THE EXPERIMENTAL STUDY OF HEAT- MASS TRANSFER AND FLOW FIELD IN THE VORTEX CHAMBER WITH CENTRIFUGAL FLUIDIZED BED

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Introduction

A fluidized bed is widely adopted in heat- and mass transfer processes [1]. In contrast to fluidization in the field of gravity forces in vortex chambers (VCh) with centrifugal pseudo-liquid layer of granular material, the bubble formation does not occur, the velocity of particle streamlining by gas may be increased up to the order of [2]. The application of centrifugal fluidized bed allows an essential increase in intensity of heat and mass transfer. For the particle layer creation different types of vortex chambers can be used. One of the important construction factors governing flow conditions is the opening angle of a cone element of guiding vane swirler. In the present work three types of flow organization are examined (Figure 1.) with angles of 0.45 and 90 degrees relative to geometric axis of chamber. We study the single-phase flow case and the flow in the chamber with centrifugal fluidized layer of dispersed material including the propane-butane mixture combustion.

Experiments in conical VCh, which layout view is shown in Figure 1A, just as in case of VCh “C”- type, displayed high stability of centrifugal fluidized bed. When using the particles with diameter of 1…3 mm the stable layer was formed, an unregulated particles ejection and abrasion of granular material was absent during long time. In the cylindrical VCh type “B” with same overall dimensions critical ejection particles out of layer and its destruction occurred during 10…15 minutes. In conical VCh “A”- type the process of “flameless” propane-butane oxidation in air flow was implemented using a rotating catalyst layer. NOx emission in effluent gases does not exceed 20 ppm.

Fig.1. The examined types of vortex chambers with centrifugal fluidized layer.A- conical vortex chamber; B- cylindrical VCh with the side slot swirler, Rk=174mm, d=60 mm; C- cylindrical VCh with the end face slot swirler, Rk=50mm, L=150 mm. 1- slot swirler, 2- body of chamber; 3- layer of rotating particles.
Numerically calculated concentration distributions of solid phase in the vortex chamber “C”-type (Figure 1.-C) satisfactorily agree with visual observation on movement of layers particles in the “C”-type chamber. Particles moved along a cylindrical surface of the chamber at angle approximately equal 30-40 degrees relative to the end wall of chamber, run the upper part of the layer and then fall to the base of the layer. Unregulated particle ejection out of the layer does not exceed 7% from the initial mass during the time of experiment (3 hour). In experiments it was showed that the particle layer in the “C”-type chamber stayed stable when the height of chamber was reduced to the height of a rotating layer. The vortex chamber with a butt swirler («C»-type) permits to organize a stable rotating layer, whose mass is greater then in the case of a cylindrical swirler («B»-type).

At combustion in the «B»-type chamber the value of tangential velocity component increases. Its maximum position displaces to the axis of chamber. The turbulence level at combustion increases at the periphery of the chamber almost twice. Close to the geometrical axis the pulsation intensity remains the same as in the isothermal flow. During combustion in the vortex chamber the stabilise layer of a dispersed phase was shown to be formed at lower (1.5...2 times) air consumption as compared with the isothermal case.

The measurements of tangential and axial velocity component distributions were carried out with the help of two- component laser- doppler anemometer in the air flow at the cross section located above the rotating layer of particles. Peculiar properties of our LDA were describe in [3]. The Al2O3. particle were used as a light scatting centres.

The granular layer retention in vortex chamber was simulated numerically by the Euler model of interpenetrated liquids. The continuity equation for each of the phases without mass transfer between phases is:

$$\frac{\partial \alpha_q \rho_q}{\partial t} + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = 0$$

Momentum equation:

$$\frac{\partial \alpha_p \rho_p \vec{v}_p}{\partial t} + \nabla \cdot (\alpha_p \rho_p \vec{v}_p \vec{v}_q) = -\alpha_p \nabla p + \nabla \cdot \vec{\tau}_q + \alpha_q \rho_q \vec{g} + \sum_{pq} K_{pq} (\vec{v}_p - \vec{v}_q)$$

Where $\vec{\tau}_q$ in question phase stress tensor, $K_{pq}$ - impulse exchange coefficient between p and q phases, $\alpha_q$ - volume fraction of q phase in the flow. The definition of impulse exchange coefficient between phases was made similar to Lagrangian models of movement of solid phase in a gas flow.

![Fig. 2. Non-dimensional angular momentum in cylindrical VCh: 1- B, single phase flow; 2- B, with layer of 50 g; 3- chamber C, particles mass of 140 g, d=20 mm.](image1)

![Fig. 3. Non-dimensional angular momentum in cylindrical VCh “C”-type: - end face slot swirler. Particles mass – 100 g, mass air consumption 24 g/s.](image2)
\[ K_{pq} = \frac{\alpha_d \alpha_s \rho_p f}{\tau_p} \], where \[ \tau_p = \frac{\rho_p d_p^2}{18 \mu_e} \] is characteristic time of relaxation, \[ f = \frac{C_D \text{Re}}{24} \] is the function of resistance, \[ C_D \] is coefficient of single particle resistance. Shear stresses were simulated with considering \( k - \varepsilon \) model for each phase. The detail description of the model can be found in the manual of FLUENT [http://www.fluent.com/solutions/brochures/fluent.pdf]. The numerical simulation was made by the FLUENT program installed in the Siberian supercomputer multiple-access centre.

The flow in the vortex chamber

The layer of particles in the vortex chamber decreases angular momentum (Fig.2.). The character of non-dimensional circulation distribution (referred to circulation value at \( r = R_K \)) in the vortex chamber with the end face slot swirler (“C”-type) is distinguished from the rule of VCh with a side slot swirler. In the chamber with a side slot swirler “B” the angular momentum in the region of \( 0.2 < r/R_K < 0.9 \) remains almost constant. When the end face slot swirler is used (“C”) non-dimensional circulation varies with radius and reaches the maximum in the region, distant from the side wall. It may be caused by the fact that the flow in the “B”-type chamber is not-cocurrent in radial dimension. This means that the main part of the flow, incoming in to the VCh, does not move to the axis of chamber along the full volume but only through a thin near-wall regions close to butt end of chamber. The modification of exit diameter of VCh with the end face slot swirler (“C”-type) from \( d=20 \text{ mm} \) to \( d=100 \text{ mm} \) slightly effects radial circulation distribution (Fig.3.). The overpatching is seemed to be caused by the presence of reverse flow in the near-axis area (see data presented in Figure 4.).

The radial profiles of tangential air velocity in the presence of solid particles in the “C”-type chamber in the cross-section at 66 mm from lower end wall of chamber are presented in Fig.5. The profiles measured by LDA are compared with those simulated with the help of \( k - \varepsilon \) model. Taking into account the fact that the presence of the dispersed phase leads to tangential velocity decrease by an order, the conformity of simulation and experimental data is satisfactory. In case of a single-phase flow the modified \( k - \varepsilon \) model of turbulence was adopted. This model considers the influence of body forces on turbulence [4] and allows us to get somewhat better agreement with experimental data than the standard model used in two-phase simulation.

Hydraulic resistance of the vortex chamber

![Graph](image1)

Fig.4. The axial velocity component distribution in the "C"-type vortex chamber.

![Graph](image2)

Fig.5. The tangential air velocity. The "C"-type vortex chamber; \( d=20 \text{ mm} \). Lines- numerical simulation: \( k - \varepsilon \) model of turbulence.
The important characteristic of heat- and mass transfer apparatus is correlation of pressure losses and rate of the air passing through the chamber. In our tests the appraisal of pressure losses were made by measuring of pressure difference between ambient atmosphere and pressure before the slot swirler. The results of measuring and analytical estimates (see under) base on formulas are shown in Figure 6. Lines correspond to calculations. As it can be seen from the data presented the correlation of pressure drop with $\rho V_0^2 / 2$ - ram air in the slots of swirling apparatus has a linear dependence.

To estimate hydraulic resistance of the vortex chamber the simple model was used. This model takes into account the following factors. Let’s assume that the pressure losses in the vortex chamber are the sum of losses on swirler, losses during gas movement in the zone from the side wall to radius of the exit hole and losses inside the zone confined by the exit hole radius:

$$\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3$$  (1)

One can define the pressure losses on swirler using the Bernoulli integral:

$$\Delta P_1 = \frac{\rho (\alpha_2 V_0)^2}{2}$$  (2)

Where $V_0$ is the total mean velocity in slots, $\alpha_2$ is velocity unevenness coefficient in slots (the ratio of maximal velocity in slot to superficial velocity of air). Taking into account that tangential air velocity passing through the particle layer decreased in $\alpha_1$ times, and besides accepting that in the area from the side wall to exit hole radius the circulation stays constant, one can describe the change of pressure inside this zone as:

$$\frac{\partial P}{\partial r} = \rho \frac{V_\psi^2}{r}$$  (3)

where $V_\psi = \alpha_1 \alpha_2 V_0 R_0 \cos \varphi / r$. From this, integrating the equation (3) from $R_0$ to exit hole radius $r_0$, one can determine the pressure drop inside the zone from the side wall to $r_0$:

$$\Delta P_2 = \frac{\rho (\alpha_2 V_0)^2}{2} \ast (\alpha_1 \alpha_2 \cos \varphi) \left[ \left( \frac{R_0}{r_0} \right)^2 - 1 \right]$$  (4)

If it is remembered that in area confined by exit hole radius that the swirl velocity may by described by the solid body rotating law $V_\psi = \omega r$, and taking into account that at the boundary of the zone of constant circulation and solid body rotation the tangential velocity stays continuous one can formulate:

$$\omega = \frac{\alpha_1 \alpha_2 V_0 R_0 \cos \varphi}{r_0^2}$$, and $V_\psi = \frac{\alpha_1 \alpha_2 V_0 R_0 \cos \varphi}{r_0^2} \ast r$.
Then integration of equation (3) from $r_0$ to zero leads to:

$$\Delta P_3 = \frac{\rho(\alpha_2 V_0)^2}{2} \left( \alpha_1 \alpha_2 \cos \varphi \right)^2 \left( \frac{R_0}{r_0} \right)^2$$

(5)

Summarizing pressure loss components by relation (1) we obtain the following correlation:

$$\Delta P = \frac{\rho \alpha_1^2 V_0^2}{2} \left[ 1 + \alpha_1^2 \cos^2 \varphi \left( 2 \left( \frac{R_0}{r_0} \right)^2 - 1 \right) \right]$$

(6)

In our estimates we accept for the conical chamber (“A”-type) $\alpha_1 = 0.38$, and for cylindrical chambers $\alpha_1 = 0.32$, the velocity unevenness in slots was not taken into account as $\alpha_2 = 1$.

**Conclusion**

The combination of centrifugal and gravity force effects on fluidized bed of a dispersed material in the vortex chamber increases rotating layer stability with conservation of the high velocity of particle flow past in the vortex chamber with the conical and end face slot swirler.

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**REFERENCES**


