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Numerical analysis of Heat Transfer from a Spheroidal Shaped Body to a Power Law Fluid at Finite Reynolds Number

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Abstract

In this paper, flow of a power law fluid past a stationary spheroid is numerically investigated. The ranges of parameters investigated in this study are: $10 \leq Re \leq 100$; $1 \leq Pr \leq 100$; $0.4 \leq n \leq 1.6$; and $0.5 \leq E \leq 2$. The variation of local Nusselt number on the surface of both oblate and prolate spheroids was obtained. The effect of modified Reynolds number, modified Prandtl number, axis ratio, power law index on average Nusselt number were also obtained. A correlation was developed using least squares regression analysis. The Nusselt numbers predicted using this correlation were found to be in good agreement with the data of earlier investigators.

Keywords: Power law; oblate spheroid; prolate spheroid; Reynolds number; Nusselt number; Prandtl number;

1. Introduction

A vast majority of operations occur in the process industry involving flow of fluid past solids. Some examples are packed beds, fluidized beds, pneumatic conveyors, filters, thickeners, cyclone separators, hydrocyclones, centrifuges etc. A comprehensive understanding of the transport processes is essential in the design, operation and control of processes carried out in such equipment. Without having a thorough knowledge of these transport processes involving a single particle, understanding the behavior of the multiparticle systems is not feasible. Although many investigations were conducted in this direction, the fluid employed was mainly Newtonian and the solids were regular shaped. Since most of the industrial fluids are non-Newtonian, these studies are of little use. To elucidate the

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complex mechanism of heat or mass transfer between a fluid and a packed or a fluidized bed, it is essential to understand the same between a single solid body and the moving fluid. Ample literature is available detailing flow patterns, drag calculations and heat and mass transfer coefficients. These studies clearly illustrate the effect of various parameters such as the body shape, the kinematic conditions of the far field and the flow and heat transfer conditions on the suspended body on bulk properties like the drag coefficient and heat transfer coefficients. The flow and heat transfer of Newtonian fluids past a solid object well understood, however, similar situation involving non-Newtonian fluids is not so extensively investigated [1-3].

Majority of the non-Newtonian fluids can be successfully represented by power law model [1,2]. Therefore, it is quite necessary to have a better understanding of the existing transfer process between a single immersed particle in a flowing non-Newtonian fluid. Once the single particle analysis is done, the multiparticle behavior can be understood by applying the cell model concept as was done for the Newtonian fluids and some non Newtonian fluids [3].

Most of the earlier investigators [4,5] simplified the mathematical analysis using the boundary layer approximations over regular and irregular shaped bodies like spheres and cylinders to obtain the local Nusselt numbers as functions of the Prandtl and Reynolds numbers. Therefore, the range of applicability of these results was limited. On the other hand Nakayama [6] adapted integral analysis method to study heat transfer over axisymmetric bodies immersed in power law fluids. Kawase and Ulbrect [7] solved the full set of governing equations for the convective heat and mass transfer in the creeping flow regime. A comprehensive review of these results and the proposed correlations was provided by Chhabra [2] and Michaelidis [8]. Dhole et al [9,10] investigated the heat and fluid flow over spherical particles with power law fluids. Very few experimental studies were carried out on the flow of a power law fluid past spherical bodies. Kumar et al [11] reported the average Sherwood numbers for benzoic acid dissolution in aqueous CMC solutions. Ogawa et al [12] conducted experimental work on the forced convective mass transfer of a viscoelastic fluid over a sphere and cylinder for Reynolds number ranging from 1 to 200. Hyde and Donalli [13] studied the dissolution of benzoic acid in power law fluids.

Many of the studies reported above were on regular shaped bodies like spheres and cylinders. Very little is known about the flow and heat transfer over spheroidal shaped bodies. Masliyah and Epstein [14,15] carried out investigations over oblate and prolate spheroidal bodies for Reynolds number upto 100. They also examined the heat and mass transfer problem in oblate and prolate spheroids in air. The correlations proposed for predicting Nusselt number were very difficult to use because the characteristic length they defined was very tough to evaluate. Tripathi et al [16] studied the power law fluid flow past an oblate and a prolate spheroidal body and did large scale numerical work on calculating the drag coefficients. Alassar [17] studied the heat transfer characteristics of air over an oblate spheroid and solved the exact problem analytically using the oblate spheroidal coordinates. Pailin and Koichi [18] examined the heat and mass transfer coefficients over oblate and prolate spheroids for Newtonian fluids and observed enhanced Nusselt numbers over spheres for oblate spheroids and a reduced Nusselt number for prolate spheroids. Several investigations [19-21] on mass transfer from spheroidal bodies to Newtonian fluids were also reported. Al-Taha [22] proposed a correlation for Nusselt and Sherwood numbers for spheroids in the range $0.1<E<5$ and $1<Re<100$. Tripathi and Chhabra [23] studied the influence of dilatancy on the drag coefficient of oblate and prolate spheroids and reported that at small Reynolds numbers, $Re < 1$, the power law index 'n' played a major role whereas at large Reynolds numbers, its influence was insignificant. A brief summary of these studies is presented in Table.1.

TABLE 1: SUMMARY OF SOME IMPORTANT STUDIES ON SPHEROIDAL PARTICLES

Author(s)	**Geometry**	**Fluid**	**Range**	**Investigation**
Dhole et al[10]	Spheres	Power Law	5 < Re < 200, 1 < Pr < 400 0.5 < n < 2	Forced convective heat transfer
Masliyah and Epstein [15]	Oblate and Prolate	Air	Re < 100	Heat and mass transfer
Tripathi et al [16]	Oblate and Prolate	Power law fluid	0.4 < n < 1, 0.01 < Re < 100, 0.2 < E < 5	Fluid flow
Alassar [17]	Oblate	Air	10 < Re < 500, 0.5 < E < 0.9	Heat transfer
Pailin and Koichi [18]	Oblate and Prolate	Newtonian Fluid	0.5 < Sc < 2, 1 < Re < 200	Heat and mass transfer
Lochel and Calderbank [19]	Oblate and Prolate	Newtonian Fluid	Re >> 1	Mass transfer
Skelland and Cornish [20]	Oblate	Air	130 < Re < 6000, 1 < E < 3	Mass transfer
Beg [21]	Oblate	Newtonian Fluid	1 < Re < 400	Heat transfer
Al Taha [22]	Oblate and Prolate	Newtonian Fluid	1 < Re < 100, 0.2 < E <5	Heat and mass transfer
Tripathi and Chhabra [23]	Oblate and Prolate	Power law fluid	1 < n < 1.8, 0.2 < E < 5 0.001 < Re < 100	Fluid flow
Dhole et al[10]	Spheres	Power Law	5 < Re < 200, 1 < Pr < 400 0.5 < n < 2	Forced convective heat transfer
Masliyah and Epstein [15]	Oblate and Prolate	Air	Re < 100	Heat and mass transfer
Tripathi et al [16]	Oblate and Prolate	Power law fluid	0.4 < n < 1, 0.01 < Re < 100, 0.2 < E < 5	Fluid flow
Alassar [17]	Oblate	Air	10 < Re < 500, 0.5 < E < 0.9	Heat transfer
Pailin and Koichi [18]	Oblate and Prolate	Newtonian Fluid	0.5 < Sc < 2, 1 < Re < 200	Heat and mass transfer
Lochel and Calderbank [19]	Oblate and Prolate	Newtonian Fluid	Re >> 1	Mass transfer
Skelland and Cornish [20]	Oblate	Air	130 < Re < 6000, 1 < E < 3	Mass transfer
Beg [21]	Oblate	Newtonian Fluid	1 < Re < 400	Heat transfer
Al Taha [22]	Oblate and Prolate	Newtonian Fluid	1 < Re < 100, 0.2 < E <5	Heat and mass transfer
Tripathi and Chhabra [23]	Oblate and Prolate	Power law fluid	1 < n < 1.8, 0.2 < E < 5 0.001 < Re < 100	Fluid flow

Many fluids encountered in the process industry are highly viscous and the flow conditions are often laminar. The existing vast literature on the Newtonian fluids has very little applicability in these practical cases. Most of the studies available in the literature with non-Newtonian fluids were focused on calculating the drag coefficients over regular and irregular shaped bodies. The limited heat transfer studies with non Newtonian fluids are restricted to only creeping flow conditions [3]. To the best of the author's knowledge, there is no work in the literature on heat transfer over irregular shaped bodies immersed in non-Newtonian fluids. It was well understood that the Carreau-Yasuda model has adequate flexibility to fit a variety of polymeric fluids. The power law model, a variant of the Carreau-Yasuda model at high shear regions, is a much simpler model and has been used successfully to model many non-Newtonian fluids. The power law model often provides a rough prediction for viscosity of non-Newtonian fluid [1]. Therefore, flow of a power law fluid over a spheroidal shaped body has been chosen for the present study. The characteristic length in present study is taken as the length of the major axis which is clearly defined unlike the earlier correlations. By choosing appropriate values for E, different bodies from needle shaped to disc shaped can be modeled. The heat transfer problem is analyzed and a simple correlation is developed that can predict the Nusselt number over a spheroid given the Nusselt number over a sphere for the same Reynolds and Prandtl numbers. It is shown that the proposed correlation predicts the Nusselt number even for the Newtonian fluids. This correlation is very much useful to the practicing engineer for his design calculations.

2. Problem Statement and Mathematical Formulation

The problem under consideration is shown in Fig 1. The maximum Reynolds number is limited so that the flow is two dimensional. A power-law fluid is streaming past a stationary spheroidal shaped body in an infinite expanse of fluid at finite Reynolds number. The objectis of length '2a' in the direction normal to flow and '2b' in the direction parallel to flow called the major and minor axes respectively. The aspect ratio defined as b/a is represented as E. Hence for an oblate spheroid $E < 1$ and for a prolate spheroid $E > 1$ and for a sphere $E = 1$. The power law fluid of constant properties has a velocity U_∞ and temperature T_∞ in the far field. The object is maintained at a constant temperature of T_w which is greater than T_∞. The heat transfer occurs by forced convection and the variation of the physical properties with temperature is neglected. The mathematical model essentially consists of the continuity, momentum and energy equations [24]. These equations are converted into dimensionless form by the scales 2a, U_∞, $m(U_\infty/2a)^{n-1}$, $(T-T_\infty)/(T_w-T_\infty)$ for length, velocity, viscosity and temperature respectively. The dimensionless groups that resulted are the modified Reynolds number and the modified Prandtl number. Final equations expressed in dimensionless form are given below.

Continuity equation: $\nabla.U = 0$ …(1)

Momentum equation: $\frac{DU}{Dt} = -\nabla p + \frac{1}{\mathrm{Re}}\nabla.\tau_{ij}$ …(2)

Energy equation: $\frac{DT}{Dt} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\nabla^2 T$ …(3)

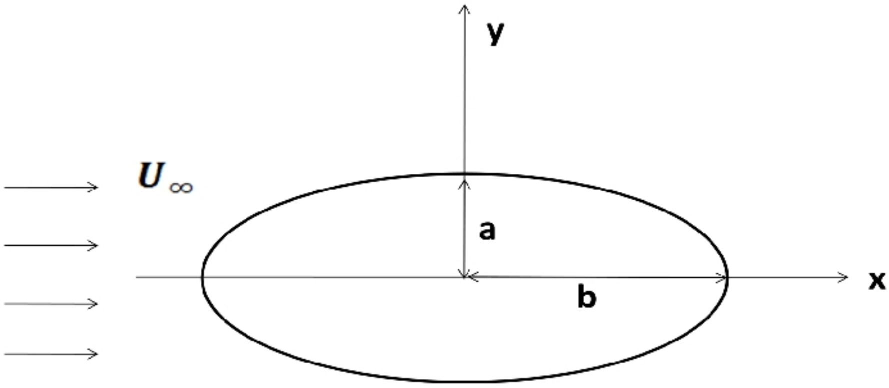
The rheology of the power law fluid is given by $\tau_{ij} = 2\eta\varepsilon_{ij}$ …(4)

where ε_{ij} is the strain rate tensor given in terms of the velocity vector as

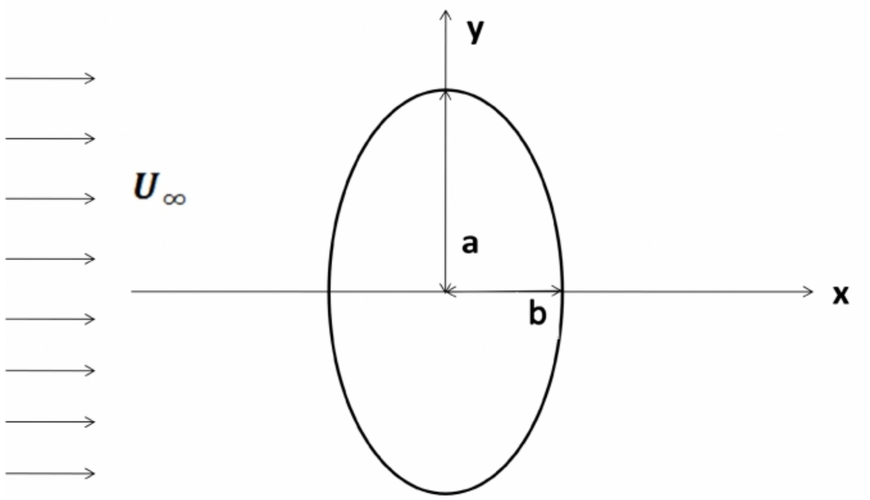
$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \qquad \ldots(5)$$

and the viscosity is given by $\eta = \left(\frac{I_2}{2}\right)^{(n-1)/2}$ …(6)

where ‘n’ is the exponent in the power law and I_2 is the second invariant of the rate of strain tensor. The usual boundary conditions are the no slip conditions on the body and the free stream conditions far away from the body.



(a) Prolate spheroid



(b) Oblate spheroid

Figure 1: Schematic representation of the problem

In the present case the characteristic length 'L' has been taken as the length equal to 2a. The dimensionless local Nusselt number is given by the relation, $Nu_\theta = -\partial T / \partial \hat{n}$ where $\hat{n}$ is the unit outward normal to the spheroid surface. Once the temperature distribution over the surface of the body is known the average Nusselt number is obtained by quadrature as

$$Nu = \frac{1}{2\pi} \int_0^\pi Nu_\theta \sin\theta d\theta \qquad \ldots(7)$$

3. Numerical Methodology and Validation

The governing partial differential equations (1) to (3) at steady state are solved numerically by the well known staggered grid method [25]. The convective terms are discretized using the QUICK scheme. Before analyzing the results of the present work it is important to make sure the correctness of the numerical scheme. Therefore, the validation is done by comparing the results for a sphere in a power law fluid with that of Dhole et al [10], Alassars [17] and Al-Taha [22] for a spheroidal body in a Newtonian fluid. These results are shown in Table 2. It can be seen that the results predicted with the present solution methodology are very close to the published literature values, thus giving confidence that the present numerical scheme is able to predict the velocity and temperature profiles with good accuracy.

TABLE 2. VALIDATION OF THE PRESENT WORK WITH THE LITERATURE

Re	Pr	n	E	Dhole et al [10]	Alassar [17]	Al-Taha [22]	Present work
10	0.71	1	0.75		3.56	3.74	3.56
20	0.71	1	0.75		4.31	4.47	4.3
40	0.71	1	0.75		5.35	5.52	5.35
80	0.71	1	0.75		6.80	6.99	6.79
100	0.71	1	0.75		7.46	7.58	7.45
10	5	0.6	1	5.83			5.84
10	5	2	1	4.77			4.74
10	200	2	1	13			13
100	5	0.6	1	14.65			14.70
100	20	2	1	15.76			15.80

4. Results and Discussion

The values of different variables considered in the present study are compiled in Table 3. This range covers the shear thickening (n > 1) and shear thinning (n < 1), from oblate to prolate spheroid cases and well beyond the creeping flow velocities where most of the earlier analytical works have been carried out. The Reynolds number upper range is limited by the wake formation as observed by Tripathi et al [16, 23] for the oblate spheroid. Hence beyond this value asymmetry in the flow may occur which could lead to three dimensional effects. Since the present study is based on the assumption of laminar conditions, Reynolds number values below 100 only are considered.

TABLE 3. RANGE OF VARIABLES COVERED IN THE PRESENT STUDY

Variable	Values
Re	10, 40, 80, 100
Pr	1, 5, 20, 100
n	0.4, 0.8, 1, 1.2, 1.6
E	0.5, 0.75, 1, 2

4.1. Variation of local Nusselt number over the spheroid surface

Figures 2(a) and 2(b) show the variation of local Nusselt number variation along the surface of the spheroid. From the plots of the figure it is conspicuous that the oblate spheroid exhibited a non-monotonic variation whereas the prolate spheroid showed a monotonic variation of the local Nusselt number. Similar behavior was also reported by Pailin and Koichi [18] for the case of a Newtonian fluid over a spheroid. The local Nusselt number exhibited a large value at the front stagnation point and then decreased till the point of separation and then again increased towards the rear stagnation point. Masliyah and Epstein [15] reported similar findings when analyzing the flow and heat transfer from air to a spheroid. Tripathi et al [16,23] also reported flow separation to occur for oblate spheroids but not for the case of the prolate. There was a perfect fore-aft symmetry for the prolate case for a wide range of flow behavior index and Reynolds numbers but the fore-aft symmetry is present in the oblate case at very small Reynolds numbers only. This asymmetry leads to wake formation and augments the convective currents resulting in enhanced heat transfer coefficients. Hence average Nusselt numbers for oblate spheroids are larger than a sphere. The sphere in turn has larger average Nusselt numbers than the prolate spheroids.

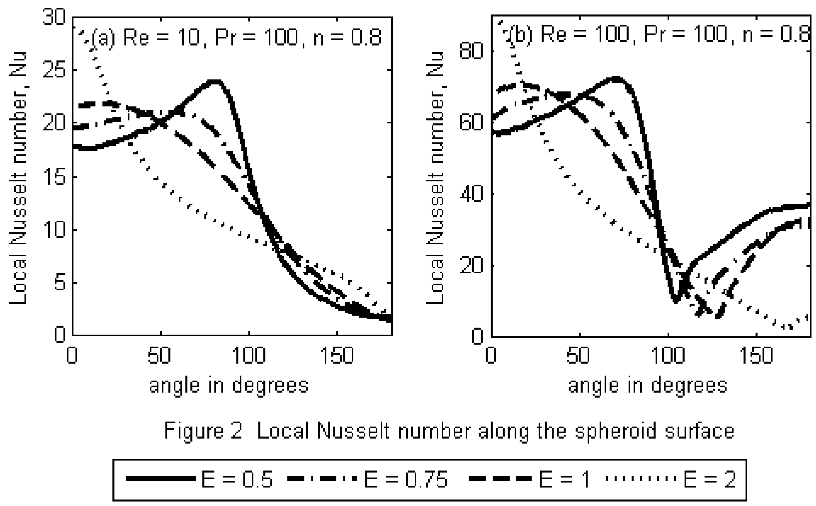


Figure 2 Local Nusselt number along the spheroid surface

4.2. Effect of power law index

Figures 3 and 4 show the effect of flow behavior index on the average Nusselt number for Re = 10 and 100 respectively. A close inspection of the plots of these figures reveals that the shear thinning fluid has resulted in larger average Nusselt numbers as a sequential effect of reduction in viscosity. This reduction in viscosity causes larger convective currents yielding enhanced heat transfer. The influence of power law index is extremely significant at higher Pr values for a given Re value. At low Prandtl numbers the convective currents are weak and hence the Nusselt numbers are small. At large Prandtl numbers strong convective currents yielded increased Nusselt numbers. These effects are more significant in the oblate case compared to the prolate case at all Reynolds numbers which is evident from Figs. 5 and 6. This is because the local Nusselt number for an oblate spheroid is always higher compared to a prolate spheroid as evident from Fig.2. The area average Nusselt number will thus be higher for oblate spheroid.

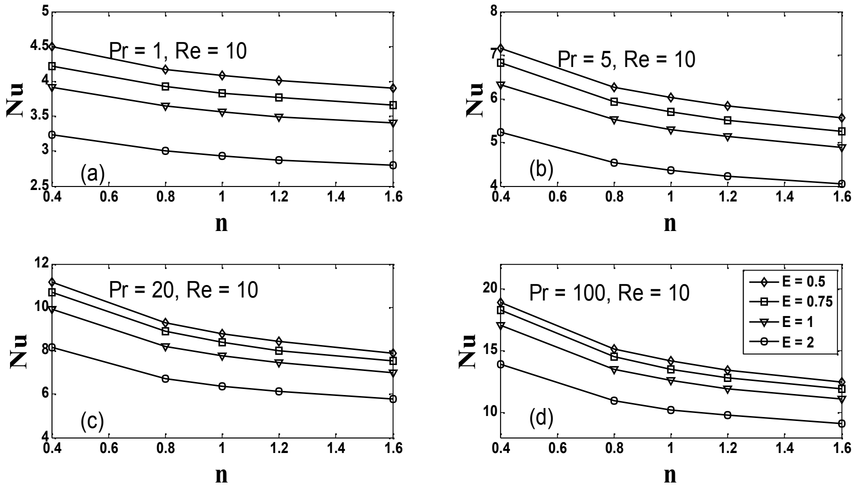


Figure 3: Average Nusselt number vs. flow behavior index for Re = 10

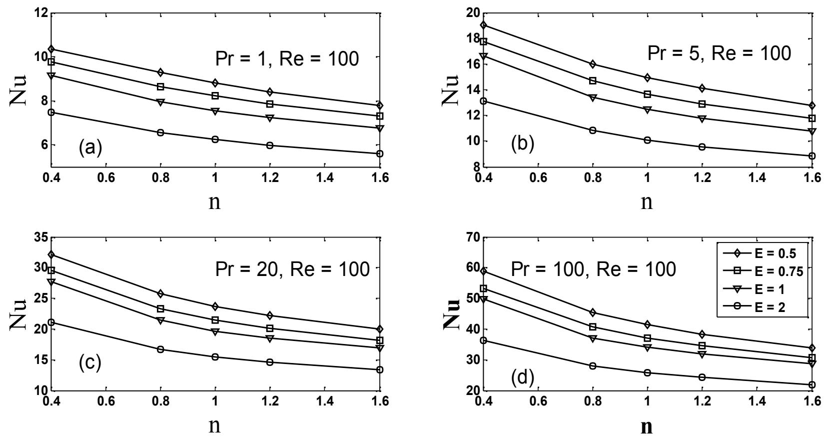


Figure 4: Average Nusselt number vs. flow behavior index for Re = 100

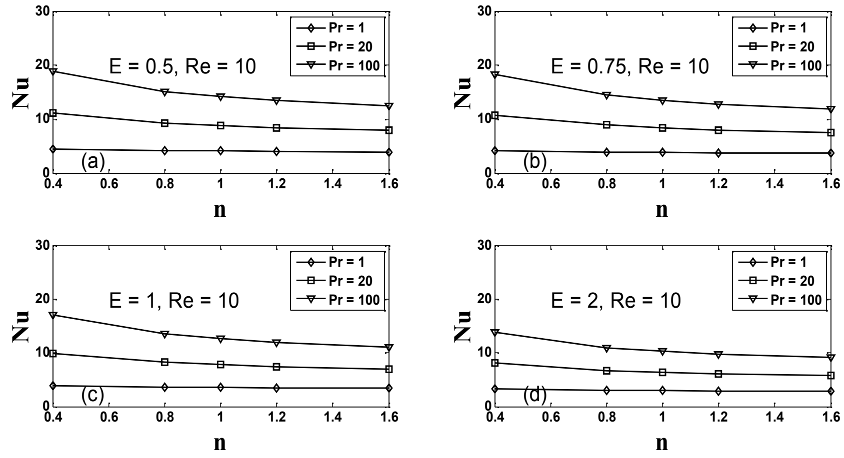


Figure 5: Average Nusselt number vs. flow behavior index for Re = 10

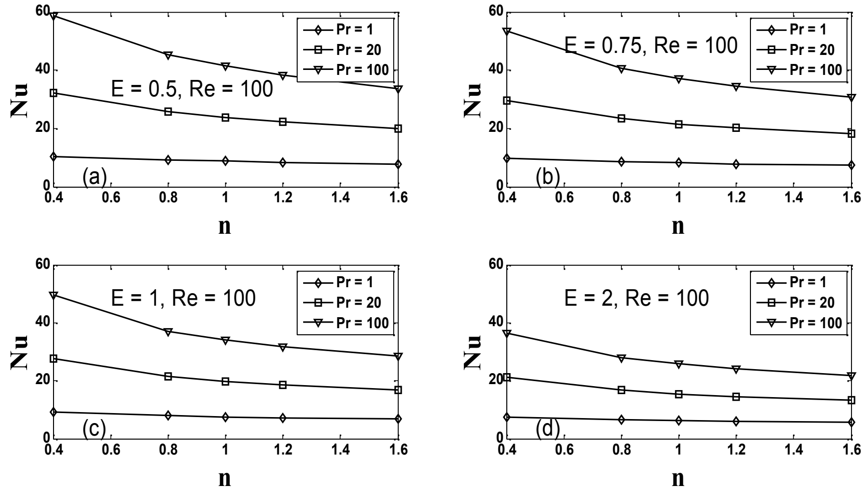


Figure 6: Average Nusselt number vs. flow behavior index for Re = 100

4.3. Effect of axis ratio

The effect of the shape of the object on average Nusselt number is shown in Fig. 7. A close examination of Figs. 7a and 7b, revealed that shear thinning along with higher Prandtl number leads to a larger Nusselt number at any given Reynolds number. It is evident from Fig. 7b that the effect of shear thinning at larger Reynolds and Prandtl numbers leads to higher Nusselt number. The reduction in thermal boundary layer accounts for this. At low Reynolds and Prandtl numbers the non-Newtonian behavior is almost unimportant. But at higher Prandtl numbers the differences begin to appear and become significant at higher Reynolds and Prandtl numbers. The influence of increase in Reynolds number has a strong effect on oblate spheroids due to the flow separation that occur at about a Reynolds number of 30 [14].

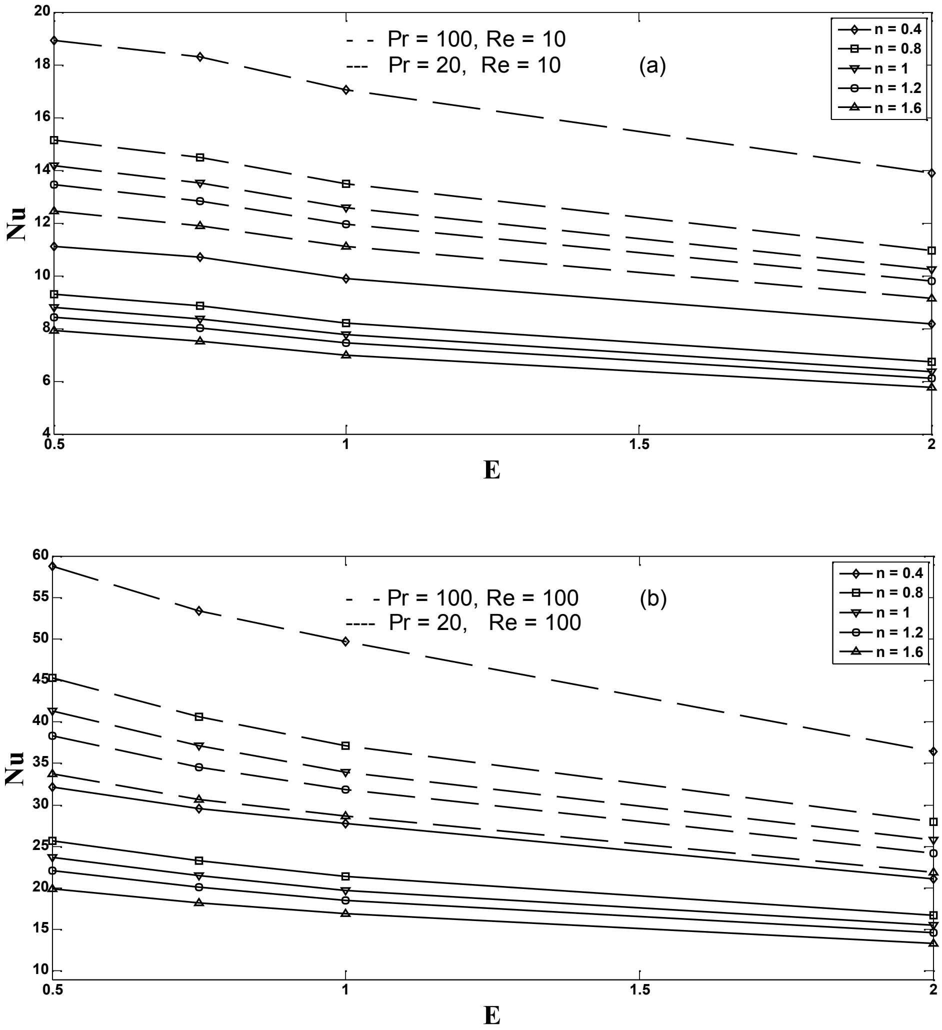
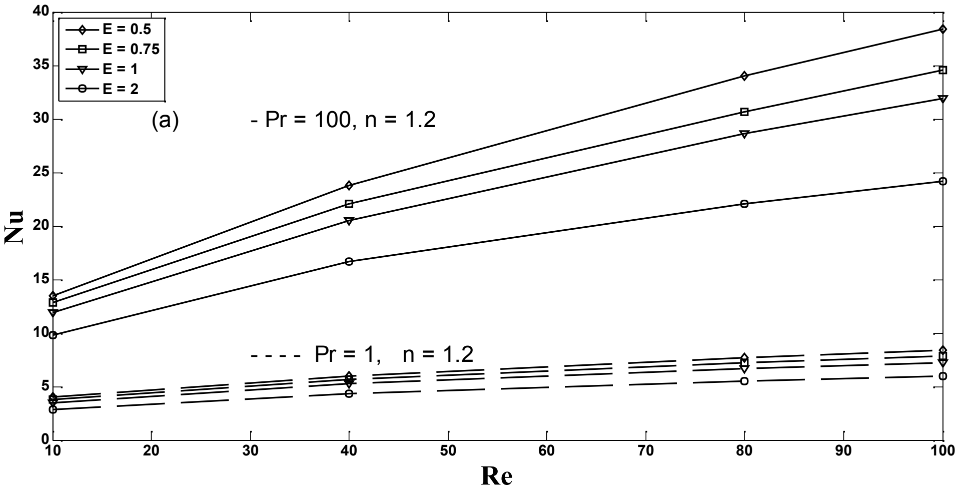


Figure 7: Effect of axis ratio on average Nusselt number for (a) Re = 10 and (b) Re = 100

4.4. Effect of Reynolds number

The effect of Reynolds number on the Nusselt number is presented in Figs. 8a and 8b. An inspection of the plots in these figures reveal that the non-Newtonian characteristics reach significance at higher Prandtl and Reynolds numbers. Also oblate spheroids have a different characteristic behavior at Reynolds numbers starting from 30 and at larger Prandtl numbers due to wake formation [14, 15]. Once the wake formation commences, enhanced heat transfer coefficients could be attained at large Prandtl numbers. At lower Prandtl numbers irrespective of the power law index, the shape of the body as represented by E has only a marginal influence on Nusselt number.



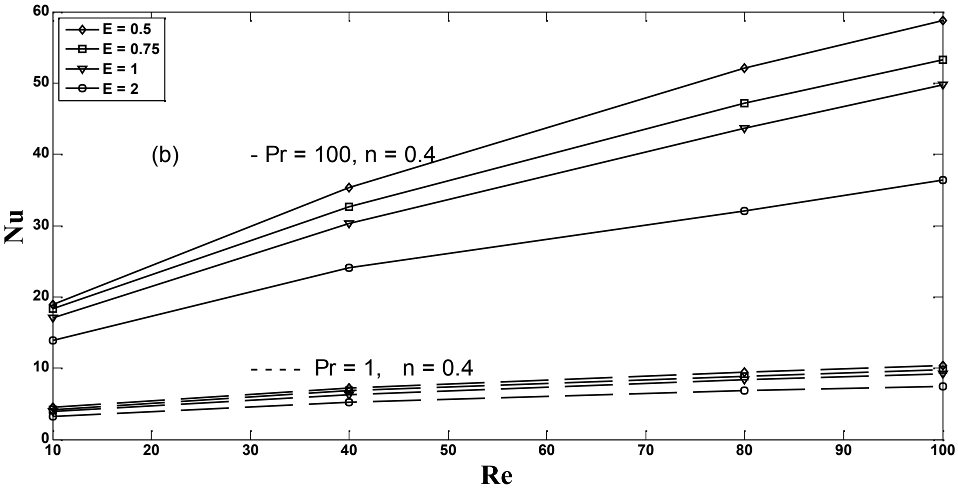


Figure 8: Effect of Re on average Nusselt number for

(a) n = 1.2 and (b) n = 0.4

5. Correlation

Having examined the effect of various parameters on the average Nusselt number it would be useful for the practicing engineer if a correlation exists by which he could compute the average Nusselt number over a spheroid. After testing various functional forms, a simple correlation has been developed which is given by

$$\frac{Nu_{E\neq 1}}{Nu_{E=1}} = 1.2917\exp(-0.256E) \qquad \ldots(8)$$

where $Nu_{E=1}$ is the corresponding Nusselt number for a sphere in the non-Newtonian fluid and is to be evaluated at the same Reynolds and Prandtl numbers as those for the spheroid. This correlation was developed using the Genetic Algorithms Toolbox in MATLAB so that a true global optima was found which minimized the sum of squares of the deviations. The correlating equation for the case of a sphere, $Nu_{E=1}$, has been developed by Dhole et al [10] in their work which is used directly in the present work. Equation 8 accurately predicts that the oblate spheroids have larger and prolate spheroids have smaller Nusselt numbers compared to spheres at the same Reynolds and Prandtl numbers. The validity of equation (8) is also shown to be applicable for the case of spheroids in Newtonian fluids when compared with the works of Alassar [17] and Al-Taha [22]. These results are compiled in Table.4.

TABLE 4. VALIDATION OF THE PROPOSED CORRELATION FOR NEWTONIAN FLUIDS

Re	**E**	$\frac{Nu_{E\neq1}}{Nu_{E=1}}$ **Alassar [17]**	$\frac{Nu_{E\neq1}}{Nu_{E=1}}$ **Al Taha[22]**	$\frac{Nu_{E\neq1}}{Nu_{E=1}} = 1.2917\exp(-0.256E)$ **Present work**
10	0.6	1.11	1.02	1.11
40	0.6	1.10	1.04	1.11
100	0.6	1.11	1.05	1.11
10	0.8	1.05	1.01	0.95
40	0.8	1.05	1.02	0.95
100	0.8	1.05	1.02	0.95

6. Conclusions

A numerical study on heat transfer characteristics has been carried over spheroidal shaped body immersed in a power law fluid. The ranges of parameters studied consist of a wide range of non-Newtonian behavior, Reynolds and Prandtl numbers. It was observed that oblate spheroids have higher Nusselt numbers and prolate ones have smaller Nusselt numbers compared to a sphere. The flow separation that takes place in the oblate spheroid case at Reynolds numbers as low as 30 is responsible for them having a larger Nusselt number compared to the prolate spheroids. This flow separation coupled with large Prandtl numbers can yield very high heat transfer coefficients for the oblate spheroids. Non-Newtonian characteristics are very signifiant at higher Prandtl numbers for all Reynolds numbers. Finally a simple correlation has been developed by which one can predict the Nusselt number over spheroidal shaped bodies in non-Newtonian fluids given the Nusselt number for a sphere at the same Reynolds and Prandtl numbers. It is remarkable that this correction factor is only a function of the aspect ratio, E. This correlation was also proved to be valid for the case of spheroids in Newtonian fluids.

Nomenclature

a= half length of the major axis, m
b = half length of the minor axis, m
c_p = specific heat of the fluid, J kg^{-1} K^{-1}
E = Axis ratio, b/a
h= heat transfer coefficient, W m^{-2} K^{-1}
I_2 = second invariant of deformation tensor, s^{-2}

k = thermal conductivity of the fluid, W m^{-1} K^{-1}
L = characteristic length equal to 2a, m
m = flow consistency index, Pa s^n
n = flow behavior index
Nu = Nusselt number, hL/k
Pr = modified Prandtl number, $c_p m(U_\infty/L)^{n-1}/k$
p = dimensionless pressure
Re = modified Reynolds number, $L^n U_\infty^{2-n} \rho/m$
T = dimensionless Temperature
U = dimensionless velocity
x = stream wise coordinate, m
y = transverse coordinate, m

Greek symbols
ε = shear strain, s^{-1}
η = apparent viscosity, Pa.s
θ = polar angle
ρ = density, kg/m^3
τ = shear stress, Pa

Subscripts
i = dummy argument
j = dummy argument
w = wall condition
∞ = far off condition

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