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Mohamed Abdi, Abdelkader Noureddine, Meryem Ould-Rouiss. LES of Turbulent Forced Convection of a Non-Newtonian Fluid in a Stationary Pipe: The Turbulence Statistics. 1 ère Conférences Sur Les Energies Renouvelables & Les Matériaux Avancés ERMA'19, Dec 2019, Relizane, Algeria. hal-04075320

HAL Id: hal-04075320

<https://hal.science/hal-04075320v1>

Submitted on 20 Apr 2023

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LES of Turbulent Forced Convection of a Non-Newtonian Fluid in a Stationary Pipe: The Turbulence Statistics

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Abstract. The overall aims of the present investigation are to provide a detailed knowledge on the thermal turbulence statistics especially at the wall vicinity and to describe the thermal and rheological behaviour of the Non-Newtonian fluid, that in order to characterise the main features of the thermal turbulence and shed further light on the transfer mechanism of the turbulent energy. In addition to ascertain the accuracy and reliability of the present LES laboratory code by comparing the predicted findings with those available in the literature. Towards these purposes, a fully developed of the turbulent forced convection heat transfer of a thermally independent shear thinning ($n=0.75$) and Newtonian fluids in a heated pipe, has been carried out numerically by means of a Large eddy simulation (LES) with extended Smagorinsky model at simulation Reynolds and Prandtl numbers of 4000 and 1 respectively. The main findings suggest that the temperature fluctuations generation and the turbulent energy transport mechanism between the flow layers of the shear thinning fluid are pronounced compared to that of Newtonian fluid, the skewness and the flatness of the temperature fluctuations are almost independent of fluid flow index. Moreover, the present LES laboratory code can be considered as a powerful tool to re-solve and predict the thermal turbulence statistics of such issue.

1 Introduction

The turbulent forced convection of Non-Newtonian fluids in an axially heated pipe is of great practical interest because of the various industrial applications of these fluids, such as in the petroleum, pharmaceutical and polymer processing industries, transportation and processing, paper making of food and polymer solutions.

A literature survey reveals that the fully developed turbulent flow of the Non-Newtonian fluids in a isothermal straight pipe has been reviewed thoroughly in the past, experimentally by [1] [2] [3] [4] [5] and numerically by [6] [7] [8] [9] [10] [11] [12] [13] [14] [15].

It is clear from this literature review that the foregoing studies on turbulent flow of the Non-Newtonian fluids in pipe have largely restricted to the focus on the hemodynamic field. To date, there is any performed study focused on the thermal characteristics of this kind of fluids. In this study, LES with an extended Smagorinsky model has been applied to investigate numerically a fully developed turbulent forced convection of a thermally independent shear thinning ($n=0.75$) and Newtonian fluids in a heated pipe at a simulation Reynolds and Prandtl numbers of 4000 and 1 respectively, with an adequate grid resolution of 65^3 grid points in r , θ and z direction respectively and a domain length $20R$. The primary aim of this paper was to ascertain the accuracy and reliability of the LES laboratory code predicted results, in addition to know to what extent the LES with the extended Smagorinsky model be able to predict and resolve the thermal turbulence statistics such as the root mean square (RMS) of the temperature fluctuations, turbulent heat flux and higher order statistics.

2 Governing equations and numerical procedure

2.1 Governing equations

The present study is concerned mainly with the fully developed of the turbulent forced convection heat transfer of a shear thinning ($n=0.75$) and Newtonian fluids in a pipe subjected to a constant uniform heat flux q_w imposed at the pipe wall, by means of a Large eddy simulation (LES) with extended Smagorinsky model at simulation Reynolds and Prandtl numbers of 4000 and 1 respectively (Fig.1).

The dimensionless temperature is defined as:

$$\Theta = \left(\langle T_w(z) \rangle - T(\theta, r, z, t) \right) / T_{ref} \quad (1)$$

T_{ref} presents the reference temperature and is defined as $T_{ref} = q_w / \rho C_p U_{CL}$, where T_w is the pipe wall temperature. The filtered equations can be expressed as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial \bar{u}_j}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_i} = - \frac{d\bar{P}}{dx_j} + \frac{1}{Re_s} \frac{\partial}{\partial x_i} \left[\overline{\dot{\gamma}^{n-1}} \left(\frac{\partial \bar{u}_j}{\partial x_i} + \frac{\partial \bar{u}_i}{\partial x_j} \right) \right] + \frac{\partial \bar{\tau}_{ij}}{\partial x_i} \quad (3)$$

$$\frac{\partial \bar{\Theta}}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_j \bar{\Theta} - T_{\Theta j}) - \bar{u}_z \frac{d}{dz} \langle T_w \rangle = \frac{1}{Re_s Pr_s} \frac{\partial^2 \bar{\Theta}}{\partial x_k \partial x_k} \quad (4)$$

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$\langle \rangle$ presents the average in time and periodic directions, where Re_s, Pr_s are respectively the Reynolds number and Prandtl number of the simulation and are defined respectively by: $Re_s = \rho U_{cl} R / \mu$, $Pr_s = \mu / \alpha \rho R U_{cl}$.

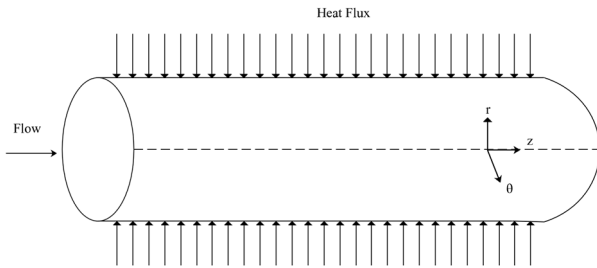


Figure 1 computational domain

2.2 Numerical procedure

The governing equations were discretized on a staggered mesh in cylindrical coordinates with a computational length in the axial direction $20R$. The numerical integration was performed by using a finite difference scheme, second-order accurate in space and in time. The time-advancement employs 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, respectively. The above mathematical model was implemented in a finite difference laboratory code.

The grid 65^3 grid points in axial, radial and circumferential directions respectively, was found to provide an accurate prediction of the turbulence statistics, in agreement with the available data of the literature, and to give a good compromise between the required CPU-time and accuracy. The various parameter settings for mesh and LES simulations are summarized in Tab.1.

Table 1. parameters of present LES simulations $Re_s=4000$

Parameters	$n=0.75$	$n=1$
Δz^+	69.89	49.75
$r \Delta \theta^+$	21.95	15.63
Δr_{min}^+	0.0506	0.0360
Δr_{max}^+	12.4	8.83
U_b / U_{cl}	0.5329	0.4943
U_c / U_{cl}	0.6863	0.6525
$U_\tau / U_{cl} \cdot 10^1$	0.3393	0.3593
$\dot{\gamma}_{d,w}$	6.6818	5.359
$\eta_{d,w}$	0.6334	1
Re_{cr}	2250	2099.2
Re_{MR}	4873.2	4448.9
Re_g	7135.8	4448.9

Re_τ	227.16	161.71
Y_1^+	0.0239	0.0170
$f \cdot 10^3$	9.2099	10.331
Nu	17.376	17.584

3 Results and discussion

The aim of this section is to critically analyse and discuss the main predicted findings results such as the root mean square (RMS) of the temperature fluctuations, heat flux of the temperature fluctuations and higher order statistics of the turbulent forced convection heat transfer of a shear thinning fluid ($n=0.75$) and Newtonian fluid ($n=1$) in heated axially stationary pipe. To ascertain the accuracy and reliability of the LES laboratory code predicted results, in addition to describe the main features of the turbulence especially in the wall vicinity. For the validation purpose, the present LES predictions compared reasonably well with the DNS data of Redjem et.al [16] at Reynolds number of 5500, the Figure.2 compares the radial turbulent heat flux distributions of the Newtonian fluid, versus the distance from the wall in wall units Y^+ at a simulation's Reynolds number of 4000.

As seen in Fig.2, the predicted profiles are in an excellent agreement along the pipe radius with the DNS data, these predicted profiles almost coincide with them; the predicted profile is slightly underestimated in comparison with that of Redjem et.al [16] especially in buffer region, this little discrepancy between them may be due to the difference in the Reynolds number and the employed approach.

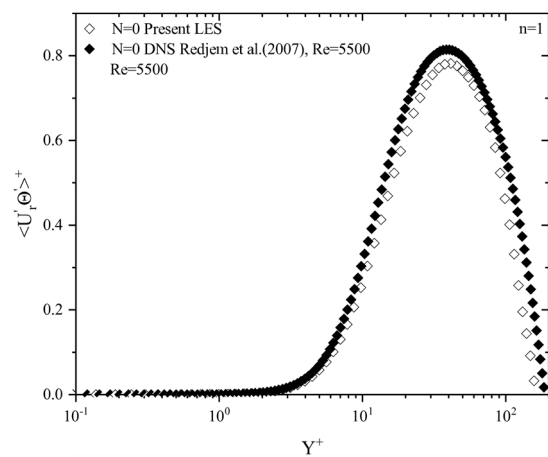


Figure 2 Validation

3.1. RMS and heat flux of the temperature fluctuations

The Fig.3 illustrates the root mean square (RMS) of the temperature fluctuation distributions of the shear thinning ($n=0.75$) and Newtonian ($n=1$) fluids against the distance from the wall in wall units Y^+ at $Re_s=4000$. Overall, the RMS profiles are enhanced gradually further

away from the wall with the distance from the wall Y^+ , these profiles drop rapidly after reaching the peak location, which indicates that the fluctuations of the radial velocity generated in the vicinity of the wall and propagated toward the remaining regions, these fluctuations fall off to zero value in the core region, this means that these fluctuations vanish in this region.

It can be seen from Fig.3 that the predicted profiles for the both fluids have the same tendency, where the profile of the shear thinning fluid coincides with that of Newtonian one near the wall region ($Y^+ < 1$). At around $Y^+ = 1$, these profiles differ considerably in the buffer and logarithmic regions with the distance from the pipe wall Y^+ . It can be said that the reduction in the fluid flow index (n) results in a pronounced enhancement in the RMS of the temperature fluctuation over the flow regions.

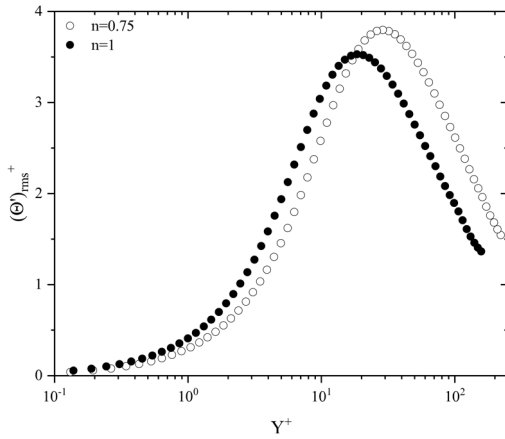


Figure 3 RMS of temperature fluctuations

The axial and radial heat flux profiles of the shear thinning ($n=0.75$) and Newtonian ($n=1$) fluids are presented respectively in Fig.4 and Fig.5, against the distance from the wall in wall unit Y^+ at $Re_s=4000$. It can be noted that the two heat flux components are identical and equal to the zero in the viscous sublayer $Y^+ < 1$, which indicates that the absence of the fluctuation in this region, where the molecular shear stress is the dominant force in this region. In the turn, the radial and axial heat flux profiles enhance gradually further away from the wall towards the central region before reaching the peak location. The heat flux components start to damping progressively in the logarithmic region, where the axial and radial velocity fluctuations begin to decrease gradually until fall off to zero value in the core region. It can be said that the axial velocity and temperature fluctuations generated at the vicinity of the wall exactly in the viscous sublayer and propagated to the logarithmic layer, these fluctuations begin to vanish in remaining region after reached their maximum values.

As shown in Fig.4 the axial heat flux profiles are almost identical for the both fluids, where they have the same tendency along the pipe radius with a little discrepancy between them especially in the logarithmic layer: the shear thinning fluid ($n=0.75$) profile lies above

the Newtonian one, due to the viscosity difference. In turn, the radial heat flux Fig.5 the profile of the shear thinning and Newtonian fluids are consistent with each other along the pipe radius

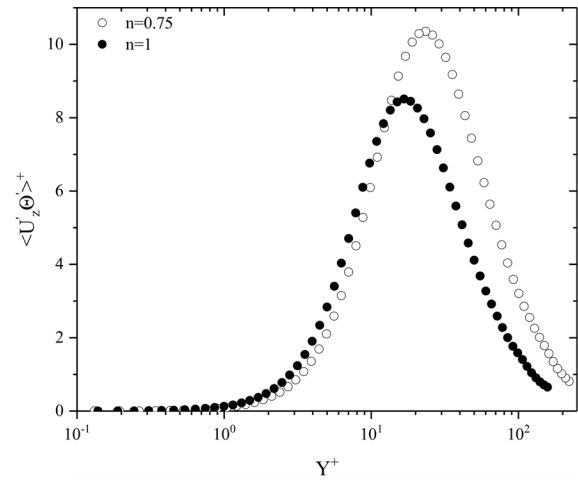


Figure 4 Axial turbulent heat flux

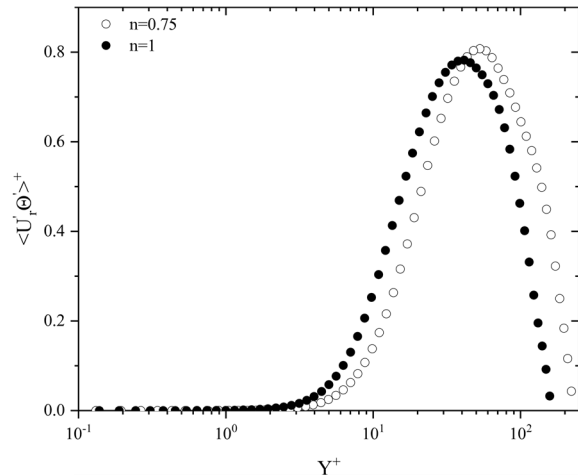


Figure 5 Radial turbulent heat flux

3.2 Higher order statistics

The skewness and flatness of temperature fluctuations are illustrated in the Fig.6 and Fig.7 respectively. It can be seen from Fig.6 that the skewness of the shear thinning and Newtonian fluids have the same trend, where these profiles are consistent with each other along the pipe radius. The skewness profiles decrease rapidly in the vicinity of the wall towards the core region with distance from the wall (Y^+), beyond $Y^+ = 50$ these profiles seem to be nearly constant in the remaining regions, where these profiles tend to the 0 (Gaussian value) for the both fluids.

As for the flatness Profile (Fig.7), the flatness of the temperature fluctuations has the same trend of the skewness one, the profile of the shear thinning fluid is almost identical with that of the Newtonian fluid along the pipe radius, where these profiles drop rapidly in the viscous sublayer and they trend to the 4 (Gaussian value).

It can be said that the profiles of the skewness and the flatness are almost independent of fluid flow index (n).

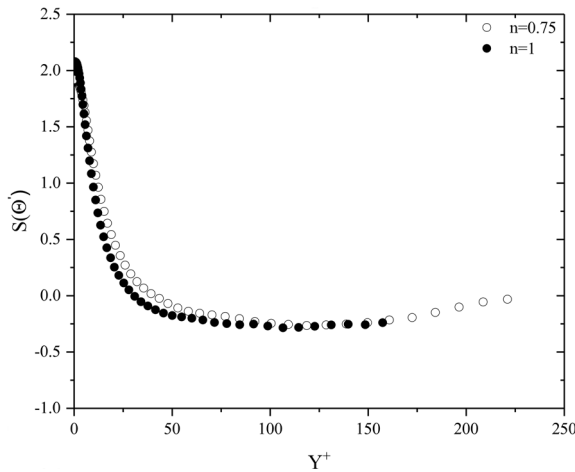


Figure 6 Skewness of temperature fluctuations

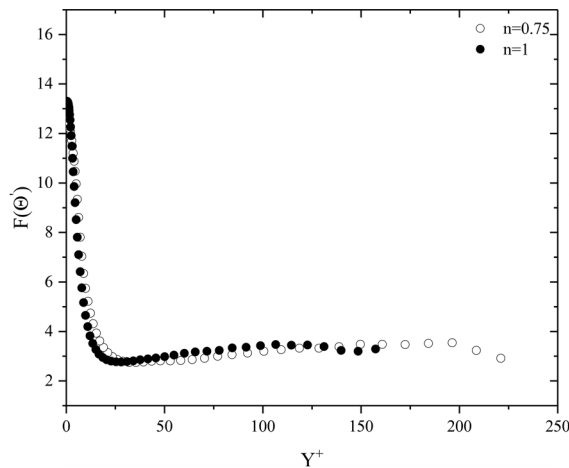


Figure 7 Flatness of temperature fluctuations

3.3 Visualisations

The Fig.8 visualises the contour lines of a snapshot of the temperature fluctuations over a cross section in r - θ plane of the shear thinning fluid ($n=0.75$), where the solid lines refer to the positive values whereas the dash ones refer to the negative values. It can be seen from Fig.8 that the smallest turbulence scales of the temperature fluctuations are mainly placed in the vicinity of the wall, these scales seem to be enlarged further away from the wall towards the core region. In addition to the highest values of temperature fluctuations are also located near the pipe wall and decreases gradually toward the pipe centre, which indicates that temperature fluctuations generated in the viscous sublayer and propagated to the remaining layers with the aid of the energy transfer mechanism.

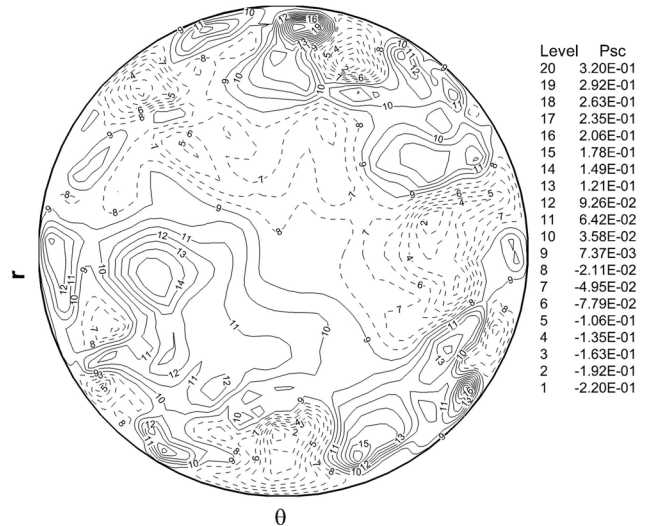


Figure 8 Contour lines of the temperature fluctuations

4 Conclusion

The present paper reports on numerical computations of a fully developed turbulent forced convection in a uniform heated axially stationary pipe flow of a thermally independent power law (shear thinning $n=0.75$) and Newtonian fluids, by applying a large eddy simulation with an extended Smagorinsky model at simulation Reynolds and Prandtl numbers of 4000 and 1 respectively. In order to ascertain the accuracy and reliability of the present LES laboratory code, shed further light on the thermal and rheological behaviour of the Non-Newtonian fluid and describe the main features of the turbulence especially at the wall vicinity. The major conclusions of this research will be summarized:

- It can be considered that the present LES laboratory code as a powerful tool, where the present LES with the extended Smagorinsky model shows a great promise in resolving and predicting the thermal turbulence statistics of the turbulent forced convection heat transfer of the shear thinning fluids.
- The root mean square (RMS) and the turbulent heat flux of the temperature fluctuations of the shear thinning are somewhat higher than that of the Newtonian fluid along the pipe radius, which indicates that the generation of the temperature fluctuations and the transport mechanism of the turbulent energy between the flow layers of the shear thinning fluid are pronounced compared to the corresponding of the Newtonian fluid.
- The skewness and the flatness of the temperature fluctuations are almost independent of fluid flow index.

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