



Heat transfer for a Giesekus fluid in a rotating concentric annulus



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ABSTRACT

Annular flow of a viscoelastic fluid described by the Giesekus model has received some attention over the years, both concerning the fluid mechanical and thermal aspects, yet no investigation has been carried out using the analytical solution for the velocity profile in the energy equation to determine temperature distribution and heat transfer characteristics. Moreover, viscous dissipation, when accounted for, is usually defined by a formulation of the Brinkman number which proves inconsistent when applied to non-Newtonian fluids.

In this work the purely tangential flow of a Giesekus fluid in an annulus with rotating inner wall subject to thermal boundary conditions of the first kind (imposed temperature) at the walls is investigated employing the analytical solution for the velocity profile. Viscous dissipation is accounted for by first deriving a consistent Brinkman number which is easily related to the one usually employed in previous studies and the temperature profiles are obtained for different values of the Deborah number and the non-dimensional mobility factor. Results for the Nusselt numbers at the inner and outer wall are also discussed.

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1. Introduction

Annular geometries are a recurring feature in many engineering applications, including heat transfer equipment, e.g. tube-in-tube heat exchanger, machining (drilling), manufacturing (food or polymer extrusion), machine elements (journal bearings), oil industry (well drilling) and viscometry. The fluid confined between the two cylindrical surfaces may flow tangentially, axially, or with a combination of both modes and is often non-Newtonian (e.g. emulsions). The latter feature significantly complicates the study of the flow and heat transfer characteristics of the phenomenon, owing to the non-linearity in the constitutive equation. Therefore, the Newtonian model is often inappropriate, whilst the Giesekus model [1] is suitable for shear-thinning fluids.

In the case of microchannels, cases where non-Newtonian fluids are employed abound: amongst applications where annular geometries are involved, micro-drilling can be quoted, [2], together with micro-extruders and micro-mixers, [3].

A review on convective heat transfer in stationary and rotating annuli for Newtonian fluids has been carried out by Childs and Long [4] in the mid-90s, whilst later on Coelho and Pinho [5] analysed viscous dissipation in annuli with axial flow subject to prescribed heat flux or surface temperature boundary conditions.

Fang et al. [6] studied numerically the forced convection of non-Newtonian fluids in concentric and eccentric annuli in the case of negligible viscous dissipation. Still concerning non-Newtonian fluids, axial flow in pipes and ducts with viscous dissipation was investigated by Pinho and Oliveira [7] for a viscoelastic fluid using a simplified Phan-Tien-Tanner model for constant heat flux and by Coelho et al. [8] for constant wall temperature. The same Authors also extended the study to the thermal entry region of a hydrodynamically fully developed flow under the same conditions in [9] and employed a different fluid model to study the same problem in [10].

Concerning purely tangential flow, Khellaf and Lauriat [11] studied the thermal and fluid dynamic behaviour of a Carreau fluid in the case of rotating inner surface and fixed outer surface, whilst Naimi et al. [12] turned their attention to a power law fluid analysing the Taylor-Couette convective vortices. In more recent years, Jouyandeh et al. [13] investigated the heat transfer characteristics for the tangential flow of a Giesekus fluid between two counter-rotating cylinders; their study accounted for viscous dissipation and employed a simplified velocity profile. The same group [14] also analysed the axial annular flow for a fixed duct using the same fluid model and extending thermal conditions to the case of imposed heat flux at the walls. The axial annular flow of a Giesekus fluid was also studied by Mostafaiyan et al. [15], who proposed an approximation to estimate radial normal stress, thus obtaining an analytic expression for the velocity and pressure profiles, whose validity was checked by comparison with the exact solution in a parametric study.

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For several technical fluids exhibiting viscoelastic characteristics, the Giesekus model suitably describes their behaviour. The model employs three physical parameters in the constitutive equation, namely viscosity, mobility factor and relaxation time [1,16]. The experimental determination of the non-linear mobility factor was carried out by Calin et al. [17] and the rheological characterisation of a high-density polyethylene employing this model is documented by Debbaut and Burhin [18].

The Giesekus model has been applied in a number of works, some directly concerned with annular geometries [19,20], other with heat transfer, usually including viscous dissipation [21,22].

The conclusion one might draw from the above discussion is that all aspects of heat transfer and fluid flow in annular geometries for viscoelastic fluids described by the Giesekus model have been investigated. In fact, this is not the case: for the purely tangential flow, an approximate solution is often employed, as discussed by Daprà and Scarpi [23], who in turn obtained an analytical solution for the case of purely tangential annular flow [24] and this directly affects the results concerning heat transfer. Also, viscous dissipation is often described by a formulation of the Brinkman number which works quite well for Newtonian fluids, [25,26] but is inconsistent for those exhibiting a viscoelastic behaviour, as discussed by Coelho and co-workers [27,28].

In this work the purely tangential flow of a Giesekus fluid in an annulus with rotating inner wall subject to first-order (imposed temperature) thermal boundary conditions at the wall is investigated using the analytical solution for the velocity profile. Viscous dissipation is accounted for by first deriving a consistent Brinkman number which is easily related to the one usually employed in previous studies and the temperature profiles are obtained for different values of the Deborah number and the non-dimensional mobility factor. Results for the Nusselt numbers at the inner and outer wall are also discussed.

2. Problem definition and governing equations

The geometry analysed in this study is shown in Fig. 1. A concentric annulus of infinite length is considered, such as that formed by two coaxial cylinders. The outer surface is fixed and has a radius R_o , whilst the inner one, which has a radius R_i , rotates with an angular velocity $\Omega_i = \frac{v_{\theta i}}{R_i}$. The outer surface of the annulus is kept at a uniform temperature T_o , whereas the inner surface is at temperature T_i , which is also uniform; moreover, $T_o > T_i$.

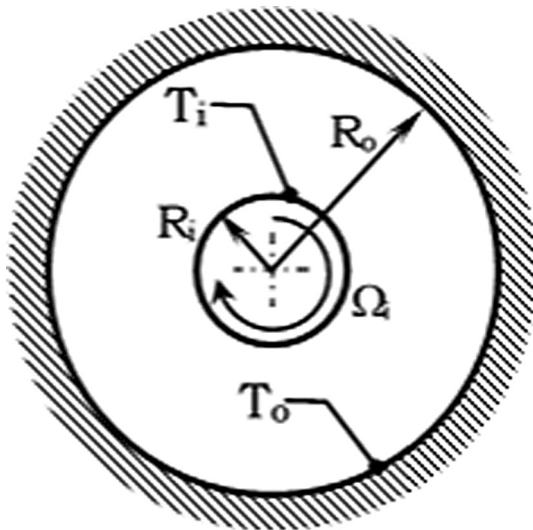


Fig. 1. Sketch of the annulus.

A Giesekus fluid fills the annulus and moves with a steady-state, laminar and purely tangential flow, which is induced by the rotation of the inner cylinder relative to the outer one.

The constitutive equation of the fluid can be written as:

$$\begin{aligned} \bar{\tau} + \lambda_r \left[\frac{\partial \bar{\tau}}{\partial t} + \bar{v} \cdot \nabla \bar{\tau} \right] - \lambda_r \left[\bar{\tau} \cdot \nabla \bar{v} + (\nabla \bar{v})^T \cdot \bar{\tau} \right] + \frac{\lambda_r \alpha}{\mu} \bar{\tau} \cdot \bar{\tau} \\ = \mu_0 \left[\nabla \bar{v} + (\nabla \bar{v})^T \right] \end{aligned} \quad (1)$$

where $\bar{v}$ is the velocity vector, $\bar{\tau}$ is the stress tensor, t is time, μ_0 is the zero-shear rate viscosity of the polymer, λ_r is the stress relaxation time, and α is the non-dimensional mobility parameter ($0 \leq \alpha \leq 1$), which accounts for the degree of anisotropy in the polymer. If $\alpha = 0$ the fluid exhibits an isotropic mobility, and the rheological equation leads to the upper convective Maxwell model (UCM); at the other end of the range, $\alpha = 1$ corresponds to the most anisotropic mobility. Supposing a purely tangential flow and using cylindrical coordinates, the velocity is limited to its tangential component, v_θ , which automatically verifies the continuity equation. The radial and tangential components of the momentum equation become

$$-\frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} (r \tau_{rr}) - \frac{\tau_{\theta\theta}}{r} = \rho \left(-\frac{v_\theta^2}{r} \right) \quad (2)$$

$$\frac{\partial}{\partial r} (r^2 \tau_{r\theta}) = 0 \quad (3)$$

where p is the pressure, r is the radial coordinate and ρ is the density.

Under the assumption that thermophysical properties and model parameters are unaffected by changes in temperature, the tangential velocity distribution in the radial direction $v_\theta(r)$ for an isothermal flow still holds. Owing to the nature of the flows in industrial applications such as journal bearings, polymer extruders or chemical/mechanical mixers, fluid viscosity or velocity gradients may be high and viscous dissipation become a relevant issue, causing an alteration in the radial temperature profile that would normally be encountered when its influence is negligible. If viscous dissipation is accounted for, the energy equation for the above-mentioned case becomes

$$\frac{\lambda}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) - (\bar{\tau} : \nabla \bar{v}) = 0 \quad (4)$$

where λ is the thermal conductivity of the fluid and $T(r)$ is the temperature; the tensor scalar product $(\bar{\tau} : \nabla \bar{v})$ gives the contribution of viscous dissipation to the temperature profile:

$$\bar{\tau} : \nabla \bar{v} = \tau_{r\theta} \left(\frac{dv_\theta}{dr} - \frac{v_\theta}{r} \right) \quad (5)$$

so that Eq. (4) can be written as

$$\frac{d}{dr} \left(r \frac{dT}{dr} \right) - \frac{r}{\lambda} \tau_{r\theta} \left(\frac{dv_\theta}{dr} - \frac{v_\theta}{r} \right) = 0 \quad (6)$$

The following non-dimensional quantities are then introduced:

$$\begin{aligned} r^* = \frac{r}{R_o} \quad T^* = \frac{T - T_i}{T_o - T_i} \quad v_\theta^* = \frac{v_\theta}{v_{\theta i}} \quad p^* = \frac{p \delta}{\mu_0 v_{\theta i}} \\ \tau_{\theta r}^* = \frac{\tau_{\theta r} \delta}{\mu_0 v_{\theta i}} \quad \kappa = \frac{R_i}{R_o} \quad De = \frac{\lambda_r v_{\theta i}}{\delta} \end{aligned}$$

where $\delta = R_o - R_i$. The Deborah number represents the ratio of the polymer relaxation time, λ_r to the characteristic time of the phenomenon, here represented by the ratio of the thickness of the annulus, δ , to the tangential velocity of the rotating wall: the lower De , the more Newtonian-like the fluid behaves. Conversely, for high values of De the shear-thinning behaviour dominates.

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