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Pulse cleaning flow models and numerical computation of candle ceramic filters

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Abstract: Analytical and numerical computed models are developed for reverse pulse cleaning system of candle ceramic filters. A standard turbulent model is demonstrated suitably to the designing computation of reverse pulse cleaning system from the experimental and one-dimensional computational result. The computed results can be used to guide the designing of reverse pulse cleaning system, which is optimum Venturi geometry. From the computed results, the general conclusions and the designing methods are obtained.

Keywords: candle ceramic filters; reverse pulse cleaning; face velocity; numerical computed models; pressure difference

Introduction

Cleaning the fine particles in high temperature (450℃ – 950℃) and high pressure condition can enhance the thermal efficiency of clean coal technologies such as IGCC or PFBC. Rigid ceramic filters of a variety of structures are under development in programs around the world, which can filtrate sufficient dust to protect downstream equipment from particle fouling and erosion effects and allows the cleaned gas to meet environmental emission requirement. The dust, which deposited on the filter's outer surface and formed the filter cake, can be removed by pulse cleaning methods.

Studies have been reported on fluid flow performances and reverse pulse jet cleaning flow system with one dimensional steady state flow. ITO (ITO, 1993) derived one dimensional gas flow models and equations in candle ceramic filter passage, demonstrated the computational results with the experimental data. It is suggested that no cleaning pressure be near the cleaning gas inlet without the Venturi tube. Ahluwalia and Geyer (Ahluwalia, 1996) derived general one dimensional steady gas flow equations in honeycomb ceramic filters passage, the pressure drop, mass flow rate and temperature ordinary differential equations were solved by using the fourth order Runge-Kutta methods. The computed flow parameters are in agreement with the experimental results in the axis symmetry direction using one dimensional flow models, but it can neither be used to predict and compute the other direction flow performance, nor be used to design the diameters. The gas face velocity in the outer surface of the filters is not uniform, if using the mean face velocity. Laux *et al*. (Laux, 1993) with the FLUENT version 3.02 software calculated the inner flow of the candle ceramic filter element on a two dimensional Cartesian computational grid by using a standard k-ε turbulent model, but the reverse pulse jet cleaning models and the boundary condition were not detailed.

1 Pulse jet cleaning apparatus

Candle ceramic filter element is a hollow cylinder suspended vertically in the tube sheet, which has a dead-end, and an open-end. The pulse cleaning gas flows forward axially into the ceramic porous wall, and outflows from the open-end along with the Venturi tube. Most particles that deposited on the outer surface of the ceramic filter and agglomerated into a cake, are periodically detached on-line by a cold reverse pulse gas. Fig.1 illustrates the apparatus of the forward filtration and the reverse pulse jet cleaning system. After reverse pulse cleaning begins, high-pressure cold air (or nitrogen) jets along the jetting pipe outlet. The flow of the cold air in the jetting pipe is considered as isentropic flow or Fanno flow. The high-speed cold air entrains hot fuel gas at the inlet of the Venturi tube and mixes completely in the tube. The mixed gas obtains static pressure in the convergence part of the Venturi tube and flows into the ceramic

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filter passage and outflows from the porous wall of the ceramic filter, by this way make the cake on the outer surface of ceramic filter detached. It is suggested that the filter cleaning performance be controlled by the pressure difference in the cake.

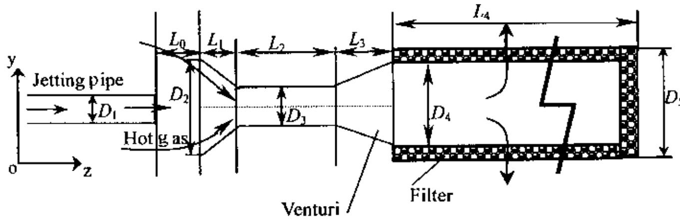

Fig. 1 The apparatus of the forward filtration and the reverse pulse jet cleaning

2 Flow models

2.1 Pulse cleaning pipe

It is considered that the flow is isentropic in the pulse cleaning, the ratio of the stagnation p_0 of the pulse reservoir to the pressure of the back p_b is as follows:

$$\frac{p_0}{p_b} \geq \left(\frac{\gamma+1}{2}\right)^{\gamma/\gamma-1}. \tag{1}$$

Where the ratio of specific heat of the air $\gamma = 1.4$, the pressure $p_b = 0.1$ MPa (environmental absolute pressure). When $p_0 = 0.1893$ MPa, the Mach number increases to 1.0. If the ratio p_0/p_b is greater than 1.893 by increasing the stagnation pressure p_0 or decreasing the back pressure p_b, the flow will be choked that the gas velocity remains sonic in the jetting pipe. In fact, the stagnation pressure p_0 is greater than 0.2 MPa. So the flow is steady and compressible and will produce sonic choke. Considering one dimensional isentropic flow model, the flow parameters (p, ρ, T, W) of the jet pipe is as follows:

$$\begin{aligned}
\rho_0 &= p_0/RT_0, \\
p &= p_0\Big/\left(1+\frac{(\gamma-1)M^2}{2}\right)^{\gamma/\gamma-1}, \\
\rho &= \rho_0\big/(p_0/p)^{1/\gamma}, \\
W &= M\sqrt{\gamma p/\rho}, \\
T &= p/R\rho.
\end{aligned} \tag{2}$$

Where the Mach number is equal to 1 ($M = 1$). The mass rate ($\dot{m}_C$) of the pulse cold air can be calculated according to the flow velocity (W):

$$\dot{m}_C = \sqrt{\gamma/RT_0}\,p_0 M\left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}} A. \tag{3}$$

2.2 Venturi tube

The gas is considered as isentropic flow, because the length of the convergent-divergent Venturi tube is short. The cold air entrains hot fuel gas at the inlet, mixes with it completely in the convergent portion. The dynamic pressure changes to the static pressure in the divergent part in order to compensate the Darcy pressure difference between the porous media wall and the friction pressure drop in ceramic filter passage. It is demanded that the less pulse jet cold air entrain the more hot fuel gas. Accounting for the flow in the Venturi tube is unsteady compressible real gas, then

$$\begin{aligned}
\dot{m} &= \dot{m}_C + \dot{m}_H, \\
E &= \dot{m}_H/\dot{m}_C.
\end{aligned} \tag{4}$$

Where E is entrainment ratio. It will produce sonic choke in the pulse pipe when $M = 1$ or W_C = 330 m/s. It is suggested that the entrainment ratio be equal to zero, the mean flow velocity and Reynolds number at outlet of the Venturi tube are as follows:

$$W = \frac{W_C}{D_4^2} D_1^2 = \frac{330}{20^2} \times 4^2 = 13.5\mathrm{m/s},$$

$$Re = \frac{\rho W D_4}{\mu} = 1.4 \times 10^4 > 2320.$$

The jet entrainment ratio $E > 0$ in fact, so the flow is turbulent in the Venturi tube. The k-ε turbulent models can be used in Venturi tube, the mass, momentum and energy conservation equations are written as following general form:

$$\frac{\partial}{\partial t}(\rho\phi) + \mathrm{div}(\rho\vec{V}\phi) = \mathrm{div}(\Gamma_\phi \mathrm{grad}\phi) + S_\phi. \tag{5}$$

Where $\phi = 1$, U, V, W, KE, EP and T respectively, it represents the mass, momentum, turbulent kinetic energy, dissipation rate and energy conservation equations.

2.3 Filter passage and porous media

The flow is turbulent at the inlet of the filter passage as before, but the axial velocity drops to zero at the dead-end of the filter passage. Therefore, the flowing state is a transited state gradually from turbulence to laminar. In the light of this complex flow case, the k-ε turbulent flow model is used to compute the flow of the filter passage and the conservation equations are as Formula (6).

The flow is laminar from the inner surface to the outer surface of the porous media wall because the velocity in porous media is very low. But the outer face velocity is greater than 0.1 m/s; the Darcy law is amended according to M. Kaviany (Kaviany, 1991):

$$\frac{\partial}{\partial t}(\rho\phi) + \mathrm{div}(\rho V\phi) = \mathrm{div}(\Gamma_\phi \mathrm{grad}\phi),$$

$$-\frac{\mu\varepsilon}{K}\phi - \frac{C_E\,\varepsilon}{K^{0.5}}\rho\phi^2 + S_\phi. \tag{6}$$

Where $\phi = V_D$, W_D. V_D, W_D is the radial or axial filtration face velocity, $-\frac{\mu\varepsilon}{K}$ is the Darcy drag force correction term, $-\frac{C_E\,\varepsilon}{K^{0.5}}\rho\phi^2$ is the Ergun inertial force correction term, C_E is the Ergun constant, $C_E = 0.55$.

3 Numerical solution methods

In the pulse pipe, the flow model is one dimensional, which can be solved by using the algebraic Eqs.(2) and (3). In the Venturi tube model and filter passage and porous media model, the partial differential Eqs.(5) and (6) are solved with the general PHOENICS version 1.6 software on a three-dimensional Body Fitting Coordinates (BFC) grid using k-ε turbulent models, which is necessary the initial value and boundary conditions as follows.

It is suggested that the cleaned hot gas be static state, the velocity in the Venturi tube and filter passage is equal to zero, the pressure is kept on 0.1 MPa. Pulse cleaning begins when the controlling valve of the pulse jet pipe is opened, and the total time of the pulse cleaning is about 0.2s. The unsteady flow models are used to obtain transited parameters. The outlet flow parameters of the pulse jet pipe are constant. The radial velocity, turbulent flow kinetic energy and dissipation are as follows:

$$V_C = 0.0,$$

$$KE_C = 0.25\,W_C^2,$$

$$EP_C = \frac{(C_\mu C_D)^{3/4}}{L_m} = \frac{0.1643}{0.2D_1} KE_C. \tag{7}$$

It is suggested that the stagnation pressure p_H be constant at the part of the hot fuel gas flow of Venturi tube inlet, then

$$p_H = p + \frac{\rho}{2}(W^2 + V^2) = C. \tag{8}$$

Considering no-slip and adiabatic boundary condition on the Venturi tube wall, and the temperature on the internal face of the filter passage is considered as adiabatic. The dependent variables of the normal gradients at the axis of symmetry are considered as zero, which is the default condition in PHOENICS.

4 Numerical computed results of example I

The pulse cleaning main parameters of candle filter are listed as (ITO, 1993): $p_0 = 0.69$ MPa, $p_H = 0.1$ MPa, $D_1 = 6$ mm, $L0 = 0.5$m. The propagation of the pressure difference Δp and the outer face velocity V_C to the time and the length is displayed in Fig. 2. The pressure difference and face velocity in any part of section of the filter passage approach steady state within 80 ms. These numerical computed results are in agreement very well with the experimental results and the computed results by using one dimensional flow models of ITO. But, ITO did not give the entrainment ratio and face velocity because the flow models are one-dimensional. The k-ε turbulent flow models and the computed method are demonstrated correctly from this example, which is suitable to calculate the problems of reverse pulse jet cleaning flow of the candle ceramic filter.

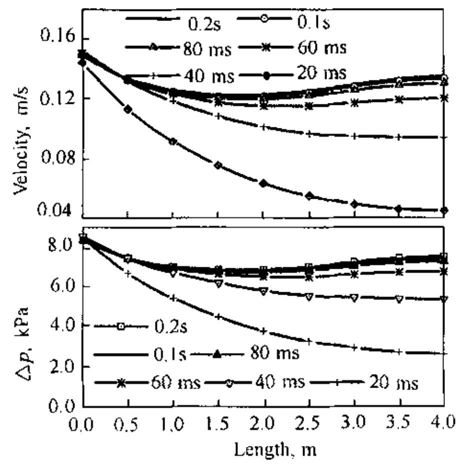

Fig. 2 Propagation of pressure difference Δp and outer face velocity V_C

5 Numerical computed results of example II

The pulse cleaning pipe parameters, Venturi tube geometry sizes, the candle filter sizes and parameters are listed as Table 1 in initial design according to the experimental condition and the structure designing criteria (Tian, 1999). The propagation of the pressure difference and face velocity as a function of permeability, filter length at any section of filter passage are show in Fig. 3 in which the Venturi tube size and the pulse stagnation parameters ($p_0 = 0.5$ MPa, $T_0 = 293$K) are fixed. The pressure drops and face velocity increases gradually from open-end to dead-end of the filter passage in the short filter passage (i.e. 0.5m) case. As the length of the filter passage increases, the pressure difference and velocity in open-end (inlet) increase, and decrease gradually in dead-end (outlet) and are characteristic dip in the middle portion of the filter passage. The more large of the permeability (such as $K = 1 \times 10^{-11}$ m^2), the more obvious the no uniform distribution. The filter length is chosen as $L4 = 1.5$m according to the face velocity which is greater than 0.1 m/s that is necessary to detach cake. The entrainment ratio will change to negative value when the permeability and the pulse stagnation pressure are very small, such as $K < 5 \times 10^{-13}$ m^2. In this case, The face velocity is small, which is not enough to detach the cake. When the permeability increases, such as $K \geqslant 1 \times 10^{-12}$ m^2, The face velocity and pressure difference can meet the necessity to detach the dust cake. The entrainment ratio decreases as the stagnation pressure increases, because the Venturi tube size is not reasonable.

Table 1 Pulse-cleaning parameters in initial design

Pulse pipe	$D1 = 4$ mm, $L0 = 0.5$m
Venturi tube	$L1 = 10$ mm, $L2 = 35$ mm, $L3 = 25$ mm, $D2 = 18$ mm, $D3 = 14$ mm
Candle filter	$D4 = 20$ mm $D5 = 30$ mm, $K = 0.5 \times 10^{-12}$—5.0×10^{-12} m^2, $L4 = 0.5 - 2.0$m, $\varepsilon = 0.5$
Reservoir	$p_0 = 0.3 - 0.5$ MPa, $T_0 = 293$K
Hot fuel gas	$p_H = 0.1$ MPa, $T_H = 303$K
Pulse time	0.2s

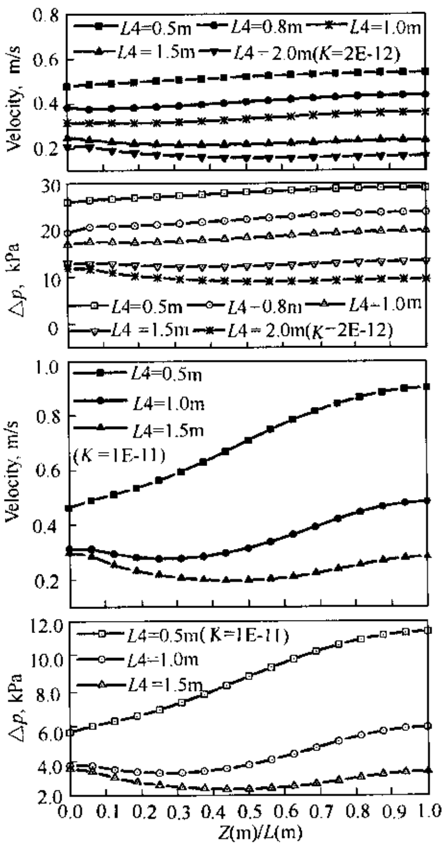

Fig.3 Propagation of pressure difference Δp and outer face velocity V_C

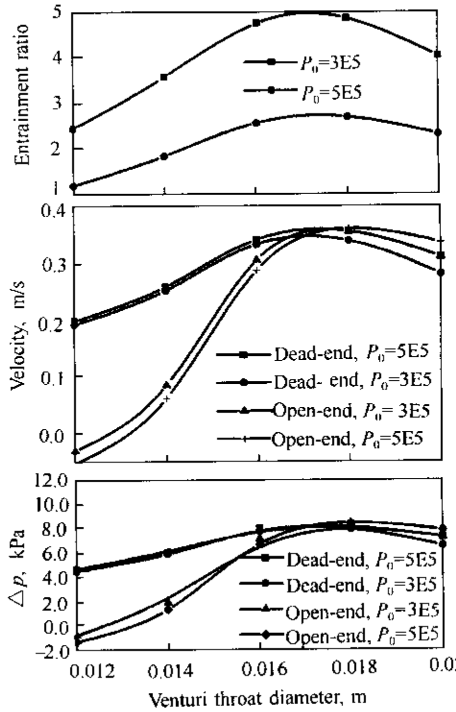

Fig.4 Effect of Venturi throat diameter on pressure difference Δp, face velocity V_C and entrainment ratio

Choosing permeability $K = 5 \times 10^{-12}$ m^2, length $L4 = 1.5$m, of the ceramic candle filter, setting the pulse reservoir stagnation pressure p_0 = 0.5 MPa, 0.3 MPa, and fixing the pulse pipe diameter $D1$ = 4 mm, Fig.4 confirms the relations between entrainment ratio, face velocity, pressure difference and the Venturi tube throat diameter. There is an optimum Venturi tube throat diameter. Where the entrainment ratio, face velocity and pressure difference have the highest value. The optimum Venturi tube throat diameter is about 17 mm in example II. The entrainment ratio, pressure difference and face velocity is effected by the inlet diameter and length of Venturi tube. Let $L1$ = 20 mm, $L2$ = 30 mm, $L3$ = 10 mm, $D2$ = 17 mm, Fig.5 shows the relation between entrainment ratio, pressure difference, face velocity and the Venturi tube inlet diameter. The face velocity and pressure difference is highest where Venturi tube inlet diameter is 30 mm in dead-end of filter passage, and is highest where Venturi tube inlet diameter is 40 mm in open-end. So, choosing the inlet diameter $D2$ = 30 mm. As a result, the final parameters of the reverse pulse cleaning system are listed as Table 2.

Table 2 The final choosing parameters

Pulse pipe	$D1$ = 4 mm, $L0$ = 0.5 m
Venturi tube	$L1$ = 20 mm, $L2$ = 30 mm, $L3$ = 10 mm, $D2$ = 28 mm, $D3$ = 18 mm
Candle filter	$L4$ = 1.5 m, $D4$ = 20 mm, $D5$ = 30 mm, $\varepsilon = 0.5, K = 5.0 \times 10^{12}$ m^2
Reservoir	p_0 = 0.5 MPa, T_0 = 373 K (cold air)
Hot fuel gas	p_H = 0.1 MPa, T_H = 773 K, P_r = 0.63, $\mu = 3.48 \times 10^{-5}$(kg·m)/s
Pulse time	0.2s

6 Conclusions

In designing reverse pulse jet cleaning system of candle ceramic filter, the computed results with the PHOENICS general software on a three dimensional BFC grid by using k-ε turbulent models are in agreement with the experimental results and the computed results with one dimensional flow models. It is verified that the standard turbulent model is suitable and the radial parameters can be obtained, but can not be obtained by using the one-dimensional flow models.

The more thin and long the filter passage is, the more no uniform the face velocity and pressure difference is in any section of filter passage. Generally, the face velocity and pressure difference is highest in the open-end and dead-end of filter passage, and is lowest in the middle portion. When the filter passage is wider and shorter, the face velocity and pressure difference increases more along the filter passage. The uniformity gets obvious when permeability increases.

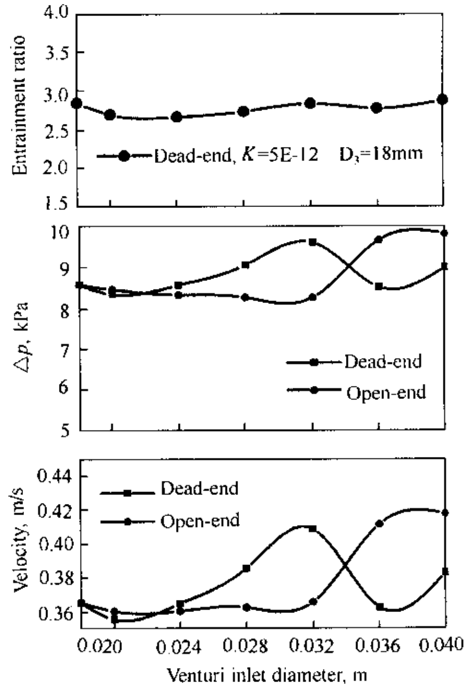

Fig.5 Effect of Venturi inlet diameter on pressure difference Δp, face velocity V_C and entrainment ratio

There is an obvious effect of Venturi tube size on the face velocity, pressure difference and entrainment ratio. In the initial designing, the throat diameter and the inlet length of Venturi tube are very small. They lead the no reasonable profiles of entrainment ratio. So, it can be used to the optimum design of geometry sizes of Venturi tube by using the standard turbulent model.

Using the unsteady compressible flow models, the profiles of flow parameters can be obtained at any time although the computational time increases. There is less effect of pulse stagnation pressure on the face velocity and pressure difference than that of geometry size of the reverse pulse cleaning system.

Nomenclature:

A: flow area; CE: Ergun constant; D: diameter; E: entrainment ratio; EP: turbulent dissipation; K: permeability; KE: turbulent kinetic energy; L: axial length; M: Mach number; $\dot{m}$: mass flows rate; p: pressure; Δp: pressure difference; p_b: back pressure; Pr: Prandtl number; R: general gas constant; Re: Reynolds number; T: temperature; U: angle velocity; V: radial velocity; V_C: face velocity; W: axial velocity; Z: axial distance; ε: porosity; γ: specific heat ratio; ρ : density; μ: viscosity; subscripts: 0: stagnation parameters; C: cold air; H: hot fuel gas.

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