Numerical investigation of Herschel Bulkley fluids mixing

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Abstract. Bitumen modification by means of introducing the components into bitumen swirling flows using an injector mixer has been investigated in this paper. The properties of mixing depending on geometry and operating conditions and the swirling intensity are presented herein. The results obtained have shown that the optimum mixing can be achieved within a strongly swirled flow when the injector mixer locates in close proximity to a swirler.

1. Introduction

A priority challenge in the field of highway engineering is to develop a set of measures and technologies for production of new high-quality bituminous binders to provide an improved type of pavement of the roads, which would increase their service life between the periods of road reconditioning. A way to solve it could be a development of new low-cost technologies and devices that would allow new asphalt binders to be produced via incorporation of new modifying components taking into account the conditions of road construction and operation \cite{1}. In \cite{2 - 7}, the authors studied the preparation of a new bituminous binder using the principle of cavitation-mixing dispersion. In some cases, however, it is necessary to use other approaches, namely, to introduce the components into the swirling bitumen flow through an injector or to combine injection mixing with the cavitation-mixing dispersion to obtain new high-quality binders. A priority application of injection mixing combined with cavitation-mixing dispersion is the preparation of polymer-bitumen binders, since it is difficult to manufacture a new high-quality binder due to the fact that polymers have complex structural bonds and making the manufacturing process difficult.

2. Mathematical model

To describe the field of flow and mixing of flows, the following assumptions were taken. The fluid flows are assumed to be stationary, axis-symmetric and swirling, depending on the law of rigid body rotation at the entrance. The model included two-dimensional rheological equations written in cylindrical coordinates, which are the most suitable for description of the axisymmetric flow \cite{8 - 11}.

\[
\frac{\partial \mu}{\partial x} + \frac{1}{r} \frac{\partial \rho v r}{\partial r} = 0
\]  

(1)
The Shvedov-Bingham fluid is characterized by the parameters \( n, m, \alpha \). The dilatant properties of a liquid manifest themselves as a decrease in its effective viscosity with increase in the rate of shear deformation of the liquid [12-15].

For description of the mixing process, the concentration transport equations were used:

\[
\frac{\partial \rho u^2}{\partial x} + \frac{1}{r} \frac{\partial \rho uv r}{\partial r} = \rho \left[ \frac{\partial}{\partial x} \left( \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial r} \right) \right] + \frac{1}{r} \frac{\partial}{\partial r} \left( D \frac{\partial C}{\partial r} \right)
\]

(6)

2. Results

Below, the process of bitumen modification in an injector mixer is considered. It has a cylindrical case with a radial nipple for the modifier input, a nozzle for molten bitumen in the face end of the case and a mixing chamber. The mixing chamber communicates with the bitumen nozzle directly and with the radial nipple through a ring nozzle. The following parameters are calculated parameters of the device: \( R = 0.1 \text{ m}, L = 1 \text{ m}, h = 0.2 \text{ m}, d = 0.05 \text{ m} \).

At first a flow with impenetrable walls is considered. Figure 2 shows the profile of the radial distribution of axial and tangential velocities in the swirling flow. In the absence of a flow swirl, the flow in the channel in the initial part is characterized by a plane profile of the axial velocity and a narrow zone of the boundary layer. In the swirling flow the axial velocity decreases in the axial zone and increases in the near-wall zone (Figure 1a).
Figure 1. Radial distribution of the axial (a) and tangential (b) velocities: $u_{in} = 10\text{ m/s}$, $\varphi = 50^\circ$, 1 – $x = 0.285\text{ m}$, 2 – $x = 0.485\text{ m}$, 3 – $x = 0.685\text{ m}$, 4 – $x = 0.885\text{ m}$.

Radial distribution of the tangential component of velocity is shown in Figure 1b. One can see three characteristic zones in the channel: near-wall zone of the boundary layer, axial zone, in which the tangential velocity varies by the law of rigid body rotation, and the central zone characterized by the constant value of the tangential velocity.

Figure 2 shows the downstream profile of the radial velocity. In the non-swirling flow and at small swirling angles ($\varphi < 50^\circ$), the fluid flow lines are parallel to the axis of symmetry, which is characterized by nearly zero radial velocities.

Figure 2. Downstream profile of the radial velocity: non-swirling flow (a) $u_{in} = 10\text{ m/s}$, $\varphi = 50^\circ$, 1 – $r = 0.076\text{ m}$, 2 – $r = 0.036\text{ m}$.

Only under conditions of intense swirling of the flow, we can observe a sharp increase in the radial velocity in the zone adjacent to the swirler owing to the flow edging by the field of centrifugal forces. Consider now the flow structure in a channel with an injector. Figure 3a shows the downstream profile of the radial velocity in the case without swirling at different distances from the flow axis. In the zones far from the injector, the radial velocity is close to zero and only in the injector zone we can see significant radial motions.
Figure 3. Downstream profile of the radial velocity: $u_{in} = 10 \text{ m/s}$, $v_{in} = 5 \text{ m/s}$, a – non-swirling flow $\phi = 0$, b – $\phi = 50^\circ$, 1 – $r = 0.076 \text{ m}$, 2 – $r = 0.036 \text{ m}$.

The highest value of the radial velocity is observed near the injector, while closer to the channel axis the radial velocity decreases. For weak ($\phi = 20^\circ$) and moderate ($\phi < 50^\circ$) swirls, there are no qualitative changes in the radial velocity observed. However, in the case of a strong swirl of the flow ($\phi \geq 50^\circ$), the plot $v(x)$ is characterized by the more complex behavior. In the case where the injector is rather far from the entrance, near the swirler one can observe a zone of positive values of the radial velocity owing to the flow edging by the field of centrifugal forces in the initial part. If the injector is located near the swirler, this feature is not observed. It should be noted that behind the injector there is a zone with positive values of the radial velocity. In this case, the smaller is the separation between the injector and the swirler, the more intense is the motion of fluid behind the injector toward the wall. Thus, the intense swirling of the flow intensifies the radial mass transfer.

Figure 4 shows the radial profile of the axial velocity (along the channel radius). It can be seen that upstream the injector the velocity profile is plane in the whole flow zone except for the near-wall area of the boundary layer. Downstream the injector, the radial distribution of the axial velocity is characterized by three zones: axial zone with high values of the axial velocity, zone of the central flow, in which the axial velocity is nearly constant, and zone of the boundary layer. It should be noted that the maximal value of the axial velocity at the channel axis decreases downstream.

Figure 4. Radial distribution of the axial velocity in the channel with an injector: $u_{in} = 10 \text{ m/s}$, $v_{in} = 5 \text{ m/s}$: a – $\phi = 0$, b – $\phi = 50^\circ$, 1 – $x = 0.285 \text{ m}$, 2 – $x = 0.485 \text{ m}$, 3 – $x = 0.685 \text{ m}$, 4 – $x = 0.885 \text{ m}$.
The flow swirl results in the formation of a zone of minimal axial velocity in the center of the channel in the section between the swirler and the injector. Behind the injector, the velocity on the channel axis increases sharply.

Figure 5 shows the radial distribution of the tangential velocity. The axial velocity includes a zone of quasi-solid rotation. In the central part of the flow, the rotation is characterized by a constant swirling angle, while near the wall the rotation is described by the potential vortex.

**Figure 5.** Radial distribution of tangential velocity in the channel with an injector: \( u_{in} = 10 \text{ m/s}, \quad v_{in} = 5 \text{ m/s}, \quad \phi = 50^\circ, \quad 1 - x = 0.285 \text{ m}, \quad 2 - x = 0.485 \text{ m}, \quad 3 - x = 0.685 \text{ m}, \quad 4 - x = 0.885 \text{ m}. \)

From the practical point of view, the radial change in the concentration is of greatest interest (Figure 6).

**Figure 6.** Radial distribution of concentration in the channel with an injector: \( u_{in} = 10 \text{ m/s}, \quad v_{in} = 5 \text{ m/s}; \quad a - \phi = 0, \quad b - \phi = 50^\circ, \quad 1 - x = 0.285 \text{ m}, \quad 2 - x = 0.485 \text{ m}, \quad 3 - x = 0.685 \text{ m}, \quad 4 - x = 0.885 \text{ m}. \)

The closer to the entrance cross section the injector is, the wider is the mixing zone. The flow swirl improves the mixing characteristics. In this case, intensive radial motions in the swirling flow result in a fast equalization of concentrations in the flow. This analysis shows that the best mixing can be achieved in a strongly swirling flow with the injector located in close proximity to the swirler.

**3. Conclusions**

The paper describes the results of investigations of a non-Newtonian fluid flow and mixing in a cylindrical channel with injector. The values of the effective viscosity of the viscoelastic Shedo-Bingham fluid in the axial zone of the channel are increased downstream. The hydrodynamic
stabilization of the flow leads to the conversion of the axial highly viscous region into a rigid zone of quasi-solid flow. The hydrodynamically unstabilized flow of the dilatant Oswald - de Weil fluid in the peripheral region of the channel is characterized by the growth of the effective viscosity. Investigations of the dilatantBulkley - Herschel fluid flow have shown that, for large values of Bulkley - Herschel number in the flow the dilatant properties are dominated and for small – viscoplastic ones. The minimum values of the effective viscosity are realized at moderate shear rates. With increasing of Bulkley-Herschel number with one and the same value of the nonlinearity parameter the effective viscosity in the axial region of the flow is reduced, and in the central and peripheral areas - increases. With increasing of the nonlinearity parameter with one and the same value of Bulkley-Herschel number the dilatant properties of the fluid are more pronounced. The flow swirl improves the mixing characteristics. In this case, intensive radial motions in the swirling flow result in a fast equalization of concentrations in the flow. This analysis shows that the best mixing can be achieved in a strongly swirling flow with the injector located in close proximity to the swirler.

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