Numerical Simulation of Flow on HCITFB with different Construction Parameters

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Abstract

Based on continuity equation, momentum equation and energy equation of mixture in honeycomb cross section inner loop three-phase biological fluidized bed (HCITFB), software "Fluent" is used to simulate the flow in HCITFB reactors with different height and diameter ratio *H/D*. Result of simulation calculation are, when height and diameter ratio *H/D* is added, bottom static pressure difference ΔP between downcomer and riser rises, as well as gas holdup and liquid circulation velocity rise too. Oxygen transfer coefficient K_{La} rising and energy consumption rising caused by *H/D* improvement are two sides of ambivalent, and fitting *H/D* should be confirmed by research. By studying on reactor bottom mixing zone height *B*, based on change rules of liquid circulation velocity and gas holdup, decided span of design parameter A_r/A_B of height *B* is 0.6~0.9.

Keywords

Gas holdup; Liquid circulation velocity; Numerical simulation; Static press difference

1. Introduction

In the past over 20 years, ITFB (Inner Loop Three Phase Biological Fluidized Bed) has been used to wastewater treatment. Some ITFB wastewater treatment projects have been built in some countries. ITFB combines the advantages of biological biofilm and activated sludge biological treatment method, with the characteristics of volume loading is high, impact loading resistance capability is strong, and without sludge bulking and so on, and all of these are because ITFB is one kind of perfect mixing flow reactor (Wei, 1996; Wei, 1998; Wei, 1999). However, promotion application of this technology is not excellent, one of the reasons is that total height and diameter ratio of double cylinders inner loop three-phase biological fluidized bed (Zhou, 1998) is large, and energy consumption is high. In addition, double cylinders structure is not stable and firm when reactor is large-scale.

One kind of HCITFB (Honeycomb Cross Section Inner Loop Three Phase Biological Fluidized Bed) reactor is designed in this paper, and software Fluent and CFD (Computational Fluid Dynamics) (Zhong, 2003) technology are used to simulate flow regime in HCITFB. Influence of height and diameter ratio *H/D* and bottom mixing zone height *B* to flow regime in HCITFB are analyzed too.

2. Object to simulation

The object to simulation is HCITFB reactor, which is actual project scale and is designed by ourselves. Fig.1. is longitudinal section of the reactor, and Fig.2. is cross section of the reactor. Fig.3. is reactor three-dimensional model used for simulation and calculation, which is made by Gambit, the pre-disposal software of Fluent.

The aim of improving double cylinders ITFB (Zhou, 1998) to honeycomb cross section ones is increasing stableness and strength of large-scale reactor which is used to water treatment project. In addition, the improved HCITFB reactor is similar to parallel connection of multiple ITFB, and can reduce the reactor height, on the same time retain the advantages of tower reactor, so the improving can reduce energy consumption.

Six HCITFB reactors with different *H/D* and bottom mixing zone height *B* are simulated in this paper, and main structure parameters of each reactor are shown in Table 1. In Table 1, $H/D = H/(D_1/n)$, (*n* is the number of air distributors), and A_d/A_r is area ratio of downcomer and riser. Meanings of other sizes are shown in Fig.1. and Fig.2.

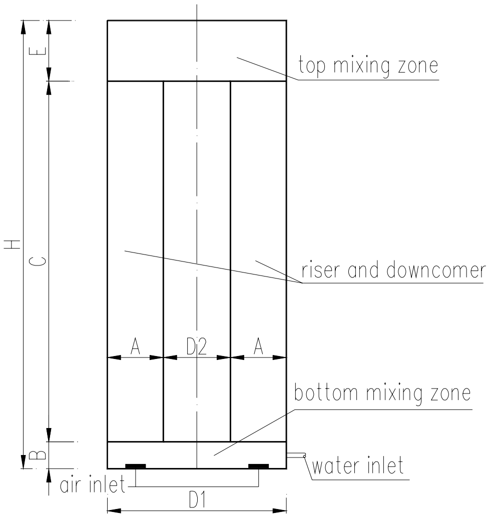


Fig.1. Longitudinal section of the HCITFB

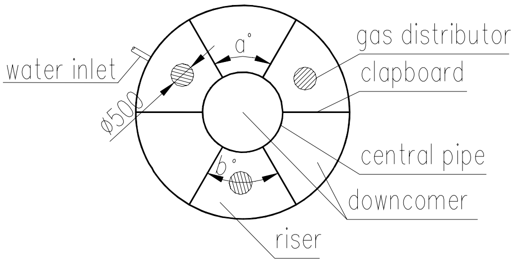


Fig.2. Cross section of the HCITFB

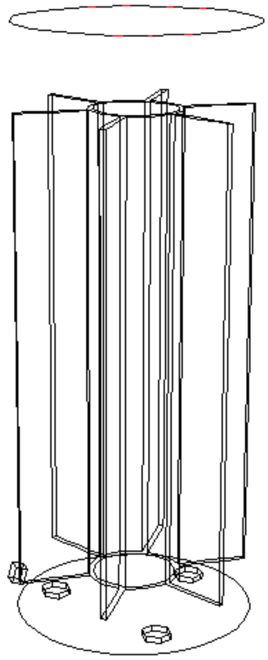


Fig.3. Tridimensional simulating model of HCITFB

Table 1 Main structure parameters of HCITFB reactors

Name	D_1	D_2	A	B	C	E	H	$a(°)$	$b(°)$	H/D	A_d/A_r
SR_1	4000	1500	1250	600	**6000**	700	**8000**	60	60	**6**	1.33
SR_2	4000	1500	1250	600	**8000**	700	**10000**	60	60	**7.5**	1.33
SR_3	4000	1500	1250	600	**13000**	700	**15000**	60	60	**11.25**	1.33
SR_4	4000	1500	1250	600	**18000**	700	**20000**	60	60	**15**	1.33
SR_5	4000	1500	1250	**300**	13000	700	15000	60	60	11.25	1.33
SR_3	4000	1500	1250	**600**	13000	700	15000	60	60	11.25	1.33
SR_6	4000	1500	1250	**1000**	13000	700	15000	60	60	11.25	1.33

Note: size unit in the table is mm.

All simulation reactors in Table 1, SR_1～SR_4 are one group, which *H/D* is rising in turn; SR_5, SR_3 and SR_6 are one group, which bottom mixing zone height is rising in turn.

Water inlet of the reactor is on below of the riser, and water flow out along all around of the reactor top. Gas distributors are on bottom of the reactor, and three gas distributors aerate symmetrically, as well as residual gas spill out from reactor top. Diameter of the gas distributor is 500mm, and air bubble diameter out of the gas distributor is 0.5mm. HRT (Hydraulic Retention Time) of each reactor is 1.5hr. Carrier volume in the reactor (solid holdup) is 10% of the reactor volume. Carrier material is rubber particles, and density is 1.1g/ml. The rubber particles are approximately spherical, and equivalent diameter is 2.5mm.

3. Mathematical model and calculation method

3.1. Basic hypothesis

Mixture in actual ITFB reactor contains three phases, and water is continuous phase, as well as gas phase and solid phase are disperse phases. Air lifting in the riser bottom is the power of circular flow of gas, liquid and solid three phases, and solid phase is evenly distribution in reactor and circular flow.

As there are some difficulties to accurately simulate mixture and flow of three phases, in the premise of reasonable hypothesis, relevant simplification can be made. Solid phase in HCITFB is rubber particles carrier, and its density is ρ =1.1g/ml, which is similar to that of water. And research in the laboratory indicates that in the condition of normal circular flow, rubber carrier is evenly distributed in the reactor. In addition, in HCITFB reactor, the main factors that influence reactor hydrodynamics are gas holdup and liquid circulation velocity.

So, according to the research of Lu (1995), solid phase and liquid phase can be regarded as “pseudo-homogeneous mixture phase”. In this way, three phases can be simplified to two phases system that only contain solid-liquid mixed phase and gas phase.

3.2. Mathematical model

Mathematical model that simulate mixture in the reactor mainly includes the continuity equation for the mixture, the momentum equation for the mixture, the energy equation for the mixture, and algebraic expressions for the relative velocities (if the phases are moving at different velocities).

3.2.1. Continuity Equation for the Mixture

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = \overline{m} \tag{1}$$

where $\vec{v}_m$ is the mass-averaged velocity: $\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k}{\rho_m}$, and ρ_m is the mixture density: $\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k$, where a_k is the volume fraction of phase k, and $\overline{m}$ represents mass transfer due to cavitation or user-defined mass sources.

3.2.2. Momentum Equation for the Mixture

The momentum equation for the mixture can be obtained by summing the individual momentum equations for all phases. It can be expressed as

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot \left[\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^{\,T} \right] + \rho_m \vec{g} + \vec{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right) \tag{2}$$

where n is the number of phases, $\vec{F}$ is a body force, and μ_m is the viscosity of the mixture: $\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k$; $\vec{v}_{dr,k}$ is the drift velocity for secondary phase k: $\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m$.

3.2.3. Energy Equation for the Mixture

The energy equation for the mixture takes the following form:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k\rho_k E_k)+\nabla\cdot\sum_{k=1}^{n}(\alpha_k\vec{v}_k(\rho_k E_k+p))=\nabla\cdot(k_{eff}\nabla T)+S_E \tag{3}$$

where k_{eff} is the effective conductivity ($k+k_f$, where k_f is the turbulent thermal conductivity, defined according to the turbulence model being used). The first term on the right-hand side of Equation (3) represents energy transfer due to conduction. S_E includes any other volumetric heat sources.

In Equation (3), $E_k=h_k-\frac{p}{\rho_k}+\frac{v_k^2}{2}$ for a compressible phase, and $E_k=h_k$ for an incompressible phase, where h_k is the sensible enthalpy for phase k.

3.2.4. Relative (Slip) Velocity and the Drift Velocity

The relative velocity (also referred to as the slip velocity) is defined as the velocity of a secondary phase (*p*) relative to the velocity of the primary phase (*q*): $\vec{v}_{qp}=\vec{v}_p-\vec{v}_q$; the drift velocity and the relative velocity ($\vec{v}_{qp}$) are connected by the following expression: $\vec{v}_{dr,p}=\vec{v}_{qp}-\sum_{k=1}^{n}\frac{\alpha_k\rho_k}{\rho_m}\vec{v}_{qk}$.

4. Results analysis and discussion

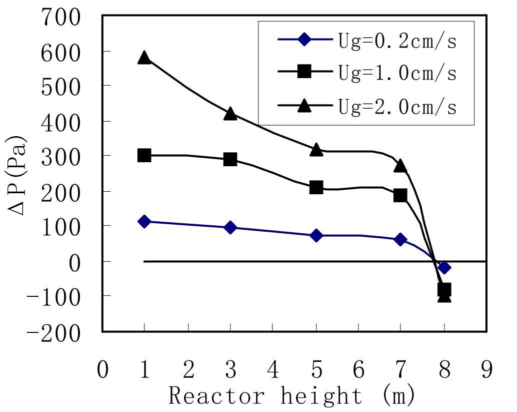
4.1.Iinfluence of H/D to HCITFB flow regime

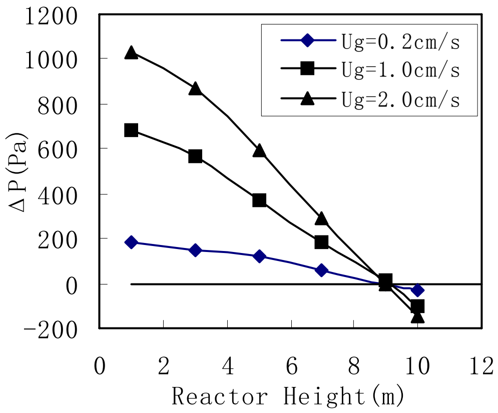
Height and diameter ratio *H/D* of reactor is one of ITFB key design parameters. Static pressure effect caused by reactor liquid depth can influence reactor performance in some degree. There are the following several aspects for influence of reactor height and diameter ratio: (1) energy consumption experiments showing, when reactor height adding 1m, adding energy consumption is about 5-6kw (Wei, 2001); (2) when height and diameter ratio is added, contact time of air bubble and wastewater is added, and oxygen transfer efficiency is improved; (3) when seek rational height and diameter ratio, there are some difficulties for double cylinders ITFB scaling-up and realizing a larger volume. Research aim should be, in the premise of reducing height and diameter ratio, improve mixing effect and oxygen transfer efficiency by improve reactor design.

In this article, by simulating four reactors with different height and diameter ratio, influence of *H/D* to static pressure distribution, gas holdup and liquid circulation velocity in reactor are analyzed.

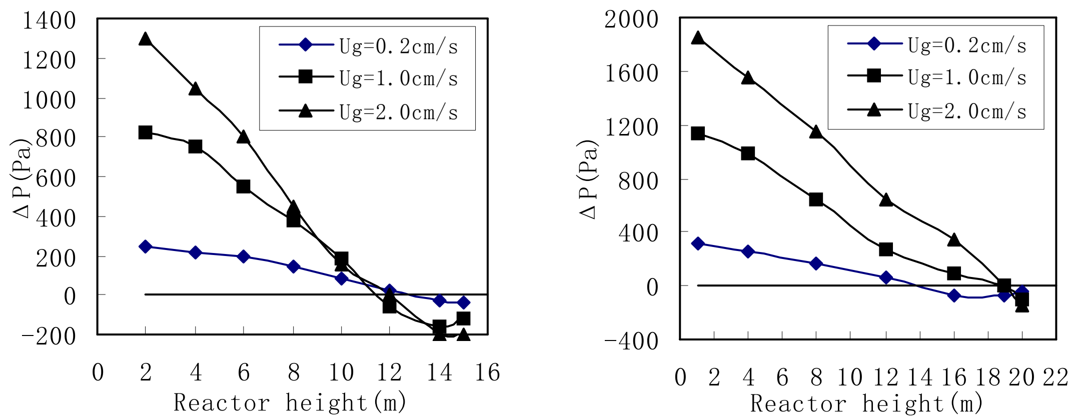
4.1.1. Static pressure distribution in reactor

Fig.4. is distribution of static pressure difference ΔP between downcomer (including central downcomer and comparted downcomer) and riser in SR_1, SR_2, SR_3 and SR_4 reactors.





（SR_1） *H/D*＝6　　　　　　（SR_2） *H/D*＝7.5



（SR_3） *H/D*＝11.25　　　　　　（SR_4） *H/D*＝15

Fig.4. Static pressure difference distribution in reactors

According to Fig.4., in reactors SR_1, SR_2, SR_3 and SR_4, static pressure difference ΔP between reactor downcomer and riser and reactor liquid depth are approximately linearity relationship, that is, along position in reactor is increased, ΔP decreases. In addition, when apparent gas velocity is added, ΔP is increased too. In bottom mixing zone of reactor, as liquid flow direction change produces larger pressure drop, static pressure difference between downcomer and riser reaches to the maximum in this position.

Compare from SR_1 to SR_4 four reactors, when height and diameter ratio *H/D* is increased from 6 to 15, and when apparent gas velocity U_g=2.0cm/s, maximal static pressure difference in reactor is increased from 580Pa to 1300Pa. This result shows, when reactor *H/D* increases, dynamic force of mixture circulation flow increases.

4.1.2. Liquid circulation velocity

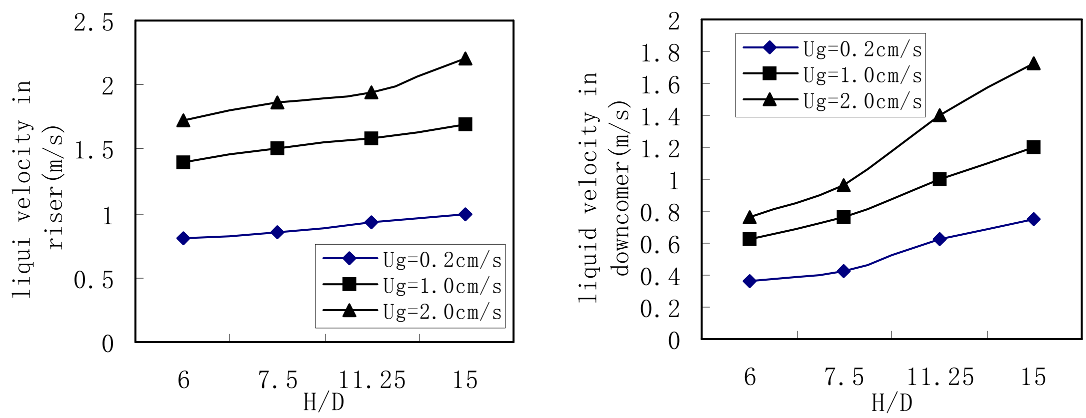


Fig.5. Liquid circulation velocity distribution in reactor

Fig.5. is comparison to liquid circulation velocity in reactor riser and downcomer. According to Fig.5., when apparent gas velocity increases, liquid circulation velocity increases. When apparent gas velocity is same, liquid circulation velocity increases along with reactor H/D increasing. This result is same with that of Russell (1994) that is, liquid circulation velocity in reactor increases along with reactor height increasing.

4.1.3. Gas holdup

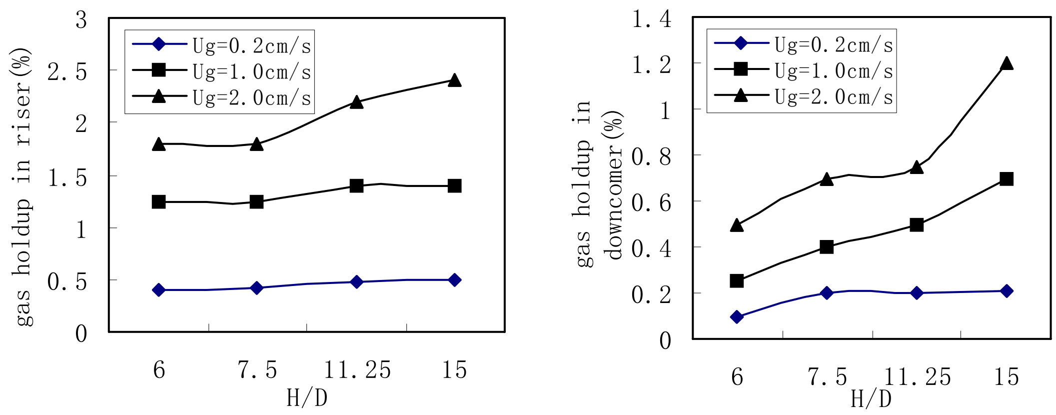


Fig.6. Gas holdup distribution in reactor

According to Fig.6., both in riser and downcomer, gas holdup increases along with reactor *H/D* increasing. But gas holdup increasing in riser is not apparent, gas holdup increasing in downcomer is apparent along with reactor *H/D* increasing. Because gas holdup in riser is mainly determined by amount of air supply (apparent gas velocity), change of gas holdup in riser is not apparent along *H/D* change when apparent gas velocity is determined. Gas holdup in downcomer mainly comes from air carried by water through reactor top mixing zone. When reactor *H/D* increases, liquid circulation velocity increases, air amount carried by water increases, so gas holdup in downcomer increases.

In addition, when apparent gas velocity in riser is increased, both gas holdup in riser and downcomer increases. Gas holdup in riser increases along with apparent gas velocity increasing is easy to understand, and gas holdup in downcomer increasing is also mainly because liquid circulation velocity increasing, leading to air amount carried into downcomer by water increases.

By study to different *H/D* reactors, when *H/D* is low, properly increasing *H/D* can improve performance of reactor. Because increasing *H/D* can improve gas holdup in reactor, and add static pressure difference, which are advantageous to oxygen transfer. But *H/D* should not too big, and there is a best value, which is fit to reactor type. Because when *H/D* increases, energy consumption of water supply and air supply to reactor is added; in addition, circulation path of air bubble flow is added, so in a given condition, chance of air bubble merging is added. Although reactor height does not influence gas holdup in reactor riser, total surface area of air bubble in unit volume mixture (that is specific surface area *a*) reduces, and leading to oxygen transfer coefficient K_{La} reduces. So, oxygen transfer coefficient K_{La} rising and energy consumption rising caused by *H/D* improvement are two sides of ambivalent, and fitting *H/D* should be confirmed by research.

4.2 Influence of reactor bottom mixing zone height to HCITFB flow regime

Bottom mixing zone height *B* is that of from reactor bottom to riser (downcomer) bottom (see Fig.1.), which is an important parameter. When air distributors and air demand are confirmed, if *B* is too small, flow resistance of liquid is big, and liquid circulation velocity and gas holdup are reduced. In addition, when biological carrier flows from downcomer to riser, shear force between water and carrier is big, and growth of biofilm is difficult. If *B* is too big, part air bubbles coming from air distributors can enter downcomer through bottom mixing zone, liquid circulation velocity and gas holdup are also reduced, and even flow regime is changed, consequently capacity of the whole reactor may be influenced.

Influence of bottom mixing zone height *B* to reactor flow is studied in SR_5, SR_3 and SR_6 three reactors.

4.2.1. gas holdup

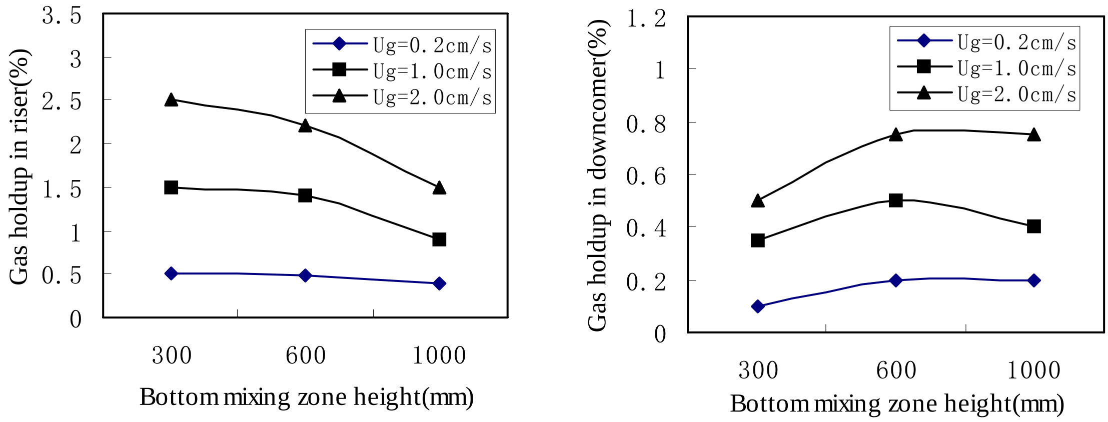


Fig.9. Gas holdup distribution in reactors

According to Fig.9., when bottom mixing zone height *B* is added, gas holdup in riser is reduced, and gas holdup in downcomer is increased. Reason of causing this phenomenon may be part air bubbles coming from air distributors enter downcomer through bottom mixing zone. If bottom mixing zone height *B* is added more, flow regime in reactor may be changed, and capability of the whole reactor is influenced.

4.22.Lliquid circulation velocity

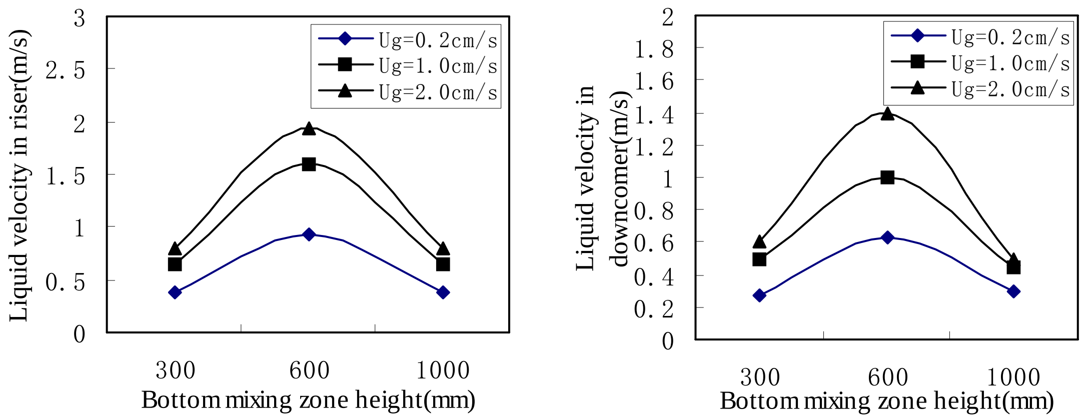


Fig.10. Liquid circulation velocity distribution in reactors

According to Fig.10., liquid circulation velocities in riser and downcomer have the same change trend along bottom mixing zone height *B* rising. That is, when bottom mixing zone height *B* is 600mm, liquid circulation velocity is maximal; and whether *B* is reduced or increased, liquid circulation velocity reduces. When bottom mixing zone height is reduced, liquid circulation velocity reduces, which is because flow resistance of mixture is added; when bottom mixing zone height *B* is increased, liquid circulation velocity reduces, which is because, according to change rules of gas holdup in Fig.9., part air bubbles coming from air distributors enter downcomer through bottom mixing zone.

According to study of Zhou (1996), when confirm reactor bottom mixing zone height *B*, A_r/A_B can be used to serve as design parameters, where A_r is area of risers, and A_B is area of flow cross section of bottom mixing zone. Rational bottom mixing zone height *B* in double cylinders ITFB reactor confirmed by Zhou is $0.4<A_r/A_B<0.8$.

In HCITFB reactor, corresponding relationship between bottom mixing zone height *B* and A_r/A_B is: when *B* equals to 300, 600 and 1000mm, A_r/A_B are 1.47, 0.74 and 0.44 separately. According to Fig.10., rational span of A_r/A_B is 0.6～0.9, which is approximate to the conclusion of Zhou.

5. Conclusions

(1) Based on continuity equation, momentum equation and energy equation of mixture in HCITFB, software "Fluent" is used to simulate the flow in HCITFB reactors with different height and diameter ratio *H/D*.

(2) Results of simulation calculation are, when height and diameter ratio *H/D* is added, bottom static pressure difference between downcomer and riser rises, as well as gas holdup and liquid circulation velocity rise too.

(3) Oxygen transfer coefficient K_{La} rising and energy consumption rising caused by *H/D* improvement are two sides of ambivalent, and fitting *H/D* should be confirmed by research.

(4) By studying on reactor bottom mixing zone height *B*, based on change rules of liquid circulation velocity and gas holdup, decided span of design parameter A_r/A_B is 0.6~0.9.

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