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An experimental investigation of pneumatic swirl flow induced by a three lobed helical pipe

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ABSTRACT

This paper presents a discussion of the results and conclusions drawn from a series of experiments conducted to investigate the swirl flow that are generated by a three lobed helical pipe mounted within a laboratory scale pneumatic conveying rig. The experiments employed Laser Doppler Anemometry (LDA) to quantify the strength of the induced vortex formations and the decay rates of the observed downstream swirl flows over a range of Reynolds number in the turbulent regime. Instantaneous point velocity measurements were resolved in three directions across regular measurement grids transcribed across parallel planes located at four distances downstream of the swirl inducing pipe section. The equivalent axial, radial and tangential velocities were subsequently computed at these grids points. The degree of swirl measured across each measurement plane was expressed in terms of a defined swirl number.

It was concluded that the three lobed helical pipe gave rise to a wall jet type of swirl whose rate of observed downstream decay is related to the Reynolds number of the upstream flow and the distance downstream of the swirl pipe. The decay rates for the swirl flows were found to be inversely proportional to the Reynolds number of the upstream flow. The swirl pipe was observed to create a redistribution of the downstream velocity field from axial to tangential, accompanied by a transfer of axial to angular momentum. The findings of this paper are believed to improve understanding to assist the selective use of swirl flow within lean phase particles pneumatic transport systems.

1. Introduction

This paper presents the results of a series of experiments performed to study the downstream flow regimes created by the insertion of a three lobed helical pipe within a pneumatic flow system. Lean phase pneumatic conveying is widely used to transport suspended solid particulate materials, with particle sizes ranging from tens of microns to tens of centimetres, in a confined gas stream. The major challenges faced by pneumatic conveying systems are: the identification and maintenance of the correct conveying velocity to avoid segregation and material blockages; the optimisation of the maximum conveying velocity to reduce the resultant high pressure loss and operating costs and pipe wear (Tashiro et al., 1997; Jama et al., 1999; Herbreteau and Bouard, 2000). For a review of lean phase pneumatic flows and the associated problems, see Fokeer et al. (2004). The results of recent experimental studies have suggested that a partial solution to these problems may be achieved by locally increasing the conveying velocity within a pneumatic circuit (Li and Tomita, 2000), following an enlargement in the pipeline cross sectional area or prior to a bend in the pipeline. A practical method to locally increase the conveying velocity is to increase the turbulence of the conveying fluid by imparting a swirling motion to the flow (Chang and Dhir, 1995; Li and Tomita, 2000; Ganeshalingam, 2002). There are a number of potential swirl flow devices that have been studied by previous researchers. These include: propeller type swirl generators (Zaherzadeh and Jagadish, 1975; Bali and Ayhan, 1999), tangential slots (Hay and West, 1975), honeycomb structures (Nishibori et al., 1987), and inserts of twisted tapes, wires or tubes mounted within the inlet to a pipe section (Narezhnyi and Sudarev, 1975; Algifri and Bhardwaj, 1985).

1.1. The anatomy of swirl flows

Kitoh (1991) and Martemianov and Okulov (2004) have suggested that the method of swirl generation can play an important role in the production of different types of swirl and axial vorticity profiles. Nevertheless, the basic characteristics of a swirling flow are a combination of primary and secondary flows. The primary flow component being parallel to the downstream flow direction, and the secondary flow component being a circulatory fluid motion about the axes of symmetry of the pipe, parallel to the primary flow (Chiu and Seman, 1971). The combination of these two flows

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Nomenclature

u	mean velocity in the x-direction (ms^{-1})
v	mean velocity in the y-direction (ms^{-1})
w	mean velocity in the z-direction (ms^{-1})
u_x	mean axial velocity (ms^{-1})
u_r	mean radial velocity (ms^{-1})
u_θ	mean tangential velocity (ms^{-1})
x	distance in x-direction (m)
r	radial distance from pipe centreline (m)
D	pipe radius (m)
S	swirl number or swirl intensity
S_0	initial swirl number or intensity
β	decay rate of swirl intensity

creates a swirl or tangential velocity component to the flow, producing a helical winding of the streamlines that are a characteristic of swirling flows.

The induced swirling flow field will eventually decay with increasing distance downstream and revert back to the upstream flow profile at a few pipe diameters downstream. As this transition occurs the radial location of the maximum tangential velocity moves away from the pipe centreline, i.e., the core region shrinks as swirl decays, as predicted by the Rankine vortex-based model (Algifri et al., 1988; Bali, 1998). During swirl decay, the magnitudes of the turbulence intensities were observed to sharply decrease at the core, whilst only a slight change was observed closer to the wall (Algifri et al., 1988). The velocity gradient of the tangential velocity component was observed to gradually deform into a concave profile (Nishibori et al., 1987).

Li and Tomita (1996, 1998) and Li et al. (1999) have recently conducted experimental investigations to study the application of swirl flows to horizontal pneumatic conveying (Swirl Flow Pneumatic Conveying). An analysis of the results of these studies concluded that the application of swirl could: lower the critical and minimum conveying velocities, the pressure drops, the fluctuations in the wall static pressure, and the power consumption as compared to the equivalent experimental rigs employing conventional axial flow pneumatic conveying. Furthermore, the particle concentration profiles were found to be symmetrically distributed with respect to the pipe axis. It was concluded that the dominating micro-physical transport phenomena in swirl flow pneumatic conveying were: the turbulent transport of particles, particle-wall collisions and inter-particle collisions. These encouraging findings promoted the execution of the lean phase pneumatic swirl flow experimental studies that form the basis of this paper. The swirl intensity or swirl number, S, is commonly used to quantify the degree or the strength of a swirl within a pipe. This non-dimensional number is defined as the ratio of the swirl/angular momentum flux to the axial momentum flux, multiplied by the hydraulic radius (Kitoh, 1991). A widely accepted simplification of the swirl number is given by the following formula (Rocklage-Marliani et al., 2003):

$$S = \frac{\int_0^R u_x u_\theta r^2 dr}{D \int_0^R u_x^2 r dr} \quad (1)$$

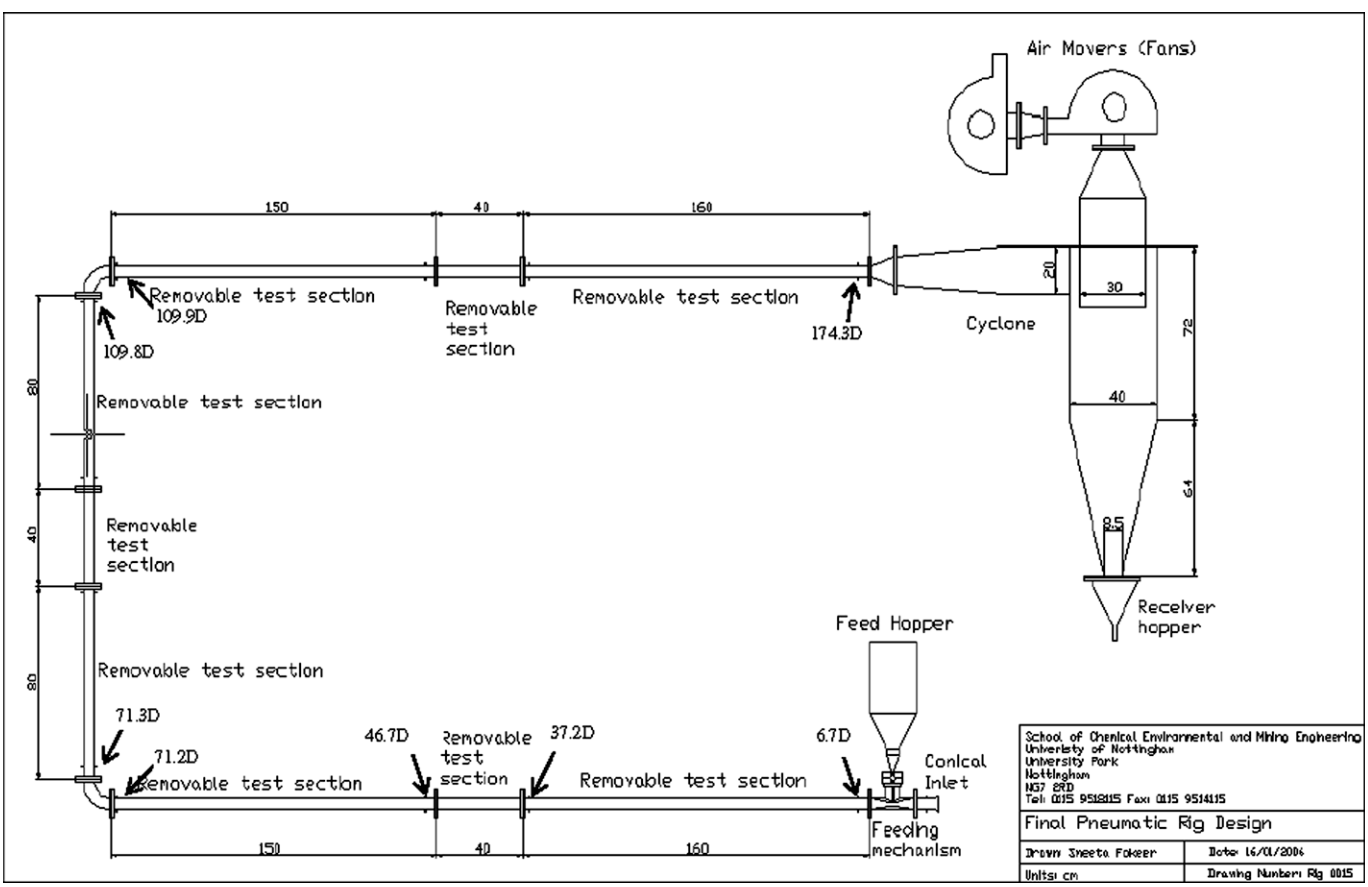

Fig. 1. Schematic illustration of pneumatic conveying rig.