# Simulation of Viscoplastic Flows in a rotating Vessel Using a Regularized Model

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**ABSTRACT**
Viscoplastic fluid characterized by the existence of a residual value for the shear stress, beyond which the material behaves, modeled first by Bingham [1]. This dramatically changes the typical property bustle of performance, quality mixture and the energy consumed by the creation of rigid zones in the mixing device. Thus, regularization methods have been proposed as"augmented Lagrangian method" developed by Fortin and Glowinski [2] and the Papanastasiou [3] model. This regularization has been used in numerous recent papers; another type of regularization suggested by Bercovier and Engelman[4]), that has not seen many applications. For this purpose and in this paper, the characterization of hydrodynamic fields of incompressible yield stress fluid with regularization model of Bercovier - Engelman in a rotating vessel equipped with gate using Fluent CFD code 6.3.

## 1. INTRODUCTION

Manufacturing and materials development often involves stirring or [5] devices for various operations, such as mixing of miscible and immiscible fluids, and particles or gas dispersion. For complex fluids, the design and selection of a stirring system are often empirical. Because of the growing importance of product quality, especially in chemical and pharmaceutical industries, a full understanding of mixing and hydrodynamic effects on operations in stirred vessel is essential.

This is particularly noticeable for viscoplastic fluids. This type of fluid also called "yield stress fluid" starts to flow only when the applied stress exceeds a threshold value called the yield stress. This dramatically changes the typical property bustle of performance, quality mixture and the energy consumed by the creation of rigid zones in the mixing device.

These operations are strongly affected by mixing which is pertinent to impeller's type and geometry. Because of increasing importance of product's quality, especially in chemical and pharmaceutical industries, a complete understanding of mixing and hydrodynamic effects on operations in stirred tanks is essential.

Agitation of such fluids results in the formation of an intense movement area around the wheel (also called the cavern) with essentially stagnant regions elsewhere [6].

To date, many efforts have been made [7] for this class of fluids by experimental works and numerical studies namely Bouaifi and Roustan [8]; Niedzielski and Kuncewicz [9]; Rajeev et al., [10]; Rudolph et al [11], and numerical studies namely Amadei and Savage [12]; Anne-Archard et al [13]; Burgos et al [14]; Rahmani et al [15]; Pedrosa and Nunhez [16]; Yan and James [17].

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For a long time, stirred vessels have been done over the years through experimental investigation for a number of different impellers, vessel geometries, and fluid rheology. Such an approach is usually costly and sometimes is not an easy task. With computational fluid dynamics (CFD) [18], we can examine various parameters contributing to the process with less time and money, an otherwise difficult task in experimental techniques. In recent years, CFD has become an important tool for understanding flow phenomena [19], development of new processes and optimize existing processes [20] .The ability of CFD tools predict the mixing behavior in terms of quality and mixing time, energy consumption, flow and velocity profiles is considered a successful realization of these methods and acceptable results have been obtained.

## 2. NUMERICAL MODEL

### 2.1. Description of the stirred system

The mixing system employed in the present study consists of a cylindrical flat bottomed vessel equipped with a gate impeller positioned at the centre of the tank rotating around a shaft.

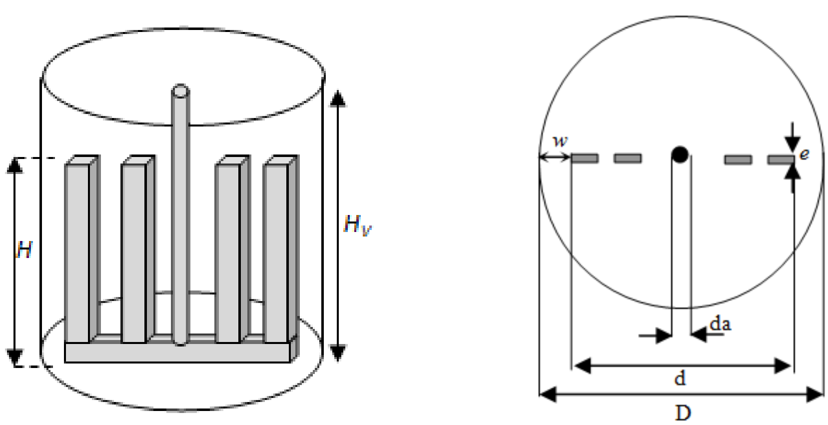


Figure 1: Mixing system

Table 1 Dimension of mixing system

| *D* | *d* | *da* | *e* | *w* |
|---|---|---|---|---|
| 1 | 0.96 | 0.023 | 0.027 | 0.067 |

### 2.2. Fluid model

To study the yield stress fluid which is the subject of this paper, we use viscoplastic fluid model of Bercovier- Engelman consists of adding a small regularization parameter $\delta$:

$$\overline{\overline{D}} = 0 \text{ for } \|\tau\| < \tau_0 \quad (1)$$

$$\overline{\overline{\tau}} = \left( \frac{\tau_0}{\dot{\gamma} + \delta} + \eta_\infty \right) \overline{\overline{D}} \quad \text{for} \quad \|\overline{\overline{\tau}}\| > \tau_0 \quad (2)$$

With:

$$\overline{\overline{D}} = \frac{1}{2}\left(\nabla V + \nabla V^{T}\right) \tag{3}$$

$$\left|\overline{\overline{\tau}}\right| = \sqrt{\frac{1}{2}\overline{\overline{\tau}} : \overline{\overline{\tau}}^{T}} \tag{4}$$

## 2.3. Governing equation

The flow of non-Newtonian fluids is governed by:

Continuity

$$\rho\frac{\partial V}{\partial t} + \nabla(\rho\vec{V}) = 0 \tag{7}$$

Momentum

$$\rho\frac{\partial V}{\partial t} + \rho\left(V.\nabla V\right) - \eta_{ap}\Delta V - 2\overline{\overline{D}}\cdot\nabla\eta_{ap} + \nabla P = 0 \tag{8}$$

## 2.4. Numerical methodology

The first step is the gambit CFD code preprocessor which has built the geometry and the generated triangular unstructured mesh through a number of discretization methods available. The second step is the solver code where we proceeded to set data, prescription to initial conditions and limitations, testing and optimizing the convergence of computing, calculation and simulation.

The CFD code was used to solve, in Cartesian coordinates, the momentum and continuity equations for a laminar flow.

The fluid model of Bercovier- Engelman was performed using the user define function and the pressure of the semi-implicit algorithm linked equation (SIMPLE) with a second-order discretization scheme, the unstructured meshes of 40272 elements was used.

The boundary conditions for velocity are fixed on the impeller and the vessel.

* On the impeller $v_r = v_t = 0$

* On the vessel $v_r = v_t = -.\pi ND$

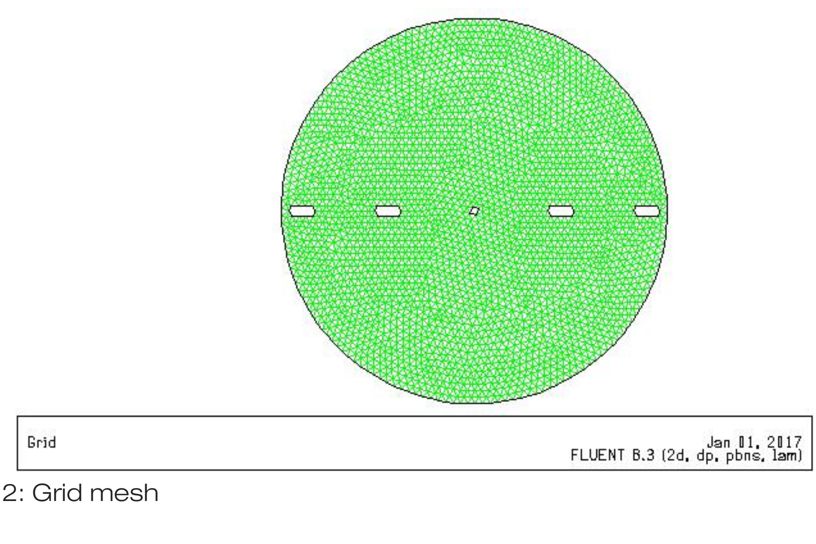


Figure 2: Grid mesh

## 3. RESULTS AND INTERPRETATIONS

Initially before the presentation of our results, we have compared our results with a numerical work of Rahmani [15], the results show a very good agreement.

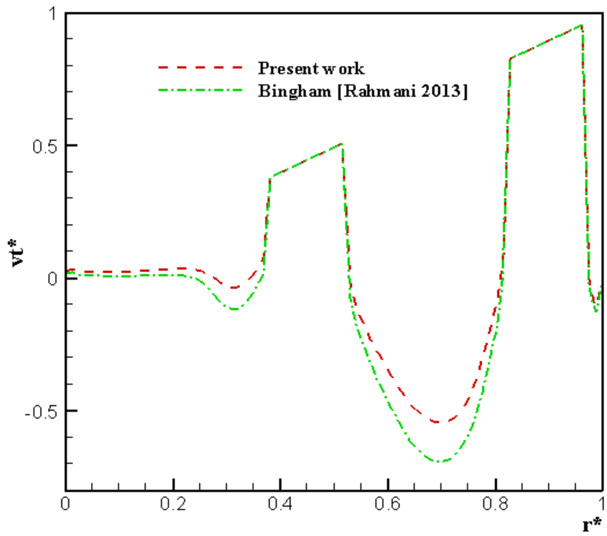


Figure 3: Tangential velocity on the median plan for Re = 13.8

### 3.1. Effect of Regularization Parameter

To get a better approximation of the ideal model, we tested the influence of regularization parameter, figures 4 and 5 show the tangential velocity on the impeller and the median plans respectively.

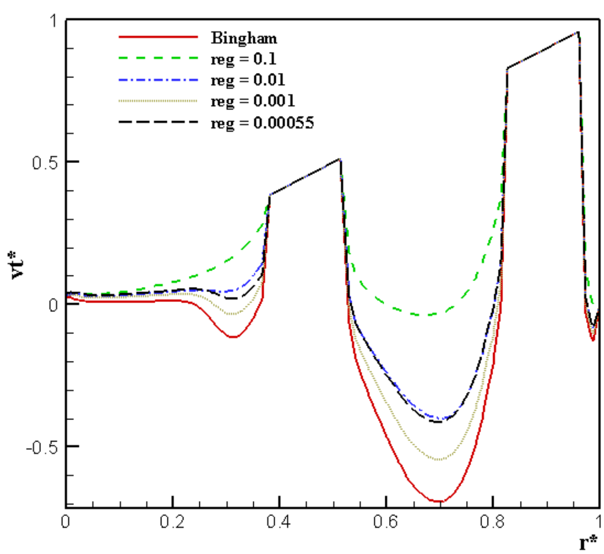


Figure 4: Tangential Velocity for Different regularization parameter on impeller plan for Re=13.8

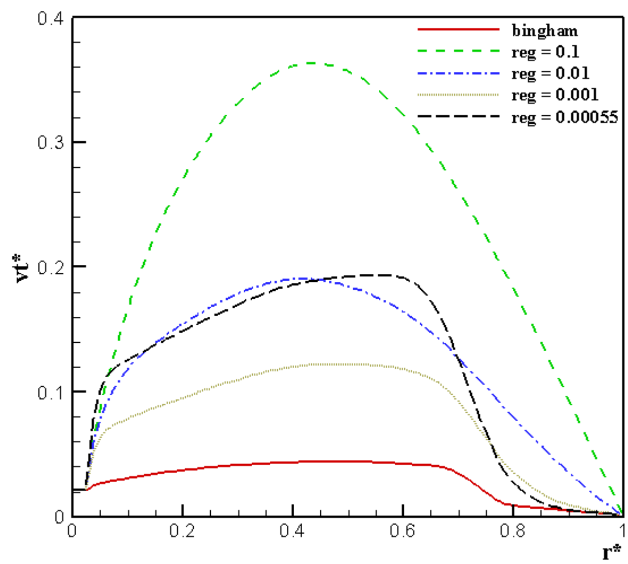


Figure 5: Tangential Velocity for Different regularization Parameters on the median plan, Re=13.8.

For different regularization parameter compared with the Bingham model, we note that the value *reg = 0.001* gives a sufficient approximation of the model.

## 3.2. Effect of inertia

For this purpose, the mobile rotational speed is studied in figure 6, with low Reynolds number, the fluid flow is less intense, but the increase of Re produces a tangential flow more powerful and mixing is then improved.

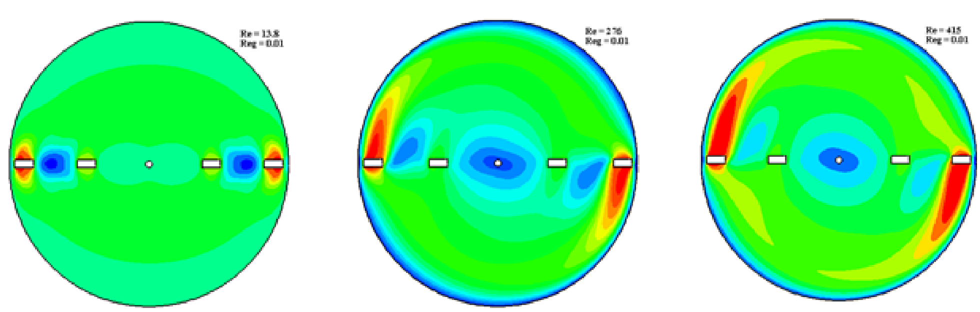


Figure 6: Velocity contour for different Reynolds number.

### 3.3. Effect of blades position

The area swept by the agitator is more ample with parallel blades and the cavern size is larger.

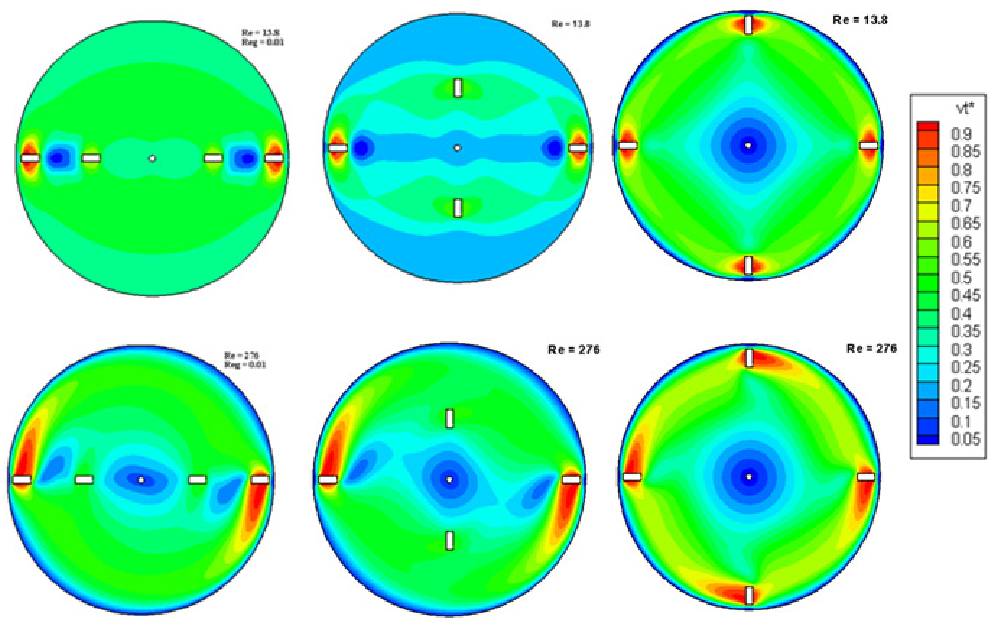


Figure 7: Velocity contour for different blades position.

### 3.3. Effect of plasticity

For the contours of tangential velocity as a function of BI It can be seen that the fields are identical and the existence of three zones: a first zone sheared at the level of the blades, the second is the recirculation zone located just in the vicinity of the axis of the agitator, the last one is a rigid zone represented by the rest of the vessel; For greatest value of BI =6000, correspond to the existence of large immobilized regions and thus to reduced sheared zones in the vicinity of each blade. In this type of flow, the viscosity is very high in most part of the field.

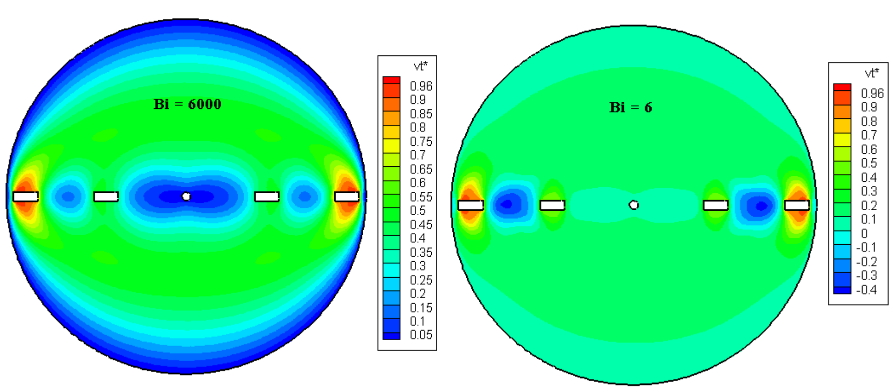


Figure 8: Velocity contour for different BI.

3.5. Power consumption

It is quite equivalent to say that the power consumption P is entirely given by the impeller to the fluid. In these conditions:

$$P = \int_{vessel\,volume} \mu \Phi_v dV \tag{9}$$

The power number is calculated according to this equation:

$$Np = \frac{P}{\rho . N^3 . d^5} \tag{10}$$

In figure 9, we can see that the increase of the regularization parameter increases the power consumption, which is explained by: the increase of regularization parameter can modify the behavior of the fluid that increases the plasticity which makes extend the rigid zone in the vessel or significant power consumption.

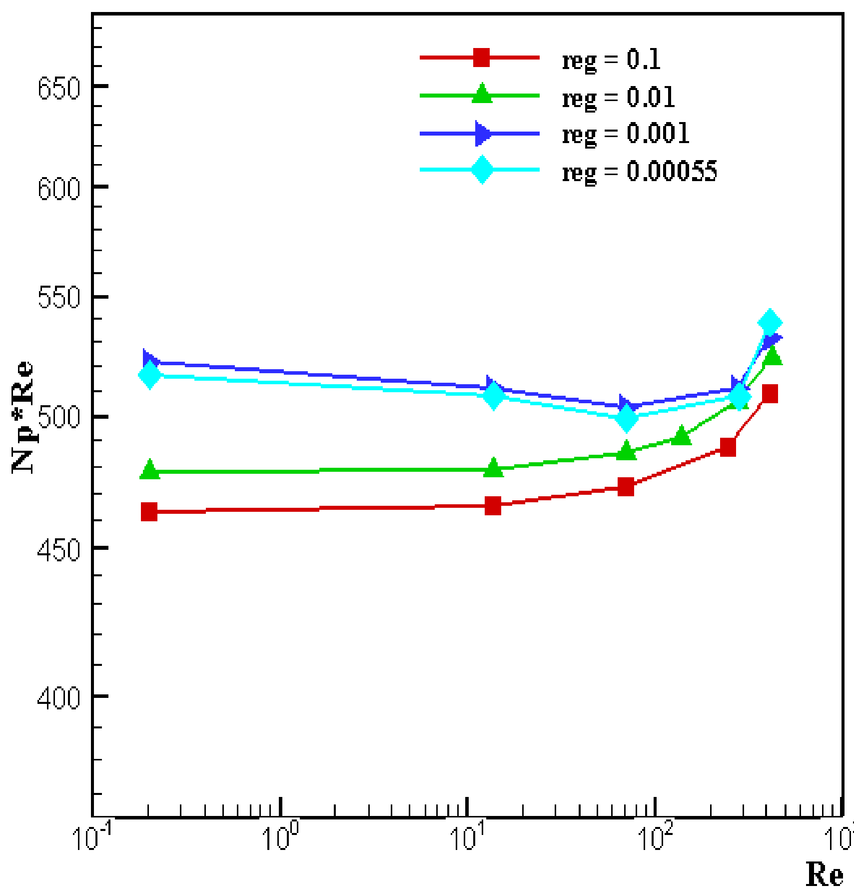


Figure 9: Variation of the product Np·Re as function of Reynolds number for different Regularization parameters

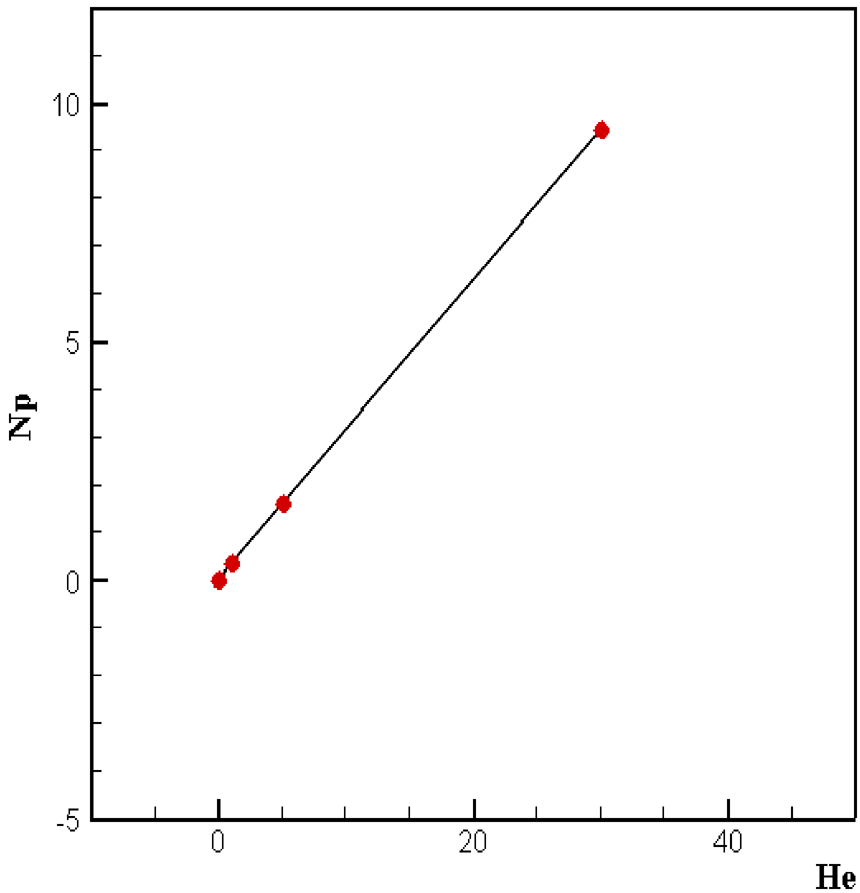


Figure 10: Variation of Np as function of Hedström number 0, 8294, 41472 and 248832.

## 4. CONCLUSION

The hydrodynamics of viscoplastic fluids in complex geometries such as the systems of agitation is modestly approached. However, it plays a significant role, in the control and the effectiveness of processing since it conditions the heat and mass transfer. The problem is analysed under the numerical aspect. The latter is treated by using an existing industrial code which is the fluent code.

An effective investigation of the influence of various parameters on the flow, shows that we can use the Bingham number to distinguish the flow regime in the case of viscoplastic fluids. We also found that for small regularization parameters (0.00055 or less) a convergence of difficulty that gives a bad approximation of the Bercovier-Engelman law is also clear for other sizes characterizing the flow.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

| | | |
|---|---|---|
| $Bi$ | dimensionless | Bingham number |
| $d$ | [m] | Impeller diameter |
| $D$ | [m] | Vessel diameter |
| $\overline{\overline{D}}$ | [-] | Rate of strain tensor |
| $da$ | [m] | Shaft diameter |
| $e$ | [m] | Impeller thickness |
| $H$ | [m] | Impeller height |
| $He$ | Dimensionless | Hedström number |
| $H_v$ | [m] | Vessel height |
| $L$ | [m] | Width |
| $N$ | [rd/s] | Rotational speed |
| $Np$ | [-] | Power number |
| $P$ | [W] | Power consumption |
| $Re$ | Dimensionless | Reynolds number |
| $w$ | [m] | Agitator to wall clearance |
| $\dot{\gamma}$ | [$s^{-1}$] | Shear rate |
| $\dot{\gamma}_c$ | | Cut off shear rate |
| $\eta_{ap}$ | [Pa.s] | Apparent viscosity |
| $\eta_0$ | [Pa.s] | Cut off viscosity for low shear rate |
| $\eta_\infty$ | [Pa.s] | Limiting viscosity at infinite shear rate |
| $P$ | [kg/m3] | Density |
| $\overline{\overline{\tau}}$ | [$N.m^{-2}$] | Stress tensor |
| $\tau_0$ | [$N.m^{-2}$] | Yield stress |