Investigation of applicability area for turbulence models in the problems of mass transfer intensification by the control of a rotary divergent flow

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Abstract. The fundamental scientific problem of this kind arises in mechanics, chemistry and catalysis in the intensification of mass transfer. The turbulent mass transfer characteristics were analyzed experimentally in a controlled rotational-divergent flow. The laser Doppler anemometry was used for turbulent mass transfer diagnostic. The verification of numerical calculations by computational hydrodynamics has been carried out according to the results of experimental studies. Calculation of turbulent kinematic is based on solving of a system of continuity and the Navier-Stokes equations. The fluid is incompressible and isothermal. For averaged equations closure, semi-empirical turbulence models were used: the k-ε model of turbulence and the Reynolds stresses transfer model. The calculation has showed the existence of a near-wall jet after a rotating device and the generation of reverse flow zones. Comparison with experimental data has shown that all models of turbulence adequately model the rotational-divergent flow only until the formation of flow gaps and the formation of reverse flow zones. The discrepancy with the experiment occurs while controlling the flow to equalize the velocity profiles.

1. Introduction

The fundamental scientific problem of this kind arises in mechanics, chemistry and catalysis in the intensification of mass transfer [1-3]. The efficiency of mass transfer is influenced by the velocity field and small-scale turbulence in the reacting flow. Reagent streams in real installations and reactors interact under conditions of complex geometry with turning and expanding sections in which wall jets are formed, flow reconnections occur, reverse flow zones are present. Such effects usually increase the hydrodynamic resistance of the flow and disturb the turbulent mass transfer uniformity. For the numerical simulation of such phenomena, verification and modernization of turbulence models are required for an adequate description of mass transfer [4]. The verification of numerical calculations by computational hydrodynamics has been carried out according to the results of experimental studies. Numerical simulation of turbulent gas flow is based on solving of a system of continuity, the Navier-Stokes and energy conservation equations. The medium is considered incompressible and isothermal.
For averaged equations closure, semi-empirical models of turbulence were used: the k-ε model [5] of turbulence (Launder 1984) and the Reynolds stresses transfer model [6-7]. Velocity fields measurements in the control sections has carried out compare the experimental data with computational one. A noncontact optical laser Doppler anemometry method for achieving the kinematic flow properties is necessary. The LAD-05 on the basis of this method system was made at the IT SB RAS.

2. Experimental setup and technique
For investigation of applicability area for turbulence models in the problems of mass transfer intensification by the control of a rotary divergent flow the experimental model was made (Fig. 1) and an experimental setup for flow characteristics investigation in this model. The test section is made from several functional blocks: the inlet; section before the bend, the bend, the control section and the section before the second bend. Fluid was through the fan. Then fluid pass through the flow meter. The temperature in the flow is measured by thermal transducer, and the overpressure by pressure sensors. The hydraulic resistance of the flow is measured on the differential pressure on a bend and a section before the second bend using the differential pressure transmitters. The working fluid was air. The flow rate was equal 50,100,150,200 and 250 n.m³/h. The maximum overpressure was 0.03 MPa. The temperature varied from 23 to 26 °C. The Reynolds varied from 10000 to 50000.

![Figure 1](image_url)

**Figure 1.** 3D geometry of the investigated model (1 - the inlet; 2 - section before the bend, 3 - bend, 4 - control section, 5 - section before the second bend)

2.1. Velocity measuring in the experiment
For numerical calculations verification, velocity fields measurements in the model cross-sections were carried out. Measurement of the two-dimensional kinematic characteristics of the flow required a modern invasive optical methodic for aerodynamic flow diagnostics. As methodic laser Doppler anemometry was used (LDA). The LAD-05 system based on LDA method was designed and manufactured at the Institute of Thermophysics SB RAS (Fig. 2). The measurement system was mounted on the actuator.
The functional scheme of the measurement system conclude a laser, two orthogonal acoustic-optical modulators, a receiving-transmitting optical system, and a photoelectron multiplier. A two-channel Doppler signal processor was connected to the photodetector and transmits the processed data to the computer. Scanning of the measuring volume is carried out by moving the optical unit by the coordinate-positioning device. To measure the velocity, the laser beam after passing the elements is sent to the acousto-optic switch-modulator (Fig. 3). The action of the modulating voltage at the output of the modulator serves to form two light beams, diffracted in zero and minus the first order. The split beams pass sequentially through the system of optical elements and are directed by the lens to the studied flow region. Intersecting in the flow, laser beams form an interference pattern with a known spatial-temporal periodic structure. When the scattering particle crosses the probing optical field at the output of the photodetector the radio pulse of photoelectric current appears. Its Doppler frequency is a known linear velocity function, and the duration is equal to the time of passage of the measuring volume by the particle. As a result, measurement system can measure two velocity vector projections with value from 0.001 to 400 m/s with relative error less than $10^{-1}$ percent. The measurement volume is 0.1x0.1x0.5 mm. The actuator can move the measuring system in the range of 250 x 250 x 250 mm with step of 0.1 mm (Fig. 4).

3. Numerical simulation methods
The validation of CFD-calculation was carried out. The velocity and pressure distribution in the test pipe were simulated. CFD-calculation of turbulent gas flow was based on the solution of the system of continuity equations and Navier-Stokes equations [4]. The medium was considered incompressible...
and isothermal. The semiempirical turbulence models is used for closing the averaged equations. These models are the k-ε turbulence model, [5] and the model of Reynolds stress transfer [6-7]. The nonuniform grid with 1 500 000 cells was used in computations. The computation grid was condensed near the walls to get resolution of laminar sublayer near the wall. Near the walls the computational grid was rectangular and in the flow core the computational grid was triangular. The cell size near the walls was about 0.2 mm and in the flow core it was about 8 mm. In the inlet the experimental measured velocity distribution was used to get better accuracy of computation. The condition on the constant pressure of 1 bar was set at exit of the gas.

Figure 5. The picture of the streamlines after the rotator, obtained using the Reynolds stress transfer model. The colour bar represent the velocity magnitude in the flow

4. Results
Vx components values were measured in the middle plane (Fig. 5). The results are shown in Figure 6. The CFD-results for the longitudinal velocity component in middle cross sections line are shown in Figure 7. Comparison of experimental and calculated data shows that for the flow after the rotation, there are noticeable differences for all models. The best comparison is for the Reynolds-Stress transfer model.

Figure 6. Velocity profiles after the bend at different values of mass flow rate

Figure 7. Comparison of experiment and calculation for flow rate G = 200 n.m3/h
As characteristics of applicability area for turbulence models the width of recirculation zone in the channel after bend was chosen. The recirculation zone width in cross-section 3 after the bend for different values of flow rate are shown in figure 8. From experimental data it can be seen that the recirculation zone width takes values X/Xmax = 0.24÷ 0.36, where Xmax is 250 mm. For Reynolds-Stresses model the recirculation zone width take close values to the experimental one till flow rate of 200 n.m3/h. For k-ε turbulence model the values of recirculation zone differ from experimental widths. The model of Reynolds stress transfer adequately describes the flow in the range of flow rates from 50 to 250 n.m3/h. And k-ε turbulence adequately describes the flow in the range 200-250 n.m3/h.

Figure 8. The recirculation zone width in cross-section 3 after the bend for different flow rate values

5. Conclusion

The turbulent mass transfer characteristics were analyzed experimentally in a controlled rotational-divergent flow. The laser Doppler anemometry was used for turbulent mass transfer diagnostic. The verification of numerical calculations by computational hydrodynamics has been carried out according to the results of experimental studies. Numerical simulation of turbulent gas flow is based on solving of a system of continuity, the Navier-Stokes and energy conservation equations. The medium is considered incompressible and isothermal. For averaged equations closure, semi-empirical models of turbulence were used: the k-ε model of turbulence and the Reynolds stresses transfer model. The model of Reynolds stress transfer adequately describes the flow in range of flow rates from 50 to 250 n.m3/h. And k-ε turbulence adequately describes the flow in the range 200-250 n.m3/h.

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