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Study of single-particle residence time in impulse, symmetric and asymmetric coaxial impinging streams

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ABSTRACT

Short particle residence time in the active area limits the engineering applications of impinging stream reactors. The single-particle residence time in the active area (t_{tot}) is measured and compared among impulse impinging streams (IIS) in which both inlet velocities exhibit step variations during one period, asymmetric impinging streams (AIS) and symmetric impinging streams (SIS). In addition, the effects of the impulse inlet velocity conditions, the reactor geometry and the particle properties on the single-particle motion behaviors and trajectories in a coaxial impinging stream reactor are investigated and discussed in this study. T denotes the variation period of the impulse inlet flows. The results show that single particles with different particle relaxation time (τ^*) exhibit different motion behaviors in an impinging stream reactor. A single particle with a short τ^* is accelerated directly by the original fluid and leaves the active area without oscillatory motion in SIS,AIS and IIS. A single particle with a long τ^* exhibits at most three oscillatory motions in SIS,AIS and IIS. However, a single particle with an even longer τ^* exhibits only three oscillatory motions in SIS and AIS but at least three oscillatory motions in IIS. The t_{tot} value in a coaxial impinging stream reactor generally varies with the inlet velocity conditions, the properties of the particles themselves and the size of the active area. In particular, at long τ^*, the t_{tot} value reaches a maximum in the IIS case when $T = T_b$. T_b is determined by τ^*, Re_m and L/D. By contrast, at short τ^*, the t_{tot} values in SIS,IIS and AIS are all the same. However, at long τ^*, the value of t_{tot} is greater in the case of IIS at $T = T_b$ than it is in the AIS case, increases with a decreasing inlet velocity ratio in the AIS case, and is the shortest in the SIS case under identical simulation conditions. On the whole, at long τ^*, t_{tot} and the particle motion distance in the active area can be significantly enhanced in the IIS case in comparison with the SIS and AIS cases at the same mean inlet velocity by reasonably designing the inlet velocity conditions.

1. Introduction

The impinging streams technique was first proposed by the Soviet scientist Elperin in 1961 [1]. Since that time, a large number of studies involving the investigation and measurement of impinging streams have been performed by many researchers [2–4]. The original basic principle of the impinging streams technique is that two coaxial fluid flows impinge on each other from opposite directions, resulting in a narrow reaction area that provides excellent conditions for enhancing the interphase mass and heat transfer. In addition, many research results indicate that almost any kind of process in chemical engineering can be achieved with impinging stream technology, and impinging streams are often more efficient and less energy-consuming than traditional methods [2]. Thus, the impinging streams technique is widely applied in absorption [5,6], combustion [7], drying [8,9], crystallization [10], nanoparticle preparation [11,12], mixing [13–15], extraction [16,17] and so on, making it highly useful for many engineering applications.

Symmetric impinging streams (SIS), in which the inlet velocities or flow rates of the two fluids are constant and equal, have been extensively studied and applied in fundamental research and engineering applications. Considerable research interest has been directed toward investigating the flow characteristics and flow regimes of the flow field and the related chemical reactions in the SIS technique via experiments and numerical simulations. Wang et al. [18] have performed many simulation studies to examine the flow characteristics of the flow fields in multiple and multi-setthree-dimensional confined turbulent round impinging streams. He found that the configuration conditions have a great impact on the flow characteristics of the impinging streams. Sievers et al. [19] have performed many studies of the fluid flow characteristics in a gas-liquid impinging stream reactor. In these works, the effects of the gas and liquid inlet flow rates on the biological degradation of various types of wastewater were investigated. Kleingeld et al. [20] have studied and examined the heat and mass transfer processes in the heterogeneous system of an impinging stream reactor.

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This work demonstrated that with a high fluid flow rate, the impinging streams technique can improve the interfacial phase area and the mass transfer coefficients compared with traditional chemical processes. Liu et al. [21] have performed many simulations to study the gas and particle flow characteristics in an impinging stream reactor. He reported that two pairs of counter-rotating gas vortices are formed in the gas flow field and that the rotation and collision of the particles make the residence time in the impinging zone shorter. Wu et al. [22] have numerically studied the particle behavior in axisymmetric impinging streams and found that the interparticle collision behavior is closely related to the particle motion characteristics, including the particle concentration distribution, the particle velocity and the residence time in the active region. Du and Zhao [23] have proposed a modified direct Monte Carlo simulation to investigate particle motion behavior while considering interparticle collisions. Their results showed that interparticle collisions occur mainly in the impingement region, with most particles spreading throughout the impinging zone after collision and only a few particles entering the opposing stream, which shortens the particle residence time in the active region. Huai et al. [24] have performed many studies on the drying and flow characteristics in a semicircular impinging stream reactor. In these works, the effects of the reactor geometry and the inlet flow conditions on the drying efficiency and particle residence time were assessed. From a review of the previous literature, it can be found that the particle motion characteristics and velocity distribution in an impinging stream reactor are determined by the fluid flow characteristics, e.g.,the inflow conditions and the reactor geometry. Thus, a better understanding of the particle residence time is mandatory for the optimization of these processes.

Furthermore, some scholars have numerically and experimentally investigated the fluid motion behaviors and flow regimes in asymmetric impinging streams (AIS), in which the inlet velocities or flow rates of the two fluids are unequal. Li and Sun [25] have performed a number of investigations on the stagnation point offset of a turbulent impinging stream reactor at unequal inlet velocities. They found that the velocity gradient and length of the impingement region on the axis remain the same when $4 \le L/D \le 8$ (where L is the impinging spacing and D is the nozzle diameter). Zhang and Liu [26] have experimentally investigated the fluid motion behaviors and turbulence characteristics in a free triple impinging stream reactor when the inlet flow rates are not equal by means of particle image velocimetry. In their work, the effects of the Reynolds number and the impinging spacing on the impinging surface, the velocity and the turbulent kinetic distribution of the flow field were examined. Hosseinalipour et al. [27,28] have performed numerical simulations of the flow, mixing and thermal characteristics of two steady two-dimensional laminar confined impinging streams when the two inlet flow rates are equal or unequal. In their work, the effects of hydrodynamic, thermal and geometric factors on the flow characteristics of and heat transfer process in AIS were investigated and discussed. Johnson et al. [29,30] have investigated and measured the flow characteristics of laminar impinging streams in a confined cylindrical chamber by means of steady and unsteady three-dimensional numerical simulations. He found that unequal flow characteristics indicate an asymmetric flow field and that the impinging zone deviates toward the fluid with the lower flow rate. To date, very few numerical simulations of the particle motion behaviors in AIS have been reported in the literature.

In view of the great potential of impinging streams for use in engineering applications, extensive studies have been conducted for many years with the aim of broadening their range of application. Thus, impulse impinging streams (IIS), in which the inlet velocities or flow rates of the two fluids are unequal and periodically varying with time, has been investigated in recent years. A few papers also have explored the flow and turbulence characteristics, flow regimes, and vortex motions of the flow field in the case of IIS. Li et al. [31] have performed extensive experimental investigations of the motion characteristics of the impinging surface in the case of axisymmetric turbulent impinging streams with modulated airflow using a hot-wire anemometer and a flow visualization technique. In their work, the impinging surface was found to exhibit oscillatory motion with an oscillation frequency close to the excitation frequency. Erkoc et al. [32] have performed many simulations to study the mixing and flow characteristics in a confined T-jet reactor with the induction of resonance. In their work, the frequency and amplitude of the inlet pulsation were found to be closely related to the flow regime and vortex motion. Ghadi and Esmailpour [33] have performed extensive experimental investigations of the vortex structures in pulsed turbulent impinging streams via the smoke-wire technique and high-speed photography. They found that impinging streams with inlet flow pulsation instantaneously exhibit different flow regimes and can induce the periodic formation of vertical structures in the flow field, resulting in better convective transport compared with that in steady impinging streams. Wang et al. [34] have carried out many simulations of the motion behaviors of gas and particles in an impinging stream reactor with oscillatory gas-particle jets. In their work, the effects of the oscillation frequency of the impinging streams on the stagnation point offset, the stream line and the turbulent kinetic energy of the gas phase were extensively studied. As seen from a review of the previous literature, however, little attention has been paid to the particle residence time in IIS.

Short particle residence time in the active area leads to inadequate related reactions and limits the engineering applications of impinging stream reactors. Thus, it is very important to investigate the single-particle motion behaviors in IIS,SIS and AIS. Although much research has been devoted to investigating the fluid motion in the flow field, little work has been published on the single-particle motion characteristics in IIS,SIS and AIS. The objective of this research is to investigate and compare the single-particle motion behaviors among IIS,SIS and AIS at the same mean inlet velocity by means of a computational fluid dynamics-discrete element method (CFD-DEM) analysis. A step inlet velocity variation is adopted in the IIS case. It is of great importance and theoretical significance to present a comprehensive and fundamental study of the particle residence time for the three different types of impinging streams mentioned above at the same mean inlet velocity. The organization of the rest of the paper is as follows. Section2 gives a brief introduction of the theoretical analysis and condition simulations of gas and particle motions in the flow field via CFD-DEM tools. Section3 analyzes and compares the particle motion characteristic and particle residence time in the active area of the impulse, symmetric and asymmetric coaxial impinging stream reactor, measures and discusses the effects of the inlet velocity conditions, the particle properties and the reactor geometry on the single-particle residence time in the active area. Section4 summarizes research work and research conclusions of this paper and next specific topics in future.

2. Model description

The CFD-DEM approach with a soft-sphere model is chosen to study the particle and gas motion behaviors in IIS,SIS and AIS. A realizable k-ε model is used to study the gas-phase turbulence in the simulated cases, as recommended by Choicharoen et al. [35].

2.1. Gas motion equations

The continuity and momentum equations as well as a turbulence model without chemical reactions and source terms are expressed as follows.

The continuity balance of gas phase is given by

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$