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## Flow separation from a spherical particle in supercritical water

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### A B S T R A C T

Flow separation from a spherical particle in supercritical water (SCW) is the basic flow structure in supercritical water fluidized bed (SCWFB). In order to study flow separation from a spherical particle in SCW in detail, a numerical model fully accounting for variations in thermo-physical properties has been developed in the pseudo-critical zone. Flow separation parameters (separation angle, length of wake vortex, width of wake vortex, and drag coefficient) for forced convection, assisting convection, and opposing convection have been obtained at intermediate Reynolds numbers. Results show that variable viscosity has a remarkable effect on flow separation, and the decreasing viscosity results in higher velocity gradient around the sphere particle surface and a larger wake vortex on the rear particle surface. A simple expression of  $C_d/C_{d_c} = (\mu_w/\mu_f)^{0.15}$  is achieved to predicate the drag coefficient of the SCW flow with  $\mu_w/\mu_f$  between 0.7 and 1.0. Free convection inhibits the flow separation of the assisting convection, but enhances the flow separation of the opposing convection. Three flow separation zones (the rear-end separation zone, the transition zone, and the reversed flow zone) are observed for the opposing convection.

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**Keywords:** Flow separation; Spherical particle; Fluidized bed; Supercritical water; Variable property; Mixed convection

### 1. Introduction

Supercritical water (SCW), with many advantages such as high reaction rate, higher dispersity, good flowability and carrying capacity, is a good medium to gasify biomass for producing high-quality fuels (Guo et al., 2010; Azadi et al., 2011). Being efficient in preventing slagging and blocking, the SCW fluidized bed has been used as a reactor which has replaced the tubular reactor in hydrogen production by gasifying biomass (Lu et al., 2008). The fluidized medium in the SCW fluidized bed is SCW, and the bed material is silica sand. To understand SCW-solid two-phase flow, with complex characteristics, requires extensive knowledge of physics at the macro-scale, meso scale and micro/particle scale. The flow separation around a particle in supercritical water (SCW) is a particle-scale flow structure in the SCW fluidized bed (Lu et al., 2013; Wei et al., 2013a,b). Fig. 1 shows the variation of the physical properties of water under a pressure of 23 MPa. The

drastic and fast property variation under temperatures near the pseudo-critical temperature greatly affects the flow separation process. Up to now, significant attention has been paid to the experimental, theoretical, and numerical investigations of constant property flow separation for forced convection, little work has concerned the mixed convection flow of supercritical fluid.

Abundant literature has documented research on the flow and heat transfer process of supercritical water in the channel, tube and pipes in the turbulence zone and the laminar zone (Azadi et al., 2011; Pizzarelli et al., 2010; Wen and Gu, 2011; Xu et al., 2005; Dang and Hihara, 2010). Heat transfer deterioration of supercritical water is always the research focus, because avoiding heat transfer deterioration is of great significance for the supercritical boiler or nuclear reactor (Liu et al., 2013; Zhang et al., 2010; Wang et al., 2009). Although SCW has been used as a chemical reaction medium for long-term gasification and oxidization, there is little work reporting

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## Nomenclature

$C_d$	drag coefficient
$C_p$	special heat (J/(kg K))
$D$	diameter of sphere particle (mm)
$F_D$	drag force
$g$	acceleration of gravity
$Gr$	Grashof number
$h$	enthalpy (J/kg)
$k$	conductive coefficient (W/(m K))
$n_s$	normal direction from sphere surface
$Nu$	Nusselt number
$r$	radius of sphere particle (mm)
$H$	diameter of computed zone (mm)
$P$	pressure (Pa)
$Pe$	Peclet number, $Pe = Re/Pr$
$Pr$	Prandtl number, $Pr = C_{p\infty}\mu_{\infty}/k_{\infty}$
$Ra$	Rayleigh number, $Ra = Pr \cdot Gr$
$Re$	Reynolds number, $Re = \rho_{\infty}u_{\infty}D/\mu_{\infty}$
$Ri$	Richardson number, $Ri = Gr/Re^2$
SCW	supercritical water
SCWFBR	supercritical water fluidized bed reactor
$T$	temperature (K)
$u$	velocity (m/s)

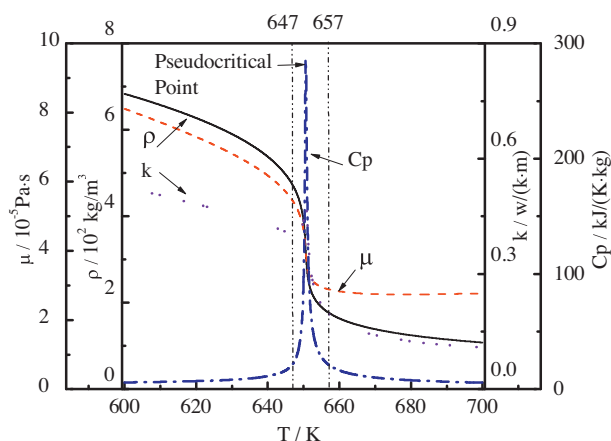
## Greek letters

$\beta$	thermal expansion coefficient
$\mu$	viscosity (Pa s)
$\rho$	density (kg/m <sup>3</sup> )
$\theta$	streamwise angle (°)

## Subscripts

$\infty$	Far field
$c$	Constant property
$f$	Forced convection
$m$	Film temperature
$n$	Natural or free convection
$P$	Pressure
$V$	Viscous
$w$	Wall surface

the flow and heat transfer in the fluidized bed reactor. More recently, supercritical fluid-solid two-phase flow in the SCW fluidized bed has been investigated through the experimental method and numerical simulation (Lu et al., 2013; Wei et al.,



**Fig. 1 – Property of SCW in pseudo-critical zone.  $P = 23$  MPa (Wei et al., 2013b).**

2013c). In these works, only the issue of two-phase flow in the total fluidized bed under certain temperature and pressure has been investigated, with no detailed information about particle-scale two-phase flow acquired, such as SCW passing over particles, which is still an open question. Flow passing over a sphere particle has been recognized as being of great significance for understanding flow and heat transfer characteristics in many industry processes such as the vaporization of fuel droplets, combustion, the pneumatic conveying system, the fluidized bed reactor, etc. Flow separation from a sphere particle is a representative case for studying important characteristics of flow passing over a bluff body. The increase in drag due to the flow separation causes great challenges to practical engineering applications.

Many experiments have reported that the flow separation from a sphere occurs at  $Re$  ranging from 20 to 25, and the flows are steady, axisymmetric, and topologically similar while the effect of gravity or stratified properties is ignored. Taneda (1956) used the flow visualization method to study the wake of a sphere when  $5 < Re < 300$ . He observed that separation from the rear of a sphere occurred at  $Re \approx 24$  and the flow kept steady and axisymmetric when the  $Re$  was about 130 at least. More recent experimental observations have found the flow stayed steady and axisymmetric when the  $Re$  was 200 at least (Wu and Faeth, 1993; Johnson and Patel, 1999). Wu and Faeth (1993) found that the recirculation region on the downstream side of the sphere remained stable and symmetric when  $Re < 200$ . Johnson and Patel (1999) visually studied the flow passing over a sphere when the  $Re$  was up to 300. Steady axisymmetric laminar flow was found when the  $Re$  was up to 200 and flow separation occurred when the  $Re$  was 20. This conclusion has also been validated by some simulation investigations. Tomboulides (1993) presented that a steady axisymmetric flow was sustained up to  $Re$  of 212 through numerical simulation work. Tomboulides and Orszag (2000) found that the recirculation region did not exist when the  $Re$  was less than about 20, based on simulation results.

Several researchers have investigated the density- and viscosity-stratified mixed convection in fluid. Torres et al. (2000) adopted the Froude number to explore the effect of stratified density on flow separation from a sphere under an assisting mixed convection condition. They found that a decrease in the Froude number caused the complete collapse of the vortex (e.g. the wake vortex at  $Re = 200$  vanished when the Froude number was reduced to 19). Approximately axisymmetric flows were observed even at a rather high Reynolds number ( $Re = 800$ ,  $F \leq 25.81$ ). An increase in the density gradient resulted in a smaller recirculation zone or even no flow separation at the rear of the sphere. Similar results were obtained by Srdic-mitrovic et al. (1999). Recently, Antar and El-Shaarawi (2002) numerically studied the mixed convection around a liquid sphere in an air stream for aiding and opposing flows. They found that decreasing the interior-to-exterior viscosity ratio delayed the flow separation.

In mixed convection, the Richardson number ( $Ri = Gr/Re^2$ ) is commonly used to determine the interaction between free convection and forced convection. Nazar et al. (2002) performed a numerical study of the locations where the separation started for both aiding and opposing flows. They found that the Richardson number played opposed roles in the determination of the flow separation of a boundary layer for the assisting flow and the opposing flow. For the aiding flow, the flow separation was delayed due to the increasing Richardson

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