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Inertial thermal convection in a suddenly expanding viscoplastic flow field

Khaled J. Hammad

Department of Engineering, Central Connecticut State University, New Britain, CT 06050, USA

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ABSTRACT

Inertial thermal convection from recirculating and non-recirculating flows of viscoplastic fluids through an axisymmetric 1:5 sudden expansion has been studied. The governing mass and fully-elliptic partial differential equations of motion and energy along with the Bingham constitutive equation were numerically solved to provide accurate predictions of the flow and thermal fields. A parametric study is implemented to study the impact of geometry, inertia, rheology, and thermo-physical properties on the thermal structure of suddenly expanding, non-isothermal, viscoplastic flows. Detailed visualizations of the velocity, viscosity, and temperature fields demonstrate the dramatic impact of yield stress presence on both the flow and thermal behavior. Furthermore, transitioning from a recirculating flow field to a non-recirculating viscoplastic flow field, within the present geometry, dramatically influences the thermal characteristics of the viscoplastic flow field. Recirculating suddenly expanding viscoplastic flows are characterized by two local compressions in the thermal boundary layer, upstream and downstream of the impingement region. However, non-recirculating viscoplastic flows display only one local compression in the thermal boundary layer, immediately downstream of the large, ramp-like, stagnant corner region.

1. Introduction

The current study attempts to improve our understanding of the impact of geometrical changes encountered in practice on the heat transfer behavior of viscoplastic flows. A viscoplastic material behaves like a solid under the application of small stresses and flows like liquids once the applied stress exceeds a critical value called the yield stress. Examples of viscoplastic materials encountered daily include mayonnaise, ketchup, toothpaste, gelled products, paint, and concrete. Flows of viscoplastic fluids can be found in important industries such as food processing, biotechnology, plastics and polymers, pulp and paper, and petrochemicals [1,2].

Axisymmetric suddenly expanding internal flows are of significant importance from practical and fundamental points of view. They are frequently encountered in practice, by design to promote mixing and enhance heat/mass transfer, or by default, in piping systems that are part of the fluid processing and transport. The gross features of the axisymmetric sudden expansion flow of a Newtonian fluid are well known. As illustrated in Fig. 1, the incoming boundary layer separates at the expansion plane, forms a free shear layer that entrains the surrounding fluid and creates a corner flow recirculation region. The separating flow reattaches at a certain downstream location called the reattachment length, L_r. The flow continues to redevelop as it travels further downstream. Suddenly expanding axisymmetric Newtonian flows are characterized by the always present corner recirculation region, even for creeping flows.

The geometrical simplicity and hydrodynamic complexity of the axisymmetric sudden expansion flow made it a long-standing numerical benchmark for computation of Newtonian and non-Newtonian fluids and the associated heat/mass transfer phenomenon [3–9]. In addition, it has been used to shed light on the physics of wall-bounded separated and reattached flows of Newtonian fluids [10–21].

Most of the performed work so far, whether theoretical and/or experimental, is related to Newtonian fluids. However, there are numerous materials that behave in a viscoplastic manner such as slurries, pastes, plastics, electro-rheological fluids, suspensions of solids in liquids, and emulsions [1,2,22,23].

Viscoplastic flows through an axisymmetric sudden expansion have been studied by [24–33]. From an experimental point of view, studying viscoplastic flows is complicated due to several factors. Almost all viscoplastic materials encountered in practice are optically opaque which prevents the deployment of non-intrusive opti-

E-mail address: hammad@ccsu.edu

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Nomenclature

d, D	diameters of small and large pipes
e_i	relative recirculation intensity, ratio of the maximum amount of backflow in the recirculation region to the inlet flow rate $-\psi_{\min}/\psi_{\max}$
ER	expansion ratio, R_d/R_u or D/d
$\bar{k}$	thermal conductivity of fluid
L_r	reattachment length
Nu	Nusselt number based on bulk temperature, $\frac{\partial\theta}{\partial r}\big|_{r_w} \Big/ \theta_b$
P	non-dimensional pressure, $P^*/\rho u_b^2$
Pr	Prandtl number, $\eta_p/\rho\alpha$
r	non-dimensional radial distance, r^*/R
R, R_o	radii of small and large pipes
Re	Reynolds number, $\rho d u_b/\eta_p$
T	temperature
u	non-dimensional streamwise velocity, u^*/u_b
u_b	inflow streamwise bulk velocity, $2\int_0^R u^* r^* dr^*/R^2$
v	non-dimensional crosswise velocity, v^*/u_b
x	non-dimensional streamwise distance, x^*/R
Bn	Bingham number, $\tau_y d/\eta_p u_b$

Greek letters

$\psi_{\max}$	maximum value of stream function
$\psi_{\min}$	minimum value of stream function
$\dot{\gamma}_{ij}$	rate of deformation tensor, $\partial u_i/\partial x_j + \partial u_j/\partial x_i$
$\dot{\gamma}_{II}$	second invariant of rate of deformation tensor, $\dot{\gamma}_{ij}\dot{\gamma}_{ij}$
η_p	plastic viscosity
θ	non-dimensional temperature, $(T - T_w)/(T_i - T_w)$
μ_{eff}	non-dimensional effective viscosity, μ^*_{eff}/η_p
ρ	density
τ_{ij}	stress tensor element
τ_{II}	second invariant of stress tensor, $\tau_{ij}\tau_{ij}$
τ_y	yield stress

Subscripts/superscripts

*	dimensional quantities
b	bulk properties
c	centerline properties
d, u	downstream and upstream properties
i, w	inflow and wall properties

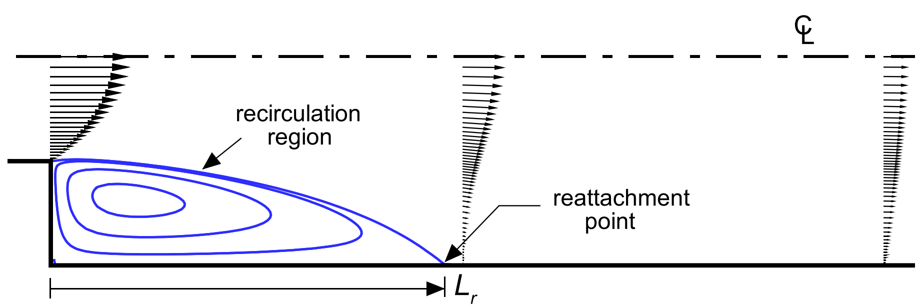

Fig. 1. Suddenly expanding axisymmetric flows of a Newtonian fluid.

cal diagnostic techniques such as particle image velocimetry (PIV), Laser Doppler Anemometry (LDA), and laser sheet visualization (LSV). Due to experimental limitations and/or difficulties, numerical simulations have been the method of choice for studying the flow behavior of complex viscoplastic flows. The limited number of available PIV, LDA, and LSV based studies deployed transparent rheological simulants of the particular viscoplastic material of interest [25,27,29,31].

Available experimental techniques for visualizing and studying opaque flows include Nuclear Magnetic Resonance (NMR), Positron Emission Tomography (PET), and Ultrasound Doppler Velocimetry (UDV). Jossic et al. [34] used NMR imaging to study the segregation of spheres suspended in a viscoplastic fluid through an axisymmetric 1:4 sudden expansion. Heath et al. [32] visualized and measured the flow of an opaque papermaking suspension through an axisymmetric 1:5 sudden expansion using PET and UDV.

The existence of recirculating and non-recirculating flow regimes for a 1:2 suddenly expanding axisymmetric yield shear-thinning viscoplastic flow was reported using planar laser sheet visualizations [25] and particle image velocimetry measurements [27]. Visualizations of yield shear-thinning viscoplastic flows through an axisymmetric 1:4 sudden expansion confirmed the existence of recirculating and non-recirculating flow regimes [29]. Surprisingly, the existence of a non-recirculating flow regime has not been reported in any of the earlier numerical studies of suddenly expanding axisymmetric expansion Bingham viscoplastic flows [24,26].

The review paper by Bird et al. [1] provided a summary of known analytical solutions for the flow and heat transfer rates of viscoplastic fluids. However, all confined flows that were described were within simple geometries, i.e., those containing an unyielded plug whose boundaries are parallel to the physical boundaries. Furthermore, more recent heat transfer studies of viscoplastic fluids focus on straight pipe or duct flows [35–41]. Despite the considerable importance of viscoplastic fluids and their diverse applications, heat transfer studies of their flows in complex geometries, where the physical boundaries are not parallel, are very limited and have received little attention so far.

Numerical simulations are used in the current study to obtain detailed information on the flow and flow and thermal structures arising from suddenly expanding, non-isothermal, viscoplastic flows. The governing mass and fully-elliptic partial differential equations of motion and energy along with the Bingham constitutive equations will be used to provide accurate predictions of the velocity and temperature fields. The study focuses on laminar, recirculating, and non-recirculating, Bingham viscoplastic flows through a 1:5 axisymmetric abrupt expansion. Viscoplastic fluids are highly viscous and most of their flows are typically laminar. Hydrodynamic conditions, such as transitioning from a non-recirculating to a recirculating viscoplastic flow regime, strongly