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# Experimental measurements of gas–solid flow and splitting mechanisms of a coal pipe splitter with a perpendicularly arranged upstream elbow

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ABSTRACT

The effect of the vertical pipe length on the performance of a coal pipe splitter with a perpendicularly arranged upstream elbow was investigated experimentally employing a fiber optic measuring system. The upstream elbow and coal pipe splitter were installed in two perpendicular planes. Contours of distributions of the particle concentration and size were obtained in different transverse sections. The experimental data show that the maximum/minimum concentration ratio in transverse sections A, B, and C decreased rapidly as the length of the vertical pipe increased. The left/right-leg average concentration ratio remained about 1, and a balanced split was thus achieved. With a perpendicularly arranged upstream elbow, the vertical pipe length had little effect on the splitter performance, which is beneficial for engineering design and convenient for industrial application.

## 1. Introduction

Many 1000-MW supercritical pulverized-coal-fired boilers have been employed in power stations in the last 10 years in China. Large-capacity supercritical plants can meet stringent pollution emission limitations and provide higher efficiencies. Many low-$NO_x$ combustion methods have been used to control $NO_x$ emissions from large-capacity boilers (Qiu et al., 2007; Zhong, Shi, & Fu, 2002; Zhou & Cen, 2006, 2007).

Burner balancing is important in pulverized coal combustion and results in lower $NO_x$ emissions, fewer operational problems, and more efficient combustion. For most 1000-MWe boilers, two fire balls form in one furnace (as shown in Fig. 1). One conveying pipe of pulverized coal services two burners, and a splitter is used to split the coal–air stream into two coal flows. In industrial application, there are two installation arrangements for the splitter and upstream elbow, namely a parallel arrangement and perpendicular arrangement. Coal balancing is essential to achieving flame stability and a heat release balance for the large-scale furnace. The balance of the coal flow rate in various burners affects the heat release of a flame directly, and poor balancing will result in a non-uniform outlet water temperature of the water-wall and, more seriously, bursting of the water-wall tube.

To fully understand the coal balancing of the whole furnace, it is necessary to investigate the performance of the coal pipe splitter. However, very few experiments have been carried out on the splitter performance. As reported by Levy and co-workers (Yilmaz & Levy, 1998, 2001; Schallert & Levy, 2000; Bilrgen & Levy, 2001), most material is located in a small outer elbow zone of the pipe's transverse section. An elbow upstream of the splitter can cause appreciable non-uniformity of the pulverized coal flow. The gas–solid flow behavior of typical elbows and junctions was studied by Giddings, Aroussi, Pickering, and Mozaffari (2004). Frank, Schneider, Bernert, and Pachlere (2003) performed a numerical simulation of the pulverized coal–air flow in bifurcator-type splitters. Our previous work (Zhou, Mo, Zhao, Li, & Cen, 2010) investigated the effect of the vertical pipe length on the splitter performance, in the case of a parallel-arranged upstream elbow of the coal pipe splitter. However, the multiphase flow characteristics of the splitter installed in a perpendicular arrangement remain unknown.

A fiber optic probe is a useful tool for measuring the velocity and size of a particle bunch. Nicolai and Reh (1995) measured such parameters, including the voidage in circulating fluidized beds, to identify various flow regimes using fiber optic probes. Morikawa, Tsuji, and Tanaka (1986) used a fiber optic probe to investigate the

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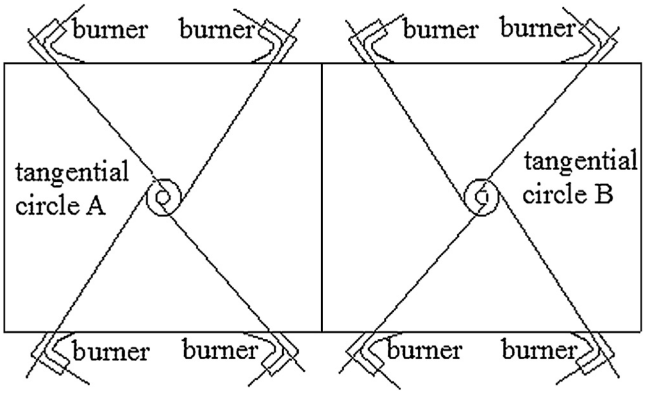

**Fig. 1.** Schematic illustrating the burner layout in a 1000-MW tangentially fired boiler (Zhou et al., 2010).

**Table 1**
Operational parameters and the dimensionless numbers of industrial and laboratory scales.

| | Industrial scale | Laboratory scale |
|---|---|---|
| Reynolds number, $Re = \rho UD/\mu$ | $1.04 \times 10^6$ | $1.76 \times 10^5$ |
| Froude number, $Fr = U/(Dg)^{1/2}$ | 14.02 | 14.31 |
| Stokes number, $St = \rho_p d_p^2 U/(18D\mu)$ | 0.079 | 0.066 |
| Dean number, $De = Re\left(D/(2R)\right)^{1/2}$ | $6.81 \times 10^5$ | $1.15 \times 10^5$ |
| Temperature, $T$ (°C) | 75 | 20 |
| Gas velocity in the pipe, $U$ (m/s) | 35 | 17 |
| Atmospheric pressure, $p$ (bar) | 1 | 1 |
| Particle density, $\rho_p$ (kg/m$^3$) | 1200 | 2700 |
| Particle mean diameter, $d_p$ (μm) | 40 | 21.3 |
| Pipe internal diameter, $D$ (mm) | 610 | 150 |
| Pipe radius of curvature, $R$ (mm) | 712 | 175 |
| Splitter installation angle, $\theta$ (°) | 90 | 90 |

solid concentration and velocity distributions in a pneumatic conveying pipe system. Lehigh University (Yilmaz & Levy, 1998, 2001; Schallert & Levy, 2000; Bilrgen & Levy, 2001) conducted many studies on roping characteristics employing fiber optic probes. Zhou, Cen, and Fan (2005a,b) and Zhou et al. (2010) investigated the gas–solid burner jet applying a fiber optic measurement system.

The present work employed a fiber optic system to investigate the splitting characteristics of a splitter with a perpendicularly arranged upstream elbow, especially the effects of the inlet vertical pipe length upstream of the splitter. Various ratios of the vertical pipe length to pipe diameter of 1, 3, 5, and 18 were investigated in experiments. The particle concentration and size distribution were measured and these experiment results will be helpful in the design and operation of a splitter.

## 2. Experimental setup

Fig. 2 shows a schematic diagram of the gas–solid test rig. Experiments were conducted in a pneumatic conveying system with an internal pipe diameter of 150 mm. The test rig provides maximum pipe air velocity of 40 m/s via a forced-draft fan. A screw feeder is used to discharge particles stored in a hopper into the pipe and the feeder is calibrated. The mass flow rate of solids can be adjusted by the rotation speed of the feeder motor. Downstream of the coal pipe splitter, a cyclone is employed to separate the particles from the air and the particles then pass into the hopper. To guarantee continuous operation and measurement, filter bags are used to collect fine particles that are then sent back to the hopper. To confirm continuous stable particle circulation, sieve analysis was performed for particles extracted from the test rig. There was no obvious attrition in a 100-h period, and the particles were therefore renewed only after a 100-h experimental period.

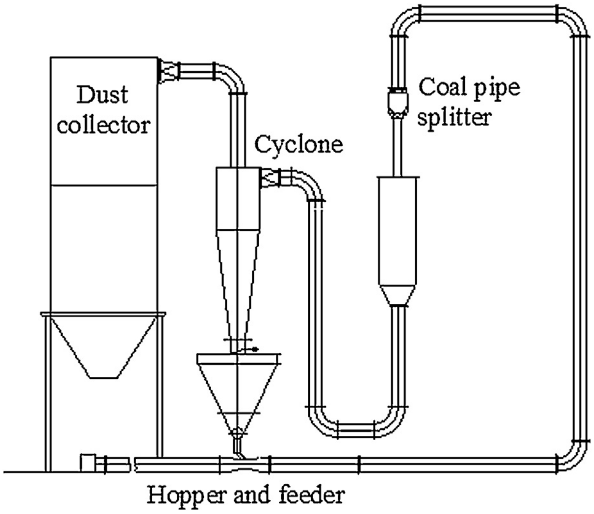

**Fig. 2.** Sketch of a pilot-scale pneumatic laboratory facility.

The test splitter is illustrated in Fig. 3 and included a splitter and an elbow and a vertical pipe installed upstream of the splitter. The plane of the coal pipe splitter was perpendicular to that of the elbow, i.e., the installation angle was 90 degrees. The pipe diameter was 150 mm, and the radius of the elbow was 175 mm. There were two legs downstream of the splitter, the diameters of which were 115 mm. Measurements were carefully made in transverse sections A–E to study the splitter performance. The distance between sections A and B was 85 mm and the distance between sections B and C was 50 mm. Various ratios of the vertical pipe length to diameter of 1, 3, 5, and 18 were used in the experiments.

The scaled splitter model was installed in the pilot system. The operational parameters are given in Table 1 for an industrial splitter and model splitter with a scale ratio of 1/4.07 used in this experiment. Similarity criteria used in the aerodynamic modeling of the industrial burner were (1) geometric similarity, (2) boundary condition similarity, (3) self-stabilizing flows, (4) the Froude criterion, and (5) the Stokes criterion.

Self-stabilizing flow can form with a sufficiently large Reynolds number $Re = \rho UD/\mu$, where $\rho$ is the density of the gas, $D$ is the pipe internal diameter, and $U$ and $\mu$ are the velocity and viscosity of the gas, respectively. The Stokes number is expressed as $St = \rho_p d_p^2 U/(18D\mu)$, where $\rho_p$ and $d_p$ are the particle's density and diameter, respectively. The Dean number is given by $De = Re\,\delta^{1/2}$, where $\delta$ is the pipe curvature expressed as $\delta = D/2R$ and $R$ is the radius of curvature. As reported by Cen (1987), a self-stabilizing flow region can be achieved if $Re$ is larger than $10^5$. In this work, the pipe flow $Re$ was $1.76 \times 10^5$, meaning that the turbulent flow pattern in the laboratory-scale splitter was similar to that in the industrial-scale splitter. The Stokes number relates to the particle size and density. In this work, particles of talcum powder with average diameter of 21.3 μm and density of 2700 kg/m$^3$ were adopted. Table 2 lists four experimental cases studied in this work.

Fig. 4 shows the measuring system for the solid concentration and particle size, consisting of an optical probe (see Fig. 4(b)), an integrated electronic circuit unit, and a signal converter system as well as the data collecting and processing system. Two fibers were used to emit light into gas–solid flow in the pipe, the light intensity