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Prandtl Number Effects on the Rheological and Thermal Behaviour of Forced Convection Turbulent Flow of the Ostwald De Waele Fluids

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ABSTRACT

The present study establishing a better understanding of the rheological and thermal behavior of forced convection turbulent flow of the Ostwald de Waele fluids and shedding further light on the transfer mechanism of the turbulent energy via examining the effects of the Prandtl numbers and the flow behavior index of the shear-thinning fluid on the mean thermal quantities and the thermal turbulence characteristics. A fully developed turbulent flow of shear-thinning fluid through a heated pipe has been investigated numerically in the present study, employing a large eddy simulation (LES) with an extended Smagorinsky model. The flow behavior index has been chosen to be 0.75 over a Prandtl number range of (3, 5, 7, 30, and 70) at a fixed simulation Reynolds number equals 5500. A uniform constant heat flux has been imposed at the wall as a thermal boundary condition, and the working fluids have been assumed to be thermally independent. The numeric resolution was chosen to be 65^3 gridpoints in axial, radial and circumferential directions, respectively, with a domain length of 20R in the axial direction. The mathematical model was implemented in the laboratory code; the computational procedure is based on a finite difference scheme and second-order accuracy in space and time. The time advancement employed a fractional step method. A third-order Runge-Kutta explicit scheme and a Crank-Nicholson implicit scheme were used to evaluate the convective and diffusive terms. The finding suggests that the impact of Prandtl numbers providing crucial insights into the prevalent heat transfer processes inside fluid flows. The investigation shows a recurrent inverse connection for lower Prandtl numbers, indicating that convective heat transport is dominant. When the Prandtl number increased, an obvious trend occurs, indicating the increasing importance of thermal diffusion over convective processes.

Keywords: LES, Turbulent, Prandlt number, Forced convection.

1. Introduction

Non-Newtonian fluids have gained significant attention in the industry in recent years due to their wide range of application in various technical fields. These fluids do not follow the traditional Newtonian flow behavior where the rate of flow is directly proportional to the applied shear stress. Instead, their viscosity and flow behavior depend on factors such as shear rate, time, and temperature. Due to their unique flow properties, non-Newtonian fluids are commonly used in applications such as food processing, oil drilling, and biomedical engineering. Redjem-Saad et al (2007) [1] presented the Direct numerical simulations of heat transfer in a fully developed turbulent pipe flow with isoflux condition imposed at the wall are performed for a Reynolds number based on pipe radius Re = 5500. Main emphasis is placed on Prandtl number effects on turbulent heat transfer in pipe flow. The scaling of mean temperature profiles is investigated in order to derive correct logarithmic law for the rms of various Pr. The rms of temperature fluctuations and turbulent heat fluxes are found to increase when increasing Prandtl number. More recently, Abdi et al. 2022 [2] and Abdi et al. 2022 [3] performed a numerical analysis of the fully developed turbulent flow of pseudoplastic and dilatant fluids in an isothermal stationary pipe using a large eddy simulation, and a conventional dynamic model was presented in this work over a wide range of flow behavior indexes 0.75,

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0.8, 1, 1.2, 1.4, and 1.6 at a simulation Reynolds number of 12000. This study investigates the effect of Prandtl number on the Rheological behavior of Ostwald de Waele fluids in a straight pipe using Large Eddy Simulation (LES) techniques. The aim is to examine the Large Eddy Simulation approach's effectiveness and reveal the Prandtl number effects on the mean flow quantities and turbulence statistics

2. Problem description

The present study dealt numerically with a fully developed turbulent flow of Pseudoplqstic (n = 0.75) fluid through isothermal cylindrical pipe at simulation Reynolds number of 5500, by mean of the LES approach, with computational domain length of 20R. The computational mesh used of LES in this study consisted of 65^3 grid points in the axial, radial, and circumferential directions. As show in Figure 1. and Figure 2.

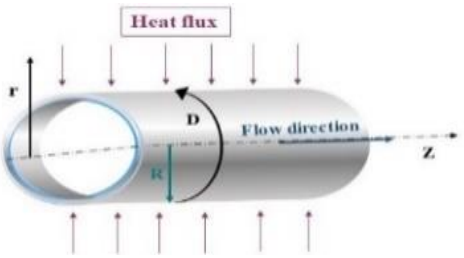

Figure 1: Computational domain.

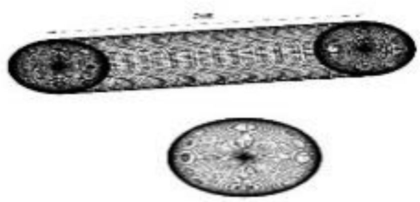

Figure 2: Mesh.

3. Results and Discussion

Fig.3 demonstrate the RMS of temperature fluctuations normalized by the friction temperature of shear-thinning fluid along the pipe radius against the distance from the wall in wall units. As illustrated in Fig.3 the RMS of temperature fluctuations generally decrease with increasing distance from the wall in wall units for all Prandtl values, signifying a stabilization of the flow as it moves away from the wall. Significant variations in temperature fluctuations are observed across different Prandtl numbers. Lower Prandtl values exhibit higher fluctuations, particularly at higher Y^+ values, in contrast to higher Prandtl values. This variability can be attributed to differences in the heat transfer mechanisms associated with each Prandtl value. Near the wall (Y^+), where viscous effects dominate, the RMS of temperature fluctuations behaves differently for various Prandtl numbers. Higher Prandtl numbers result in smoother temperature profiles near the wall due to increased thermal diffusivity, while lower Prandtl numbers display more abrupt changes in temperature fluctuations near the wall. Overall, these findings underscore the significance of the Prandtl number in modulating turbulent flow characteristics and heat transfer in a heated pipe.

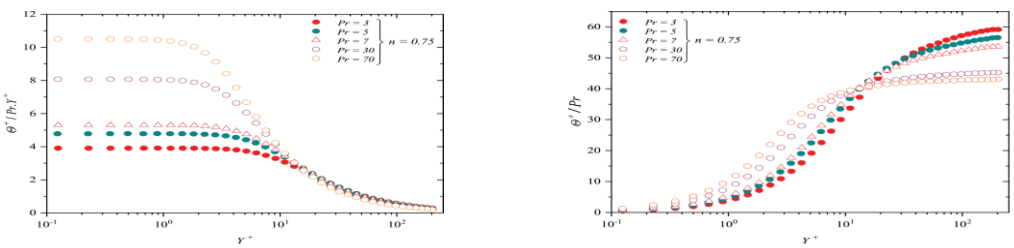

Figure 3: RMS of temperature fluctuation (Re = 5500).

4. Conclusions

The present study has been reported on the LES with an extended Smagorinsky to investigate numerically the fully developed turbulent forced convection heat transfer of thermally independent Ostwald de Waele fluid through a heated cylindrical pipe. The major conclusions of this research will be summarized:

The results obtained through Large Eddy Simulation (LES) have demonstrated the significance of Prandtl numbers in heat transfer processes within fluid flows. This study highlights a recurring inverse relationship for lower Prandtl numbers, indicating the dominance of convective heat transport. As the Prandtl number increases, a clear trend emerges, signifying the growing importance of thermal diffusion relative to

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convective processes. For higher Prandtl numbers, thermal diffusion becomes more dominant compared to convective heat transfer. The increasing RMS of temperature fluctuation with decrease in distance from the wall in wall units might be less pronounced due to the higher Prandtl number, suggesting a transition in heat transfer mechanisms.

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