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Laminar momentum and heat transfer phenomena of power-law dilatant fluids around an asymmetrically confined cylinder

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ABSTRACT

The present study focuses on the flow across an asymmetrically confined (heated) cylinder in a channel for fluids obeying Ostwald-de Wale (power-law) equation for the settings: Reynolds number (Re) = 1−40, power-law index (n) = 1−1.8, gap ratio (γ) = 0.375−1, blockage ratio (β) = 0.2−0.5 and Prandtl number (Pr) = 1−50. Total drag coefficient and its individual components have been analyzed as a function of Re, β, γ and n. The overall drag coefficient was found to increase with blockage and behavior of fluid, while it drops gradually for increasing Re. The asymmetrical configuration is seen to mitigate the overall as well as individual drag coefficients. The surface heat transfer coefficient in the form of average Nusselt number and the Colburn heat transfer j_h factor has been thoroughly discussed. Heat transfer rate is found to increase with increasing Reynolds number and wall confinement, while increasing dilatant behavior impedes the same. As expected, heat transfer results have been reconciled in a single curve by way of the Colburn j_h factor. The j_h factor is found higher for the symmetric case as compared to the asymmetric case.

1. Introduction

The phenomena of flow and heat transfer around a circular cylinder are a conventional problem in fluid mechanics, and the problem also embodies an idealization of many practical flows. Typical examples include flow around pipes in tubular heat exchangers, instrumentation probes, in hot-wire anemometry, flow past dividers in polymer processing, piping installations, offshore cylindrical drilling rigs and others. Extensive investigation in the form of experimental, analytical and different numerical methods has been carried out in the past for Newtonian fluids with respect to various aspects of this flow configuration [1–3].

In literature, researchers give sufficient insight into the symmetric wall confinement effects around a circular cylinder on momentum and heat transfer. Chen et al. [4] experimentally studied the formation of steady twin vortices behind the confined cylinder. It has been found that the first appearance of the vortices is not associated with a bifurcation of the full dynamical problem, but probably bifurcation of a restricted kinematical problem. The experimental study involved perturbation of steady flow to record time dependent motions. For a fixed blockage ($\beta = d/H$) in the range 0.1−0.95, the perturbations were found to die away at low Reynolds number (Re), but above critical Reynolds number disturbance settled to periodic motion. Anagnostopoulos et al. [5] studied the same flow configuration at a constant Re of 106 and demonstrated the effect of β on the wake characteristics for $\beta = 0.05$, 0.15 and 0.25. After that, Sahin and Owens [6] notably studied the wall effects on flow characteristics for a range of blockage ratios $0.1 < \beta < 0.9$, and $0 < Re \leq 280$, mainly focusing on stability and transition from symmetric vortex shedding to asymmetric vortex shedding. Chakraborty et al. [7] also studied the wall effects, but for a wider range of β (0.05−0.65) and for $0.1 \leq Re \leq 200$. This study primarily established the effect of Re and β on drag coefficient and recirculation zones. Afterward, Ben Richou et al. [8] extended the scope of study to a different range of β (0.01−0.6) and Re (10^{-4}−1). They calculated the drag force exerted on a circular cylinder due to Poiseuille flow at low Re. They showed how pressure term prevails over the viscosity term in the lubrication regime. Their findings can be utilized in determining the translatory velocity at which a force-free cylindrical body would move perpendicularly to its axis midway between two planar walls in Poiseuille flow. Later, Bharti et al. [9] studied the wall effects on drag coefficient for the varying ranges of $1 \leq Re \leq 40$, $0.2 \leq n \leq 1.9$, $0.25 \leq \beta \leq 0.91$ and concluded

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Nomenclature

C_D	total drag coefficient
C_{DF}	friction drag coefficient
C_{DP}	pressure drag coefficient
C_L	lift coefficient
C_p	heat capacity, J/kg K
d	diameter of a cylinder, m
e_x, e_y	unit vectors
f	body force, N/m^3
F_D	total drag force per unit length of the cylinder, N/m
F_{DF}	frictional component of total drag force per unit length of cylinder, N/m
F_{DP}	pressure component of total drag force per unit length of cylinder, N/m
F_L	lift force per unit length of the cylinder, N/m
h	local heat transfer coefficient, W/m^2 K
$\overline{h}$	average heat transfer coefficient, W/m^2 K
H	height of the channel, m
I_2	second variant of the rate of the strain tensor, s^{-2}
j_h	Colburn heat transfer factor
k	thermal conductivity, W/m K
L_d	downstream length, m
L_u	upstream length, m
m	power-law consistency index, Pa s^n
n	flow behavior index
n_x	x-component of the direction vector
n_y	y-component of the direction vector
n_s	direction vector normal to the surface of the cylinder
Nu_L	local Nusselt number
Nu	average Nusselt number
p	pressure, Pa
Pr	Prandtl number
Re	Reynolds number
T	temperature, K
T_w	temperature at the surface of the cylinder, K
T_∞	temperature at the channel inlet, K
U_{avg}	average velocity of the fluid at inlet, m/s
U_x	x-component of the velocity, m/s
U_y	y-component of the velocity, m/s
x	stream-wise coordinate, m
y	transverse coordinate, m
Greek symbols	
β	blockage ratio ($=d/H$)
Δ	minimum distance from the surface of the cylinder to the nearest wall, m
γ	gap ratio
η	viscosity, Pa s
θ	angular displacement from the front stagnation ($\theta = 0$), degrees
ρ	density of the fluid, kg/m^3
$\boldsymbol{\sigma}$	stress tensor
$\boldsymbol{\tau}$	shear stress, Pa
τ_x, τ_y	x- and y-components of the shear stress, Pa
ε	strain tensor

that, for a fixed value of the blockage ratio, the drag coefficient increases as the shear-thickening tendency ($n > 1$) increases, and vice-versa for shear-thinning behavior ($n < 1$). Subsequently, Bharti et al. [10] illustrated the effects of Re (1–40), n (0.2–1.8) and β (0.25 and 0.625) on the heat transfer for varying Prandtl numbers ($1 \le Pr \le 100$) in the steady regime. They reported that the heat transfer is enhanced with increasing degree of shear-thinning behavior. Similarly, decreasing the value of the blockage ratio further enhances the heat transfer rate as the fluid behavior changes from Newtonian to dilatant fluids. Hussam et al. [11] numerically studied the effect of wall confinement (0.1–0.4) on fluid flow and heat transfer from a heated circular cylinder to liquid metal ($Pr = 0.022$) flowing in a rectangular duct under the influence of a strong magnetic field for Re ranging from 50 to 3000. They demonstrated critical Reynolds number increasing with increasing blockage ratio for the flow past a confined cylinder damped by a transverse magnetic field. Recently, Bijjam and Dhiman [12] investigated the symmetrical confinement for the momentum transfer in the ranges $50 \le Re \le 150$, $0.4 \le n \le 1.8$ and $\beta = 0.25$. The shear-thinning behavior was reported to yield a decreasing value of time-averaged drag coefficient than Newtonian fluid and the behavior was opposite for dilatant fluids. The role of wall confinement across a symmetrically confined cylinder between two parallel walls has also been examined by Rao et al. [13] for the Re range 40–140 for both shear-thinning and shear-thickening behaviors ($0.4 \le n \le 1.8$). For shear-thickening fluids, the flow remains steady for $Re < 140$ at $\beta = 0.5$, while for lower blockage $(\beta) = 0.25, 0.34$ this transition is observed somewhere in the range $50 \le Re \le 100$. The similar configuration has been studied analytically for different blockage ratios ($0.2 \le \beta \le 0.8$) by Khan et al. [14] to investigate its effect on heat transfer. The modified von Karman–Pohlhausen method is incorporated to solve integral boundary layer momentum equation. Outside the boundary layer, potential flow exists and the velocity is obtained by the method of images. They further extended their work into non-Newtonian fluids [15]. They found that shear-thinning fluids offer less skin friction and higher heat transfer coefficients than shear-thickening fluids. Unlike above studies, for Newtonian fluids at $\beta = 0.66$, Semin et al. [16] conducted experimental and numerical analysis on a tethered cylinder for explaining the stability studies. They have found a new regime (characteristic of a blockage effect) called confined induced vibration (CIV) which is visible prior to the regime, vertex induced vibration (VIV). The onset of this new regime has been described using a Von der Pol model in terms of a supercritical Hopf bifurcation depicting the free oscillations. Subsequently, Fani and Gallaire [17] worked on the similar conditions at different confinement regions. They reported a CIV periodic unstable mode at higher blockage ratios but a steady diverging instability at a moderate confinement region.

The next phase of investigation after symmetrical confinement is devoted to analysis of flow and heat transfer over asymmetric positioning of a circular cylinder in the confined channel. Further, the kinematic flow behavior of the power-law fluids across an asymmetrically confined circular cylinder between two rectilinear parallel walls is different from that of its symmetrical orientation due to the change of interaction between the wall boundary layer and the wake at the rear part of the obstacle. In this field of research, Zovatto and Pedrizzetti [18] demonstrated the effects of placement of a cylinder in a plane channel on the pattern of vortex shedding and showed that the interaction between the cylinder wake and the wall boundary layer results in delay in the onset of vortex shedding when cylinder is placed closer to one wall. The transition from a steady flow to periodic vortex shedding regime has been analyzed for $Re \le 1600$. They also calculated lift and drag coefficients for a range of gap parameter (Δ/d) between 0 and 2; whereas, β was