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Experimental Investigation on Flow and Drying Characteristics of Impinging Stream Drying

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Abstract: Based on the experimental investigation of one-stage semi-circular impinging stream drying, the experiments with the two-stage semi-circular, as well as the vertical and semi-circular combined impinging stream drying were conducted. The variations of system pressure drop, the mean residence time of particles with the mass flow-rate ratio and air velocity etc. were determined. The influences of inlet air temperature, mass flow-rate ratio, initial moisture content of particles and air velocity etc. on drying characteristics were also studied. The results indicate that the vertical and semi-circular combined impinging stream drying can make full use of the advantages of both the vertical and semi-circular impinging stream drying. Reasonable mass flow-rate ratio, air velocity, and higher inlet air temperature should be used for less energy consumption and cost during drying process.

Key words: two-stage semi-circular impinging stream drying; combined impinging stream drying; flow characteristics; drying characteristics

Fast and high strength drying is the important way that makes the drying process high efficiency and quality. Impinging stream drying is one of the most prospective ways in the drying field, and has wide application foreground. Because of the materials' fast and unsteady motion in the impinging zone, the system has the advantages of great drying intensity, short time, high efficiency and good quality etc. Making full use of the advantages of various impinging stream dryers to get the even higher drying rate is one of the useful approaches of enhancing the impinging stream drying. Vertical and semi-circular combined impinging stream drying can use both of their advantages and is more suitable for the drying of sticky and high moisture content materials [1]. So far, only few scholars have studied on them. This paper aims to study an effective drying approach.

1 Flow Characteristics

The setup for drying process is sketched in **figure 1**. The system consists of adjustable centrifugal blower, electrical heater, vertical impinging stream chamber, semi-circular impinging stream dryer, gas-solid separator, and measure devices. Semi-circular impinging stream dryer is made of steel pipe (d=65 mm), circular diameter is 965 mm, the feeders lie in the inlet of vertical impinging stream chamber and the inlet of circle, respectively. For two-stage semi-circular impinging stream drying, particles are added in the inlet of circle. For vertical and semi-circular combined impinging stream drying, particles are added in the inlet of vertical impinging stream chamber, particles first come into the vertical impinging stream chamber to remove some water, then come into the semi-circular impinging stream dryer to further remove water, then gas and particles are separated in the separator, finally, particles are collected by collector and exhaust gas is ejected into the atmosphere. The measure devices have balance, orifice flow-meter, U shape tube, hot ball breeze meter, digital temperature circuit measure meter, fiber-optic probe and computer data collecting system etc.

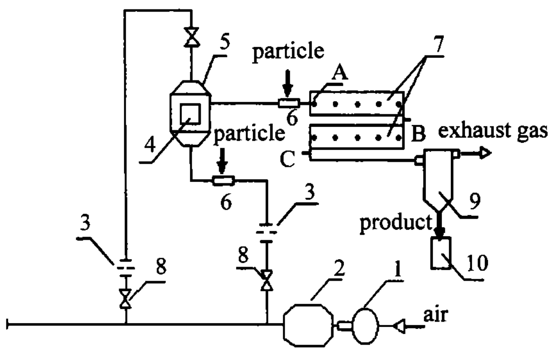

Figure 1 Schematic diagram of the experimental equipment of impinging stream drying, 1—blower; 2—electric heater; 3—orifice flow-meter; 4—window; 5—vertical impinging stream chamber; 6—feeder; 7—semi-circlar impinging equipment; 8—valve; 9—cyclone separator; 10—collector; A, B, C— pressure measure points of semi-circular.

Figure 2 shows the Euler number for only air flow (Eu_g) versus Reynolds number (Re) in combined impin-

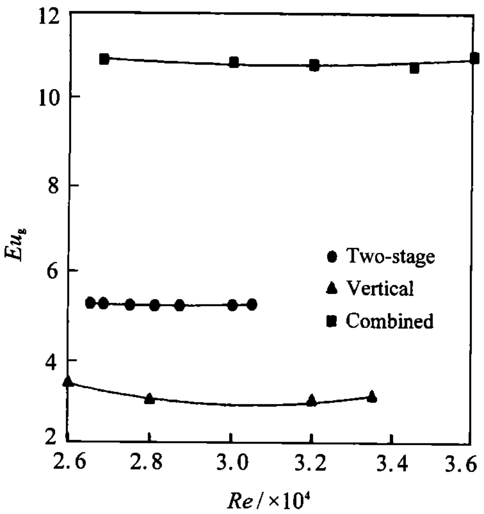

Figure 2 The variation of Eu_g versus Re in different systems.

ging dryer, two-stage semi-circle, vertical impinging chamber. As shown in figure 2 the Eu_g of combined impinging system is the highest, but the variation relationships are similar, the optimum Re scopes are existed in three systems, it's useful for controlling operation parameters.

Applying formula $\tau_m = M_s / m_s$, the mean residence time of particles (τ_m) is determined by measuring hold-up quantity (M_s) and mass flow-rate of particles (m_s), and air velocity have important influence on the flow and heat and mass transfer in the process of materials drying.

Figure 3 shows the relationship between the mean residence time of particles and mass flow-rate ratio (μ) in one-stage semi-circular, two-stage semi-circular, as well as the vertical and semi-circular combined impinging stream drying system. It can be seen that mean residence time of particles decreases with the increasing of mass flow-rate ratio μ. Mean residence time is the longest in combined impinging stream system, and the shortest in one-stage semi-circular impinging

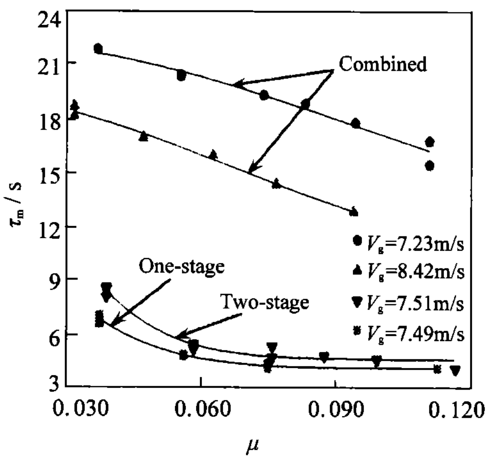

Figure 3 Mean residence time (τ_m) versus mass flow-rate ratio (μ).

stream system. So considering the mean residence time, combined impinging stream system is favorable for materials drying.

It can also be seen that the bigger of the gas velocity, the shorter of the mean residence time. So considering the mean residence time, increasing the gas velocity is not favorable for materials drying. But on the other hand, with the increase of gas velocity, the increase of gas-solid relative velocity and system temperature as well as the decrease of gas relative humidity are favorable for materials drying. So, increasing the gas velocity whether or not favorable for materials drying needs to combine the experimental results to confirm.

2 Drying Characteristics

The water removal is very complicated and related with many factors during the materials drying in impinging stream dryer. In the process of experiment, millet was used as the materials, and the effects of inlet air temperature, mass flow-rate ratio, initial moisture content and air velocity etc. on drying process were investigated.

Figure 4 shows the variation of water removal along the L direction during the two-stage semi-circular impinging stream drying. Where, the inlet air temperature t_{gi} were 51, 60, 70, 75 ℃ respectively, and initial moisture content w_{si} were 38.57% and 41.17%. As shown in figure 4, the water removal of the first-stage increases with the increasing of initial moisture content. When the initial moisture content of materials is higher, the water removal is more in the first stage and less in the second stage. When the initial moisture content is lower, the proportion of water removal in the second-stage is bigger. Therefore, choosing the stage number properly is very important for improving the water removal.

Figure 5 shows the relation between the water removal and the inlet air temperature during two-stage semi-circular impinging stream drying. Where, the mass

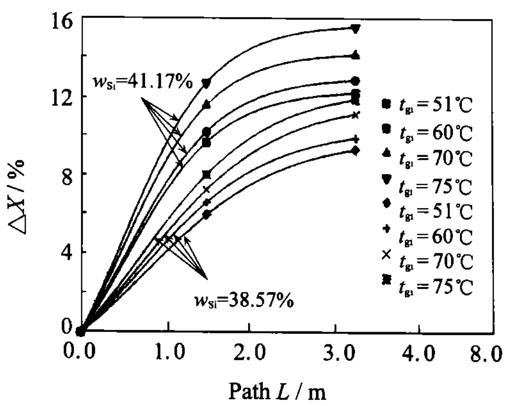

Figure 4 The variation of water removal (ΔX) along L direction.

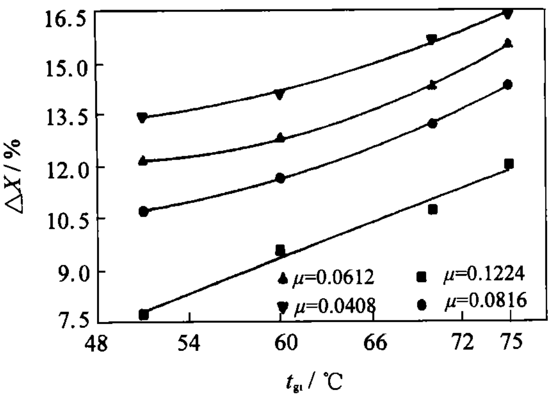

Figure 5 The relation between water removal (ΔX) and inlet air temperature (t_{gi}), w_{Si} = 41.17%.

flow-rate ratios were 0.040 8, 0.061 2, 0.081 6 and 0.122 4 respectively, and moisture content was 41.17%. As shown in the figure, similar to one-stage semi-circular impinging stream drying, water removal increases with the increasing inlet air temperature. As such, during the materials drying, higher inlet air temperature should be used to improve the drying rate. Because the residence time of materials in the impinging stream drying system is very short, the inlet air temperature can be increased to a larger extent than that in the traditional drying equipment.

Figure 6 shows the relation between the water removal and the mass flow-rate ratio during two-stage semi-circular impinging stream drying. Where, the inlet air temperature were 51, 60, 70, 75 ℃ respectively, and the initial moisture content was 41.17%. It can be seen that water removal decreases with the increasing mass flow-rate ratio. In order to improve the drying rate, mass flow-rate ratio can not be too high. If the mass flow-rate ratio is too low, the dryer's capacity will be too low, and drying energy consumption and cost will be too high. Therefore, reasonable mass flow-rate ratio should also be used.

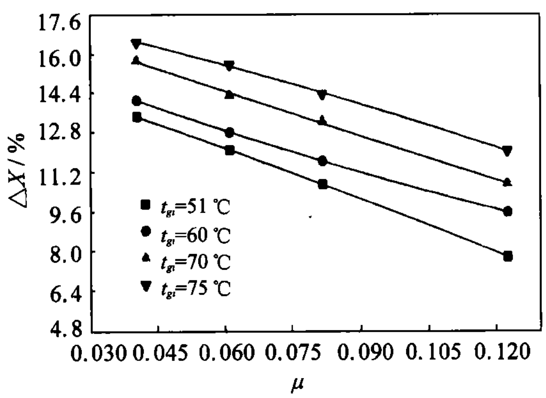

Figure 6 The relation between water removal (ΔX) and mass flow-rate ratio (μ), w_{Si} = 41.17%.

Figure 7 shows the relation between the water removal and the initial moisture content of materials during two-stage semi-circular impinging stream drying. Where, the inlet air temperature was 60 ℃, and the mass flow-rate ratio were 0.040 8, 0.081 6, 0.122 4 respectively. As shown in the figure, water removal increases with the increasing of the initial moisture contents of materials, and the higher of the initial moisture content, the more water can be removed. So, two-stage semi-circular impinging stream drying is fit for higher moisture content materials.

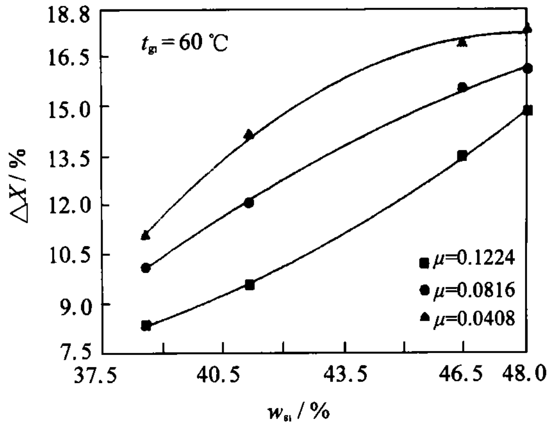

Figure 7 The relation between water removal (ΔX) and mass flow-rate ratio removal (μ) and initial moisture content (w_{si}).

Figure 8 shows the relationship between the water removal and the mass flow-rate ratio of the vertical and semi-circular combined impinging stream drying. Where, the inlet air temperatures were 60 and 70 ℃, and gas velocity was 9.42 and 10.49 m/s respectively, initial moisture content was 47.62%. It can be seen from the figure, the bigger the gas velocity, the more the water removal, and the effect of mass flow-rate ratio on water removal is smaller when the gas velocity is higher. It also indicated that as the increasing of the gas velocity, the favorable factors of gas-solid related velocity increasing and gas relative humidity decreasing

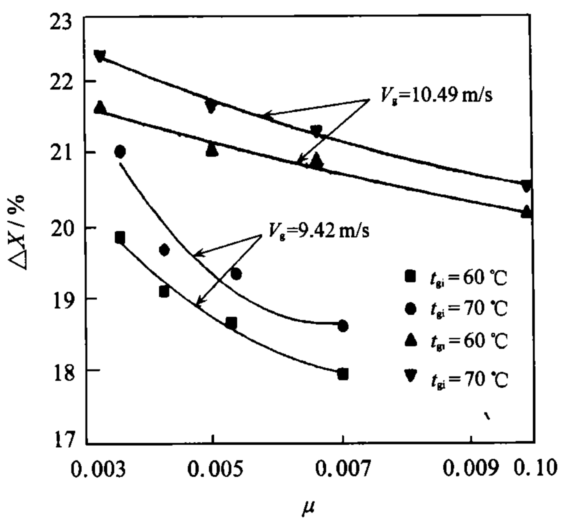

Figure 8 Water removal (ΔX) versus mass flow-rate ratio (μ), w_{Si} = 47.62%.

play the important role during the materials drying. But if the gas velocity is too high, drying energy and cost are also too high. So reasonable gas velocity should be used during the materials drying in order to make the drying rate bigger, energy consumption and cost lower.

Figure 9 shows the relationship between the water removal and mass flow-rate ratio in vertical and semi-circular combined impinging stream drying. Where,

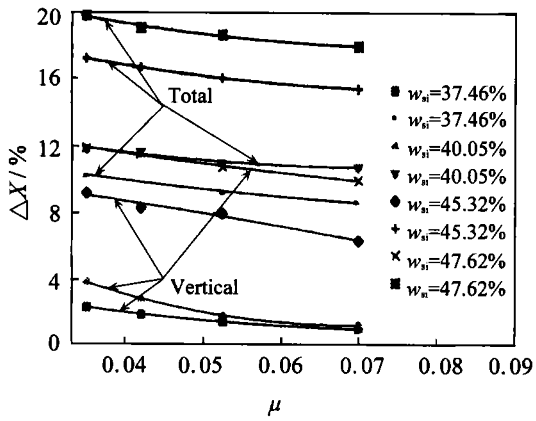

Figure 9 Water removal ($\triangle X$) versus mass flow-rateratio (μ).

the inlet air temperature was 60 ℃, and the initial moisture content were 37.46%, 40.05%, 45.32%, 47.62%. It can be seen that water removal decreases with the increasing mass flow-rate ratio. When the initial moisture content is lower, the water removal is more in vertical impinging chamber and less in the semi-circular impinging stream dryer. Water removal in vertical impinging stream chamber increases with the increasing of the initial moisture content. The higher of the initial moisture content, the more water can be removed in vertical impinging stream chamber. So combined impinging stream drying is fit for the higher initial moisture content materials. In addition, owing to the materials uniformly distributing in the vertical impinging stream chamber, sticky phenomena between particles and particles with pipe wall do not occur easily. Therefore, for sticky and higher moisture content materials, using the combined drying can make full use of the advantages of both the vertical and semi-circular impinging stream drying, and get the satisfied results.

As shown above, inlet air temperature, mass flow-rate ratio, initial moisture content of materials and air velocity are important factors of affecting the drying process. The relationship of inlet air temperature, mass flow-rate ratio, materials' initial moisture content and gas velocity can be expressed as:

$$\triangle X = 7.86\times10^{-5}\, t_{gi}^{0.78}\cdot\mu^{-0.30}\cdot w_{si}^{2.14},$$

the duplicate correlated coefficient is $R^2=0.92$ (two-stage);

$$\triangle X = 2.65\times10^{-7}\, t_{gi}^{0.37}\cdot\mu^{-0.10}\cdot w_{si}^{3.25} V_g^{1.63},$$

the correlation coefficient $R^2 = 0.991\,295$ (Combined).

4 Conclusions

(1) The variation of Eu_g for only air flow versus Re are similar in three systems, which are useful for controlling operation parameters.

(2) The mean residence time τ_m of particles decreases with the increasing mass flow-rate ratio μ and gas velocity V_g.

(3) With the increasing moisture content of materials, more water is removed in the first-stage semi-circle than in the second-stage semi-circle, choosing the stage number properly is very important.

(4) Water removal increases with the rising inlet air temperature and initial moisture content of materials, and decreases with the increasing mass flow-rate ratio.

(5) Vertical and semi-circular combined impinging stream drying can make full use of the advantages of both the vertical and semi-circular impinging stream drying, and obtain satisfactory drying results.

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