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Modeling of nonlinear processes of transfer in channels of the complex shape

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Results of application of $k - \varepsilon$ turbulence model for description of spatial fluid flow in the complex shape channels are presented.

The research of a configuration of considered flows in technological equipment elements with internal riffle forming of heat exchange surfaces was executed.

The zones of increased vortex formation are revealed, power characteristics of turbulence depending on the thermodynamic characteristics of flows and parameters of riffle forming of channels are investigated.

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1. Introduction

Large-scale reactors usually have the economic necessity of being made out of stationary parts.

Baffled reactors are very common in the process industry. Such reactors need to be optimized as too much baffling can create unnecessary turbulence and pressure drops.

As in other reactors an indication of residence time is a pointer toward the effectiveness of a reactor design. The maximum, minimum and average time that a tracer element is present within a reactor can be measured as provide information toward the reactor design and extent of mixing. It can also show dead zones and areas of stagnation, which can cause problems with silt build-up and regions for secondary reactions.

This model studies the residence time in a turbulent reactor. It does so by first solving for a stationary turbulent flow in the reactor, using the $k - \varepsilon$ model, and then solving for a mass balance on top of this flow field in the time-domain. Mass transport is described through convection and diffusion, where the turbulent viscosity from the $k - \varepsilon$ model is used to describe the species diffusion in the mass balance. A tracer species is introduced as a "burst" of concentration, and its journey through the reactor is studied.

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2. Problem Definition

Fig 1 shows the cross section of the reactor we will study. The model is inspired by a water treatment process, where flow enters from the left and leaves the reactor at the right.

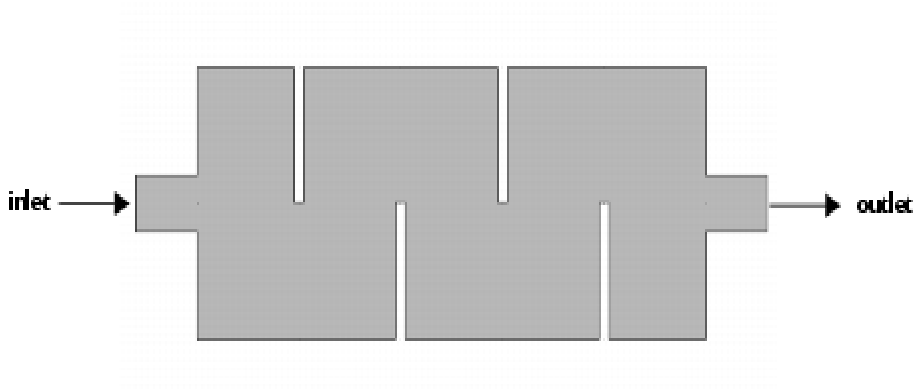

FIG. 1: Depiction of the reactor geometry.

The $k - \varepsilon$ model is used to describe turbulent flow in the reactor. The equations for the momentum balances and continuity are defined by: .

$$\rho\frac{\partial U}{\partial t} - \nabla * \left[\left(\eta + \rho\frac{C_\mu k^2}{\sigma_k \varepsilon}\right) * (\nabla U + (\nabla U)^T\right] + \rho U * \nabla U + \nabla P = 0$$

$$\nabla * U = 0$$

where ρ denotes the density of the fluid $(kg * m^{-3})$, U represents the averaged velocity $(m * s^{-1})$, η the dynamic viscosity $(kg * m^{-1} * s^{-1}$, P pressure (Pa), k the turbulent energy $(m^2 * s^{-2})$, ε the dissipation rate of turbulence energy $(m^2 * s^{-3})$ and C_μ is a model constant. The turbulence energy is given through solving:

$$\rho\frac{\partial k}{\partial t} - \nabla * \left[\left(\eta + \rho\frac{C_\mu k^2}{\sigma_k \varepsilon}\right)\nabla k\right] + \rho U * \nabla k = \rho\frac{C_\mu k^2}{\varepsilon} * (\nabla U + (\nabla U)^T)^2 - \rho\varepsilon$$

and the dissipation through solving:

$$\rho\frac{\partial \varepsilon}{\partial t} - \nabla * \left[\left(\eta + \rho\frac{C_\mu k^2}{\sigma_\varepsilon \varepsilon}\right)\nabla \varepsilon\right] + \rho U * \nabla \varepsilon = \rho C_{\varepsilon 1} C_\mu k * (\nabla U + (\nabla U)^T)^2 - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

The model constants in the above equations are determined from experimental data and are set to the values in Table 1.

CONSTANT	VALUE
C_μ	0.09
$C_\varepsilon 1$	0.1256
$C_\varepsilon 2$	1.92
σ_k	1.0
σ_ε	1.6

Table 1: Model constants.

The concentration of the traces is modeled with the convection and diffusion equation:

$$\frac{\partial c}{\partial t} + \nabla * (-D\nabla c + cu) = 0$$

where, c denotes the concentration ($kg * m^{-3}$), D denotes its diffusion coefficient ($m^2 * s^{-1}$) and u the velocity vector ($m * s^{-1}$). The velocity vector is given by the stationary solution of the $k - \varepsilon$ equations and the diffusivity is given by the turbulent viscosity ν_T form the $k - \varepsilon$ simulation.

3. Results

Two different techniques of flow turbulization in the reactor are considered in this paper: by means of ribs; by means of pumping of turbulizing flow through jets.

The stationary velocity field is shown in Fig 2.

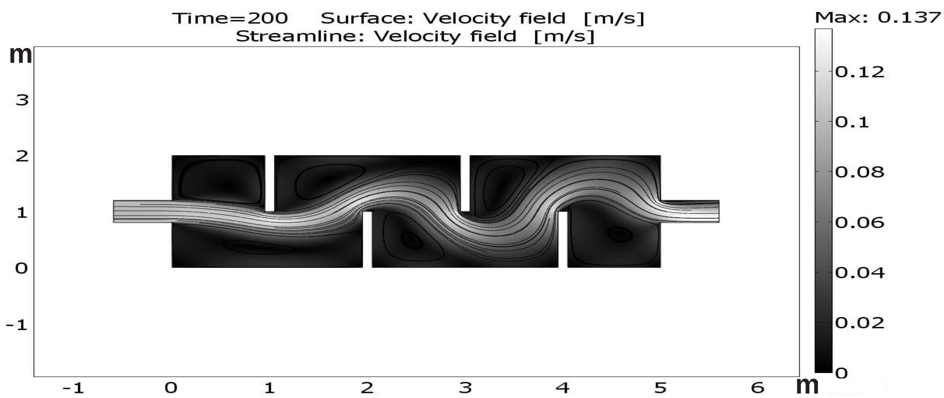

FIG. 2: Velocity field and flow lines for the reactor.

Regions of circulation, and therefore of mixing, increase with the number of baffles that are passed. Evident from the figure is the fact that dead zones occur in the corners and in the first baffle-chambers. Also evident from the flow is the fact that a stream or "short-circuit" of velocity occurs through the middle of the reactor. The residence-time in this short-circuit, in comparison to the velocities in the recirculation areas, gives an indication of the reactor effectiveness.

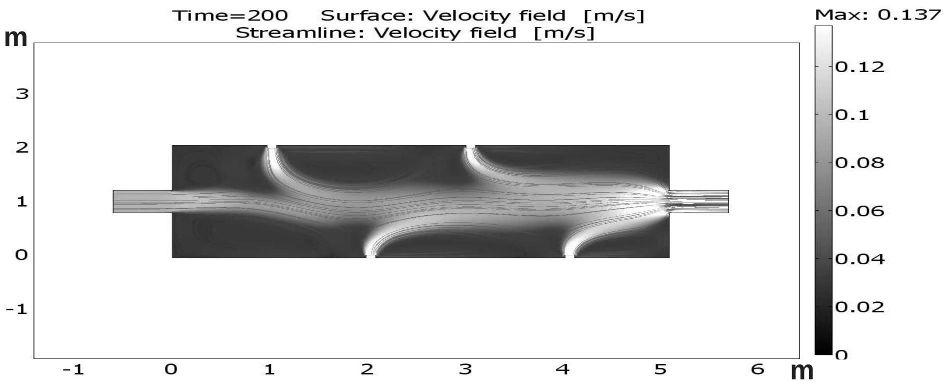

FIG. 3: Velocity field and flow lines for the baffled reactor.

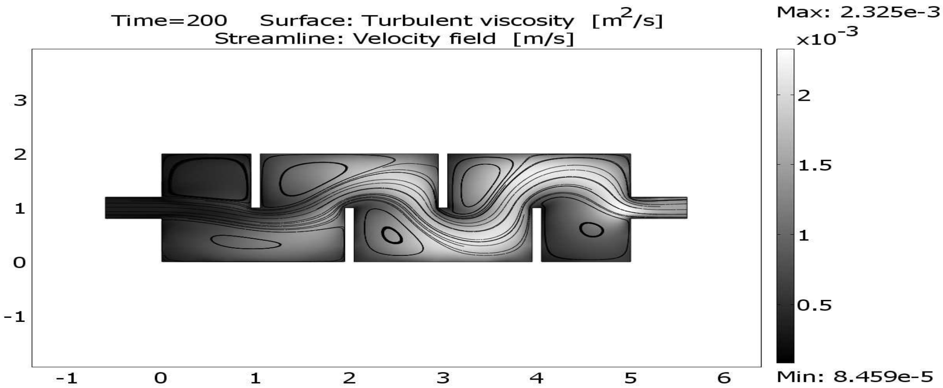

FIG. 4: Turbulent viscosity.

Turbulent viscosity is an important quantity in this model since it is used to simulate the diffusive properties in the mass balance (see Fig. 2). The figure shows that relative turbulence increases downstream in the reactor. Whereas Fig. 3 shows the regions of recirculation, which are good for mixing, Fig. 2 shows the chaotic behavior of the velocity vector on a smaller scale. Both show that mixing is far better in the last baffle-chambers than in the first.

Snap-shots of the concentration field are shown in Fig. 4. The figures clearly shows that the tracer is kept small in the first third of the reactor. When it passes over to the second third, it dilutes somewhat. In the last section of the reactor, the tracer is strongly diluted due to the large turbulent viscosity in that section. Regions behind the baffles, even in the first chambers, also show a growing amount of tracer species and the mixing effect that recirculation zones have on the reactor.

By monitoring the integral of the concentration at the outlet (Fig 5), we can determine the residence time of the reactor. Fig 6 shows the integral of the concentration over the outlet. The figure shows that the residence time is roughly 100 seconds.

4. Conclusion

According to application of $k - \varepsilon$ turbulence model for description of spatial fluid flow in the complex shape channels the response function for technological equipment elements with internal riffle was drawn.

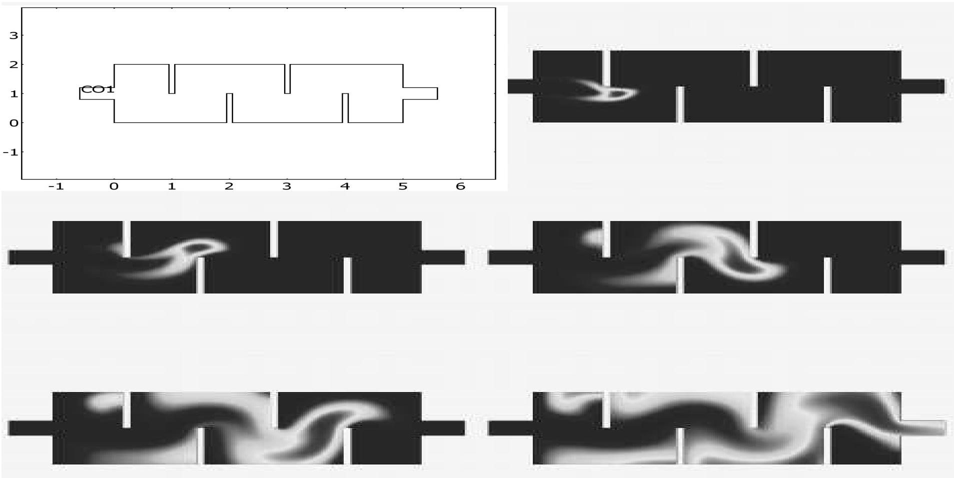

FIG. 5: Concentration snapshots at t=10, 20, 30, 45, and 90 s.

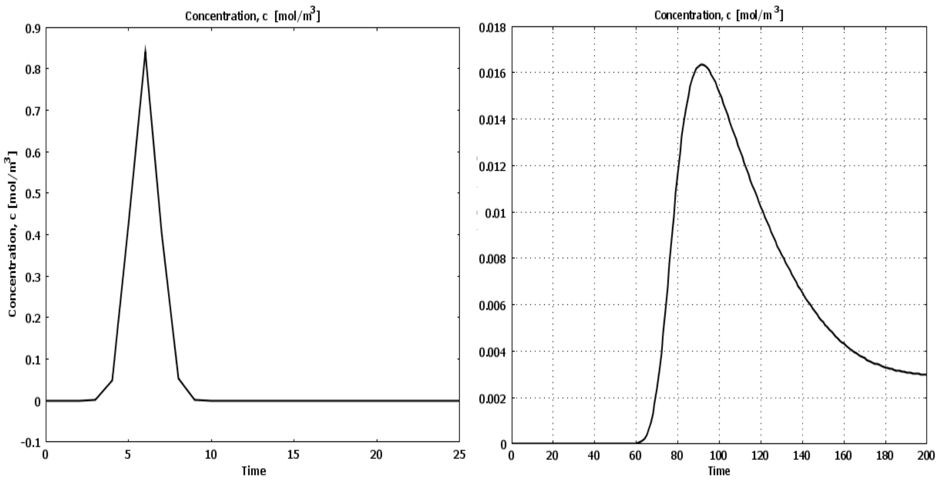

FIG. 6: Integrated concentration at the inlet (left) and the outlet (right).

The zones of increased vortex formation are revealed, power characteristics of turbulence depending on the thermodynamic characteristics of flows and parameters of riffle forming of channels are investigated.

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