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Flow characteristics and pressure drop across the Laval nozzle in dense phase pneumatic conveying of the pulverized coal

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ABSTRACT

Experimental studies were performed to describe the physical phenomena occurring in dense phase pneumatic conveying of the pulverize coal with a Laval nozzle installed in the pipeline. The maximal coal mass flow rate decreased from 0.87 kg/s to 0.35 kg/s and an obvious decrease in the solids loading ratio was revealed after the Laval nozzle was installed. In addition, the Laval nozzle showed a better capacity of resisting disturbance, which made it easier to control the coal mass flow rate precisely and promoted the stable conveying process. These specific physical phenomena were proved to result from the high pressure drop of the Laval nozzle. Thereby, a mathematic model was developed to predict the two-phase pressure drop across the Laval nozzle. The pressure drop model described the experimental data within the 15% deviation. The main influence factors contributing to the pressure drop of the Laval nozzle were discussed using the model. Then the effects of gas mass flow rate, solids loading ratio, convergence angle, throat diameter and throat length were revealed.

1. Introduction

There is considerable interest in the use of the Laval nozzle as a gas–solid two-phase flow meter [1,2]. In the 1960s, Fox Company [3] designed a variable throat Laval nozzle and used it to control the fuel flow rate in aerospace industry. The metering error within ±2% achieved the request of the measurement. In coal fired power stations, the Laval nozzles are used to control the distribution of the pulverized coals to the furnace [4].

Most of the published work focuses on the gas–solid flow with a low solids loading ratio μ. Goldberg and Boothroyd [5] demonstrated that pressure drop across the Laval nozzle was related to solids loading ratio because the quantity of particles present affected the ratio of the particle response time and the gas residence time. In the range of solids loading ratio μ tested from 0 to 5, Tang et al. [6] researched on a 25 mm diameter Laval nozzle with a diameter ratio 0.5, throat length 19D_t, inlet and diffuser angles of 21° and 12°, respectively. Later, Peng et al. [7–9] discussed the gas–solid flow in the Laval nozzle and developed a mathematic model for the prediction of the nozzle pressure drop, but the solids loading ratio μ in their researches was smaller than 0.6 kg/kg. Azzopardi et al. [10] proposed a quasi-one-dimensional model to predict the behaviors for gas–solid flow in the Laval nozzle with the solids loading ratio μ only between 0 and 1.8 kg/kg. Giddings et al. [4] used a single long throat Laval nozzle to measure of pneumatically conveyed powder and published the following equations for the Laval nozzle pressure differentials (pressure drop to the throat ΔP_T, overall pressure drop ΔP_R).

$$\frac{\Delta P_T}{1/2\rho_g u_{gT}^2} = 1.1088\mu + 0.9228 \quad (1)$$

$$\frac{\Delta P_R}{1/2\rho_g u_{gT}^2} = 0.0067\mu + 0.6911 \quad (2)$$

The solids loading ratio μ ranged from 0 to 0.6 kg/kg in his work and also belonged to the dilute phase.

The application of the Laval nozzle in dense phase (μ > 50 kg/kg) pneumatic conveying is promising but rarely reported. The pressurized entrained-flow gasification process is being used more and more widely, which calls for stable feeding of the pulverized coal to gasifier under high solids loading ratio μ. The early work of Albright et al. [11] was prompted by the need to use the minimum amount of gas to feed coal into gasifier. Gong et al. [12] studied on the high solids pneumatic conveying of pulverized coal and considered that the Laval nozzle played an important part in controlling the coal mass flow rate. In addition, the Laval nozzle has been used to raise the pipeline pressure in the process of Shell Coal Gasification Process (SCGP). However, no further information was provided.

In the pressurized entrained-flow gasification process, the Laval nozzle is proposed to install in the pipeline based on two aspects as follows: (1) generally, the pulverized coal used in the gasification falls into Geldart group A [13], which is easy to be conveyed

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Table 1
Physical properties of the pulverized coal.

Mean particle diameter/μm	Particle density/kg m^{-3}	Bulk density/kg m^{-3}	Moisture content/wt%
41.13	1400	543.9	2.4

pneumatically. The capacity of φ15 mm ID dense phase pneumatic conveying reaches as high as 1.0 kg/s. In many situations, the coal mass flow rate needs to be controlled. For example, the pilot plant in Shandong (China) requires a coal mass flow rate only about 0.35 kg/s [14]. It is not advisable to reduce the pipe diameter to decrease the coal mass flow rate. On one hand, on-line measuring instrument such as mass flow meter requires the pipe diameter not less than ~φ15 mm ID. On the other hand, impurities might cause the jam in the small-bore conveying pipe. In addition, solid flow adjusting valve cannot meet the demand of regulating such a small flow rate as well. Besides, the solid flow adjusting valve always costs much and shows short of service life. In this case, a suitable designed Laval nozzle can play a great role. The coal mass flow rate can be lowered significantly by installing the Laval nozzle in the conveying pipeline, which can therefore meet the demand of the pilot plant test. (2) In industry, a cyclic system is always established to adjust the coal mass flow rate before the pulverized coal is conveyed into the gasifier (1.0–4.0 MPa) [15]. The receiver vessel of the cyclic system is always at a normal atmosphere, while the pressure of the gasifier is as high as 4.0 MPa. It is necessary to raise the pressure of the cyclic system to satisfy the pressure requirement of the gasifier. This can be achieved by installing a high pressure drop Laval nozzle in the conveying pipeline.

This paper describes the physical phenomena occurring in dense phase pneumatic conveying of the pulverize coal with a Laval nozzle installed in the pipeline. The solids loading ratio reaches as high as 250 kg/kg in our experiment, where the interaction between particles and gas becomes more complicated and is quite different from that in the dilute phase [16,17]. A mathematic model was developed to predict the two-phase pressure drop by taking into account the conveying conditions and the special configuration of the Laval nozzle. And the main factors influencing the pressure drop were further discussed using this model.

2. Experimental set-up and methods

Compressed air is used as the carrier gas. Pulverized coal is the conveyed medium. Its physical properties are shown in Table 1.

A schematic representation of the dense phase pneumatic conveying of the pulverized coal is shown in Fig. 1 [18]. It mainly consists of air source, vessels, Laval nozzle, valves, pipeline, dust removers and MCGS (Monitor and Control Generated System). The mass flow rates of three gaseous streams (M_g) feeding the conveying system were individually controlled to achieve the desired operating conditions. The gas flow rate (M_g) was regulated by a valve and measured with a gas meter. The tests were carried out by maintaining a normal atmosphere of receiver vessel (P_0) and increasing the gas flow rate (M_g) to increase the pressure of feeder vessel (P_f). The pulverized coal discharged pneumatically from the feeder vessel, was conveyed along a 4-m-long vertical section, a 6-m-long horizontal section, and finally entered the receiver vessel. The Laval nozzle was mounted at the vertical pipe 1.5 m away from the feeder vessel. In order to obtain its pressure drop (ΔP_{exp}), pressure taps were installed 15 mm from the inlet and outlet of the Laval nozzle, respectively. The strain gauge transducers were used with MCGS to collect the pressure signals during the experiments. The solid mass flow rate (M_s) was determined from the weight-versus-time curve of the receiver vessel.

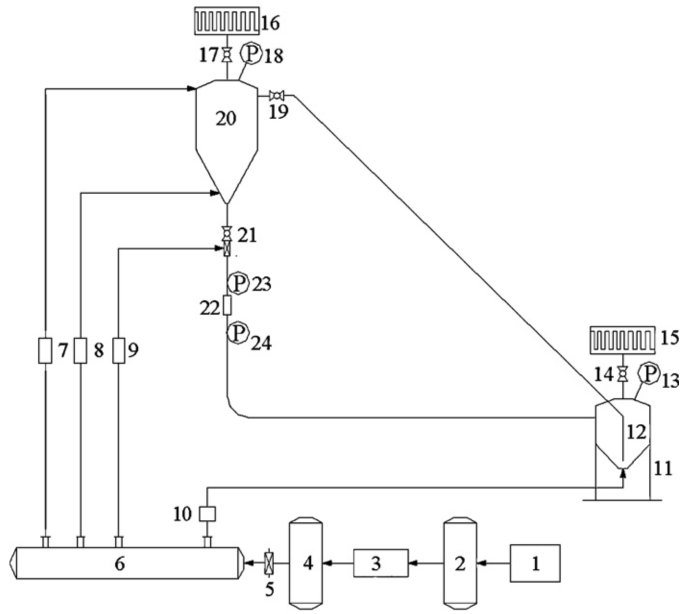

Fig. 1. Schematic of the dense phase pneumatic conveying. (1) Air compressor, (2 and 4) buffer tank, (3) drier, (5) relief valve, (6) gas distributor, (7–9) gas meter, (10) gas flow meter, (11) weigh cell, (12) receiver vessel, (13,18,23,24) pressure cell, (14, 17, 19, and 21) pneumatic valve, (15 and 16) dust remover, (20) feeder vessel, (22) Laval nozzle.

Fig. 2 shows the configuration of the Laval nozzle, which is designed in modular form to allow for subsequent alteration of the components. The convergent section, throat and divergent section were made in three separate parts and held together. θ_1 is the convergence angle, d is the throat diameter, L is the throat length, θ_2 is the divergence angle. The internal diameter of the conveying pipe D is 20 mm.

The Laval nozzles #1–#6 were manufactured and used in the experiments. The parameters acquired during the conveying trials such as gas mass flow rate M_g, coal mass flow rate M_s, the pressure of feeder vessel P_f and the pressure drop of the Laval nozzle ΔP_{exp} are detailed in Table 2.

3. Flow characteristics

Generally, the Laval nozzle applied in the pneumatic conveying system is usually used to ensure the stability of the gas flow rate [19,20]. However, in our research, a new version was proposed for the Laval nozzle to adjust and control the solid mass flow rate. As shown in Fig. 3, the maximal coal mass flow rate decreased from 0.87 kg/s to 0.35 kg/s after the Laval nozzle was installed. In our experimental range, the Laval nozzle causes about 60% decrease in the coal mass flow rate. It is considered that gas and particles

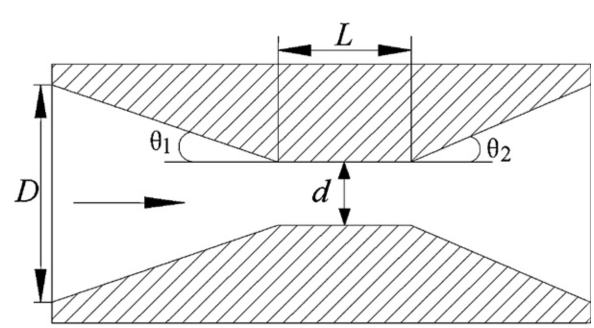

Fig. 2. Structure diagram of a Laval nozzle.