Stress Analysis of Mixing of Non-Newtonian Flows in Cylindrical Vessel Induced by Co-Rotating Stirrers

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ABSTRACT

The impacts of rotational velocity and inertia on velocity gradients and stresses are addressed under present study. The non-Newtonian behaviour of inelastic rotating flows is predicted by employing Power law model. A numerical model has been developed for mixing flow within a cylindrical vessel along a couple of stirrers. A time marching FEM (Finite Element Method) is employed to predict the required solution. Predicted solutions are presented for minimum to maximum values in terms of contour plots of velocity gradients and shear stresses, over the range. The long term application of this research will be used to improve the design of mixers and processing products. The predicted results are used to generate the capability and are in good agreement with numerical results to the mixer design that will ultimately effect the processing of dough products.

Key Words: **Mixing Flows, Non-Newtonian Fluids, Rotational Flow, Co-Rotating Stirrers.**

1. INTRODUCTION

To predict stresses in a cylindrical vessel, with co-rotating stirrers is of great importance, specially in the field of food industries. Cylindrical domain is considered responsible for mixing flow in container and remains challenging for the processing field researchers. Some studies have been made to investigate numerical as well as experimental simulations for predicting rotational mixing flows in cylindrical vessel having fixed and rotating stirrers [1-3]. Various attempts have been made to simulate three dimensional mixing flows [4]. Experimental studies for inelastic rotational mixing flows have been performed in various mixing industries to investigate part filled [5] and fully filled domains [6]. Whilst, numerical computations have been made in finite vessels by incorporating generalised Navier-Stokes equations [7].

This study is focused to simulate numerically, two dimensional complex flows between cylindrical vessel and couple of stirrers rotating in same direction. A semi implicit Taylor-Galerkin/Pressure-correction finite element scheme has been incorporated [8]. Under this study, effects of inertia and rotational velocity at half and double speeds has been investigate. The predicted results of velocity gradient and shear stress are computed for Power Law

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model fluid with fixed index at Pn=0.6 and solutions are displayed through contour plots.

2. PROBLEM SPECIFICATION AND BOUNDARY CONDITIONS

Two dimensional mixing flow between cylindrical vessel and rotating stirrers is investigated, with application to processing industries. Simulations for mixing purpose are performed by rotating cylindrical vessel with two co-rotating stirrers, which are attached with top of the vessel eccentrically.

To simulate the problem, initial and boundary conditions are necessarily to be specified. Initial conditions are to be fixed as (υ_r=υ_θ=p=0). Whilst, boundary conditions are fixed as Radial velocity is treated as fixed for rotating stirrer, whereas azimuthal velocity is imposed with three dimensional values i.e., v_θ =0.5, 1.0; 2.0 against the constant velocity of container, v_θ=1.0. Zero pressure is treated for this stirrer case as well as on container wall.

3. GOVERNING SYSTEM OF EQUATIONS AND NUMERICAL SCHEME

The system of equations can be represented through the conservation of mass and momentum equations for predicting rotational flows as:

$$\nabla.\upsilon = 0 \tag{1}$$

$$\rho\frac{\partial u}{\partial t} = \nabla.\sigma + \rho\left(\upsilon.\nabla\upsilon\right) \tag{2}$$

The fractional numerical scheme is followed as:

Stage l(a):

$$\left[\frac{2\,\mathrm{Re}}{\Delta t}M - \frac{1}{2}S_V\right]\left(V_r^{n+\frac{1}{2}} - V_r^n\right)$$
$$= \left(\left[-S_{rr}V_r - S_{r\theta}V_\theta\right] - \mathrm{Re}\,N\left(V\right)V_r - N_1\left(V_\theta\right)V_\theta - L^T P\right)^n \tag{3}$$

Stage l(b):

$$\left[\frac{\mathrm{Re}}{\Delta t}M - \frac{1}{2}S_V\right]\left(V_r^* - V_r^n\right)$$
$$= \left[-S_{rr}V_r - S_{r\theta}V_\theta + L^T P\right]^n - \mathrm{Re}\left[N\left(V\right)V_r - N_1\left(V_\theta\right)V_\theta\right]^{n-\frac{1}{2}} \tag{4}$$

Stage 2:

$$K\left(P^{n-1} - P^n\right) = \frac{2}{\Delta t}LU^* \tag{5}$$

Stage 3:

$$\frac{\mathrm{Re}}{\Delta t}M\left(U^{n-1} - U^*\right) = \frac{1}{2}L^T\left(P^{n-1} - P^n\right) \tag{6}$$

for more details of Equations (1-6), reader can refer [1-2,9].

4. NUMERICAL RESULTS AND DISCUSSIONS

The predicted solutions are analysed with the changing stirrer's speed for inelastic Power Law model fluid at fixed index Pn=0.6. The computed results are displaced along contour plots of velocity gradient and shear stresses. The effects of inertia being set at increasing levels i.e. 0.08, 0.8; 8.0 are analysed with rotational speeds at v_θ=0.5; 2.0 and presented in the form of contours of velocity gradient and shear stresses. Maximum and minimum values of each interested variables shown with square and oval shapes respectively.

Impact of inertia at various Reynolds numbers is being displayed in Fig. 1 in the form of contour plots of the velocity gradients and shear stresses at half speed of stirrers. Contours of velocity gradient at Re=0.08 inertial level illustrate that the maximum value of velocity gradient is observed on stirrer lip in gap between stirrer and vessel wall. Whereas, the minimum value of velocity gradient is noted on upper and lower lip of stirrer inner gap between stirrers. Symmetry in contours is observed on both the stirrers. Contour plots are observed identical at inertial levels 0.08 and 0.8, whilst, significant changes take place at Re=8.0 inertial level. In the rotational direction of the stirrers, the minimum value of velocity gradient is observed on the upper lip of left stirrer and lower lip of right stirrer respectively.

Shear stresses presented in Fig.1, illustrate that the maximum is seemed at same point as located in case of velocity gradient. Whereas, the minimum value of shear stress takes place at inlet and outlet of the both stirrers in the gap between vessel wall and stirrers at value of inertia 0.08. At Re=8.0, maximum value of shear stress is noted at the same place as in Re=0.08, but minimum value is noticed only on inlet of both stirrers in narrow gap between vessel wall and stirrers.

Contours of velocity gradient and shear stresses at double speed of stirrers displayed in Fig. 2 at Re=0.08, 0.8; 8.0. In contrast to half speed of stirrers, maximum value of both interested variables is observed at lip of the stirrer in the gap between stirrers in the horizontal direction, at Re=0.08. Minimum value is noticed on the lip of the stirrers in narrow gap between stirrer and outer cylinder wall. The behaviour of contours is found identical at both values of inertia, Re=0.08 and 0.8. At inertial level 8.0, the change is observed that the maximum value of shear stress at inlet of the stirrers in the rotational direction and minimum value at the lower lip of both stirrers in the wide gap.

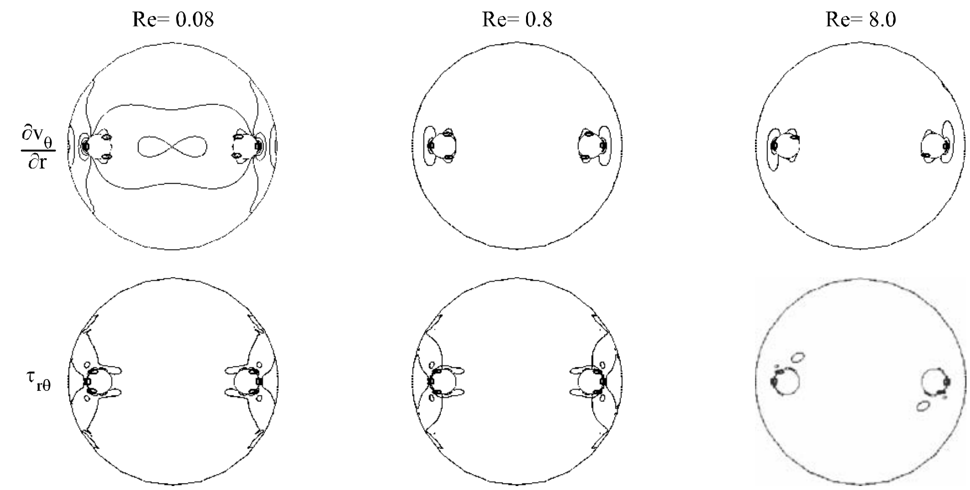

FIG. 1. CONTOURS OF VELOCITY GRADIENTS AND SHEAR STRESSES AT HALF SPEED OF STIRRERS

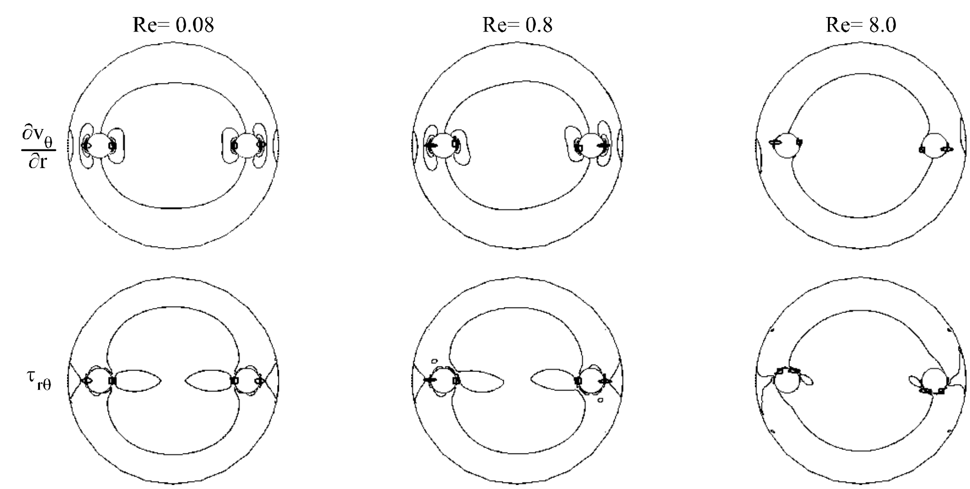

FIG. 2. CONTOURS OF VELOCITY GRADIENTS AND SHEAR STRESSES AT DOUBLE SPEED OF STIRRERS

Throughout this study, it has been worked out that high shear stresses are observed in the vicinity of the vessel wall and solid boundaries of stirrers. Ideal mixing process is observed due to the maximum values of stresses near the solid boundaries. Hence in long term, this application will be used for optimal mixing processes.

5. CONCLUSION

The effects of rotational velocity and inertia on velocity gradients and shear stresses are discussed throughout this analysis. It has been concluded that with increasing Reynolds numbers at half speed of stirrers, maximum value of velocity gradient is observed on stirrers lip and the minimum value on upper and lower lip of stirrers. Whilst, the minimum value of shear stress noticed at inlet and outlet of the both stirrers. Further it is concluded that with increasing Reynolds numbers at double speed of stirrers, maximum value of velocity gradients and shear stresses is observed at lip of the stirrers at the horizontal line across the diameter of vessel and stirrers. Whereas, the minimum values of velocity gradients and shear stresses is noticed on the lip of the stirrers in narrow gap between stirrer and outer cylinder wall.

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