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STEADY STATE HEAT TRANSFER TO BLOOD FLOWING IN THE ENTRANCE REGION OF A TUBE

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Abstract—In the present work we have obtained the numerical solutions of the momentum and energy equation for blood flowing in a tube. It is assumed that the non-Newtonian behavior of blood can be expressed through the Casson equation. The numerical procedure used is that of Patankar and Spalding [1]. The results have been obtained for the two cases, (i) the uniform surface temperature and (ii) the uniform surface heat flux and for the yield number $Y(=\tau_y D/\bar{u}\mu) = 0, 0.1, 1, 2, 5, 10$ and 20.

NOMENCLATURE

C_p, heat capacity;
D, tube diameter;
F, defined equation (4.5);
h, heat-transfer coefficient;
h^*, heat-transfer coefficient;
K, thermal conductivity;
N, number of radial grid divisions;
Nu, Nusselt number;
Nu^*, Nusselt number;
p, pressure;
Pr, Prandtl number;
$\dot{q}''$, heat flux per unit area;
R, defined equation (4.5);
r, radial direction;
S, defined equation (4.5);
T, temperature;
T_c, centerline temperature;
T_E, entrance temperature;
T_m, mean temperature;
T_w, wall temperature;
u, axial velocity component;
$\bar{u}$, average velocity;
v, radial velocity component;
x, downstream distance;
y, normal direction;
$\bar{y}$, defined in equation (4.5);
Y, yield number;
Z, dimensionless downstream distance $(=x/DRePr)$;
Z_1, dimensionless downstream distance $1/Z$.

Greek symbols

α, thermal diffusivity;
η, shear rate of strain;
θ_H, dimensionless temperature constant heat flux;
θ_T, dimensionless temperature constant surface temperature;
μ, constant equation (2.5);
ρ, density;
τ, shear stress;
τ_w, wall shear stress;
τ_y, yield stress;
ϕ, dependent variable;
Ψ, parameter equation (4.1);
ω, dimensionless stream function.

Subscripts

c, position of equation (4.1);
eff, effective.

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1. INTRODUCTION

LITTLE is known definitely about the effect of the temperature of human blood. From a physiological standpoint the ideal temperature for blood is 37°C. However, blood can function with reduced ability to absorb oxygen and desorb carbon dioxide in a range of temperatures from 30 to 45°C. Blood can survive for a long period of time if frozen (−5° to −10°C) and thawed in an appropriate manner. Above 45°C the proteins in the blood will start to precipitate out of the plasma and will coagulate. Enzymes in the blood do not function well above 45°C. Change of blood temperature of this degree is unlikely to occur within a body as the normal body temperature regulation system will activate in an attempt to reverse this effect.

Many situations now exist in which the blood is removed from a body to be processed (for example, oxygenation, hemodialysis, etc.) and returned to the body. While in the body, temperature control of the blood is almost never a problem; however, whenever the blood is out of the body, temperature control becomes important in order to prevent damage. The information about the temperature field for blood flowing in a tube is, therefore, of practical significance.

Fluid entering a tube with uniform velocity and temperature profiles undergoes development during its course of flow. The development of velocity and temperature profiles is due to the growth of hydrodynamic and thermal boundary layers on the wall of a tube. As fluid progresses, the boundary layers grow until they intersect with the layers from the opposite side. After the point of intersection, the flow is considered fully developed. The portion of the tube wherein the boundary layers are developing is called the entrance region. The velocity and temperature profiles may develop at different rates. Whether the velocity profile developed faster or slower than the temperature profile depends on the Prandtl number of the fluid.

The subject of entrance flow has always been a subject of great interest because of its direct engineering application. Because of the mathematical difficulties on account of the non-linear inertia term, most of the solutions in the past were approximate. It is only since the last few years, with the advances in computer technology, that the numerical solutions for many cases have been attempted.

In the present work, we have obtained the numerical solutions in the past were approximate. It is only since the last few years, with the advances in computer have assumed that the Casson relation accurately described the stress rate of strain relation for blood. The numerical procedure used is that of Spalding and Patankar [1]. The results have been obtained for a wide range of yield numbers, and for Prandtl numbers equal to 0.7 and 25. The accuracy of the results have been checked by comparing the profiles at large axial distances with those for fully developed case and the developing profiles for $Y = 0$, with the available results for a Newtonian fluid.

2. GOVERNING EQUATIONS

For a steady, axisymmetric flow with constant properties, the conservation equations of mass, momentum and energy are

$$r\frac{\partial u}{\partial x}+\frac{\partial}{\partial r}(rv) = 0, \tag{2.1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}x}+\frac{1}{r}\frac{\partial}{\partial r}(\tau r), \tag{2.2}$$

and

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial r}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right). \tag{2.3}$$

Here T is the temperature and u and v are the velocity components in the axial direction x, and the radial direction r (or normal direction y), respectively. The boundary conditions are:

$$u = 0;\quad v = 0;\quad T \quad \text{or} \quad \frac{\partial T}{\partial r} = \text{constant at } r = \frac{D}{2},$$

$$\frac{\partial u}{\partial r} = 0;\quad \frac{\partial T}{\partial r} = 0 \quad \text{at} \quad r = 0, \quad \text{and}$$

$$u = \bar{u};\quad T = T_E \quad \text{at} \quad x = 0. \tag{2.4}$$

We have assumed that blood can be represented rheologically as a Casson fluid. Charm and Kurland [2] have shown that for blood the shear stress–shear rate relation, which is applicable in the range (0–100 000 s^{-1}) of shear rates is

$$\sqrt{(\tau)} = \sqrt{(\tau_y)}+\sqrt{(\mu\eta)}. \tag{2.5}$$

Here τ is a shear stress, τ_y is the yield stress, η is a shear rate of strain, and μ is a constant. The effective viscosity μ_{eff} and the effective Prandtl number Pr_{eff} can, therefore, be defined in the following way.

$$\mu_{\text{eff}} = \frac{\tau}{\left|\frac{du}{dy}\right|} = \frac{\left[\sqrt{(\tau_y)}+\sqrt{\left(\mu\left|\frac{du}{dy}\right|\right)}\right]^2}{\left|\frac{du}{dy}\right|}, \tag{2.6}$$

$$Pr_{\text{eff}} = \frac{C_p\mu_{\text{eff}}}{k} = \left(\frac{C_p\mu}{k}\right)\left(\frac{\mu_{\text{eff}}}{\mu}\right) = Pr\left(\frac{\mu_{\text{eff}}}{\mu}\right). \tag{2.7}$$

Here Pr is a constant and can be considered as a laminar Prandtl number. Our literature survey [Table 1] shows that the value of laminar Prandtl number for blood is about 25. All our computations, therefore, were carried out for $Pr = 25$. In addition, the results for $Pr = 0.7$ were obtained in order to check the accuracy of our solution with the published results for $Pr = 0.7$.

Table 1. Properties of blood

Value	Solution	Reference
Specific heat		
0.94 cal/g°C	Plasma	3
0.77	RBC	3
0.87	Plasma and RBC	3
0.92	Whole blood	4
0.94	Plasma	4
Relative viscosity (ratio to water)		
3.5–4.0	Whole blood	5
2.5–4.0	Whole blood	6
4.71	Whole blood at 20°C	4
3.00	Whole blood at 37°C	4
1.32–1.22	Plasma	4
3.5–5.4	Whole blood	7
Apparent viscosity		
0.012 P	Plasma	8
0.035 P	Whole blood	2
Thermal conductivity		
0.5 w/m°K	Whole blood	9
0.506 w/m°K	Whole blood	10
0.582 w/m°K	Plasma	10
0.481 w/m°K	Corpuscles	10
1.365 cal/cm s°C × 10^3	Plasma	11
1.265 cal/cm s°C × 10^3	Blood 43% hemocrit	11

It can be seen that for yield stress τ_y equal to zero (i.e. yield number $Y = 0$) the effective viscosity μ_{eff} is constant and thus a Casson fluid with zero yield number is a Newtonian fluid.

3. PROCEDURE

The numerical procedure used is the one that was developed by Spalding and Patankar [1]. The coordinates employed are the dimensionless stream function ω and the distance in the flow direction x. The finite-difference equations are formed from integrals of the differential equations over small regions corresponding with the individual nodes of the grid. The numerical procedure employed is of the 'implicit finite difference marching integration type'. Therefore, at every step in the integration from the values of ϕ (dependent variable) known at a discrete value of ω for one value of x, the values of ϕ at the same values of ω, but for a slightly greater value of x are evaluated. By step-wise repetition of this basic operation, the whole field of interest can be covered. For a more detailed description of the program one may refer to Patankar and Spalding [1].

4. MODIFICATIONS

There were two major modifications that the program required to obtain the solution. One was to prescribe the effective viscosity and effective Prandtl number relations appropriate to blood in the program.

The second modification was necessary to evaluate the velocity and temperature profiles near the surface. In the finite difference equations used, it is assumed that the profiles are linear between the grid points. However, the changes in the profiles are quite large near the wall and without modification considerable error could be introduced. Therefore, it was recommended by Patankar and Spalding to use a Couette flow solution near the tube surface. This solution is used in the program to obtain the value of the wall shear stress and the parameter Ψ where

$$\Psi = \frac{\int_0^{y_c} \rho u r \, dy}{(\rho u)_c \int_0^{y_c} r \, dy}. \tag{4.1}$$

Here the subscript c represents a position halfway between the wall and the last grid point next to it.

The Couette flow is characterized by the assumption that the axial velocity does not change with axial distance. Since this region is so thin, the variation due to radius can be ignored. With these assumptions, the continuity and momentum equations (2.1) and (2.2) simplify to

$$\frac{d\tau}{dy} = \frac{dP}{dx}. \tag{4.2}$$

After integrating and substituting the Casson's relation (2.5) with the boundary condition that $u = 0$ at $y = 0$, we obtain the following expression for velocity. Here y is the distance from the surface.

$$u = \frac{1}{\mu}\left\{\frac{dP}{dx}\frac{y^2}{2} + (\tau_w + \tau_y)y + \frac{4}{3}\frac{\sqrt{(\tau_w)}}{\left(\frac{dP}{dx}\right)}\left[\tau_w^{3/2} - \left[\left(\frac{dP}{dx}\right)y + \tau_w\right]^{3/2}\right]\right\} \tag{4.3}$$

or in a dimensionless form

$$u^* = R_c\left\{\frac{F}{2y^2} + (S + S_y)\bar{y} + \frac{4}{3}\frac{\sqrt{(S_y)}}{F}S^{3/2} - (F\bar{y} + S)^{3/2}\right\} \tag{4.4}$$

here $u^* = u/u_c$,

$$F = \frac{dP}{dx}\frac{y}{(\rho u^2)_c},$$
$$S = \frac{\tau_w}{(\rho u^2)_c},$$
$$R_c = \frac{(\rho u y)_c}{\mu},$$
$$S_y = \frac{\tau_y}{(\rho u^2)_c},$$
$$\bar{y} = y/y_c, \tag{4.5}$$

and τ_w is the wall shear stress. Therefore, the relations for the wall shear stress and the parameter Ψ needed by the computer program in terms of the property values at a position "c" are

$$S = \frac{1}{R_c} - \frac{F}{2} - S_y - \frac{4}{3}\frac{\sqrt{(S_y)}}{F}(S^{3/2} - (F+S)^{3/2}) \tag{4.6}$$

and

$$\Psi = R_c\left\{\frac{F}{6} + \frac{S+S_y}{2} + \frac{4}{3}\frac{\sqrt{(S_y)}}{F}\left[S^{3/2} - \frac{2}{5}\frac{(F+S)^{5/2}}{F} + \frac{2}{5}\frac{S^{5/2}}{F}\right]\right\}. \tag{4.7}$$

For $F = 0$, these equations (4.6, 4.7) simplify to

$$S = \left[\frac{1}{\sqrt{(R_c)}} + \sqrt{(S_y)}\right]^2 \tag{4.8}$$

and

$$\Psi = \frac{R_c}{2}[\sqrt{(S)} - \sqrt{(S_y)}]^2. \tag{4.9}$$

In addition, the program was modified to incorporate calculation of a number of parameters of interest to this problem.

5. GRID DISTRIBUTIONS N, ω AND ΔZ

The grid size is intrinsically linked with the accuracy of the solution, the smaller the grid the better the results up to a point. After that, any more increase in the number of grid points increases the round off error. For this problem a value for N equal to 40 was found to be the optimum. N represents the number of radial grid divisions. This number was sufficient to produce very accurate results so that increasing N should have little additional effect and decreasing it to 30 has limited additional error introduced.

The ω distribution represents the radial position on the grid points. As the profile variations are steeper near the surface, the ω distributions were selected such as to provide finer grid lines near the surface and at the axis. This was to handle the larger gradients which occur in those regions.

The dimensionless forward marching step size is defined as

$$\Delta Z = \frac{\Delta x}{D \, Re \, Pr}. \tag{5.1}$$

Table 2. Values of ΔZ

Used for steps	$Pr = 0.7$	$Pr = 25$
0–1000	8.155×10^{-8}	4.567×10^{-9}
1001–2000	2.446×10^{-7}	2.740×10^{-8}
2001–3000	7.337×10^{-7}	1.644×10^{-7}
3001–4000	2.201×10^{-6}	9.865×10^{-7}
4001–5000	6.603×10^{-6}	5.919×10^{-6}
5001–6000	2.641×10^{-5}	4.735×10^{-5}
6001–7000	1.057×10^{-4}	3.788×10^{-4}
7001–8000	4.226×10^{-4}	3.030×10^{-3}

Since the changes in the velocity and temperature profiles are large in the entrance region, the step size was chosen to be very small in the beginning and was increased as the flow proceeded downstream (see Table 2). A higher Prandtl number causes the thermal boundary layer to develop slower than the momentum boundary layers. In order to obtain the results in a reasonable number of integration steps, the step size for a $Pr = 25$ was made larger than that for $Pr = 0.7$.

6. COMPARISON AND ACCURACY OF THE SOLUTION

There are only two ways to really determine if the computer program is indeed solving the problem correctly, (i) comparing the fully developed profiles generated at the end of the entrance region with the analytical solution for a fully developed case [12, 13], and (ii) comparing the entrance region results for a Newtonian fluid ($Y = 0$) with those previously published results for a Newtonian case.

6.1 *Comparison with fully developed case*

The first point of comparison is the comparison of analytical to numerical solutions of the velocity profile. Figure 1 shows that the two profiles agree almost exactly for yield numbers of 0 and 10. The next point of comparison is the temperature profiles at the fully developed region. The dimensionless temperature chosen was different for each of the heat-transfer boundary-conditions. For the case of constant heat flux,

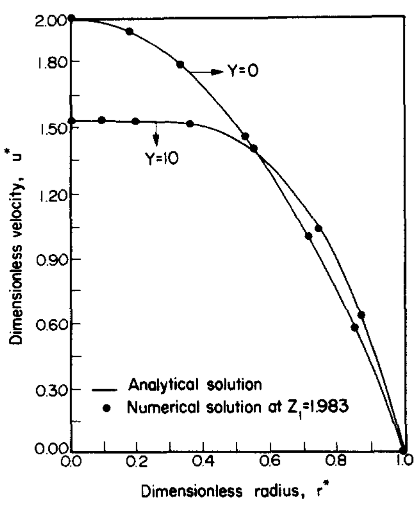

FIG. 1. Comparison of numerical and analytical velocity profiles.

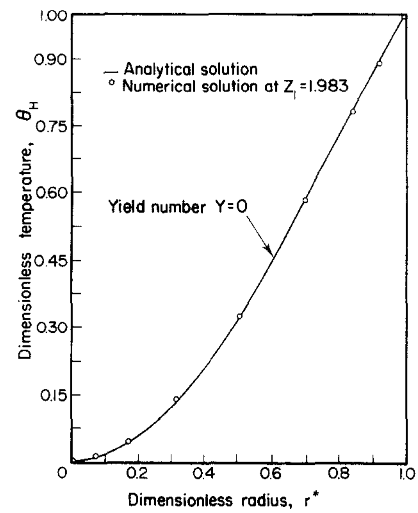

FIG. 2.

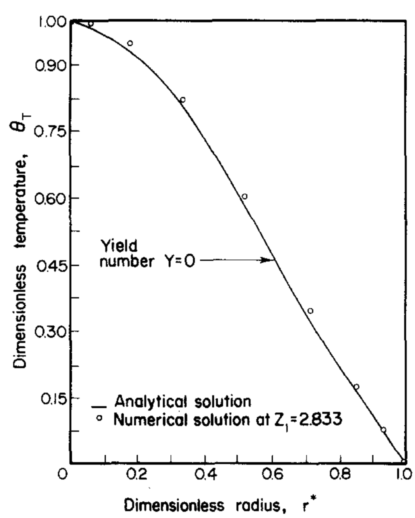

FIG. 3.

$\theta_H = (T - T_c)/(T_w - T_c)$ and the numerical results are shown in Fig. 2 to be in very close agreement with the analytical expressions [12] for yield number = 0. For the case of constant surface temperature, $\theta_T = (T_w - T)/(T_w - T_c)$, again, the numerical results and the analytical results are in good agreement (see Fig. 3). Finally the asymptotic values of the Nusselt number were also found to be in agreement with the fully developed flow case [12, 13] solution.

6.2 *Comparison with Newtonian flow case*

The second method of checking if the numerical solution is correct is to compare it to the case of a Newtonian fluid flowing in a tube subjected to the same boundary conditions. The case of Newtonian fluid flow has been attempted by many investigators [14–16], each with variations which make each one slightly different. Probably the best solution obtained was by Manohar [14], as he used a method which should have produced little or no linearization error in the computation which was not the case in a previous case that

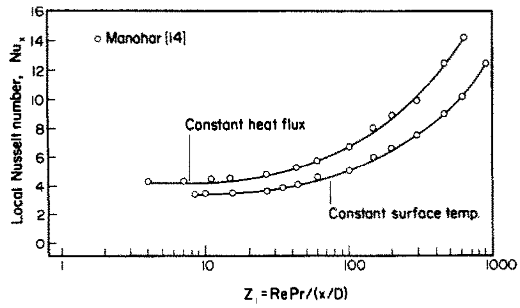

FIG. 4. Comparison of entrance region solution for Newtonian flow (Prandtl number = 0.7).

included the radial velocity term [16]. Figure 4 shows that the numerical procedure used is in good agreement with the results of Manohar for both the case of constant heat flux and constant surface temperature.

6.3 *Comparison with experimental work*

As far as the experimental work is concerned, there are only two references, Mitvalsky [17] and Charm [18], that deal with heat transfer to blood flow. In Charm's work it was noted that there is essentially no difference in heat-transfer rates between whole blood and plasma indicating that the blood cells have little influence so heat transfer or the inherent assumption of a homogeneous fluid Casson's relation should not be a significant problem. Their data is represented in Fig. 5,

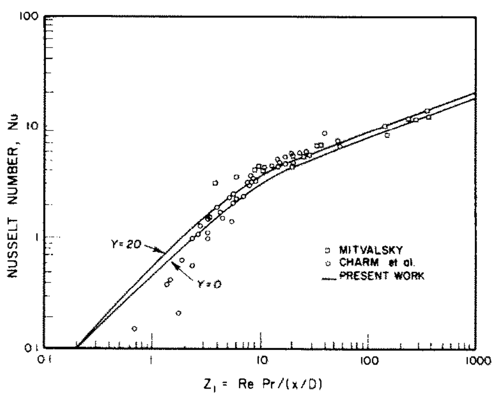

FIG. 5. Prandtl number = 25, constant surface temperature case.

along with our numerical solution for $Pr = 25$. It can be seen that our numerical results are in agreement with the experimental measurements of Mitvalsky and Charm in the entrance region. It should be noted here that their Nusselt number

$$Nu^* = \frac{h^*D}{K} = \frac{\dot{q}''}{T_w - \left(\dfrac{T_E + T_m}{2}\right)} \frac{D}{K} \tag{6.1}$$

is referenced to a mean temperature that is the average between the entrance of the tube and the downstream point under consideration. While in our work the Nusselt number

$$Nu = \frac{hD}{K} = \frac{\dot{q}''}{(T_w - T_m)} \frac{D}{K} \tag{6.2}$$

is referenced to the average temperature at the point under consideration.

7. PRESENTATION OF THE RESULTS

The results of the heat transfer in the entrance region for blood were obtained for yield numbers of 0, 0.1, 1, 2, 5, 10, and 20, and Prandtl numbers of 0.7 and 25. Figures 6 and 7 represent the local Nusselt number

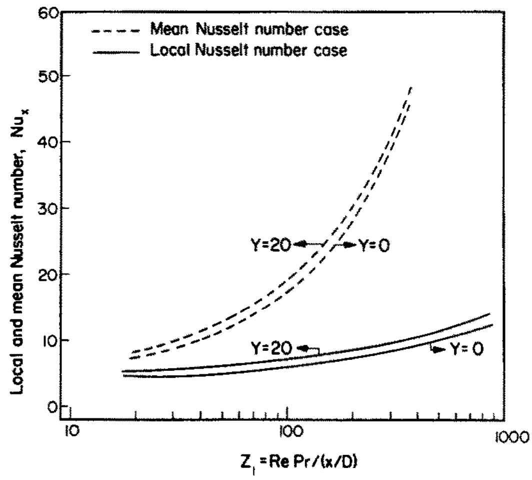

FIG. 6. Local and mean Nusselt number vs downstream distance for the constant heat flux case Prandtl number = 25.

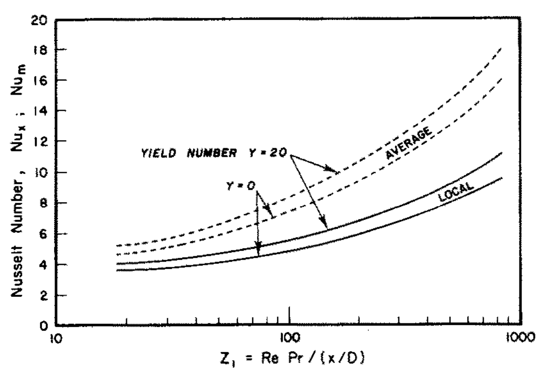

FIG. 7. Nusselt number vs downstream distance for the constant surface temperature case Prandtl number = 25.

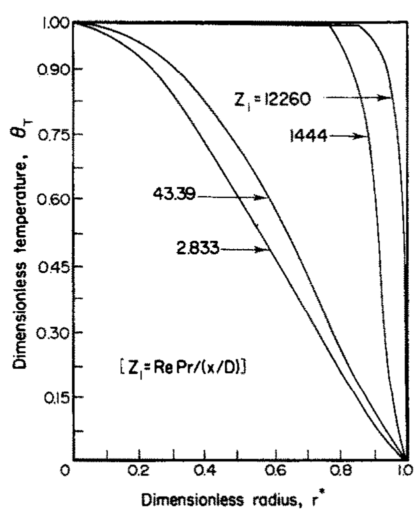

FIG. 8. Developing temperature profiles for the constant surface temperature case, yield number = 5, Prandtl number = 0.7.

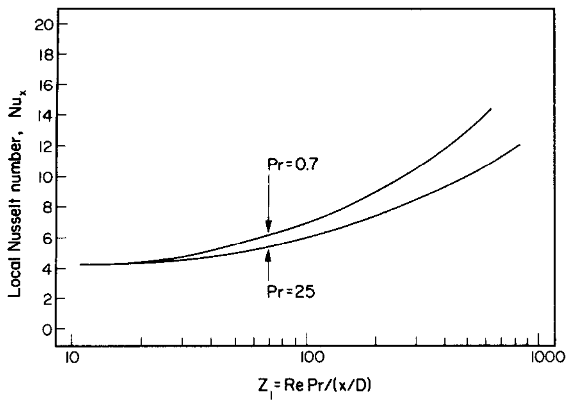

FIG. 9. Effect of Prandtl number constant heat flux case.

and mean Nusselt numbers for the entrance region for Prandtl numbers of 25. The development of the temperature profiles for a yield number of 5 is shown in Fig. 8 for $Pr = 0.7$, and the effect of Prandtl number on heat-transfer rate is shown in Fig. 9.

8. CONCLUDING REMARKS

So far as we know there is no known solution available for heat transfer either in the entrance region or in the fully developed region for a fluid which obeys the Casson stress–strain relation. Having confirmed that these results are in excellent agreement with (i) the fully developed region for all yield numbers, and (ii) the entrance region for a zero yield (Newtonian fluid), it can be inferred that the results obtained are accurate to within the limits of the computational round off error. In fact, the solution of the momentum equation is more accurate than Shah and Soto's [19], due to a finer grid size and better definition of the apparent viscosity.

In a set of results obtained for Prandtl number = 0.7, it was observed that the yield number does not have much of an influence on the Nusselt number in the early parts of the thermal entrance region. This may be due to the fact that the flow is still developing and that the velocity profiles are similar in shape in the developing region for all yield numbers. Because the velocity profiles are nearly identical, the resulting temperature profiles will also be nearly the same. This results in the Nusselt number being almost independent of yield number while in the entrance region. However, as the flow develops the effect of the yield stress will become more pronounced as the plug flow region remains for higher yield numbers, but disappears for a Newtonian fluid. The higher the yield number, the earlier this effect takes place and the higher the resulting fully developed Nusselt number.

The effect of increasing the Prandtl number (see Fig. 9) is to delay the development of the thermal boundary layer in comparison to the velocity boundary layer. Therefore, the yield number has influence on the Nusselt number in the entrance region and the resulting Nusselt number is lower for the same value of Z_1 for a Prandtl number of 25 than for a Prandtl number of 0.7. In the fully developed region the Prandtl number has no influence.

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CONVECTION, EN REGIME PERMANENT, D'UN ECOULEMENT SANGUIN DANS LA REGION INITIALE D'UN TUBE

Résumé—Le présent travail a permis l'obtention de solutions numériques des équations du mouvement et de l'énergie pour un écoulement sanguin dans un tube. On a supposé que le comportement non-newtonien du sang pouvait être décrit par l'équation de Casson. La procédure numérique utilisée est celle de Patankar et Spalding [1]. Les résultats ont été obtenus dans les deux cas suivants: (i) température de paroi uniforme et (ii) flux pariétal constant pour les valeurs suivantes du groupement $Y = \tau_y D/\bar{u}\mu$: 0; 0,1; 1; 2; 5; 10 et 20.

DER STATIONÄRE WÄRMEÜBERGANG AN BLUT IM EINGANGSBEREICH VON ROHREN

Zusammenfassung—Es werden numerische Lösungen der Impuls- und Energiegleichung für Blut, das in einem Rohr strömt, angegeben. Es wird angenommen, daß das nichtnewton'sche Verhalten von Blut durch die Casson-Gleichung beschrieben werden kann. Zur Berechnung wird das Patankar–Spalding-Verfahren [1] verwendet. Für die beiden Fälle gleichförmiger Oberflächentemperatur bzw. gleichförmiger Wärmestromdichte werden die Ergebnisse für die Kennzahlen $Y(=\tau_y D/\bar{u}\mu) = 0$; 0,1; 1; 2; 5; 10 und 20 angegeben.

СТАЦИОНАРНЫЙ ПЕРЕНОС ТЕПЛА К ПОТОКУ КРОВИ В НАЧАЛЬНОМ УЧАСТКЕ ТРУБЫ

Аннотация — В данной работе получены численные решения уравнения количества движения и энергии для течения крови в трубе. Предполагается, что неньютоновское поведение крови можно описать с помощью уравнения Кэссона. Используемый численный метод аналогичен методу, описанному Патанкаром и Сполдингом в [1]. Результаты получены для двух случаев: (1) постоянной температуры поверхности и (2) постоянного теплового потока на поверхности при индексе текучести $Y(=\tau_y D/\bar{u}\mu) = 0$; 0,1; 1; 2; 5; 10 и 20.