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Agglomeration rate and action forces between atomized particles of agglomerator and inhaled-particles from coal combustion

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Abstract: In order to remove efficiently haled-particles emissions from coal combustions, a new way was used to put forward the process of agglomeration and the atomization was produced by the nozzle and then sprayed into the flue before precipitation devices of power station boiler in order to make inhaled-particles agglomerate into bigger particles, which can be easily removed but not change existing running conditions of boiler. According to this idea, a model is set up to study agglomeration rate and effect forces between fly ash inhaled-particles and atomized agglomerator particles. The developed agglomeration rate was expressed by relative particle number decreasing speed per unit volume. The result showed that viscosity force and flow resistance force give main influences on agglomeration effect of inhaledparticles, while springiness force and gravity have little effect on agglomeration effect of theirs. Factors influencing the agglomeration rate and effect forces are studied, including agglomerator concentration, agglomerator flux and agglomerator density, atomized-particles diameters and inhaled-particles diameter and so on.

Keywords: inhaled particles; agglomerator; effect forces; agglomeration rate

Introduction

Recently, hazards caused by inhaled particles of diameter smaller than 2.5 μm from coal combustion are getting a matter of environmental concern(Zheng, 2002). In China, 70% of power stations have been adopting coal combustion operation to generate electricity, which leads to a high inhaled-particles emission content from coal combustion. It is very difficult for traditional removing equipments to control emissions of inhaled-particles. Currently, some measures are put forward that agglomeration pretreatments are set up to make inhaled-particles agglomerate into bigger particles which can be easily removed by traditional removing manners. Many pretreatment methods, including electrostatic agglomeration(Watanabe, 1995), magnetic agglomeration (Wei, 2003), sound agglomeration (Ricra, 1986), heating agglomeration(Lind, 1996) and light agglomeration(Di, 1996), are studied. However it is difficult for these measures to use in the industry because of their shortcomings(Wei, 2003).

A new effective method is put forward that agglomerators of high viscidity and high water-solubility are sprayed into the flue gas before precipitators, which can not change existent removing manners and the running operations of the boilers. A model about agglomeration rate and effect forces between agglomerators and inhaled particles was set up. Agglomeration rate has been developed by the expression of decreasing speed of particle number per unit volume. Some influencing factors are also studied and analyzed.

1 Agglomeration theory and method

According to the movement ways of inhaled particles, the agglomeration phenomena are plotted into two kinds: self-agglomeration of quiet particles and agglomeration phenomena brought by particle movement. All of the two sorts are including soft agglomeration effect and solidity agglomeration effect. Soft agglomeration is mainly generated by Vander Waals force, coulomb force, which can be easily eliminated by chemistry effect, machine effect and other effects. Solidity agglomeration is mainly generated by Vander Waal force, coulomb force, liquid bridge force and absorbed layer force, which are commonly difficult to eliminate by chemistry effect and machine effect.

An agglomerating test device was designed and set up in order to simulate full-scale flue gas flow before the removing device of power stations, as shown in Fig.1. The instrument is mainly made up of one blower, one air preheated, one mixer, one particulate provider, two temperature controllers, one agglomeration chamber, one atomization nozzle, one flue gas analyzer, one induced draught fan and one particulate collector. It can be operated that certain quantity of an agglomerator is atomized by an atomizing nozzle and forms many fine liquid particles that are sprayed into the agglomeration chamber. The agglomerator is a water solution and formed by solving a material of high water-solubility, high viscidity, good stability under high temperatures in water. Because atomized liquid particles of the agglomerator have high viscidity surfaces, they can be stick with fly ash particles only if atomized particles are contact with fly ash particles. In addition, water composition of liquid particles is further vaporized as time passes due to high gas temperature, which can make plenty of inhaled particles closely agglomerate into bigger particles. The method is based on the theory of solidity agglomeration. According to the agglomeration method, an agglomeration model has been set up and studies the agglomeration effect of an agglomerator on inhaled particles, which is important guidance meaning for experimental studies.

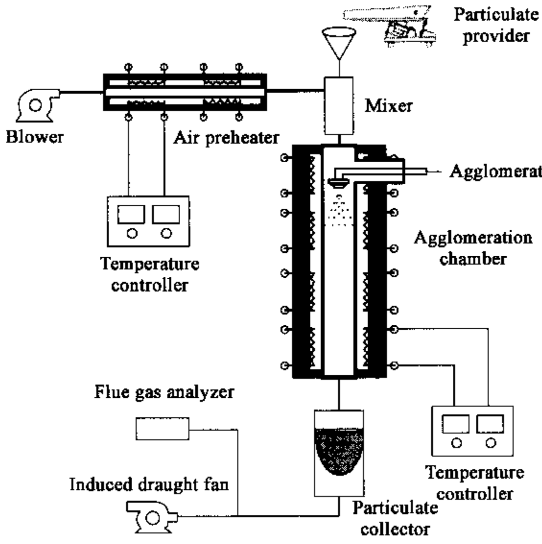

Fig.1 Sketch of haled particles agglomerating test device

2 Agglomeration forces model

2.1 Hypotheses of agglomeration model

Foundation of the model has its theory meaning to study agglomeration mechanism of fly ash inhaled particles and guide experiments of fly ash agglomeration. Then, hypotheses are showed in

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the following: (1) Supposing that fly ash particles and atomizing particles of agglomerators are of roundness. Volumes and qualities of which are uniform; (2) supposing that movements of fly ash particles are continued in the gas flow processes; (3) only if fly ash particles are contact with atomized particles, they will adhere to atomized particles. Sediment number of fly ash particles on each atomized particle is the same; (4) taking no account of the varies of difference materials.

2.2 Agglomeration rate calculation

Based on the model put forward by literature (Watanabe, 1995) and the theory of atomizing double-stream nozzle (Hou, 2002), the agglomeration model is set up. Through the third hypothesis, it is known that the sediment number of fly ash particles on atomized particles depends on theirs sediment speed. Through the theory of atomizing double-stream nozzle, average diameter of atomized liquid particles is obtained:

$$\overline{d_{w2}} = \frac{585\sqrt{\sigma}}{u\sqrt{\rho_{w1}L}} + 597\left(\frac{\mu}{\sqrt{c\rho_{w1}}}\right)^{0.45}\left(1000\frac{Q_w}{Q_k}\right). \tag{1}$$

Through conservation of mass, the number of atomized particles per unit time is obtained:

$$n_w = \frac{6Q_w\rho_{w1}}{\pi d_{w2}\rho_{w2}}. \tag{2}$$

For the same reason, the number of fly ash particles per unit volume:

$$n_p = 6Q_p/(\pi\rho_p d_p^3). \tag{3}$$

Where n_w is the number of atomized particles per unit time, n/s; Q_w is the flux of agglomerator solution before atomizing, m^3/s; ρ_{w1} is the density of an agglometrator solution before atomizing, kg/m^3; ρ_{w2} is the density of liquid particles after atomizing, kg/m^3; $\overline{d_{w2}}$ is the average diameter of atomized liquid particles, μm; L is the length of blend chamber of double-flow nozzle, m; σ is the surface tension of an agglomerator, dyn/cm; μ is viscidity of an agglomerator, cP; c is the correlation coefficient; Q_k is the volume flux of atomize air, m^3/s; n_p is the particle number of flue gas per unit time, s^{-1}; Q_p is the gas quality flux per unit time, kg/s; d_p is the inhaled particle diameter, um; ρ_p is the inhaled particle density, kg/m^3.

Then, sediment speed of haled particles in the surface of atomized liquid particles F is (Lind, 1996):

$$F = \frac{2\pi d_{w2}\eta}{RT} \times D \times \Delta P \times C_{Fs}, \tag{4}$$

where ΔP is the pressure difference, $\Delta P = P - P_0$, P_0 is the pressure in the agglomeration chamber and P is the pressure of atomized liquid particles; D is the number concentration of atomized liquid particles, s^{-1}m^{-3}.

$$C_{Fs} = \frac{1 + k_n}{1 + 1.71k_n + 1.333(k_n)^2},$$

$$\eta(T) = 1.0 \times 10^{-5} \times \left(\frac{T}{298}\right)^{1.75}.$$

Where T is the temperature of the agglomeration chamber, $k_n = 1$, $C_{Fs} = 1$.

Supposing that n is the sediment number of haled particles in each atomized liquid particles and t is the residence time of agglomerator in agglomeration chamber.

$$n = \frac{6F_tM_{w2}}{\pi\rho_p d_p^3}. \tag{5}$$

So agglomeration rate η is:

$$\eta = \frac{n \times n_{w2}}{n_p}. \tag{6}$$

2.3 Effect forces between agglomerated particles (Fig.2)

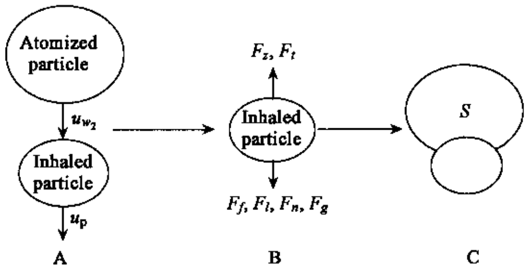

Fig.2 Effect forces between agglomerated particles

Agglomeration effect forces between single atomized particle and single haled particle are flow resistance, Vander Waal force, liquid bridge force, gravity, surface layer viscosity force and surface elasticity force. The following is obtained by force balance of agglomerated particles:

$$F_f + F_L + F_N + F_G - F_t - F_z = 0. \tag{7}$$

Flow resistance F_z (Tan, 1998) is:

$$F_z = 0.055\pi\rho_{w2}d_{w2}^2(u_p - u_{w2})^2\varepsilon^{-4.8}. \tag{8}$$

Surface elasticity force F_t is (Visser, 1976):

$$F_t = \left[\frac{3000k_p^{1/2}m_p^3m_{w2}^3}{\pi^5(m_p + m_{w2})}\left(\frac{d_pd_{w2}}{d_p + d_{w2}}\right)\right]^{\frac{1}{5}}. \tag{9}$$

Vander Waal force F_f (He, 2003):

$$F_f = \left[\frac{A}{12Z_0^2} + \frac{B}{6Z_0^3}\right]\left(\frac{d_pd_{w2}}{d_p + d_{w2}}\right). \tag{10}$$

According to the theory of surface-layer viscosity (Melanie, 1997), surface-layer viscosity force F_N is expressed by the following:

$$F_N = \lambda\frac{\partial u(y - \Delta y/z)}{\partial y}\Delta y\Delta z. \tag{11}$$

Due to agglomerated particles lying in force balance condition, then:

$$\frac{\partial u(y - \Delta y/z)}{\partial y} = u. \tag{12}$$

Then,

$$F_N = \lambda uS_0. \tag{13}$$

Where S_0 is the interface area of two particles; λ is the viscidity coefficient of an agglomerator; u is the balance velocity of agglomerated particles and obtained by momentum conservation theorem.

Apparent gravity (also called gravity errand) F_G is:

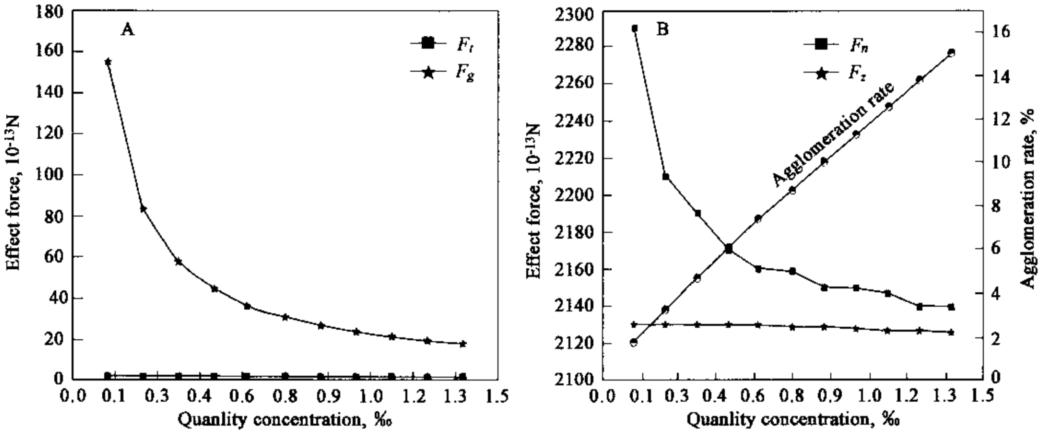

Fig.3 Impact of agglomerator quality concentration on agglomeration rate and effect forces

$$F_C = G_P - G_{w2} = \frac{1}{6}\pi g(d_p\rho_p - d_{w2}\rho_{w2}). \qquad (14)$$

Then, interface area S of liquid particle and haled particles is obtained by Formula (7).

Where ε is defined as interspaced rate of agglomeration chamber; c is the particle concentration in flue gas, kg/m^3; c_{w2} is the atomized liquid particle flux, kg/m^3; u_p, u_{w2} are the velocities of liquid particles and haled particles, respectively, m/s; m_p, m_{w2} are the mass of liquid particles and haled particles, respectively; k_p, k_{w2} are their elasticity coefficient of liquid-and holed particles respectively. Due to viscosity particles, then $k_{w2} = 0$, $k_p = \frac{1-\nu^2}{\pi E}$, ν is the Poisson ratio, E is the polar-surname module measure; A is the Hamaker constant; B is the adsorption constant of Vander Waal force.

3 Results and discussion

According to the model above, the results showed that the quantity-level unit of most effect forces effecting agglomeration are consistent with that of result calculated by Tang *et al.* (Tang, 2001). Especially, Vander Waal force and gravitation are neglected for particles of diameter more than 1.0 μm. It is discovered in the results that agglomerator flux, agglomerator concentration, flue gas flux, agglomeration density, atomized-particle diameter and inhaled particle diameter have impact on each effect forces, as follows.

3.1 Agglomerator quality concentration effect

Fig.3 shows the impact of agglomerator quality concentration on agglomeration rate and effect forces under the same conditions. Fig.3 shows the flow resistance and the surface-layer viscosity force has two quantity-level units higher than elasticity force and apparent gravity, which means the main impact of gas flow and agglomerator viscosity on agglomeration between inhaled particles. Apparent gravity decreases when agglomerator concentration increases. When agglomerator concentration is lower than 0.2‰, apparent gravity decreases rapidly. When agglomerator concentration is above 0.2‰, apparent gravity decreased slowly more and more. However elasticity force does not change with agglomerator concentration. Fig.3b shows the agglomeration rate is increasing with agglomerator concentration, while flow resistance is not changing and viscosity force is decreasing.

3.2 Agglomerator flux effect

Fig.4 shows the impact of agglomerator flux on agglomeration rate and agglomeration effect forces at other same conditions. It has been known that flow resistance and surface-layer viscosity force have two quantity-level units higher than elasticity force and apparent gravity and all the effect forces are not changing with agglomerator flux. However it is known from Fig. 4b that agglomeration rate was increasing with increasing agglomerator flux because greater agglomerator flux leads to greater atomized particle number of agglomerator and then increases contact opportunity with inhaled particles.

3.3 Gas flux effect

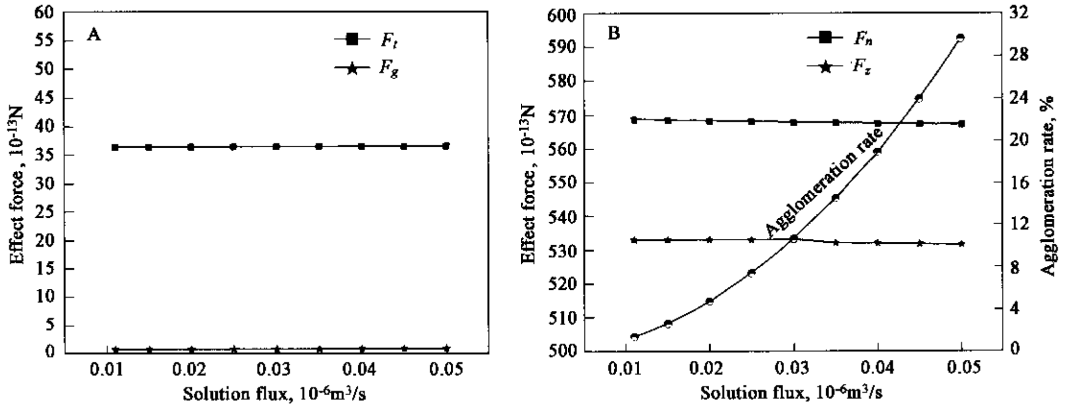

Fig.4 Impact of agglomerator flux on agglomeration rate and effect forces

Fig.5 shows the impact of flue gas flux on agglomeration rate and agglomeration effect forces at the same conditions. It has been known that flow resistance and surface-layer viscosity force has two quantity-level units higher than elasticity force and apparent gravity, which are not changing with flue gas flux. When flue gas flux is increasing, surface-layer viscosity force and flow resistance increases and agglomeration rate decreased because great flue gas flux lead to greater inhaled particle number.

3.4 Agglomerator density effect

Fig.6 shows the impact of agglomerator density on agglomeration rate and effect forces at the same conditions. It has been known that flow resistance and surface-layer viscosity force has two quantity-level units higher than elasticity force and apparent gravity. Elasticity force is not changing and flow resistance increases slowly with agglomerator density. When agglomerator density is increasing, both weight errand and viscosity force rapidly increase, while agglomeration rate decreased.

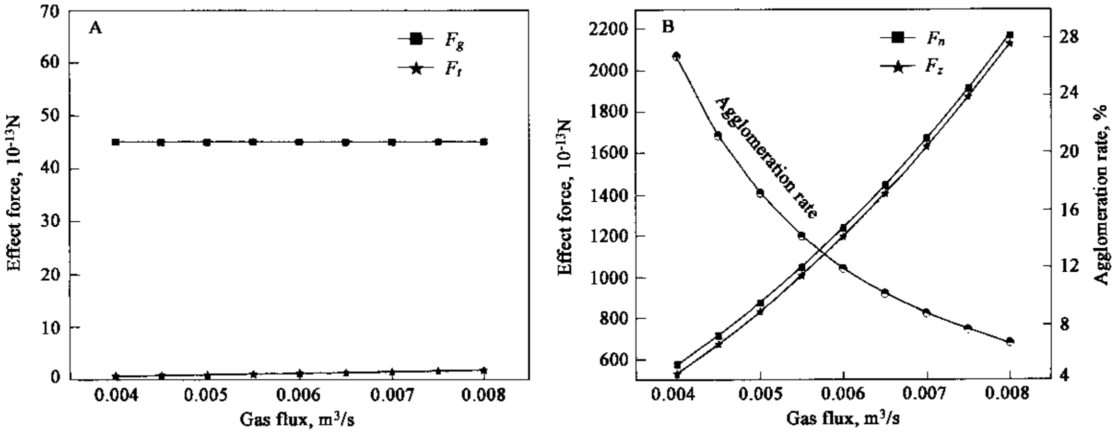

Fig.5 Impact of flue gas flux on agglomeration rate and effect forces

3.5 Inhaled-particle diameter effect

Fig. 7 shows the impact of inhaled particle diameter on agglomeration rate and effect forces at the same conditions. Fig.7a shows that elasticity force increased very slowly with inhaled particle diameter. Apparent gravity could not nearly change when diameter of inhaled particles is lower than 1.0 μm, while apparent can rapidly decrease until it is finally equal to elasticity force when diameter of particles is greater than 1.0 μm. Fig.7b shows that the flow resistance and agglomeration rate can not change with diameter of inhaled, while viscosity force could changed when diameter of inhaled particles is lower than 2.5 μm viscosity force toboggans when diameter of inhaled particles is greater than 2.5 μm until it is less than flow resistance.

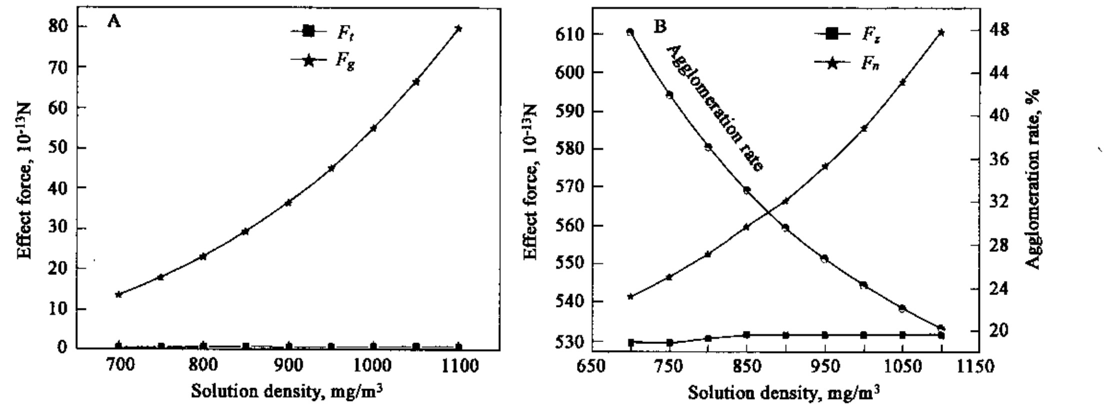

Fig.6 Impact of agglomerator density on agglomeration rate and agglomeration effect force

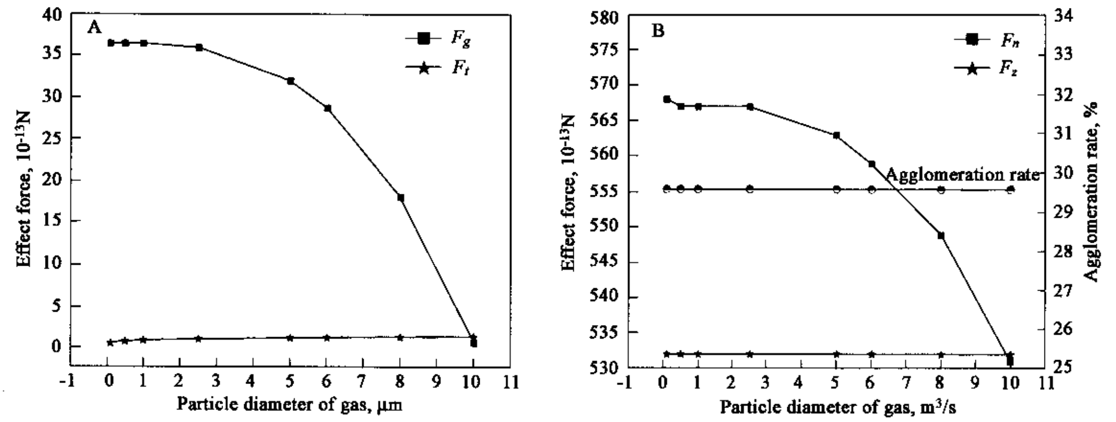

Fig.7 Impact of fly particle diameter on agglomeration rate and effect forces

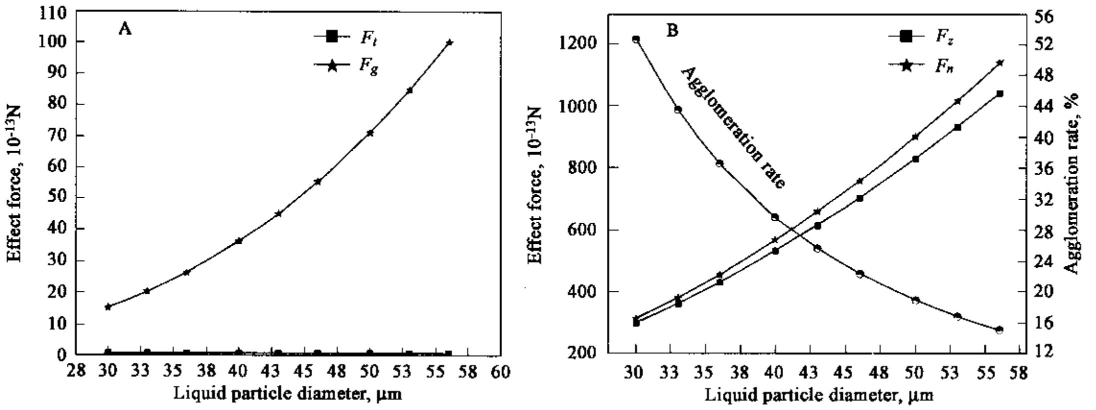

Fig.8 Impact of atomized liquid particle diameter on agglomeration rate and effect forces

3.6 Atomized particle diameter effect

Fig. 8 shows the impact of atomized particle diameter on agglomeration rate and effect forces. It has been known that flow resistance and surface-layer viscosity force has two quantity-level units higher than elasticity force and apparent gravity. Fig.8a shows that the elasticity force does hardly change and apparent gravity can increase. Fig.8b shows the viscosity force and flow resistance have resemble rising trend when atomized particles diameter is less than 40 μm. Viscosity force increases more quickly when atomized particles diameter is greater than 40 μm. However, agglomeration rate is decreasing with atomized liquid particle diameter.

4 Conclusions

The model has been set up to study agglomeration rate and effect forces between fly ash inhaled-particles and atomized particles of agglomerators. The following results are obtained: (1) When agglomerator flux and concentration are rising at other same conditions, agglomeration rate are also much increasing. When flue gas flux, agglomerator density and atomized particle diameter are rising, agglomeration rate is decreasing. (2) It has been known under all the conditions that flow resistance and surface-layer viscosity force have two quantity-level units higher than elasticity force and apparent gravity, means the main impact of gas flow and agglomerator viscosity on agglomeration between particles. (3) Viscosity force can also rapidly increase with agglomerator density, flue gas flux and atomized particles diameter, it can decrease with agglomerator concentration and inhaled particle diameter. Apparent gravity increases with agglomerator density and atomized particle diameter, it decreases with agglomerator concentration with inhaled particle diameter. Flow resistance has grater relation with the atomized particle diameter and flue gas flux. Flow resistance increases with atomized particle diameter and flue gas flux.

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