Powder Technology 268 (2014) 401–411

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Experimental study on flow characteristics and pressure drop of gas–coal mixture through venturi

Kai Liu, Haifeng Lu, Xiaolei Guo, Xiaolin Sun, Shunlong Tao, Xin Gong *

Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, Shanghai Engineering Research Center of Coal Gasification, East China University of Science and Technology, Shanghai 200237, PR China

ARTICLE INFO

Article history:
Received 6 December 2013
Received in revised form 10 July 2014
Accepted 14 July 2014
Available online 22 July 2014

Keywords:
Venturi
Pulverized coal
Flow characteristic
Pressure drop

ABSTRACT

The present work details the flow characteristics and pressure drop of the gas–coal mixture through venturi under high pressure and concentration. A series of experiments of both single-phase gas and gas–coal mixture flows through the venturi were carried out, and the distribution of pressure, volumetric loading ratio and superficial gas velocity were obtained and compared. The results show that a sharp decrease in static pressure and volumetric loading ratio was observed inside the venturi. The degree of the decrease of pressure in the diffuser section is the lowest ($\leq 20\%$). When keeping the average throat gas velocity same, the inlet gas velocity of gas–coal mixture flows is lower than that of single-phase gas flow, while the outlet gas velocity is higher. In addition, the variation of throat gas velocity is more remarkable. It may indicate a greater energy transfer with the presence of particles. The pressure drop of the gas–coal mixture increases with the increase of superficial gas velocity, volumetric loading ratio and gas density. Further, the pressure drop models of single-phase gas flow and gas–solid flows through the venturi have been established by adopting the Farbar's approach based on the mathematical regression analysis. The models contribute to predict the pressure drop of venturi with deviations below 25%.

1. Introduction

As an important component, the venturi is widely applied in the field of multi-phase flows. It has been frequently used in the transportation process to keep the gas flow rate and air pressure steady [1]. And it is often adopted as a scrubber in the research field of gas–liquid flows [2]. Also it is key fluidic equipment as a reverse flow diverter (RFD) in RFD pumps, which is more valuable for transporting hazardous liquid–solid mixtures or three-phase slurry catalytic [3–5]. In addition, it is also a typical metering device which enables metering the gas–solid flows in power stations [6,7].

Not too common but very important is that the entrained-bed flow gasification of pulverized coal system also benefits from the utilization of venturi. Surely, the good performance of gasifier is strongly dependent on the stable operation of dense phase pneumatic conveying. In the process of pneumatic conveying of pulverized coal, the conveying pressure and volumetric loading ratio are high with up to 4 MPa and 400 kg/m^3, respectively. The problem of coal feeding under high pressure and concentration conditions needs to be solved urgently. Consequently, a circulation system for the coal feeding is often established prior to the pulverized coal entering the gasifier. In the circulation system, the venturi is introduced, and produced a surprising pressure drop when the mixtures flow through. Thereby, a remarkable increase in the pipeline's pressure ahead of the venturi occurred. The pressure of venturi inlet mostly equals to that of the gasifier. The stable and smooth switch from the circulation system to the feeding system is subsequently fulfilled due that a required pipelines' pressure and coal mass flow rate accorded with feeding system was realized. This application is typically in Shell technology. Meanwhile, sometimes the low coal feedings are often required in the gasification process. Due to the resistance characteristic of venturi, it is directly applied in that process, so that the solid mass flow rate of pulverized coal is significantly decreased. This approach is preferably adopted by Guo in Shandong (China) pilot plant [8].

In the last three decades, the studies of Lee [6], Payne [7], Doss [9], Wang [10], Shaffer [11], Azzopardi [12], and Giddings [13,14] proposed that a linear relationship exists between the mixture-to-gas differential pressure ratio (the ratio of mixture pressure drop to the pressure drop of single-phase) and the mass loading ratio for the traditional venturi system in coal-fired power stations. The Stocks number, *St*, has been used for a venturi design, and also for a measure of the degree to which the particle accelerates in a venturi. But the pressure of the systems mentioned above was often atmospheric, and the mass loading ratios were almost less than 10 kg/kg except for the Shaffer system which was no more than 35 kg/kg [11]. Kmeic [15] and Bohnet [16] studied the injector system, of which the initial flow process was

---

* Corresponding author. Tel.: +86 021 6425 2521.
E-mail address: gongxin@ecust.edu.cn (X. Gong).

http://dx.doi.org/10.1016/j.powtec.2014.07.019
0032-5910/© 2014 Elsevier B.V. All rights reserved.

distinct from that of this paper. In their system, the particles were initially static, and then were accelerated by the high-speed air jet, and continued to flow through the convergence section, the throat section, the diffuser section and through the following conveying parts.

So far, the performance of pulverized coal flow through venturi under high pressure and concentration was rarely reported. The effects of the presence of pulverized coal on the flow field under high pressure and concentration were not clear. Therefore, it was urgent to study the flow characteristics of gas–coal mixture through venturi under high pressure and concentration.

There has been some information on the pressure drop model for venturi performance applying to meter gas–solid flows. Generally, two ways were adopted to establish the preliminary pressure drop models. One way was experimental technique. As mentioned above, that was to build the linear relationship between pressure ratio and mass loading ratio pressure with the aid of the Stocks number. Another way is numerical prediction. The numerical models have two major types. One is Conservative Variable and Source (CONVAS) model. The typical cases were in Lee [6], Doss [9], and Shaffer [11] studies. Another is Particle Source in Cell (PSI-Cell) model. The typical case was in Payne's work [7]. Almost all of the two types of numerical models could provide good predictions of the pressure drop to the throat of the venturi. Azzopardi [12] considered the change in the thickness of the boundary layer, and used a momentum integral approach, to improve the prediction of the pressure drop in the diffuser for a wide range of conditions. Actually, all numerical models were indirect, and required to be validated by the pressure-flow data. More importantly, most experimental correlations and numerical models were only applied in low-mass loading ratio (<35 kg/kg) and atmospheric-pressure systems. Farbar [17], Liu [18] modified the correlations to meter gas–solid flows under the condition of high pressure and concentration. However, little detail has been given.

In previous investigations, several studies have been completed on the pressure drop model of pulverized coal through venturi under high concentration in the low pressure system (less than 100 kPa). Lu [19] built a pressure drop model by introducing the additional pressure drop method, and adopted the model to analyze the total resistance characteristics of venturis with different structures. In the present work, a much broader ranges of system pressure, which extends to 800 kPa are realized. A series of experiments on the flow characteristic of single-phase gas and gas–coal mixture have been studied and compared. The influencing factors of pressure drop have been analyzed. The venturi was simplified to two sections by adopting the Farbar's approach, the pressure drop models of single-phase gas flow and gas–solid flows through venturi have been established by applying the mathematical regression analysis. The models contribute to predict the pressure drop of venturi with deviations below 25%.

2. Experimental materials and setup

2.1. Experimental materials

Compressed air and high pressure nitrogen were adopted as the carrier gas. Beisu coal was selected as the test material. The basic physical properties of Beisu coal were shown in Table 1.

The pulverized coal was greatly cohesive and easily agglomerated, which belonged to the Geldart C type powder. The particle size was small, and the specific surface was large. Because of the high non-sphericity and roughness, it was easier for coal particles to follow the carrier gas in the flow field. Meanwhile, the particle size distribution of pulverized coal was wide. Hence, particles with different sizes would be subject to different aerodynamic drag forces.

Table 1
Physical properties of Beisu coal.

Mean particle size (μm)	Moisture (%)	Particle density (kg/m^3)	Bulk density (kg/m^3)	Specific area (m^2·g)
42.5	4.2	1400	418.7	1.15

2.2. Experimental setup and process

The experimental program was undertaken on the facility of dense phase pneumatic conveying of pulverized coal, where the venturi was installed on the vertical pipeline. The schematic diagram was illustrated in Fig. 1. The whole system consisted of a gas supply system, feeding and receiving vessels, pipelines, a venturi, a measuring system, a filter unit, and a data acquisition system.

The venturi consisted of the convergence section, the throat section and the diffuser section, was made of stainless steel, with good pressure-tolerant characteristic. In Fig. 2, D is the pipe diameter, θ_1 is the convergence angle, d is the throat diameter, L_t is the throat length, θ_2 is the diffuser angle, and β is the diameter ratio. Pressure tappings were located along the venturi (P_1–P_7). To reduce the disturbance of the flows influenced by the external devices or configuration as much as possible, the pressure holes were selected flushing with the inner wall of the pipe. The same way was also selected after the diffuser to keep a uniform way of measuring pressure consistent with the previous holes. The differential pressure transmitters were settled between P_1 and P_2 (ΔP_c), P_2 and P_4 (ΔP_t), P_4 and P_5 (ΔP_d). The total pressure drop (ΔP_T) was expressed by the sum of ΔP_c, ΔP_t, and ΔP_d. The location of P_1 and P_5 were both 40 mm upstream and downstream of the venturi. In the following descriptions, the pressure drop and pressure recovery were both given. The differential pressure was described as pressure drop or pressure recovery, respectively, when the variation of the pressures was positive or negative value.

The detailed structural parameters were shown in Table 2.

In experiments of single-phase gas flow, the valve of feeding vessel was closed. In the experiments, the gas flow rate was regulated by a valve and measured with a gas flow meter. A controllable back pressure (P_b) was realized by the electromagnetic valve, which is above the receiving vessel. In experiments of gas–coal mixture flows, the operating methods were described in details in Cong's work [20]. The fully fluidized pulverized coal flowed out from the feeding vessel and through the pipelines, venturi, and finally into the receiving vessel. A comprehensive series of experiments on venturi at different pressures and concentrations were carried out. The operating parameters of conveying system and venturi were summarized in Tables 3 and 4, respectively.

Generally, the system pressure of dilute gas–solid flows was atmospheric, and thereby the gas density variations were usually ignored. And there were small differences between the volumetric loading ratio and the mass loading ratio, which were both used to analyze the venturi flow characteristics. However, in dense phase flows, more attentions need to be paid to the difference of gas density due to the condition of high pressure. In consequence, there were great differences between mass loading ratio and volumetric loading ratio. The volumetric loading ratio could give more information on the study of the effect of the presence of solid particles on venturi flow characteristics. In addition, the information about particles such as particle velocity and particle concentration at the venturi inlet could be given by the solid mass flow meter.

Actually, the temperature variation inside the loop (<5 K) was negligible, compared to the room temperature (298 K). And in gas–solid flow with high loading ratio, the flow process can be approximated as the isothermal flow due that the temperature variation of the gas caused by compression or expansion can be compensated by the heat transfer of particles [21]. Consequently, the influences of temperature variation on the flowing parameters were neglected in our work. And thereby, the gas volumetric flow rate associated with the temperature could be obtained by the measured pressure and gas mass flow rate.