NUMERICAL MODELING AND CORRELATIONS ON THE COAL-CONVEYING GAS FLOW IN STRAIGHT AND CURVED PIPES

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Abstract: CFD modeling and simulations are made on the key flow elements, vertical, horizontal and elbow pipes used in pneumatic coal-transport system. The coal-particle laden gas flow inside the flow elements are modeled by combining the Reynolds-stress averaged Navier-Stokes equations solver (RANS), k-ε turbulence model and discrete phase model(DPM) of the ANSYS Fluent code. Using the present coal-gas flow analysis model, computations are carried out to investigate the gas flow path, the coal particle behavior and the pressure loss characteristics of flow elements at various coal/gas loading ratio and coal mass flux. The present prediction results show the coal-gas flow behavior of each flow element is changed from dilute-flow to dense-flow pattern at specific coal/gas loading ratio, and this flow pattern transition results in abrupt the increase of pressure loss. The present numerical results also give the correlations for the pressure losses in horizontal, vertical and elbow pipes, from which limiting coal/gas loading conditions to secure stable coal feeding can be obtained.

Keywords: Pneumatic Coal-Transport; Coal-Gas Flow, Dense Phase Flow; Dilute Phase Flow

I. INTRODUCTION

Recently many R&D efforts in power and energy industries are devoted to develop clean coal power plants with higher energy utilization efficiency and lower greenhouse gas emission than the conventional boiler system[1]. A key technology of clean coal power plants is fluidized-bed gasification of small-sized coal particles mixed with oxidizer, and it requires the subsequent processes of the feeding, the mixing and the reaction of coal particles. Because, for stable and steady operation of fluidized-bed coal gasification facility, coal should be transported pneumatically to reactor without any plugging and discontinuous coal feeding problems, how to feed coal more continuously and steadily is one of important technical concerns in coal gasification plant design.

In general, coal used for fluidized-bed gasification is crushed into about 300μm sized particles, and its moisture content ranges up to 30%. Because of these coal properties, pneumatic coal-transport system must be carefully designed to avoid the plugging and the blockage in coal-transport pipe line. In order to overcome these technical problems, many experimental studies have been performed to find efficient and reliable pneumatic transport technology [2].
In the present study, numerical modeling and simulations by using CFD method are made to investigate how coal is transported with conveying gas and its particle behavior is related with gas pressure loss inside the key flow elements of coal transport system. In addition, with changing coal/gas loading condition, the present prediction results give correlations that can be used for the design criteria and guidelines of reliable and efficient coal-transport system.

II. CFD MODELS AND ANALYSIS METHOD

2.1. Description of Coal-transport System

Fig. 1 shows typical coal-transport system where coal is conveyed pneumatically with nitrogen gas from blow tank (reservoir) to gasifier reactor through the coal-transport line composed of horizontal, vertical and elbow(bend) pipes.

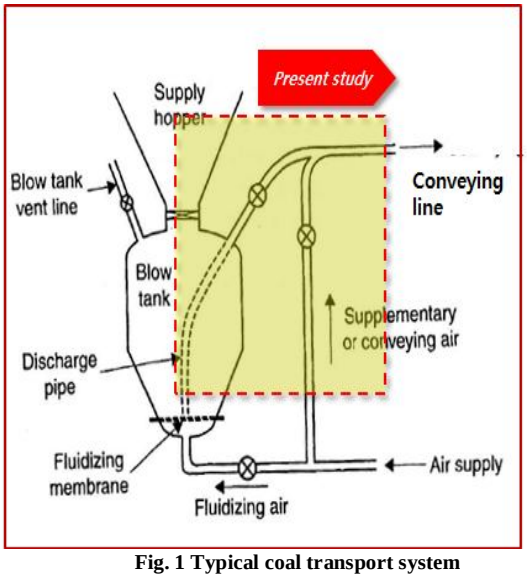


Fig. 1 Typical coal transport system

The pressure loss equations for horizontal, vertical and elbow pipes[3] are defined in the equations (1) and (2) as

Horizontal & vertical pipes: $\Delta p = K \frac{1}{2} \rho V^2$ (1)

Elbow pipe: $\Delta p = K \frac{1}{2} \rho V^2$ (2)

where ρ, V, L and D represent gas density, gas velocity, pipe length and pipe diameter respectively,

and f and K are friction factor and pressure loss coefficient.

The gas flow and particle track behaviors inside the three key flow elements mainly affect the pressure loss, the coal feeding capability and the reliability of coal-transport system. Fig. 2 depicts typical flow regimes and patterns of coal-gas flow at various gas flow velocity conditions[4]. As shown in Fig. 2, plug and dune flows are the dense-phase flow patterns with discontinuous coal feeding while saltation and dispersed flows being the dilute-phase with continuous one. Therefore, for continuous and steady coal feeding through pneumatic conveying line, it is necessary to determine the transition flow condition from dense to dilute phase and to reflect its result as a design criteria of coal-transport system.

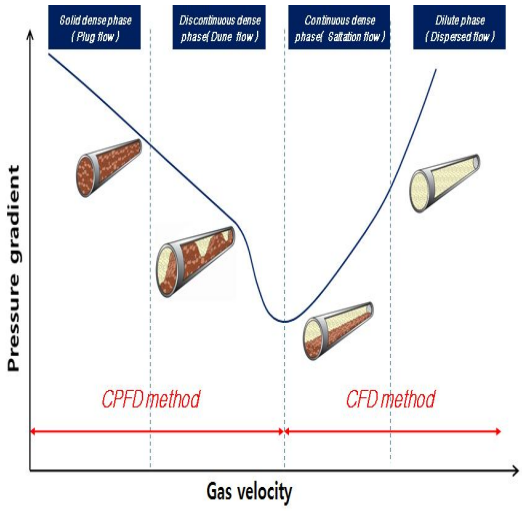


Fig. 2 Flow regimes and patterns of coal-gas flows

2.2. CFD models and technique

The present analyses are conducted on the three flow elements by using CFD method of the ANSYS FLUENT code[5]. The numerical schemes of the present analysis are based on the RANS equation solvers coupled with standard k-ε turbulence and discrete phase models. In calculating coal-gas flow interaction, continuous gas- and discrete coal particle-flows are analyzed by Eulerian and Lagrangian approaches separately, and their calculation results are coupled through iterative computation processes. The effect of turbulence on coal particles behavior is considered by using random walk model.

The properties of coal used in the present study are summarized in Table 1, and coal-conveying pipe diameter is set to 12.7mm.

Table 1 Coal properties and flow conditions

Coal type	Low-rank coal
Coal particle size	350 μm
Coal particle density	1,550 kg/m^3
Transport gas	Nitrogen
Coal/gas loading ratio(μ; wt.-based)	0.5～ 20
Coal mass flux(G)	61.6 or 123.2
Gas superficial velocity(V_{sg})	0 ～ 100

III. RESULTS AND DISCUSSION

3.1. Straight pipe analysis results

Fig. 3 shows the coal particle tracks of coal-gas flow inside horizontal pipe. As shown in Fig. 3 at μ=1.7, gas flow is uniformly distributed over the cross section of pipe, and coal particles are well-dispersed and transported with the gas flow. This kind of coal-gas flow behavior is considered as a typical dilute phase flow pattern to secure continuous and steady coal feeding. However, the result at μ=20 of Fig. 3 shows remarkably different behaviors for coal particle flow and coal particles are being transported along the lower section of pipe in dune flow manner. From these analysis results, it is concluded that coal-gas loading ratio should be maintained less than 5 in horizontal coal-transport pipe to secure continuous and steady coal feeding.

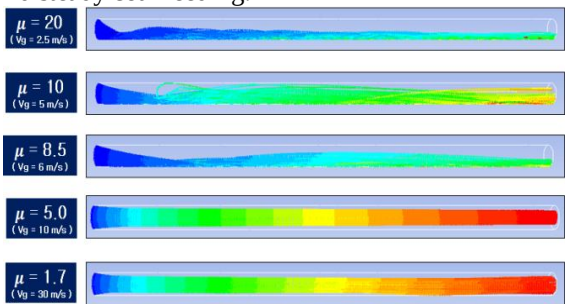


Fig. 3 Coal particle tracks in horizontal pipe

Figs. 4 and 5 also show the coal particle tracks of coal-gas flow inside vertical pipes. It is noted upflow or downflow condition is defined as the gas flow direction opposing or parallel to gravity force. As shown in Fig. 4 at σ μ=1.7, coal particles are well-dispersed and transported vertically along gas flow.

The coal-gas flow behavior can be considered as a typical dilute phase flow pattern to secure continuous and steady coal feeding. However, the result at μ=10 or 20 shows remarkable non-uniformity of coal particle flow and a few coal particles are flowing upward with gas stream along pipe length while the most of coal particles not being conveyed. Unlike the Fig. 4, Fig. 5 shows coal particles are well-dispersed and transported along pipe at any coal/gas loading ratio because gas is flowing in the direction parallel to the gravity.

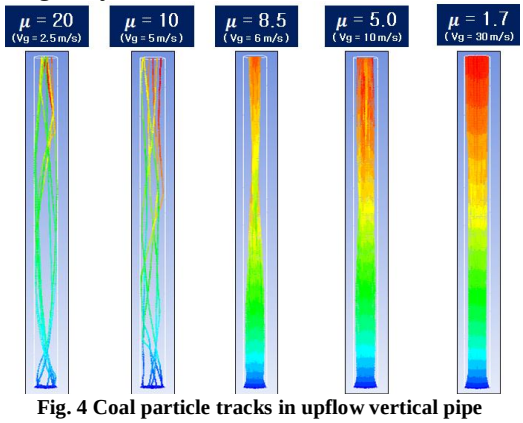


Fig. 4 Coal particle tracks in upflow vertical pipe

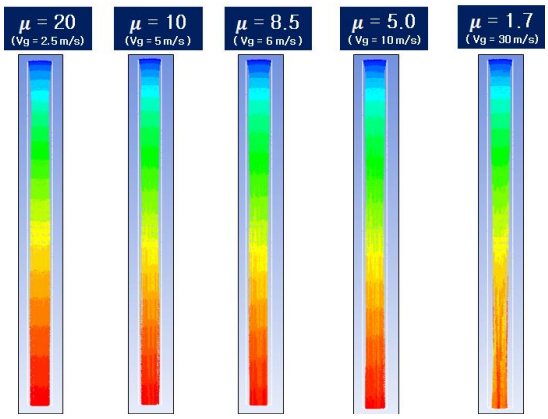


Fig. 5 Coal particle tracks in downflow vertical pipe

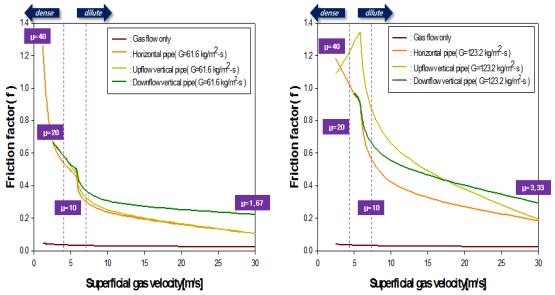
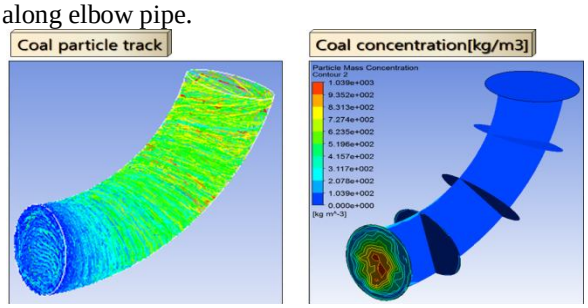


Fig. 6 Overall friction factors of horizontal and vertical pipes

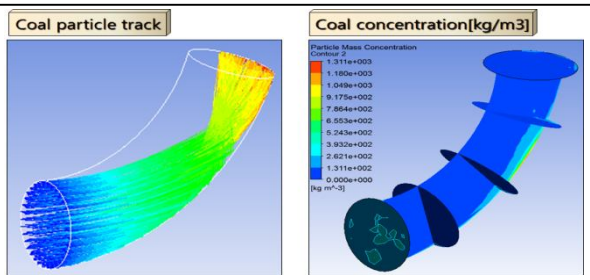
Fig. 6 shows the comparison between the overall friction factors of horizontal, upflow and downflow vertical pipes. As shown in Fig. 6, in spite of pipe type, overall friction factor is abruptly increased due to the transition from dilute to dense phase flow when coal/gas loading ratio is larger than 10 or 5. From the results of Figs. 4, 5 and 6, it is also concluded that coal-gas loading ratio should be maintained less than 5 in coal-transport pipe line design.

3.2. Curved pipe analysis results

Figs. 7 and 8 show the coal particle tracks inside upflow and downflow elbow pipes. As shown in Fig. 7 at μ=2, coal particles are dispersed with gas stream and transported along concave surface of pipe. However, Fig. 7 at μ=10 shows a few coal particles are conveyed in helical motion along pipe length while the most of coal particles remain as agglomerated at pipe inlet. As shown in Fig. 8, similar analysis results are observed on coal particle tracks at μ=2 and 10. Increasing coal/gas loading ratio, the most of coal particles are not transported along elbow pipe.

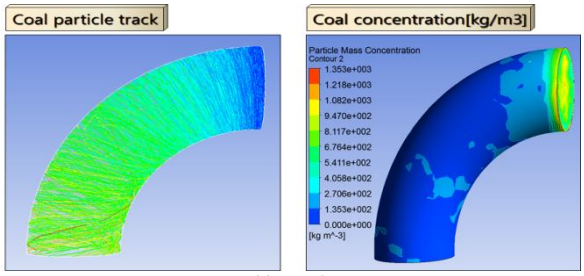


(a) μ = 10

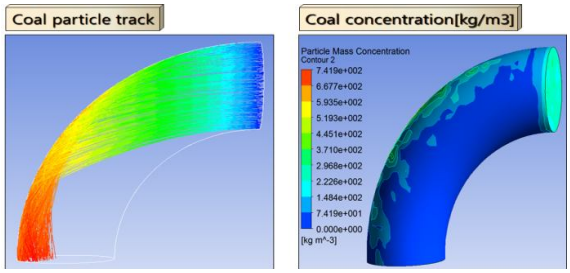


(b) μ = 2

Fig. 7 Coal particle tracks in upflow elbow pipe



(a) μ = 10



(b) μ = 2

Fig. 8 Coal particle tracks in downflow elbow pipe

Fig. 9 shows the comparison between the overall pressure loss coefficients of upflow and downflow elbow pipes. As shown in Fig.9, in spite of flow direction, overall pressure loss coefficient is abruptly increased due to the transition from dilute to dense phase flow when coal/gas loading ratio is larger than 10 or 5.

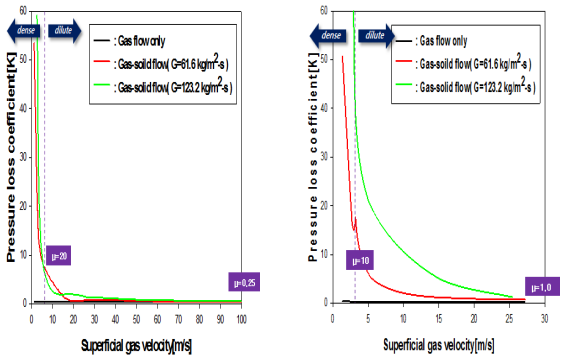


Fig. 9 Overall pressure loss coefficients of upflow(left) and downflow(right) elblow pipes

3.3. Correlations for pipe pressure losses

Based on the computation results on overall friction factors and pressure loss coefficients in Figs. 6 and 9, solid friction factor(f_s) and pressure loss coefficient(K_s) can be deduced under the assumption that overall

pressure loss is composed of the gas and the solid ones as follows:

$$\Delta p_{overall} = \Delta p_g + \Delta p_s = \sum \left(f_g + f_s \right) \frac{L}{D} \frac{1}{2} \rho_g V_{sg}^2 \qquad (3)$$

$$\Delta p_{overall} = \Delta p_g + \Delta p_s = \sum \left(K_g + K_s \right) \frac{1}{2} \rho_g V_{sg}^2 \qquad (4)$$

Here the gas friction factor and pressure loss coefficients are calculated from well-known fluid mechanics correlations[3].

Therefore, from the present analysis results and the definitions of equations (3)-(4), new set of the correlations for solid friction factors and pressure loss coefficients can be deduced as

Table 2 Correlations for solid friction factor and pressure loss coefficient

Type	Correlation
Horizontal pipe	$f_s = 2.00 x 10^{5} \mu^{1.0} Fr^{-1.94} \left(\frac{\rho_s}{\rho_g} \right)^{-1.8} \left(\frac{G}{61.6} \right)^{1.5}$
Vertical pipe (Upflow)	$f_s = 2.86 x 10^{-4} \mu^{1.0} Fr^{-0.026} \left(\frac{\rho_s}{\rho_g} \right)^{0.73} \left(\frac{G}{61.6} \right)^{0.16}$
Vertical pipe (Downflow)	$f_s = 2.13 x 10^{-4} \mu^{1.0} Fr^{-0.026} \left(\frac{\rho_s}{\rho_g} \right)^{0.73} \left(\frac{G}{61.6} \right)^{0.16}$
Elbow pipe (Upflow)	$K_s = 6.58 x 10^{11} \mu^{1.0} Fr^{-1.31} \left(\frac{\rho_s}{\rho_g} \right)^{-3.7} \left(\frac{\pi R}{2D} \right) \left(\frac{G}{61.6} \right)^{1.2}$
Elbow pipe (Downflow)	$K_s = 4.0 x 10^{11} \mu^{1.0} Fr^{-1.31} \left(\frac{\rho_s}{\rho_g} \right)^{-3.7} \left(\frac{\pi R}{2D} \right) \left(\frac{G}{61.6} \right)^{1.2}$

where Fr is Froud number and ρ_s, ρ_g are coal particle, gas densities.

CONCLUSIONS

Numerical modeling and simulations by CFD technique are conducted to investigate the coal-gas flow behavior inside key flow elements of pneumatic coal-transport system. With changing gas superficial velocity(or changing coal-gas loading ratio), dense-to-dilute phase flow transition point and its related pressure loss characteristics are examine by using CFD method. From the present analysis results, it is concluded that coal-gas loading ratio should be maintained less than 5 in all the flow elements for continuous and steady pneumatic coal-transport system. The present study also provides the correlations on solid friction factor and pressure loss coefficient of horizontal, vertical and elbow pipes, which can be used in coal-conveying system design.

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