

Direct Numerical Simulation of a shear-thinning fluid in a T-junction cross flow

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Résumé :

Le phénomène fluidifiant est fréquemment étudié en industrie. Depuis Lumley [5] et DeGennes et al. [2], un de progrès a été achevé sur le mélange turbulent des fluides rhéofluidifiants. Nous nous intéressons à l'écoulement dans une T-jonction où nous nous retrouvons des gradients forts de vitesse et une zone de recirculation. En considérant Nguyen [6] et Georgiou [3] comme références principales, nous arrivons à faire les Simulations Numériques Directes dans un T-jonction de section carré en utilisant un fluide Newtonien "l'eau" et un fluide non-Newtonien "Xanthan Gum" (XG). Le code est du logiciel open source OpenFOAM. Le modèle appliqué pour XG est de classe Bird-Carreau. Nous produisons la turbulence non-Newtonienne à Reynolds nominal 2400 et 4000 basé sur la viscosité minimum de la solution XG. Un scalaire passif a été introduit dans le calcul pour mieux comprendre l'effet du mélange. Nous avons fait varier le taux de débits entre les deux entrées pour pouvoir produire le régime "deflecting" et le régime "impinging" [1, 8]. L'efficacité de mélange a été introduit et nous avons comparé l'efficacité entre ces deux régimes.

Abstract :

Mixing phenomena in a shear-thinning fluid is frequently applied in industry. However since Lumley [5] and DeGennes et al. [2], few progress was carried out in terms of shear thinning turbulent mixing. In this article, we present the mixing in a T-junction involving shear thinning fluid. In this particular geometry, we have a sharp velocity gradient as well as a re-circulation zone. Taking Nguyen [6] and Georgiou [3] as reference, we have carried out Direct Numerical Simulations in a square-shaped T-junction containing Newtonian fluid "water" and shear thinning fluid "Xanthan Gum". The code we have used is from open source project OpenFOAM. We manage to produce non-Newtonian turbulence at a nominal Reynolds number 2400 to 4000 based on the minimum viscosity of XG solution. A passive scalar is introduced to mark the turbulent mixing. We have made variations on flow rate ratio at two entries in order to produce the "deflecting" regime and the "impinging" regime [1, 8]. Mixing efficiency is introduced and compared between the two regimes.

Mots clefs : Mixing, DNS, Non Newtonian, Shear Thinning

	\mathbf{u}	p	c
inlet1	$\mathbf{u}_1(y, z)$	$\nabla p \cdot \mathbf{n} = 0$	$c = 0$
inlet2	$\mathbf{u}_2(x, z)$	$\nabla p \cdot \mathbf{n} = 0$	$c = 1$
outlet	$\nabla \mathbf{u} \cdot \mathbf{n} = 0$	$\nabla p = const.$	$\nabla c \cdot \mathbf{n} = 0$
wall	$\nabla \mathbf{u} \cdot \mathbf{n} = 0$	$\nabla p \cdot \mathbf{n} = 0$	$\nabla c \cdot \mathbf{n} = 0$

TABLE 1 – Boundary conditions for DNS Simulations.

1 Numerical Method

OpenFOAM is a open source Finite Volume based software. In OpenFOAM multiple fluid constitution equations are implemented and complex geometry can be managed. As shown in FIGURE 1(a), we have a square-shaped T-junction with $D = 8mm$. There are two inlets *inlet1* and *inlet2* and one outlet. Therefore two streams will join at the junction and produce a mixing layer and a re-circulation zone after the trailing edge. The length of ducts are chosen to be approximately $10D$ in order to isolate effect of the junction from boundary conditions as well as to give a enough distance for the fluid to develop a steady Hagen-Poiseuille flow before the junction.

The governing equations of fluid and passif scalar are listed here :

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p^* + \nabla \cdot \nu_s \nabla \mathbf{u} \quad (1a)$$

$$\text{div}(\mathbf{u}) = 0 \quad (1b)$$

$$\nu_s(\dot{\gamma}) = \nu_\infty + (\nu_0 - \nu_\infty)[1 + (\lambda \dot{\gamma})^\alpha]^{\frac{n-1}{\alpha}} \quad (1c)$$

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = D_c \Delta c. \quad (1d)$$

Eq. 1a and Eq. 1b are adressed as the incompressible Navier-Stokes Equations with variable dynamic viscosity ν_s . Eq. 1c gives the general relation between the viscosity and shear rate for a Bird-Carreau fluid. In a shear thinning fluid, we have $\nu_0 \geq \nu_\infty$ as showed in FIGURE 1(b) : larger the shear rate is, less viscous the fluid is. It means that, in the T-junction flow, the mixing layer where we have strong shear, shear thinning fluid will result in getting less viscous. Finally, Eq. 1d gives the convection and diffusion of a passif scalar c in the velocity field \mathbf{u} . Diffusivity of passif scalar is D_c . p^* in Eq. 1a is the kinematic pressure.

In our simulations, the non-Newtonian fluid XG is chosen to be the same as used in Nguyen's work [6] : 0.1% XG solution. We approximate its shear thinning property using the Bird-Carreau Model (see FIGURE 1(b)) which means parameters ν_0 , ν_∞ , λ , n and a are then fixed. The Newtonian fluid used in simulations is water which is 2 times less viscous than ν_∞ . We then expect that flows using XG will have a smaller Reynolds number than flows using water.

Boundary conditions for variable \mathbf{u} , p and c are given in the TABLE 1 where at *inlet1* and *inlet2* we impose respectively $\mathbf{u}_1(y, z)$ and $\mathbf{u}_2(x, z)$. Typically a 2-D mean velocity profile is imposed corresponding to the respective Hagen-Poiseuille solution of a square-duct. Controlling the flow rate at *inlet1* (q_1) and *inlet2* (q_2), we can achieve different flow regime : "wall jet", "deflecting jet" and "impinging jet" [1, 8].

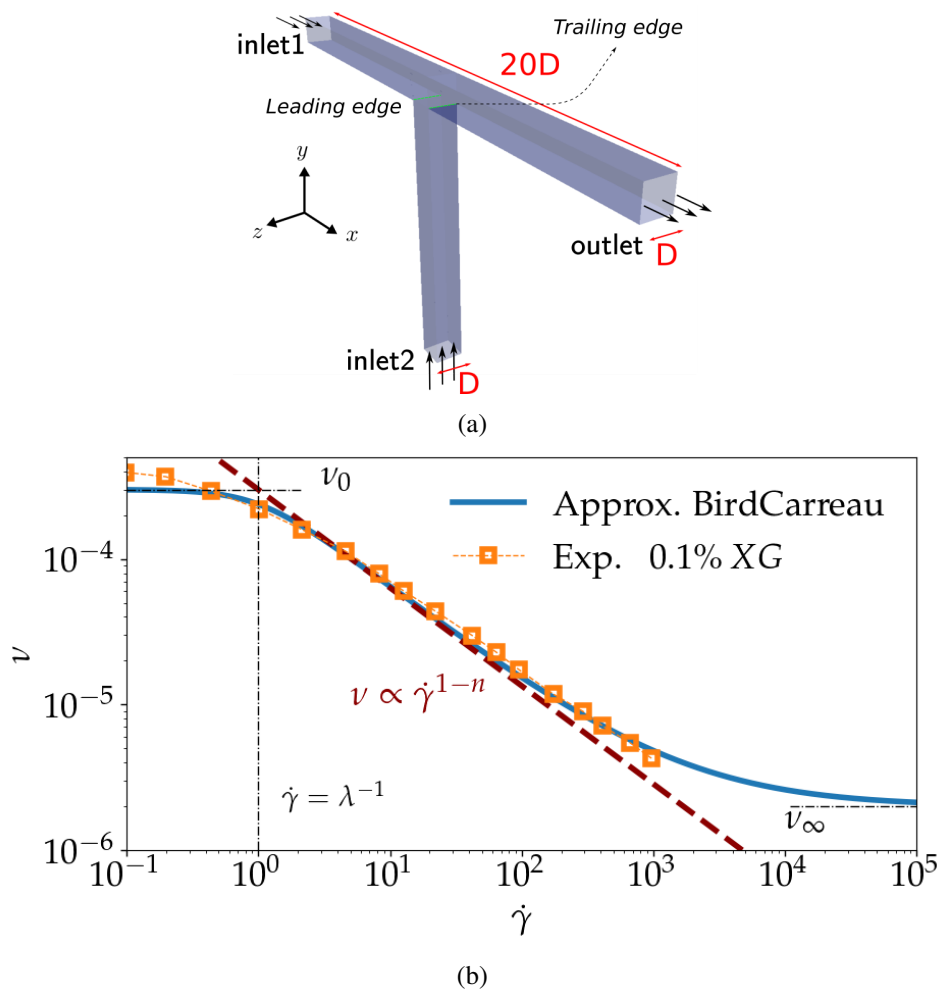


FIGURE 1 – (a) Dimension of the computational domain for the T-junction mixing with 2 inlets and 1 outlet. Square-shaped cross section's side width $D = 8\text{mm}$. (b) Variable viscosity law of XG and its power-law $\nu \propto \dot{\gamma}^{1-n}$ approximation in the intermediate shear range. Characteristic parameters are taken from Nguyen [7].

When the flow rate at *inlet2* is very small comparing to that at *inlet1*, due to the large momentum from *inlet1* a near-wall jet is observed. When *inlet2* has a large flow rate comparing to that at *inlet1*, we then have a "impinging jet" where we observe a clear penetration by current from *inlet2*. In both Nguyen [7] and Georgiou et al. [?], only "deflecting regime" is considered. Apart from reproducing results at "deflecting regime" where $q_1 = q_2$, in order to have a larger range of regime, we have investigated the case where $4q_1 = q_2$ which is considered as "impinging jet". Note that from boundary condition, passive scalar is introduced at *inlet2*. We are able to visualize the difference by using contour plots on c (see FIGURE 2).

As we have a simplified rectangular section, the mesh is strictly orthogonal. The total cell count is 21 million. After personalize boundary conditions that we have mentioned above, we applied the PISO based transient solver to perform simulations. Δt is of order 10^{-6}s . CFL number is hold to be less than 0.35 in all cases. Spatial discretization is second order accurate and time advancement is "backward implicit". The calculations are achieved by using 512 MPI processes in parallel. The total consumption is around 600000 cpu hours.

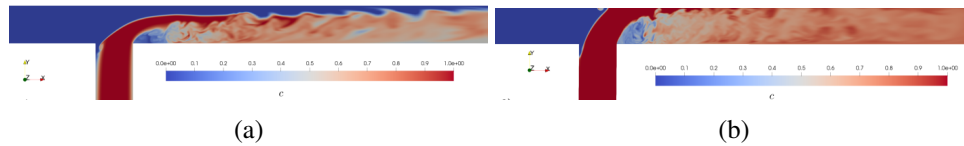


FIGURE 2 – Contour plot on c : (a) Deflecting regime and (b) impinging regime

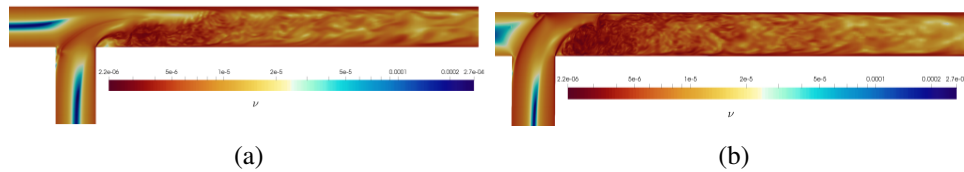


FIGURE 3 – Contour plot on ν in a shear thinning T-junction flow : (a) Deflecting regime and (b) impinging regime

2 Result and Discussion

As for simulation results, we see in FIGURE 3 that for both regimes two viscous cores joins at the junction and breaks into small-scale less viscous structures. Approaching the outlet, the flow regains its viscosity due to dissipation. A relaminazation is expected if we have a longer outlet. To investigate the possible relaminazation, we have pulled out statistics on transversal slices from the junction to the outlet. Similarly, to have a mesure of mixing efficiency, we have performed slice-by-slice statistics on c field for both FIGURE 2(a) and 2(b). We found that for shear thinning fluid, mixing is favored and much more efficient in the "impinging regime" than in the "deflecting regime".

Moreover, to our knowledge there's no 3D flow-structure visualization on such non-Newtonian flows. We applied the Q-criteria and used the non-dimensionalized Q^+ iso-surfaces [9] to get a visual of the presence of vortex structures (See FIGURE 4). We confirm the presence of the non-Newtonian "kidney vortex pair" [4] from FIGURE 4(a). Much more complex vortex pairs are also observed in FIGURE 4(b). A clearly different flow structure resides between the "deflecting regime" and the "impinging regime".



FIGURE 4 – Vortices visualization based on iso-surfaces $Q^+ = 0.3$ in a shear thinning T-junction flow : (a) Deflecting regime and (b) impinging regime. Red is plotted where vorticity's x-component is positive whereas as blue denotes the counter-rotating negative vortices.

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