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Drag force modelling in CFD simulation to gain insight of packed columns

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A three dimensional CFD model was developed to analyze the flow behavior of countercurrent gas-liquid flow on an inclined plate. The influence of countercurrent gas flow was analysed by varying gas flow rates for each liquid flow rates. Liquid film thickness and local velocities in the flow direction are the two parameters considered in this work. From the simulation results, it can be found that increasing the gas flow rate for a constant liquid flow rate, increases the local film thickness and also decrease the local velocity along the flow direction which is mainly due to the influence of the drag force from the countercurrent gas flow.

1. Introduction

In the area of separation, distillation and absorption are the most widely used processes in chemical industries. Due to the advantages like high separation efficiency and low pressure drop, packed columns are of more interest than tray columns during recent days. The efficiency of the packed columns strongly depends on the flow behaviour of liquid inside the packing. It is very important to understand the same for designing the packed column and also to optimise the process. Experiments can be done to analyse the flow behaviour which is always time consuming and expensive. With the recent computational developments, CFD (Computational Fluid Dynamics) is used to investigate the flow behaviour.

Two-phase countercurrent flow has been studied for different geometries. Szulczweka et. al (2003) studied the countercurrent flow in the plate-type structured packing using 2D CFD simulation. Gu et. al (2004) studied the hydrodynamics of falling film flow on inclined plate and wavy plates corresponding to the surface texture of structured packing using 2D CFD simulation. Ataki (2006) also performed the 3D CFD study to analyse the wetting behaviour in structured packing elements without countercurrent flow and also validated with experimental studies. The flow behaviour of 3D countercurrent flow is not yet studied in detail.

Due to very complex geometry size it is very tedious to study the flow behaviour inside the packed columns directly. However it is very important to understand the flow behaviour inside the small packing structure and then to use the results for further scale

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up studies. To simplify the problem initially, 3D smooth inclined plate will be used to study the flow behaviour using CFD model. Further the work will be extended to complicated packing structure which resembles the packing used in industrial applications.

In our previous work, Hoffmann et. al, (2006) already investigated the influence of different parameters like contact angle, inclination angle and surface tension for multiphase flows, but without considering the effect of countercurrent flow using three dimensional CFD and validated with experimental studies. Xu et. al. (2008) analysed the gas-liquid flow on an inclined plate considering the mass transfer into account using three dimensional CFD model.

The main aim of this work is to study the hydrodynamics behaviour of multiphase countercurrent flow on an inclined plate using three dimensional CFD model considering the influence of the parameters like surface tension, contact angle and drag force between the phases. To show the influence of countercurrent gas flow, local film thickness and local velocity profiles will also be compared with the profiles without countercurrent flow. The long term target of the project is to develop a model for multiphase operations which also take mass and heat transfer into account.

2. Details of Numerical Study

To analyse the fluid flow behaviour, a three dimensional smooth inclined plate is considered in this work. Hoffmann et. al (2006), described in detail the geometry and the boundary conditions used in the simulations which has a dimension which resembles the experimental set up of 0.06m* 0.05m*0.01m steel plate held by steel supports on the left and on the right side. Water-Air is used as a testing system. The physical properties of the liquid and gas used in the simulations are given in Table 1.

Table 1 Physical properties of the used system.

Physical Properties	Water	Air
Density ρ (kg/m^3)	997	1.185
Kinematic viscosity ν (m^2/s)	$8.926*10^{-7}$	$1.545*10^{-5}$
Surface Tension γ (N/m)	0.0728	-
Static contact angle with air-steel θ	70 - 80°	-

The simulations are carried out with the commercial tool Fluent 6.3, ANSYS Inc. The Volume of Fluid (VOF) model with geometric reconstruction scheme was used which is one of the limiting cases of Euler-Euler homogenous model (Fluent 6.3, 2007). The model considers that the gas and liquid phase are not interpenetrating. The influence of surface tension source term is taken into account by Continuum Surface Model (CSF) proposed by Brackbill et. al (1992).

As the aim of this work is to analyse the local flow behaviour of the gas-liquid countercurrent flow, the influence of mass and heat transfer has been neglected. The influence of the drag force cannot be neglected while studying the hydrodynamic behaviour. Woerlee et.al (2001) developed a model for frictional pressure drop which can described as in eqn. (1)

$$\frac{\partial P_{fi}}{\partial X} = - a_e \cdot f_i \cdot \rho_g \cdot \left(\bar{u}_{eff} - u_x \right) \left| \bar{u}_{eff} - u_x \right| \qquad (1)$$

Where a_e is the effective interfacial area per unit volume and f_i is the interfacial friction factor. Stephan et. al (1992) developed a new correlation to describe the interfacial friction in countercurrent flow which can be described as in eqn. (2)

$$f_i = 0.079 \cdot \mathrm{Re}_g^{-0.25} \cdot (1 + 115 \cdot \delta^{*N}) \qquad (2)$$

Where Re_g is the gas phase Reynolds number which can defined as $Re_g = (u_{eff} * \rho_g * D_h)/\mu_g$ and $N = 3.95 * (1.8 + 3.0/Bo)\delta^*$ is the dimensionless ratio of film thickness and Bo is the Bond number.

These models have been implemented considering the necessary changes according to our geometry in Fluent by using User Defined Function (UDF). Since the two phases share a common velocity field, the algebraic sign of the drag force source term is opposite to the interfacial velocity so as to ensure it as resistance. The flow in the simulation is considered as laminar, as the liquid phase Reynolds numbers are always lower than 300 and the velocities of the gas phase are also not very high.

Nicolaiewsky (1999) illustrated that only experiments with decreasing liquid loads were more reproducible than increasing liquid loads. So the same strategy is also adapted in the simulations. The simulation without countercurrent gas flow was continued until it reaches quasi-stable state. To confirm the quasi stable state, parameters such as mass flow rate and force on the plate are also monitored other than residuals.

3. Results and Discussion

The influence of countercurrent gas velocity in the film flow is only focused in this work. During film flow, local film thickness and the local velocity profile along the film thickness are two important factors to be studied.

In Fig. 1 (a & b), the local velocity profiles of two different liquid Reynolds number (left, Re = 168 and right, Re = 224) have been shown. For each case, the profile has been shown for the case without and with countercurrent flow. To know the influence of countercurrent gas flow, the study has also been performed for different gas phase velocity. F-factor used to express countercurrent gas velocity in distillation and absorption can be defined as

$$F = u_{eff} * \rho_g^{0.5} \qquad (3)$$

In both cases, the local velocity exhibits a semi-parabolic profile. With the influence of countercurrent gas velocity, the reduction of liquid velocity can be clearly seen. The influence is very less for lower gas velocity with an F-factor of 0.54 Pa$^{0.5}$.

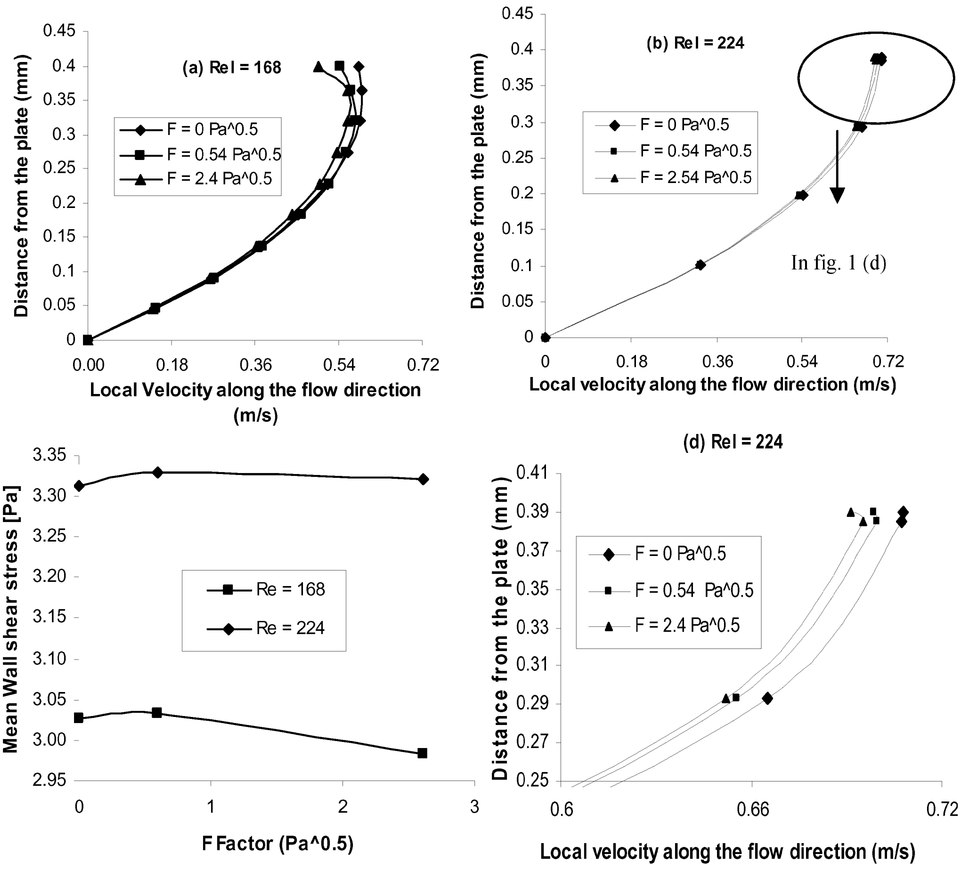

Fig 1 Comparison of local velocity profile with and without countercurrent flow for the system of water and air at (a) Re = 168 (b) Re = 224 at position Z = 25mm; (c) Mean wall shear stress against different gas velocities at the bottom of the plate. (d) Zoomed area of Fig. 1(b), Re = 224.

But the influence is higher while increasing the gas velocity, which can be seen for higher gas velocity with F factor of 2.4 Pa$^{0.5}$. This is mainly due to the influence of drag force factor, which increases with the increase of gas velocity. For the case without counter current gas flow, maximum velocity exists at the interface. With the influence of countercurrent gas velocity, the maximum velocity does not exist at the interface and the velocity at the interface is lesser.

The influence can be clearly seen for the case of Re_l = 168 (Fig. 1, (a)), than for the case with Re_l = 224 (Fig. 1, (b)). Because for the case with Re_l = 224, the liquid flow rate is high enough to overcome the influence of the countercurrent air flow rate without more change in velocity profile and in film thickness. While reducing the liquid flow rate i.e, Re_l = 168, the changes in velocity has more influence. This can also be shown by studying the behaviour of total force on the plate. Total force on the plate can be understood by analyzing the mean wall shear stress along the length of the plate as shown in Fig. 1 (c). With the increase of countercurrent gas velocity, mean wall shear stress tends to decrease slightly, which is again due to the influence of the drag force.

In Fig. 2, the behaviour of mean film thickess for F-factor has been shown for two different liquid Reynolds number. It can be noticed in Fig. 2, that the mean film thickness increases with increase of gas velocity which is due to the hold up of liquid on the plate and liquid flow rate is not enough to withstand the countercurrent air velocity.

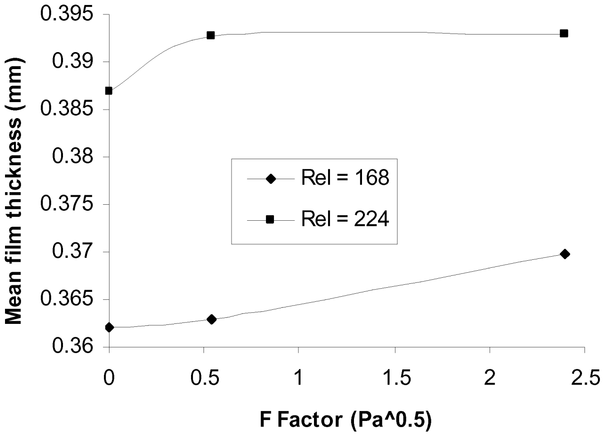

Fig 2 Mean Film thickness along the length of the plate for Rel = 168 & 224 at Z = 25mm

The influence of countercurrent gas velocity is more visible in the profile of mean film thickness for the case with Re_l = 168 than for the case with Re_l = 224. This is also due to the influence of drag force by countercurrent gas flow as explained above.

4. Conclusion

To analyse the local flow behaviour of the countercurrent flow, a three dimensional CFD model based on VOF model has been developed. The influence of countercurrent gas flow rate was studied by varying gas flow rate for each liquid flow rate. From the simulation results it can be seen that increasing the countercurrent gas flow rate, increases the film thickness and also decreases the local velocity of liquid along the flow direction. This can be clearly seen from the profiles of local velocity and film thickness. To further assure the influence of countercurrent gas velocity, simulations should be carried out for higher gas velocity against the same liquid flow rate.

Furthermore, rivulet flow which will occur by further reducing the liquid flow rate and cases considering the influence of the mass transfer and validating the simulations with experimental studies will also be considered for future work.

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Nomenclature

a_e	effective interfacial area per unit volume	(m^2/ m^3)
Bo	Bond Number	(--)
d_h	Hydraulic Diameter	(m)
f_i	Interfacial friction factor	(-)
F	F-factor	$(Pa^{0.5})$
N	Dimensionless constant	(-)
P	Pressure	(bar, Pa)
Re	Reynolds number	(-)
δ^*	dimensionless ratio of film thickness	(-)
u_{eff}	Effective gas velocity	(m/s)
μ	Viscosity	(kg/m s)
ρ	Density	(kg/m^3)
Subscripts		
g	Gas phase	
l	Liquid phase	

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