Simulation of the hydrodynamic characteristics of ebullated bed

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Introduction

Ebullated bed reactors are used in hydroprocessing technologies and deep conversion of oil residues. The packed catalyst bed is fluidized by an upward flow of liquid feed mixed with a hydrogen-containing gas. Moreover, only part of the solid particles are in suspension. The relatively small degree of fluidization and expansion of the bed along the height allows the catalyst particles to move apart and significantly reduce the pressure drop in the bed. This allows more efficient use of the hydrogenation catalyst by reducing its size [1, 2].

Model and solver

The study of the hydrodynamic characteristics of the ebullated bed was carried out using CFD simulation. The Euler multiphase approximation (TFM - Two Fluid Model) was used to study the behavior of solid catalyst particles in a two-phase gas-liquid flow. CFD code Fluent 6.1.22 was used.

The interphase interaction of solid particles-liquid and solid particles-gas was taken into account according to the Gidaspow model, the interaction of liquid-gas phases was calculated according to the Schiller and Naumann model [3]. In the simulation, surface tension forces were also taken into account, the surface tension coefficient was $\sigma = 0.028$ N/m.

The reactor model was a cylindrical column with a diameter of 0.15 m and a height of 2.25 m. The computational grid consisted of hexahedral cells with an average edge size of 10 mm. The total number of cells in the model was N=39240.

Free-slip wall conditions were used to minimize the effect of the walls on the flow pattern in the bed.

The Reynolds number determined from the parameters of the liquid was in the range $45 < Re_l < 1200$. The laminar flow regime was adopted in the simulation.

Initial conditions.

Before starting the calculations, a fixed bed of catalyst particles with a height of H_o=1.3 m and a porosity of ε_o=0.37 was placed in the column. This corresponded to the initial value of the calculation time t_o=0 s. The calculations were performed with a time step Δt=0.001s and ended at t_{max}=75.0 s. This time interval was chosen for the passage of liquid and gas through the column and achieve a pseudo-stationary state.

Some data of the mediums

The parameters of the two-phase flow and catalyst particles used in the simulation are shown in Table.

No	Parameter	Unit	Range
1	Liquid density	kg/m^3	703
2	Liquid viscosity	kg/(m*s)	0,00012
3	Superficial liquid velocity	m/s	0,005--0,13
4	Superficial gas velocity	m/s	0,015
5	Particle density	kg/m^3	1814
6	Volume equivalent diameter	mm	0.25--3.0
7	Pressure	Pa	$1.038*10^7$
8	Temperature	K	700

Results and discussion

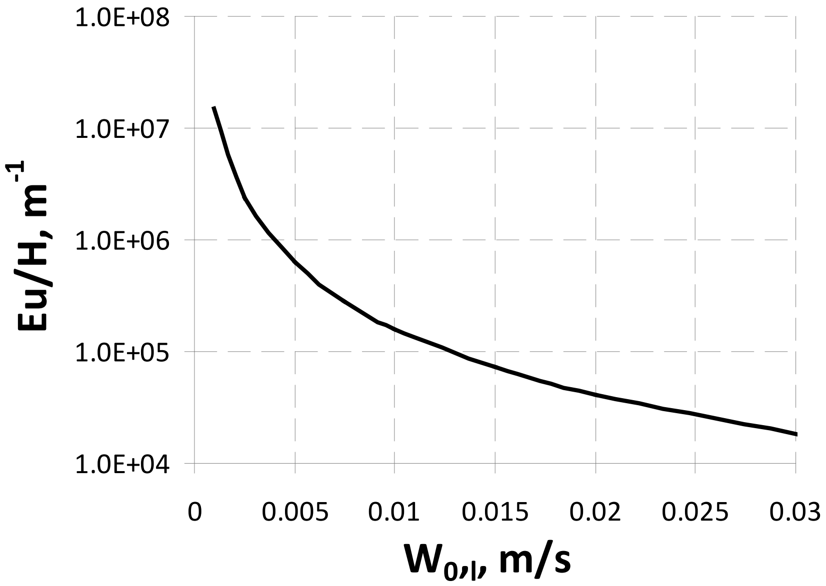

Fig. 1. Dependence of the value of the Euler number on the velocity of the liquid phase.

The influence of the velocity of the liquid phase and the particle size of the catalyst on the pressure drop and porosity in the ebullated bed was investigated.

Figure 1 shows the effect of the superficial liquid velocity on the value of the Euler number divided by the height H of the ebullated bed $Eu=\Delta P/\rho_l W^2_{0,l}$.

$W_{0,l}$ is the superficial input velocity of the liquid phase. The calculations were performed for a superficial gas velocity of $W_{0,g}$=0.015 m/s. It is shown that an increase in the velocity of the liquid phase leads to a decrease in the Euler number in inverse proportion to the square of the velocity of the liquid phase, $Eu/H \sim W^2_{0,l}$.

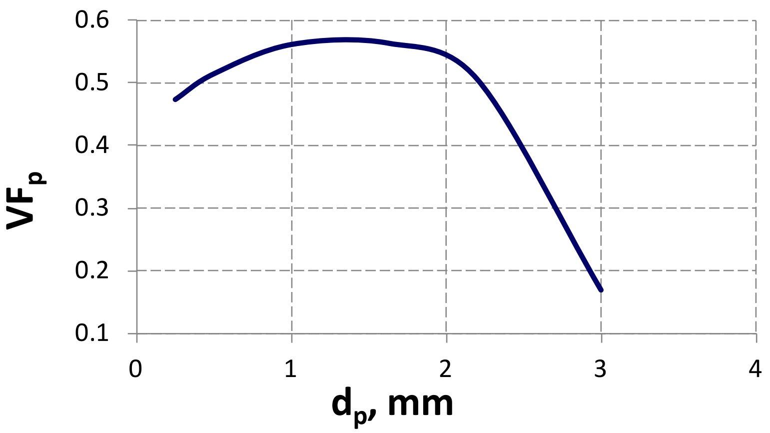

Fig. 2. The effect of the particle size of the catalyst on the volume fraction of the catalyst VF_p, averaged over the volume of the ebullated bed.

Figure 2 shows the effect of the particle size of the catalyst on the volume fraction of the catalyst VF_p averaged over the volume of the ebullated bed. $VF_p = 1-\varepsilon$, where ε is the porosity of the bed.

The dependence $VF_p = \Phi(d_p)$ has a maximum for particles with an equivalent diameter in the range $1.0<d_p<2.0$ mm. The calculations were carried out for a superficial velocity of $W_{0,l}$=0.01 for a liquid and $W_{0,g}$=0.015 m/s for a gas.

This dependence $VF_p = \Phi(d_p)$ can be explained by the influence of competing factors: gravity and momentum exchange between a liquid and a solid.

The force of gravity is proportional to the particle diameter as $Fg \sim d_p^3$.

The interaction of the fluid flow with the particle can be described as $F_{pl}=K_{p.l} * (W_l-W_p)$, where $K_{p.l}$ is the solid-liquid exchange coefficient, and W_l and W_p are the fluid and particle velocities, respectively. Let us assume that $W_p \sim 0$ and the volume fraction of the liquid in the layer $VF_l \sim (1-FV_p)$. Then, following the Gidaspow model,

$$F_{pl} \sim \left(A \frac{VF_p^2 \cdot \mu_l}{(1-VF_p) \cdot d_p^2} + B \frac{VF_p \cdot W_l}{d_p} \right) \cdot \vec{W}_l$$

The ebullated bed is characterized by relatively low fluid velocities and the viscous term makes the main contribution to the interaction of the flow with the particle. Therefore, $F_{pl} \sim d_p^{-2}$.

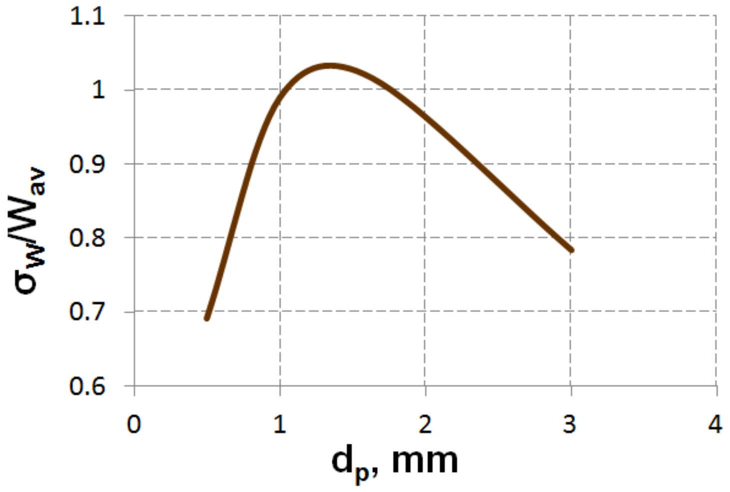

Fig. 3. The effect of the particle size of the catalyst on the liquid velocity inhomogeneity σ_W.

The degree of fluctuation of the liquid velocity magnitude W_l in the volume of the ebullated bed was estimated as a function of the equivalent diameter of the catalyst particles d_p. The estimation was made according to the value of the standard deviation σ_W, defined as:

$$\sigma_W = \sqrt{\frac{\sum_{i=1}^{n}(W_i - W_{av.})^2}{n}}$$

The calculations were carried out for the superficial velocity of $W_{0,l}$=0.01 for a liquid and $W_{0,g}$=0.015 m/s for a gas. The effect of the catalyst particle size on the value of the liquid velocity fluctuation σ_W, normalized to the average value of the liquid velocity in the bed, is shown in Fig. 3.

The dependence of the degree of inhomogeneity of the liquid velocity magnitude in the bed on the equivalent particle diameter $VF_p=F(d_p)$ has a maximum for particles with an equivalent diameter in the region d_p ~ 2.0 mm. The magnitude of velocity fluctuations at the extremum point exceeded the average velocity W_{av} in the bed. The position of the extremum approximately corresponds to the particle size d_p, at which the densest ebulation bed was formed (see Fig. 2).

Conclusions

A study of the properties of the ebullated bed fluidized by a two-phase flow of liquid and gas has been carried out.

It is shown that the pressure drop across the ebullated bed is proportional to the square of the superficial input velocity of fluid, which corresponds to the classical concepts of the bulk bed.

The particle size of the ebullated bed affects the average value of the volume fraction of the bed. The densest packing of the bed occurs with an equivalent particle diameter in the range of 1–2 mm.

The intensity of fluid velocity fluctuations in the volume of the ebullated bed also depends on the size of the solid particles. The maximum level of fluctuation was calculated for an equivalent particle diameter of about 2 mm.

References:

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3. FLUENT 6.1. User's Guide. Fluent Inc. 2003.

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