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Heat transfer enhancement in suddenly expanding annular shear-thinning flows

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A B S T R A C T

Heat transfer enhancement in suddenly expanding annular pipe flows of Newtonian and shear-thinning non-Newtonian fluids is studied within the steady laminar flow regime. Conservation of mass, momentum, and energy equations, along with the power-law constitutive model are numerically solved. The impact of inflow inertia, annular-diameter-ratio, k, power-law index, n, and Prandtl numbers, is reported over the following range of parameters: $Re = \{50, 100, 150\}$, $k = \{0, 0.5, 0.7\}$; $n = \{1, 0.8, 0.6\}$; and $Pr = \{1, 10, 100\}$. Heat transfer enhancement downstream of the expansion plane, i.e., Nusselt numbers greater than the downstream fully developed value, $Nu/Nu_{fd} > 1$, is only observed for $Pr = 10$ and 100. In general, higher Prandtl numbers, power-law index values, and annular-diameter-ratios, result in more significant heat transfer enhancement downstream of the expansion plane. Heat transfer augmentation, for $Pr = 10$ and 100, increases with the annular-diameter-ratio. For a given annular-diameter-ratio and Reynolds numbers, increasing the Prandtl number from $Pr = 10$ to $Pr = 100$, always results in higher peak Nu values, Nu_{max}, for both Newtonian and shear-thinning flows. All Nu_{max} values are located downstream of the flow reattachment point, in the case of suddenly expanding round pipe flows, i.e., $\kappa = 0$. However, for suddenly expanding annular pipe flows, i.e., $\kappa = 0.5$ and 0.7, Nu_{max} values appear upstream the flow reattachment point. For $Pr = 10$ and 100, shear-thinning flows display two local peak Nu/Nu_{fd} values, in comparison with one peak value in the case of Newtonian flows. The highest heat transfer enhancement, $Nu_{max}/Nu_{fd} \approx 5$, is observed at $\kappa = 0.7$, $n = 0.6$, and $Pr = 100$.

1. Introduction

Slurries, pastes, suspensions of solids in liquids, and emulsions often display a shear-thinning non-Newtonian behavior. Industries where shear-thinning materials are encountered include those dealing composite materials, rubber, pharmaceuticals, biological fluids, plastics, petroleum, soap and detergents, cement, food products, paper pulp, paint, light and heavy chemicals, oil field operations, fermentation processes, plastic rocket propellants, electrorheological fluids, ore processing, printing, and radioactive waste [1–3].

Understanding the thermal phenomenon of an annular pipe flow of a shear-thinning non-Newtonian fluid over an axisymmetric sudden expansion is important to the design of chemical reactors, heat exchangers, mixers, polymer mixing and injection molding devices, and biomedical applications. Most of the performed work so far is related to flow and heat transfer in suddenly expanding round pipe flows of Newtonian [4–8] and non-Newtonian fluids [9–11]. Suddenly expanding round pipe flows are characterized by a corner recirculation region in the case of Newtonian [11–27] and shear-thinning non-Newtonian fluids [28–35]. However, for yield stress non-Newtonian fluids, corner flow recirculation may or may not exist, depending on the combination of yield stress and flow inertia [36–39].

In the case of annular pipe flows over an axisymmetric sudden expansion, the sharp fluid exit causes flow separation. As the flow proceeds further downstream of the expansion plane, it entrains the surrounding fluid, which induces a slight flow of the surrounding fluid toward the expanding flow. This results in the creation of a large corner recirculation region, a counter rotating central recirculation region, a wall reattachment point, and a stagnation point along the centerline, as shown in Fig. 1 for a fully developed annular pipe inflow.

The evolution of the expanding flow is generally characterized by radial spreading, centerline velocity development, and flow redevelopment and transition to a fully developed pipe flow further downstream. Evolution of the expanding annular pipe flow and characteristics of the resulting recirculation regions depend on the inflow velocity profile, inertia, and the fluid's rheology.

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Nomenclature

BR	annular blockage ratio, $BR = (d/D)^2 = \kappa^2$
ER	expansion ratio, $ER = D_o/D = 2$
$d,\ D$	inner and outer nozzle diameters
D_o	downstream pipe diameter, $D_o = 2D$
D_h	hydraulic diameter of annular nozzle, $D_h = D - d$
e_i	relative recirculation intensity, ratio of the maximum amount of backflow in the recirculation region to the inlet flow rate $\lvert\psi_{\min}/\psi_{\max}\rvert$
$\bar{k}$	thermal conductivity of fluid
K	consistency index
L_r	reattachment length, axial extent of outer recirculation region
L_x	axial extent of the computational domain
n	Power-law index
Nu	Nusselt number based on bulk temperature, $\partial\theta/\partial r\rvert_{r_w}/\theta_b$
P	non-dimensional pressure, $P^*/\rho u_b^2$
Pr	Prandtl number, $K(u_b/D_h)^{n-1}/\rho\alpha$
r	non-dimensional radial distance, r^*/R
R	outer nozzle radius, $R = D/2$
Re	Reynolds number, $\rho D_h^n u_b^{2-n}/K$
T	temperature
u	non-dimensional streamwise velocity, u^*/u_b
u_b	inflow bulk velocity, $8\int_{d/2}^{D/2} u^* r^* dr^*/(D^2 - d^2)$
x	non-dimensional streamwise distance, x^*/R

Greek letters

α	thermal diffusivity
$\psi_{\max}$	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, $\dot{\gamma}_{ij}\dot{\gamma}_{ij}$
κ	annular pipe inner-to-outer diameter ratio, $\kappa = d/D$
θ	non-dimensional temperature, $(T - T_w)/(T_i - T_w)$
μ_{eff}	non-dimensional effective viscosity, $\mu^*_{eff}/K(u_b/D_h)^{n-1}$
ρ	density
τ_{ij}	stress tensor element

Subscripts/Superscripts

$*$	dimensional quantities
b	bulk properties
c	centerline properties
cen	central recirculation region properties
cor	corner recirculation region properties
$d,\ u$	downstream and upstream properties
i	inflow, i.e. properties at $x = 0$
fd	fully developed properties
w	wall properties

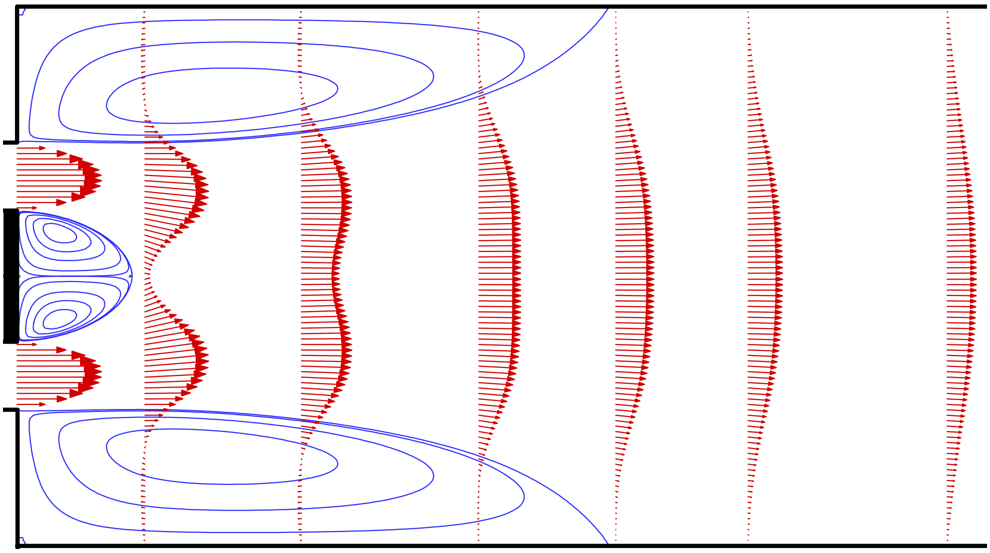

Fig. 1. Schematic of a suddenly expanding annular shear-thinning flow.

Studies focusing on annular flows over an axisymmetric sudden expansion are scarce. Sheen et al. [40] experimentally investigated the flow patterns arising from a concentric annular flow of a Newtonian fluid over an axisymmetric sudden expansion using flow visualization and laser-Doppler anemometry (LDA). The observed flow patterns, downstream the sudden expansion, were classified according to the characteristics of the central and corner recirculation regions. They were open annular flow, closed annular flow, vortex shedding, and stable central flow. The resulting flow pattern, depended on the value of the Reynolds number and whether the Reynolds number was increased or decreased over the $Re =$ 165–5800 range. Further, they reported flow bifurcation for $Re >$ 230, and transition from laminar to turbulent flow when the Reynolds number was about 1600.

Del Taglia et al. [41] numerically investigated the spontaneous break of symmetry for annular incompressible Newtonian flows in the steady laminar flow regime. Transition to asymmetry was found to depend on the combination of the blockage ratio, BR, and the Reynolds number, *Re*. BR is defined as the annular inner-to-outer-area-ratio, i.e., $BR = \kappa^2$, where κ is the annular pipe inner-to-outer diameter ratio, i.e., $\kappa = d/D$. The critical Reynolds number needed to transition from steady symmetric to steady asymmetric laminar flow was found to decrease with increasing the blockage ratio. For BR = 0.5 (or $\kappa = 0.707$), and 0.7 (or