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An experimental and numerical study of two-way splits and junctions in mine airways

R.K. Jade
Anna University, Chennai, 600025, India

B.S. Sastry
Indian Institute of Technology Kharagpur, 721302, India

ABSTRACT: Although several studies in combining and bifurcating flows in two-way junctions and splits are reported, deviations persist in the estimated shock loss coefficients (SLCs). Due to their complex nature, more work has to be done to be able to correctly predict flow losses at these locations. In two-way splits, the flow at bifurcation is known to be characterized mainly by two recirculating zones in the downstream branches, whereas, in a junction one recirculating zone is observed immediately downstream of the main branch. The relative flow rate in the branches (quantity ratios) is treated as the only parameter defining the losses at these locations. However, the effect of wall roughness, if any, on SLCs becomes important for mine ventilation. This paper presents the critical determinants of shock losses at splits and junctions at varying quantity ratios. The flow at 90º split and junction was examined both experimentally and numerically for Reynolds number in the range of 1.0×10^4 to 1.6×10^5. With a well designed laboratory setup, using precision instruments, velocity and pressure measurements were carried out, by using two scales of wall roughness. 3D numerical simulations for these experiments were conducted by using ANSYS CFX modeling tool. CFD simulations yielded results that are reasonably close to experiments, providing high degree of satisfaction in numerically predicting losses across the splits and junctions. However, comparisons of these numerical simulation results with existing literature standards showed significant under-estimation of shock losses by the standard literature by as much as 50%. A clear rise in the magnitude of shock losses was noted in both the approaches, with increased wall roughness. Based on the current studies, predictor equations incorporating quantity ratios are developed for accurate estimation of shock losses. Further investigations on roughness are needed, before one is able to incorporate wall roughness into the prediction of SLC.

1 Introduction

Underground ventilation serves many functions, in addition to the modest requirements for sustenance of human life. Because of the extent of the demand and the distance that air must travel from the surface to the working face, ventilation may become complicated and costly. As air travels from the surface to the workings and back, energy transitions and losses are involved in such a process. Of prime importance, hence, is the accurate determination of these energy losses.

The energy supplied to flow accounts for overcoming losses, changes in pressure, temperature, momentum, and elevation of the fluid. The flow in underground involves every feature of the fluid physics, simple or complex. Frictional loss component is well established and can be precisely defined. Frictional formulations are relatively reliable in their application to underground scenarios. In addition to linear friction losses, shock losses occur at places of change in the direction of airflow, area changes, division or combination of air currents or obstructions within the airflow. In case of shock loss, the complexity of flow phenomenon has revealed little to be defined in precise mathematical terms. For cases like bend, area change, obstruction, split and junction, the shock loss coefficient (SLC) are typically established on the basis of scale model studies or by using numerical simulations. The SLC depends upon relative dimensions and flow characteristics. Hence, every geometry in underground ventilation system leading to creation of shock loss needs critical evaluation of the governing parameters.

Estimation of minor or shock losses in mine aerodynamics has been an area mostly dependent on empirical knowledge. One can only make use of findings derived from scale model studies that replicate real life situations of shock losses as closely as possible. These findings from scale model studies become useful provided the laws of geometric and dynamic similitude are maintained between scale model investigations and real world phenomenon.

The present paper highlights the shock loss investigations for air flow in rectangular 90^0 airway intersections. The investigations involved splitting as well as combination of air flows at intersections.

2 Shock Loss Estimation

The shock loss can be measured directly or can be interpreted by indirect methods. An indirect way of incorporating shock loss in the total loss is by to the frictional loss in the airway. In the direct methods the shock loss is expressed in terms of number of velocity heads expended in the flow process. This number is known as the shock loss coefficient.

In case of shock loss, the loss coefficient is given as:

$$X = \frac{\text{Pressure Head Loss}}{\text{Velocity Head}} = \frac{\Delta P}{(\frac{\rho v^2}{2})} \qquad (1)$$

where X is shock loss coefficient of the design geometry; v is flow velocity; ρ is fluid density; ΔP is pressure loss contributed explicitly by shock source. The X value, which is the shock loss coefficient, is dimensionless and is considered a constant for a particular set of conditions.

3 Factors Governing Shock Loss

The shock loss is observed to be a function of the Reynolds number (Re), wall roughness, compressibility, geometric parameters and flow parameters. The total shock loss can be attributed to ordinary duct friction and true form loss.

In the laminar and transient flow regimes the shock loss is found to be a function of geometry and Re (Jamison and Villemonte, 1971). However, in the turbulent zone, this loss is independent of Re (Hecker, 1977, Benedict, 1980, Vazsonyi (page 372, Benedict, 1980)), although the geometric aspect always dictates the flow losses.

In case of junctions or splits, the mean velocity of flow is observed to cause no change in the SLC. However, from the existing literature studies it is observed that the relative ratio of velocities in the branches governs the losses in respective branches.

Hecker, et. al. (1977) and Bernhard and Hsieh (1996) observed that the condition of the bounding wall surface, which relates to the complex size, shape, and spacing of the protrusions on the inner wall of a pipe, directly changes the velocity profile shape. Powe and Townes (1973), Calizaya, et. al. (1991), Taylor, et. al. (1993) and Rij, et. al. (2002) demonstrated the effect of geometrical aspects of protrusions and their orientation on the nature of flow profiles. Pigott (1950) established that the SLC is found to vary with relative roughness in case of bends and postulated that these changes were principally due to changes in velocity profile because of roughness elements.

The geometry parameters of flow configurations influence the form loss. For the splitting or joining of flows, the geometry is defined by angle of branching, area of each branch, shape of opening, width/height ratio, and radius ratio at edge of branching. In estimating pressure loss for an application, the geometric configuration should be similar to that of the pilot-scale models.

The total shock loss for all types of incompressible flows is independent of type of fluid (Benedict, 1980). The SLC for compressible flows were higher by as great as 30% above those of constant – density fluids (Benedict, 1966).

In a split or junction, the form loss is found to be a function of aspect ratio, velocity ratio, deflection angle, area ratio, relative roughness of the wall, and Re.

4 Literature Studies

Considering the above interdependent factors governing shock loss, researchers have worked on the determination of SLC for the commonly used designs. Shock loss is marked with disturbance in the mass flow, generation of separated regions, multiple vortices hurled in the downstream, steep pressure gradients, and prolonged regain of all flow parameters.

Research investigations on shock losses have been carried by workers from the fields of mechanical, civil, architecture, geology and mining.

Investigations in division and combination of flows by Mathioulakis, et. al. (1997), Sierra-Espinosa, et. al. (2000), Ramamurthy, et. al. (1996), Hecker, et. al. (1977), Travers and Worek (1996), Serre, et. al. (1994), Barkdoll, et. al. (1998), Peng, et. al. (1996), Rodkiewicz and Roussell (1973) focus on the change in velocity profile, turbulence parameters, secondary flows, vortices, recirculation flow characteristics, wall shear, and changes in pressure gradient at such locations. Mathioulakis, et. al. (1997), Sierra-Espinosa, et. al. (2000) Peng, et. al. (1996) Taylor, et. al. (1993) studied the mechanisms of such disturbances by using Laser Doppler Velocimetry (LDV) and visualization techniques to describe the physics of flows at intersections.

Shock loss coefficients were determined experimentally by Hartman (1982), Vazsonyi (Benedict, 1980), Ito and Imai (1973), Idelchik (ASHRAE, 1989), Jamison and Villemonte (1971) and Misra (1986). Numerical simulations were conducted by Edwards and Perlee (1977), Liu and Wang (1987), Mathioulakis, et. al. (1997), and Sierra-Espinosa, et. al. (2000). Some research workers examined the flows experimentally and modeled the same computationally to investigate the applicability of the numerical codes in simulating these flows. Efforts are made to extend the applicability of computational approach in simulating such flows in domains that are not experimented.

Investigations were carried under different flow regimes. However, the empirical relations given by Hartman (1982), Vazsonyi (Benedict, 1980), Idelchik (ASHRAE, 1989) are of significance for application to mining. The values established by Idelchik (ASHRAE, 1989) strictly adhere to certain flow and geometry relations in circular and rectangular duct flows. The work of Vazsonyi (Benedict, 1980) and Ito (1973) is applicable to circular pipe flows. Except for Idelchik, no known literature exist which deals with shock losses at three-way intersections. In the existing literature the SLC is expressed as a function of quantity ratio, velocity ratio, Re and branch deflection angle. The effect of wall roughness on shock loss is unfound in literature; perhaps, because, wall roughness is not a matter of serious consideration in fluid flow systems other than in mine ventilation.

The authors conducted investigation on flows at intersections to understand the effect of the governing parameters on shock loss. In order to replicate conditions similar to the underground mine, the shape of the opening, the aspect ratio, the surface roughness of mine openings and the Reynolds number are considered as important determinants for estimation of shock losses. A complementary blend of experimental and computational procedures was worked in the estimation of SLCs.

5 Experimental Investigations

The actual experimental setup was conceptualized by applying the laws of geometric similarity and dynamic similarity. Experiments were conducted in the mine ventilation laboratory on duct work of 20 cm x 15 cm cross-section fabricated using Plexiglas and Masonite sheets (6mm thick particle board used for light construction work) as shown in Figure 1. The wall friction of the model is defined by non-dimensionalized variable of relative roughness (e/D). Effect of roughness on SLCs was studied by pasting bubble plastic sheeting to the interior of the duct work. Using the laboratory scale ventilation fans (centrifugal and axial flow) splitting and combining flow situations were created. Figure 2 depicts the set up with centrifugal flow fan for performing experiments in combining flows. One of the side-way limbs is isolated in order to perform the two-way experiment. The experimental Re varied in the range of $1.0x10^4$ to 1.6×10^5. Using micro-manometer of precision 0.01 mm w.g and Pitot tube of dimensions 2 mm diameter, velocity head measurements are taken by precise traversing method.

The shock loss coefficient was investigated as a function of quantity ratio which is the ratio of quantity in the branch under consideration and the main branch that carries total flow. The surface roughness is also considered as another critical variable. Experiments are conducted by operating on one variable while keeping the other constant. Thus, under hydraulically smooth flows, the quantity ratio is varied from 0 to 1 for all the flow configurations.

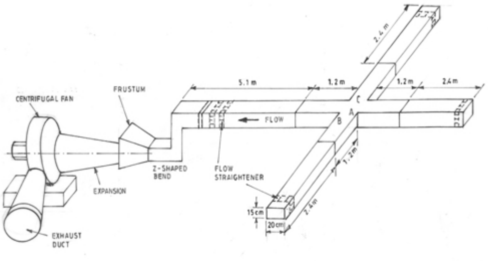

Figure 1. Experimental setup for two-way and three-way junctions

This process is followed for hydraulically rough flows for a changed relative roughness obtained by pasting the bubble plastic sheeting to the inner walls of the duct (e/D = 0.0291), the Atkinson's friction factor being 0.00795 (Figure 3).

6 Computational Investigations

Computational Fluid Dynamics (CFD) investigations were performed under conditions that replicate the experimental investigations. The flow under study was treated as incompressible, viscous, steady state and turbulent. ANSYS CFX was used to study the scope and applicability of 3D simulations to shock loss phenomena. The computational investigations were relatively of higher

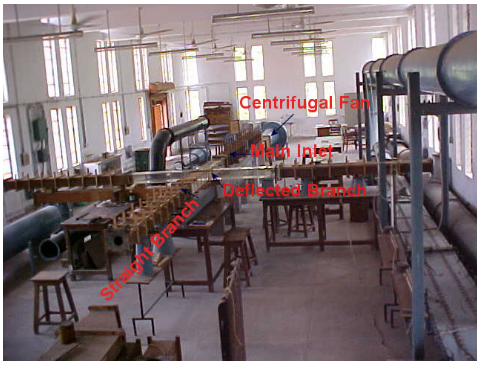

Figure 2: Laboratory setup for testing the flow in junctions and splits.

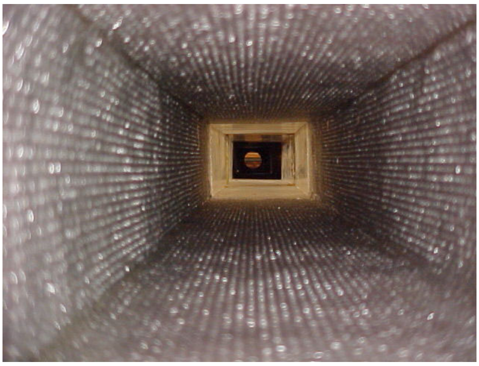

Figure 3: Inside view of the rough duct while impregnating the walls with bubble plastic.

complexity and involved typically tasks like geometry creation, mesh independence studies, rough wall simulations, input velocity profiles generation for boundary conditions, besides incurring the usually high computational time in model runs and post-processing of results. The model mesh of the two-way junctions involved 4,89,651 elements, which incorporated high mesh density near the walls and intersection. Each model had to be processed through mesh-independence study and then modification of the former till it satisfies the mesh-independence criteria. Besides this, the simulation for each model required generation of the inlet velocity profiles, which involved long processing and data-decoding time.

7 Results Summary

The shock loss coefficients are calculated with reference to the velocity pressure head in the respective branch. The SLC from the experiment is compared with that obtained from the computational analysis for smooth and rough wall flows in the case of two-way and three-way junctions and splits.

From the comparison of the shock loss coefficients obtained from the CFD and experiment for the smooth and rough duct flow, it is observed that the results of CFD agree well with experiment in the flow domain of 20% to 80% for splits as well as junctions. This is observed in case for both the branches, straight and deflected. The computational models are validated well with the experimental data. As an example, this comparison in case of two-way junctions is depicted in Figure 4.

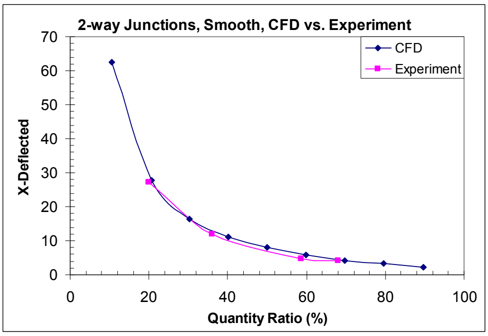

Figure 4: Computational and experimental shock loss coefficient of deflected branch for smooth ducts.

To understand the effect of wall roughness on the SLC in two-way splits and junctions, comparisons are made between the SLC values for smooth and rough conditions. The comparison reveals that around 20% increase of SLC value is observed in both branches under the roughness conditions with e/D ratio of 0.0291.

The results of SLC are compared with the literature studies of Idelchik (1989) and Hartman (1982), Ito and Imai (1973) and Vazsonyi (page 372, Benedict, 1980). A comparison of SLC of both the branches for smooth duct flow in two-way junction with literature standards of Hartman and ASHRAE are shown in Tables 1 and 2. Table 3 shows a similar comparison for the deflected branch of a two-way split.

It must be highlighted that the existing literature does not give SLC values for flow under rough conditions. The results obtained from the two tools, i.e., the experiment and the CFD were compared with the existing literature standards (Idelchik (1989) and Hartman (1982)) and other literature studies of Ito and Imai (1973) and Vazsonyi (page 372, Benedict, 1980). The comparisons were possible only with the smooth duct conditions. As an example, in case of two-way junctions, the comparison of branch SLC with literature is shown in Tables 1 and 2.

For two-way junctions, the literature underestimates the SLC substantially for both the branches by 50% or more. In case of two-way splits, the literature underestimates the SLC for the straight branch by 20% or more. However, the SLC values for deflected branch of the split are found to be near to the CFD values.

Table 1: Comparison of SLC of straight branch for smooth duct, two-way junction with literature standards.

Two-way Junction					
$Q_{straight}$ /Q_{main} (%)	X- Straight			Hartman	Idelchik (ASHRAE)
	CFD	Hartman	Idelchik (ASHRAE)	% change	% change
90	0.726	1.359	0.736	-87.3	-1.5
79	1.698	1.731	0.954	-2.0	43.8
70	2.923	2.244	1.216	23.3	58.4
60	4.973	3.047	1.595	38.7	67.9
50	8.147	4.358	2.121	46.5	74.0
40	13.793	6.743	2.848	51.1	79.4
30	24.922	11.860	4.138	52.4	83.4
20	57.157	25.996	6.445	54.5	88.7
10	210.801	99.613	14.635	52.7	93.1

Table 2: Comparison of SLC of deflected branch for smooth duct with literature standards.

Two-way Junction					
$Q_{deflected}$/ Q_{main} (%)	X- Deflected			Hartman	Idelchik (ASHRAE)
	CFD	Hartman	Idelchik (ASHRAE)	% deviation	% deviation
10	62.577	-105.156	-47.317	268.0	175.6
21	27.743	-12.997	-5.605	146.8	120.2
30	16.429	-2.618	-0.870	115.9	105.3
40	11.225	0.032	1.979	99.7	82.4
50	7.955	0.881	1.679	88.9	78.9
60	5.855	1.195	1.593	79.6	72.8
70	4.229	1.318	1.482	68.8	65.0
80	3.261	1.363	1.360	58.2	58.3
90	2.336	1.378	1.235	41.0	47.2

Table 3: Comparison of SLC of deflected branch for smooth duct with literature standards.

Two-way Split					
$Q_{deflected}$/ Q_{main} (%)	X- Deflected			Hartman	Idelchik (ASHRAE)
	CFD	Hartman	Idelchik (ASHRAE)	% deviation	% deviation
21	23.668	21.103	20.775	11	12
25	15.840	14.168	-	11	-
36	8.421	6.420	7.125	24	15
51	3.373	3.265	3.653	3	-8
62	2.488	2.431	2.508	2	-1
66	2.166	2.239	-	-3	-
72	1.975	2.011	2.117	-2	-7
80	1.657	1.838	1.887	-11	-14
99	0.788	1.636	-	-108	-

8 Conclusions

Investigations were done by conducting experiment as well as CFD modeling. These two tools were found to give similar results. Hence, the CFD models run under the similar conditions were valid and reliable to express predictions. The 3-D CFD reproduces the experimental results with good agreement.

Both the widely accepted methodologies (Hartman, Idelchik (ASHRAE, 1989)) tend to underestimate shock loss coefficient by a significant value in case of two-way splits and junctions.

Regression analysis is performed on the SLC data obtained from investigations. The predictor equation for two-way 90º splits and junctions is generated for each branch and is summarized in Table 4.

Table 4. Summary of coefficients for the prediction of SLC values

SLC[*1] for	**A**	**B**	**R^2 value**
Two-way Junction-straight branch	1.0746	-2.4985	0.96
Two-way junction deflected	2.8135	-1.3355	0.98
Two-way split straight branch	0.1835	-2.3050	0.99
Two-way split deflected branch	0.9137	-2.1075	0.99

[*1] *$SLC = Ax^B$, where x is (ratio of quantity in branch considered to the quantity in main branch)*

These predictor equations can be used with high accuracy for the turbulent flow conditions.

A pronounced increase in the SLC values is observed with the change in wall roughness. A great amount of SLC data for various scales of roughness can enable in establishing a formulation which precludes the effect of wall roughness.

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