Numerical simulation on gas–liquid flow, heat, and mass transfer characteristics in a dual-contact-flow absorption tower

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Received 6 November 2012; Revised 15 February 2013; Accepted 19 February 2013

ABSTRACT: Because of the limitation of accurate measurement of microscopic parameters in the dual-contact-flow absorption tower, the diameter, velocity, temperature of a single droplet, and the concentration of matter in it are difficult to be obtained through experimental methods. However, these data are of crucial importance to understand the behaviors of liquid phase in the absorber. In this paper, the microscopic motion, heat, and mass transfer characteristics of droplets in the dual-contact-flow absorption tower have been numerically simulated, and the results have been validated by experimental data. The motion trails of droplets under different initial jetting velocities and gas velocities are studied, and the fall-back characteristics have been obtained. The critical diameters of droplets increase remarkably with the increase of gas velocity but have limited relationship with the liquid initial jetting velocity. The heat and mass transfer capacities of droplets have also been investigated. It is found that because of the diversity between the concentration relaxation time and the temperature relaxation time, there may be considerable difference between heat and mass transfer behaviors. All the work above is a complement of the basic performance of droplets in the dual-contact-flow absorber and can supply guidance for estimating the practical application performance. © 2013 Curtin University of Technology and John Wiley & Sons, Ltd.

KEYWORDS: dual-contact-flow absorption tower; numerical simulation; motion; heat transfer; mass transfer

INTRODUCTION

Sulfur dioxide (SO₂), mainly generated from fossil-fuel combustion, poses numbers of environmental and human-health hazards.1,2 Among numerous kinds of desulfurization techniques, wet flue gas desulfurization (WFGD) has been widely used in most power plants worldwide because of its high utilization rate of sorbent and low operation cost.3,4 In recent years, also lots of researchers focus their lights on integrated removal of pollutants in flue gas, such as SO₂, NOₓ, CO₂, heavy metal, and particulates, using the existing WFGD systems in power plant only by changing the additives.5–13 The efforts to experimentally characterize the WFGD performance have been carried out, and influencing factors on efficiency of flue gas removal14–21 are the hot topics mostly discussed.

Beyond experimental studies, mathematical modeling, notably for those mathematical models describing the chemical process,23–27 flow field,28–32 heat, and mass transfer process,33,34 has been proved to be a useful tool for investigation and design of complex WFGD systems.22 However, few numerical studies emphasized on the detailed flow characteristics, such as matter concentration, temperature, and velocity of droplets, have been carried out in the dual-contact-flow absorption tower.

The schematic of a dual-contact-flow absorption tower is shown in Fig. 1. As shown in Fig. 1, liquid in the absorption tower is shattered into small droplets after leaving the nozzles arranged at the bottom of the absorption tower. The gas–liquid two phases first meet as droplets go up to the top of the liquid bed, and then meet the second time during the course of droplets falling back to the slurry tank. Because of the simple absorption setup, long contact time between the gas and liquid phase, large quantity of holding liquid, and intensive mixture, the dual-contact-flow absorption tower designed for WFGD is one of the most promising reactors for SO₂ reduction35–38 and has been widely applied36 in recent years. Because of the limitation of the measurement methods on microscopic parameters, few results have been obtained on the diameter, velocity,
temperature of a single droplet, and the concentration of matter in it in the dual-contact-flow absorber experimentally. These data and mechanisms are of crucial importance to understand the behaviors of liquid phase in the absorption tower. Therefore, the simulation method takes its role in the present study.

In this paper, numerical simulation on the mechanisms of motion, heat, and mass transfer characteristics of droplets in the dual-contact-flow absorption tower has been carried out and the simulation results have been experimentally validated. The mechanism of the fallback characteristics of droplets in the dual-contact-flow absorption tower has been studied and the critical diameter has been obtained. Temperature, matter concentration, and residence time of droplets have been lucubrated to explain the law of heat and mass transfer and microscopic gas–liquid interaction in the absorber. All the studies above are considered as complement of the basic performance of droplets in the dual-contact-flow absorption tower and can supply guidance for estimating the practical application performance.

**PRINCIPLES AND METHODS**

The following models are applied to describe the motion, mass, and heat transfer of the droplet in the absorption tower in the present study.

**Motion models**

Lagrangian motion equation of a single particle is applied to analyze the motion process of a single droplet in the dual-contact-flow absorption tower, as shown below:

\[
m_{p} \frac{d\mathbf{v}_{p}}{dt} = \sum F, \quad m_{p} = \frac{1}{6} \pi d_{p}^{3} \rho_{p}
\]  

The one-dimension motion model is used to describe the motion of the droplet, and the side force is ignored as well. Hence, Lagrangian motion equation above can be simplified as follows:

\[
\frac{1}{6} \pi d_{p}^{3} \rho_{p} \frac{d\mathbf{v}_{p}}{dt} = \frac{1}{4} \pi d_{p}^{2} C_{d} \left( \frac{1}{2} \rho_{g} (v_{g} - v_{p}) \right)^{2} + \frac{1}{2} \frac{1}{6} \pi d_{p}^{3} \rho_{g} \left( \frac{dv_{g}}{dr} - \frac{d\mathbf{v}_{p}}{dt} \right) \\
+ \frac{3}{2} d_{p}^{2} \sqrt{\pi \rho_{g} \mu} \int_{-\infty}^{t} \frac{dv_{g}}{dt} \sqrt{t - \tau} d\tau \\
+ \frac{1}{6} \pi d_{p}^{3} \left( \rho_{g} - \rho_{p} \right) g_{y}
\]  

If the Basset force is also ignored, and \( \rho_{g}/\rho_{p} < 1 \) is taken into consideration, the following equation can be obtained:

\[
\frac{dv_{p}}{dt} = \frac{3}{4} \frac{C_{d} \rho_{g}}{d_{p} \rho_{p}} (v_{g} - v_{p})^{2} + g_{y}
\]  

where, \( C_{d} \) is the resistance coefficient which can be expressed as \( C_{d} = \frac{24}{Re} f(Re) \). Moreover, \( f(Re) \) can be calculated by the following piecewise functions:
Velocity relaxation time in our study, namely velocity relaxation factor, is defined as follows:

$$\tau_v = \frac{\rho_p c_p^2}{18\mu}$$  \hspace{1cm} (5)

where $\tau_v = \frac{[\rho_p][d_p]^2}{[\mu]} = \frac{ML^{-3}t^2}{ML^{-1}T} = t$ has the same dimensionality as time.

According to the analysis above, motion equation of a single droplet can be expressed by the velocity relaxation time and resistance coefficient, shown as follows:

$$\frac{dv_p}{dt} = \frac{v_g - v_p}{\tau_v} f(Re) + g_y$$  \hspace{1cm} (6)

**Heat transfer models**

Suppose that the interior temperature of a droplet is uniform, the unsteady state heat transfer equation between the droplet and gaseous phase can be expressed as follows:

$$\frac{1}{6} \pi d_p^3 \rho_p c_p \frac{dT_p}{dt} = \pi d_p^2 h(T_g - T_p)$$  \hspace{1cm} (7)

Then the following equation may be derived:

$$\frac{dT_p}{dt} = \frac{6h}{d_p \rho_p c_p} (T_g - T_p) = \frac{h_d}{2} \frac{h_d}{2} \frac{(T_g - T_p)}{d_p^2 c_p}$$  \hspace{1cm} (8)

Temperature relaxation time, with the same dimension of time, is defined as follows:

$$\tau_T = \frac{\rho_p c_p d_p^2}{12\lambda}$$  \hspace{1cm} (9)

Together with the definition of $Nu = \frac{h_d}{2}$, the following heat transfer equation of a single droplet can be derived:

$$\frac{dT_p}{dr} = \frac{Nu(T_g - T_p)}{2\tau_T}$$  \hspace{1cm} (10)

In the sense of physics, temperature relaxation time refers to the time at which the temperature gap between the droplet and gaseous phase decreases to 36.8% of the initial one.

Because the velocity slips between the droplet and gaseous phase cannot be neglected, the following empirical equation is applied in the simulation analysis:

$$Nu = 2 + 0.6Pr^{1/3}Re^{1/2}$$  \hspace{1cm} (11)

The heat transfer equation above can be solved by simultaneous equations of velocity and temperature.

**Mass transfer models**

According to the same principle as heat transfer equations, the interior concentration of matter in a droplet is assumed to be uniform. The unsteady state mass transfer equation between the droplet and gaseous phase can be expressed as follows:

$$\frac{1}{6} \pi d_p^3 \frac{dC_p}{dt} = \pi d_p^2 h_m(C_g - C_p)$$  \hspace{1cm} (12)

Then the following equation can be derived:

$$\frac{dT_p}{dt} = \frac{6h_m}{d_p} (T_g - T_p) = \frac{h_m}{2} \frac{D}{d_p^2} (T_g - T_p)$$  \hspace{1cm} (13)

The concentration relaxation time is defined as follows:

$$\tau_m = \frac{d_p^2}{12D}$$  \hspace{1cm} (14)

Together with the definition $Sh = \frac{h_m}{D}$, the following mass transfer equation of a single droplet can be deduced:

$$\frac{dC_p}{dr} = \frac{Sh(C_g - C_p)}{2\tau_m}$$  \hspace{1cm} (15)

Similar to temperature relaxation time, the physical interpretation of concentration relaxation time $\tau_m$ is the time at which the matter concentration gap between the droplet and gaseous phase decreases to 36.8% of the initial one.

Because the velocity slips between the droplet and gaseous phase cannot be neglected, the following empirical equation is applied in the present simulation:

$$Sh = 2 + 0.6Sc^{1/3}Re^{1/2}$$  \hspace{1cm} (16)

The mass transfer equation above can also be simultaneously solved with velocity equations.
Numerical implementation

Velocity, temperature, and concentration equations of the droplet motion which can be solved simultaneously are shown as follows:

\[
\begin{align*}
\frac{dv_p}{dt} &= \frac{v_g - v_p}{\tau_v} f(Re) + g_y \\
\frac{dT_p}{dt} &= \frac{Nu(T_g - T_p)}{2\tau_T} \\
\frac{dC_p}{dt} &= \frac{Sh(C_g - C_p)}{2\tau_m} \\
\end{align*}
\]

Initial boundary conditions are as follows:

\[
\begin{align*}
t &= 0 \\
  v_p &= v_{p0} \\
  T_p &= T_{p0} \\
  C_p &= C_{p0} \\
\end{align*}
\]

Fourth-order Runge–Kutta method\(^{39}\) is used to solve the equations above in the present study.

RESULTS AND DISCUSSION

Numerical simulation on gas–liquid flow characteristics

Velocity and motion trail of the droplet

Figure 2 shows the numerical simulation results of velocity and motion trail of the droplet with different initial jetting velocities when the gas velocity is equal to 2 m s\(^{-1}\). Considering that droplets with diameters less than 100 \(\mu\)m is so easy to be carried away by gaseous phase that has been approved afterwards, and through observation during experiment process, the diameters of the droplets are no more than 10,000 \(\mu\)m; the diameters of droplets numerically studied in our research are in the range of 100 to 10,000 \(\mu\)m. In Fig. 2, the gas velocity is kept unchanged. Effects of droplet initial jetting velocity and diameter on the gas–liquid flow performance have been analyzed.

It can be noted from Fig. 2 that the smaller the droplet diameter is, the weaker the influence of \(v_{p0}\) impact on the motion trail of the droplet. Droplets with diameters \(d_p < 400 \mu\)m show almost the same motion trail feature at different droplet initial jetting velocities. These small droplets are taken off from the top of the tower directly without any fall-back trend at a constant terminal settling velocity under the balance between the friction force and the gravity. From Fig. 2, it can also be observed that the variation of droplet velocity and the motion trail are converged with the increase of droplet diameters \((d_p = 1000–10000 \mu\)m\). Hence, all the larger fall-back droplets have similar velocity and motion trail, and a clear interface can be obtained in the liquid bed. It enables us to research the motion characteristics of droplets in the absorber with a unified law, which is of great benefit to simplify the study models.

It can also be seen from Fig. 2 that the fall-back height of the droplet increases with the increase of the droplet initial jetting velocity \(v_{p0}\). This implies that the actual bed height increases with \(v_{p0}\), which is consistent with the experimental results published by Sun et al.\(^ {37}\) However, the critical diameters of fall-back droplets are almost the same. In other words, the initial jetting velocity of the droplet can influence the bed height, but does not considerably determine whether the droplets fall back or not.

Figure 3 shows the numerical simulation results of the velocity and the motion trails of droplets with different gas velocities when the liquid initial jetting velocity \(v_{p0}\) is equal to 5 m s\(^{-1}\). Effects of droplet size and gas velocity on the gas–liquid flow behaviors have been investigated.

It can be seen from Fig. 3 that the droplets with different diameters are quite different when the gas velocity changes. When \(v_g = 0\) m s\(^{-1}\), all droplets can fall back; when \(v_g = 2\) m s\(^{-1}\), only droplets with diameters \(d_p > 400 \mu\)m can drop back; when \(v_g = 4\) m s\(^{-1}\), the droplets of diameters less than 1,000 \(\mu\)m are all carried away by gaseous phase. As shown in Fig. 2, when the gas velocity increases from 0 to 4 m s\(^{-1}\), the heights where droplets begin to fall back shows little variation. Hence, the gas velocity only influences the fall-back characteristics of droplets and has little impact on the liquid bed height of the dual-contact-flow absorption tower.

Actual bed height and critical diameter of the fall-back droplet

Figure 4 shows the change of jetting height \(y_{pmax}\) with gas velocity \(v_g\) for droplets of different diameters at different initial jetting velocities. As shown in Fig. 4, droplets of different diameters reach \(y_{pmax} = 2\) m one after another with gas velocity \(v_g\) increasing from 0 to 4 m s\(^{-1}\), which suggests that droplets are carried off from the top of the absorber.

Numerical simulation results indicate that all the droplets which are not carried off have close value of \(y_{pmax}\) under the same initial jetting velocity \(v_{p0}\). In other words, the actual jetting heights of almost all droplets that have not been carried away are roughly equal, although the liquid is broken into droplets of different size after spraying out from the nozzles. Therefore, a quite obvious vapor–liquid interface exists and the actual bed height could be obtained through experiments.
As shown in Fig. 4, the dotted line is the experimental data measured in the dual-contact-flow absorption tower introduced in Fig. 1. It can be seen from Fig. 4 that, in most cases, data of simulation solutions is consistent with the results of experimental actual bed height, which confirms the reliability of numerical simulation. However, it should be noted that when \( v_{p0} > 4.86 \text{ m s}^{-1} \) and \( v_g > 2 \text{ m s}^{-1} \), the simulation
solutions are inconsistent with experimental results. The experimental actual bed height decreases with the increase of gas velocity gradually, and this is mainly caused by the dramatically increased interaction between gaseous phase and droplets with the increase of gas and droplet velocity. Turbulence intensity increases with the increase of gas velocity, which results in the rise of resistance coefficient. Therefore, Stokes resistance cannot describe the resistance of the spherical droplet under these circumstances in the simulation. Further improvement of simulation models is necessary in the future. Although numerical simulation may only be obtained with certain assumptions, they may certainly supply quantitative description of gas-liquid two-phase flow in the absorption tower in many aspects for the present study.

Figure 5 shows the change of critical diameter $d_c$ with gas velocity $v_g$ and droplet initial jetting velocity $v_{p0}$. The critical diameter is defined as the maximum droplet diameter which can be carried off from the top of the absorption tower at different $v_g$ and $v_{p0}$. It can be seen from Fig. 5 that $d_c$ increases dramatically with the increase of $v_g$. However, with $v_{p0}$ increasing from 1 to 7 m s$^{-1}$, $d_c$ increases slightly. That means when gas velocity increases, there will be more and bigger droplets to be carried off from the top of the absorption tower. When $v_{p0}$ increases to 7 m s$^{-1}$ and $v_g$ is greater than 2.5 m s$^{-1}$, $d_c$ increases sharply. The fall-back height of all the droplets is higher than the height of tower during the calculation process. The liquid is sprayed out of the tower and all the droplets are carried off, with $d_c$ approaching infinity.
Numerical simulation on gas–liquid heat and mass transfer characteristics

Change of temperature and matter concentration

Figure 6 shows the numerical simulation results of the change of droplet temperature and matter concentration in the droplet when the initial jetting velocity $v_{p0}$ is kept unchanged at 5 m s$^{-1}$. It can be noted from Fig. 6 that the temperature of droplets and the concentration of matter in it both approach to constant values exponentially. Nevertheless, the analytic curves of temperature and matter concentration are slightly different as the diameters of droplets vary. As shown in Fig. 6, both the temperature and the concentration of matter in smaller droplets rise faster because smaller quality brings smaller inertia. Hence, the no matter temperature or concentration in smaller droplets can change faster than those of bigger ones with the same surrounding conditions. The primary difference of temperature analytic curves is the disparity in curve length, although there is little difference in curve shape. This is due to the retention time of droplets that differs considerably under different gas velocities, but the influence of gas velocity on heat transfer coefficient is not significant. It can also be noted that the concentration relaxation time $t_{m}$ is shorter than the temperature relaxation time $t_{T}$.

Figure 4. The actual bed height: simulation results vs experimental data. This figure is available in colour online at www.apjChemEng.com.
Heat and mass transfer performance of the droplet at different bed heights

Figure 7 shows the change of heat transfer quantity between gaseous phase and droplets when the gas velocity equals 2 m s$^{-1}$. The simulation results in Fig. 7 present changes of heat transfer intensity and performance at different liquid bed heights.

From Fig. 7(a), it can be found that the heat transfer quantity of droplets decreases remarkably with the increase of tower height as the initial liquid jetting velocity equals 1 m s$^{-1}$. As the initial jetting velocity is relatively low, there is no enough time for gaseous phase to heat the droplets before they drop back to the slurry tank.

From Fig. 7(b), (c), it can be observed that the heat transfer quantity of droplets increases first and then drops sharply with the increase of tower body height when the initial liquid jetting velocity is equal to 3 and 5 m s$^{-1}$. The peak of heat transfer quantity displays at the top of the liquid phase bed as shown in Figs. 7 and 4 contrastively. It is because the velocity of droplets is uniform and the liquid distribution density is varying obviously with the change of bed height. The top of the liquid bed, where the liquid distribution is the densest, is the place where heat transfer conducts most intensively. Furthermore, there are few liquid droplets in the space of tower body up the liquid bed, so there is almost no heat transfer conducting between liquid phase and gaseous phase here.

Figure 7(d) shows that the heat transfer quantity curves almost horizontally at a relatively low level with the increase of tower body height as $v_{p0} = 7$ m s$^{-1}$. Under an initial jetting velocity that is so fast, large quantities of droplets fly out of the tower directly. There is no fixed liquid bed and the residence time becomes shorter. Hence, the heat transfer quantity between gaseous phase and liquid droplets drops sharply.

In short, the heat transfer quantity falls sharply and the heat transfer performance deteriorates apparently if the liquid droplets fly out of the top of the absorption tower, no matter, because of an excessive high gas velocity or initial jetting velocity of droplets.

Figure 8 shows the change of mass transfer quantity between gaseous phase and droplets with bed height when the gas velocity $v_g = 2$ m s$^{-1}$. The simulation results in Fig. 8 present the change of mass transfer intensity and performance at different bed heights.

It can be noted from Fig. 8(a), (b) that the mass transfer process is in accordance with the heat transfer process. However, the change curves of mass transfer shown in Fig. 8(c), (d) are quite different from those of heat transfer illustrated in Fig. 7(c), (d). No peak occurs in Fig. 8(c), (d) when $v_{p0}$ equals 5 or 7 m s$^{-1}$. This is because $\tau_m$ is smaller than $\tau_v$, thus the mass transfer process has been nearly completed before all the droplets reach the top of the liquid bed. This is consistent with the analytic results of the concentration of matter in droplet in Fig. 6(b), (d), (f).

Hence, different length of temperature and concentration relaxation time may bring considerable disparity between heat and mass transfer behaviors in spite of the similarity between heat and mass transfer process.

The total heat and mass transfer quantity of the droplet during the whole residence time

Droplet behaviors in the absorption tower are highly related to the residence time of droplets. Thus, numerical simulation is employed in analyzing the total heat and mass transfer quantity of droplets during the whole residence time.

Figure 9 shows the total heat transfer quantity of droplets as $v_g = 2$ m s$^{-1}$ during the whole residence time. As illustrated in Fig. 9, the length of curves indicates the residence time of droplets. Simulation results show that the total heat transfer quantity of droplets increases obviously with the increase of droplet diameter. The droplet diameter rises by ten times, whereas the heat transfer quantity increases by about 25 times. Hence, the heat transfer quantity per mass of a larger droplet is less than that of a smaller one. With the increase of $v_{p0}$, the residence time first increases and then decreases. Moreover, when $t = 0.2$ s, slopes of curves corresponding to $v_{p0} = 3$ m s$^{-1}$ first become smaller and then become larger. The conditions in which $t = 0.5$ s and $v_{p0} = 5$ m s$^{-1}$ are almost the same because the slippage velocity between droplets and gaseous phase decreases and the heat transfer coefficient reduces gradually as the droplets move to the top of the liquid bed. As the droplets fall back, the slippage velocity gets larger. Therefore, the heat transfer coefficient increases and the slopes of curves ascend again.

On the whole, the total heat transfer quantity in the dual-contact-flow absorption tower increases with the increase of the droplet diameter from 100 to
However, the heat transfer quantity per mass decreases with the increase of droplet diameter. Because of the long temperature relaxation time, a long period of time is necessary for droplets to conduct heat transfer sufficiently. Hence, the temperature of the droplets can reach a relatively steady condition. In other words, smaller droplet diameter and longer residence time are both crucial to promote the total heat transfer quantity.

Figure 10 presents the total mass transfer quantity of droplets during the whole residence time as $v_p = 5 \text{ m s}^{-1}$. It can be observed from Fig. 10 that the total mass transfer quantity of droplets increases with the increase of the droplet diameter. Ten times rise of the droplet diameter will result in 1000 times increase of the mass transfer quantity. This indicates that the mass transfer per mass of a larger droplet is the same as that of a smaller one, so the shapes of curves shown in Fig. 10 are almost the same except the length of residence time. Moreover, when $t = 0.2 \text{ s}$, the slopes of curves corresponding to $v_p = 3 \text{ m s}^{-1}$ first become smaller and then become larger. This is also because that the slippage velocity between droplets and gaseous phase becomes smaller with the droplets reaching the top of the liquid bed. And after the droplets falling back, the slippage velocity between droplets and gas grows. Therefore, the mass transfer coefficient increases, and the curve slope becomes larger again. In addition, there is no slope change on curves of $v_p = 5 \text{ m s}^{-1}$ or $v_p = 7 \text{ m s}^{-1}$, which differs from heat
Figure 7. Change of heat transfer quantity between gaseous phase and droplets when $v_g = 2 \text{ m s}^{-1}$. This figure is available in colour online at www.apjChemEng.com.

Figure 8. Change of mass transfer quantity between gaseous phase and droplets when $v_g = 2 \text{ m s}^{-1}$. This figure is available in colour online at www.apjChemEng.com.
Figure 9. The total heat transfer quantity of droplets when $v_g = 2 \text{ m s}^{-1}$. This figure is available in colour online at www.apjChemEng.com.

Figure 10. The total mass transfer quantity of droplets when $s_g = 2 \text{ m s}^{-1}$. This figure is available in colour online at www.apjChemEng.com.
transfer process. It is generally attributed to the smaller relaxation time of mass transfer.

On the whole, the total mass transfer per mass in the dual-contact-flow absorption tower is almost the same, with nearly no influence by the variation of the droplet diameter. Because of the large diffusion coefficient of SO₂ in gaseous phase, the concentration relaxation time is quite short. Therefore, either large or small droplets may carry out the mass transfer process in a short time. In other words, neither smaller droplet diameter nor longer residence time is necessary to enhance mass transfer performance. This is considerably different from the heat transfer process.

CONCLUSIONS

In this paper, numerical simulation on gas–liquid flow, heat and mass transfer characteristics in the dual-contact-flow absorption tower have been carried out.

The results show that the motion behaviors of droplets change with the droplet diameter obviously. The initial jetting velocity of droplets can influence the bed height of dual-contact-flow absorption tower but not determine the fall-back characteristics of droplets, whereas the gas velocity only influence the fall-back characteristics and has little effect on the bed height.

The actual jetting heights of almost all the droplets that have not been carried away from the absorption tower are roughly equal. Therefore, a quite obvious vapor–liquid interface can be obtained in the absorption tower. In most cases, simulation results of bed height are consistent with experimental data. The droplet critical diameter increases dramatically with the increase of gas velocity but has limited relationship with liquid velocity.

The temperature of droplets and the concentration of matter in it both approach to constant values exponentially after jetting out from the nozzles. Nevertheless, because of the diversity between the concentration relaxation time and the temperature relaxation time, there may be considerable difference between heat and mass transfer behaviors. Smaller droplet diameter and longer residence time are both crucial to promote the total heat transfer, although neither is dominant to enhance the total mass transfer.

NOMENCLATURE

- \( C_{p0} \): Initial concentration of matter in the droplet, mol m\(^{-3}\)
- \( D \): Mass diffusivity, m\(^2\) s\(^{-1}\)
- \( d_c \): Critical diameter of the droplet, \( \mu \)m
- \( d_p \): Diameter of the droplet, m or \( \mu \)m
- \( F \): Force, N
- \( g_y \): Acceleration of gravity in vertical direction, m s\(^{-2}\)
- \( h \): Coefficient of heat transfer, W m\(^{-2}\) K\(^{-1}\)
- \( h_{m0} \): Coefficient of mass transfer, mol s\(^{-1}\) m\(^{-2}\) K\(^{-1}\)
- \( m_p \): Mass of the droplet, kg
- \( Nu \): Nusselt number
- \( Pr \): Prandtl number
- \( q_{mp} \): Mass absorption in space (mol s\(^{-1}\))
- \( q_p \): Heat absorption in space (J s\(^{-1}\))
- \( Q_{mp} \): Mass absorption of the droplet during the whole residence time, mol
- \( Q_p \): Heat absorption of the droplet during the whole residence time, J
- \( Re \): Reynolds number
- \( Sc \): Schmidt number
- \( Sh \): Sherwood number
- \( t \): Time, s
- \( T_g \): Temperature of gaseous phase, K
- \( T_p \): Temperature of the droplet, K
- \( T_{p0} \): Initial temperature of the droplet, K
- \( v_g \): Velocity of gaseous phase, m s\(^{-1}\)
- \( v_p \): Velocity of the droplet, m s\(^{-1}\)
- \( y \): Position in vertical direction, m
- \( y \): Position of the droplet, m
- \( y_{pmax} \): Actual jetting height of the droplet with effect of gaseous phase, m
- \( y_{p0} \): Initial position of the droplet, m

GREEK LETTERS

- \( \lambda \): Coefficient of thermal conductivity, W m\(^{-1}\) K\(^{-1}\)
- \( \rho_g \): Density of gas, kg m\(^{-3}\)
- \( \rho_p \): Density of droplet, kg m\(^{-3}\)
- \( \mu \): Dynamic viscosity, kg m\(^{-1}\) s\(^{-1}\)
- \( \tau \): Relaxation time, s
- \( \tau_v \): Velocity relaxation time, s
- \( \tau_m \): Concentration relaxation time, s
- \( \tau_T \): Temperature relaxation time, s

Acknowledgements

This work is supported by National Natural Science Foundation of China (51076127, 51106127), and the clean combustion and gas–solid two-phase flow group in Xi’an Jiaotong University.
REFERENCES