solid particles and air downstream the fitting; for this reason, the whole pressure profile is used for the evaluation of ΔP_b.

In order to minimize transient effects and pressure fluctuations in the system, all the transducers were scanned 15 times during each run, and the readings were transmitted to the VAX computer. The duration of each scan was < 1 s, and scans were regular and about 10–15 s apart. The time average of each transducer's reading and the standard deviation of it were calculated. If the deviation exceeded 0.5%, the data were discarded because of the high-pressure fluctuations in the pipe, and the experiment was repeated. Thus, steady state and smoothness in the pressure profile was assured.

From the pressure profile, the straight lines due to the pressure gradients in the straight parts of the pipe were obtained with a least-square fit method. For the calculation of these gradients, the transducers in the acceleration and recovery regions were excluded as well as the last transducer upstream the bend; it was found that the latter was influenced by the presence of the bend and recorded lower pressures. Such observations of the influence of the bend on the upstream flow were made in other similar experiments (Degliobizzi *et al.* 1983; Mikhail *et al.* 1981). Thus, the pressure drop through the bend ΔP_b was obtained by taking the tangent lines to the pressure profile as shown in figure 2a.

All the experimental data on ΔP_b, and solid flow rates and other details of the calculation methods are reported in the thesis by Lai (1985).

4. CORRELATION OF DATA

A preliminary analysis of the data revealed that the total pressure drop ΔP_b is best correlated if it were expressed as the sum of two functions. The first represents the losses due to the air alone,

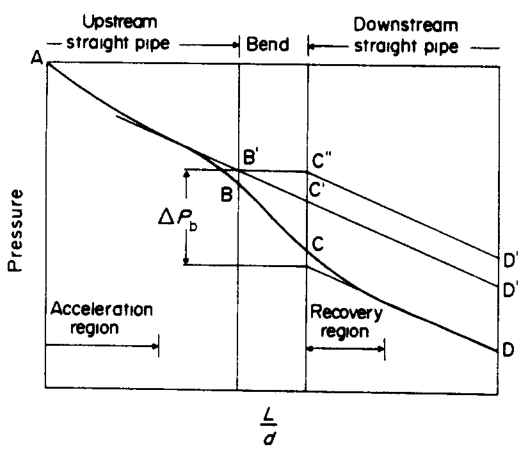

Figure 2a. Pressure drop, acceleration and recovery region.

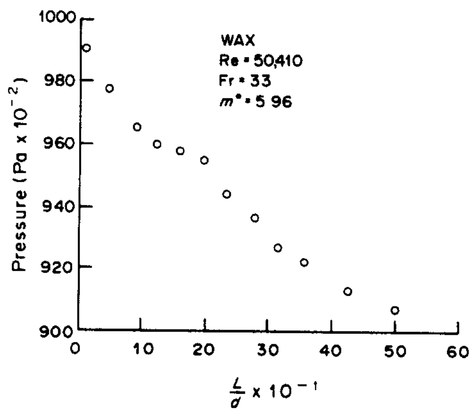

Figure 2b. Typical profile.

and the second is related to losses due to the presence of solid particles:

$$\zeta_b = \frac{\Delta P_b}{\frac{1}{2}\rho_a U^2} = \zeta_{ba} + \zeta_{bs} = f_1\left(\frac{r}{R}, \mathrm{Re}\right) + f_2\left(m^*, \mathrm{Fr}, \frac{r}{R}, \frac{\rho_s}{\rho_a}, \frac{r_s}{r}\right), \qquad [2]$$

where r is the radius of the pipe, R is the radius of curvature of the bend, r_s is the equivalent radius of the particles, U is the air superficial velocity, m^* is the loading, Re is the Reynolds number of the flow ($\mathrm{Re} = 2\rho_a rU/\mu$), Fr is the Froude number ($\mathrm{Fr} = u/\sqrt{gd}$), ρ_s is the density of the materials, ρ_a is the density of the air and μ is the viscosity of air.

Since only dimensionless numbers are used, the proposed correlation is valid in all systems of units. Furthermore, ζ_b, ζ_{ba} and ζ_{bs} may be considered as pressure-drop coefficients for the mixture, for the air alone and for the additional pressure loss due to the solid particles.

The correlation of all the data was achieved with the aid of multivariable linear regression subroutines and graphical output which indicated the regression model to be followed (e.g. form of the function and functional relationships). The final forms of the functions f_1 and f_2 are as follows:

$$\zeta_{ba} = f_1 = 86624\,\mathrm{Re}^{-1.035}\left(\frac{R}{r}\right)^{0.241} \qquad [3]$$

and

$$\zeta_{bs} = f_2 = 0.0514\, m^{*0.681}\,\mathrm{Fr}^{-0.359}\left(\frac{R}{r}\right)^{0.369}\left(\frac{\rho_s}{\rho_a}\right)^{0.128}\left(\frac{r_s}{r}\right)^{-0.695}. \qquad [4]$$

These correlations are valid for the range of Froude numbers from 15 to 60, ($24{,}000 < \mathrm{Re} < 95{,}000$) and for big solid particles such as those given in table 1.

Figure 3 shows the observed and calculated results for the total pressure drop ΔP_b. The average deviation for the set of data is -3.34×10^{-4}, and the average absolute deviation is 0.16. These deviations, although high for single-phase flows, are quite acceptable in flows of complex mixtures and especially air-solid flows were a large number of uncontrolled parameters act (Martin & Michaelides 1985).

Comparisons of the data and correlation in the present study were made with the correlation by Uematu & Morikawa (1961). In general, there is fairly good agreement between the two studies at low and intermediate loadings as may be seen in figure 4. The two correlations diverge at higher loadings where the present set of data strongly support nonlinear behavior with respect to m^*. A comparison was made with the correlations of 90° bends, as reported in Morikawa *et al.* (1978).

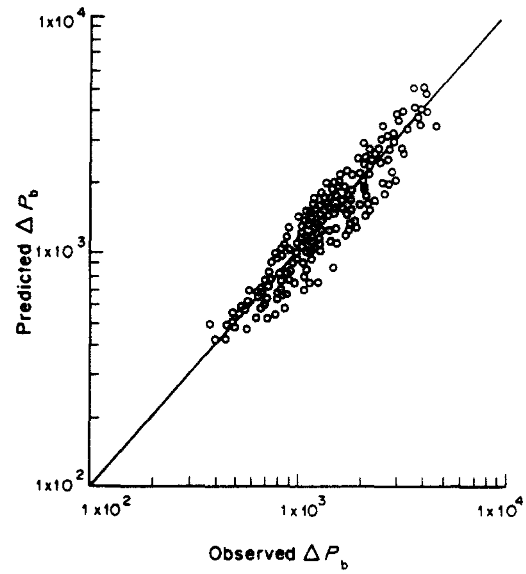

Figure 3. Experimental vs predicted pressure drop (using [1]–[3]) for all experimental data.

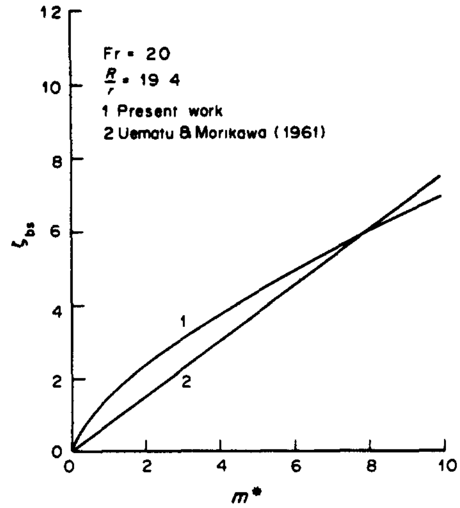

Figure 4. Comparison of the two correlations.

A second comparison was made with the correlation by Marcus *et al.* (1984). It was observed in both cases that the excess pressure loss due to a return bend is always less than twice the pressure loss due to a 90° bend. This observation supports the view that return bends cannot be treated as two 90° bends in tandem.

5. CONCLUSIONS

The experiments conducted for the determination of the pressure loss in return bends showed that this pressure loss is best correlated as the sum of two quantities: (a) excess pressure loss due to the air alone; and (b) excess pressure loss caused by the solids. The first is a function of the curvature and the Reynolds number; the second is a function of the curvature, the solid properties and dimensions, the Froude number and the loading. The data were obtained from the whole pressure profile in the experimental loop; several readings of the pressure profile were obtained to ensure steady-state operation and minimization of the fluctuations' effects in the final results. Calculations revealed that ΔP_b for a return bend is less than twice the corresponding quantity obtained from 90° bends.

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