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TRANSIENT NATURAL CONVECTION HEAT TRANSFER IN NON-NEWTONIAN SECOND ORDER FLUIDS

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The paper presents the numerical solution to the problem of transient natural convection in viscoelastic fluid of the second order in vicinity of vertical surface temperature of which suddeny rises. To solve partial differential equations resulting from balance of mass, momentum and energy for the item discussed, the method of finite differences has been applied. As a result of solution to balance equations transient fields of temperature and velocity, and also transient runs of changes of the Nusselt number, dimensionless shear stress and relative difference of normal stresses have been determined. The results obtained have been compared with the available experimental data for Newtonian fluid in the steady-state case.

1. Introduction

Failures of cooling systems often give rise to transient convection flows. Failure-free performance of machines in electronics, lighting, chemical and power industries depends on natural convection processes. The results coming from the analysis of processes of natural convection can be used either to bring intensification of heat transfer or to bring minimization of heat losses to environment, for example. Majority of published papers to the process of natural convection for Newtonian fluids (cf Jaluria (1980), Petukhov and Polakov (1986)).

Owing to the degree of complexity of discussed processes of natural convection in non-Newtonian fluids, and especially in viscoelastic fluids, the number of published papers is limited. The analysis of steady-state natural convection in viscoelastic fluid by means of approximate integral method was presented by Shenoy and Mashelkar (1978). Shenoy and Mashelkar (1978) observed that the self-similar solution to balance equations existed only in the case of visco-elastic second order fluid in the outer region of horizontal cylinder of constant temperature. Problem of transient natural convection in Walter's B fluid in the vicinity of vertical plate is presented by Soundalgekar (1971). The method of perturbation was applied to determine temperature and velocity fields in fluids. Soundalgekar (1971) took into consideration a constant velocity of fluid suction on warmed vertical surface. Ropke and Schummer (1982) presented an analysis of transient natural convection in 4-parameter Oldroyd fluid filling up rectangular, two-dimensional space. Using the method of finite differences temperature and velocity fields in the area filled up with viscoelastic fluid were determined. Ropke and Schummer (1982) obtained transient runs of average Nusselt number on one of the vertical surfaces of two-dimensional space. Rup (1994) dealt with the analysis of transient processes of natural convection in viscoelastic second order fluid in the vicinity of vertical surface, temperature of which suddenly rises. By means of the finite difference method transient fields of temperature and velocity in viscoelastic second order fluid of constant material coefficients were determined. Subba Reddy Gorla et al. (1994) analyzed the problem of laminar free convective flow of the Ostwald de Waele of constitutive equation fluid over a vertical frustrum of cone with uniform surface heat flux boundary conditions. The coupled nonlinear partial differential equations for the momentum and energy equations have been reduced with a powerful nonsimilar transformation and then solved numerically. Bian et al. (1994) reported analytical and numerical study of steady-state natural convection in a two-dimensional rectangular porous cavity saturated by a non-Newtonian fluid. The modified Darcy model of power constitutive equation is used to characterize the non-Newtonian fluid behavior. Numerical solutions for the flow and temperature fields and Nusselt numbers are obtained in terms of a modified Rayleigh number, the aspect ratio of the cavity, and the exponential formula index, respectively.

The present paper deals with numerical solution to transient natural convection problem in viscoelastic second order fluid of variable material coefficients α_1 and α_3. The fluid under consideration is placed in the vicinity of vertical surface, temperature of which rises suddenly at a given moment. The discussed variability of material coefficients of tested viscoelastic fluid has been allowed for in form of their power dependence on second invariant of the rate of deformation tensor II only. The paper studies the effect of indices values n and s, and the Weissenberg number on: transient changes in the Nusselt number, dimensionless shear stress, and relative difference of normal stresses, respectively, determined on the heated vertical surface.

2. Problem formulation

Transient, laminar momentum and heat transfer driven by natural convection in viscoelastic fluid in the vicinity of vertical surface, temperature of which at the moment $\tau = 0$ suddenly rises (Fig.1) is considered.

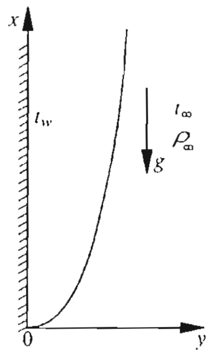

Fig. 1. Layout of flow geometry

Due to degree of complexity of general differential equations resulting from balance of mass, momentum and heat, we are going to introduce the following simplifying assumptions:

- The geometry of flows analysed justifies the use of the boundary layer theory
- Oberbeck-Boussinesq approximation is assumed
- The viscous dissipation motion pressure and volumetric energy source are neglected.

Taking into account the simplification resulting from the boundary layer theory (cf Bilgen (1973); Jaluria (1980)) and changes in fluid density according to the Oberbeck-Boussinesq approximation

$$\frac{\rho_\infty}{\rho} = 1 + \beta(t - t_\infty) \tag{2.1}$$

one gets the following system of equations

$$\begin{aligned} &\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \\ &\frac{\partial u}{\partial \tau} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho}\frac{\partial}{\partial y}\sigma_{xy} + \frac{1}{\rho}\frac{\partial}{\partial x}(\sigma_{xx} - \sigma_{yy}) + g\beta(t - t_\infty) \end{aligned} \tag{2.2}$$

$$\frac{\partial t}{\partial \tau} + u\frac{\partial t}{\partial x} + v\frac{\partial t}{\partial y} = \frac{\lambda}{c_p\rho}\frac{\partial^2 t}{\partial y^2}$$

The above system of partial differential equations together with the following boundary conditions

– for $\tau < 0$

$$u = v = 0 \qquad t = t_\infty \tag{2.3}$$

– for $\tau \geq 0$

$$\begin{array}{lll} x = 0 & u = v = 0 & t = t_\infty \\ y = 0 & u = v = 0 & t = t_w \\ y \to \infty & u = v = 0 & t = t_\infty \end{array} \tag{2.4}$$

formulates the mathematical description of momentum and heat transfer driven by the transient natural convection in viscoelastic fluid. Assuming in Eq $(2.2)_2$ that $\sigma_{xx} - \sigma_{yy} = 0$ one gets the classical momentum boundary layer equation for the natural convection of Newtonian fluid or for viscous fluid.

3. Constitutive equations

The general equations for the modified second order fluid model (cf Bilgen (1973); Zahorski (1978)) are of the form

$$\boldsymbol{\sigma} = -p\mathbf{I} + f[\mathbf{A}_1, \mathbf{A}_2, ..., \mathbf{A}_n] \tag{3.1}$$

in which the $\mathbf{A}_n$ are kinematic tensors. Viscometric flows may be defined by the requirement that $\mathbf{A}_n = 0$ for $n \geq 3$, and Eq (3.1) takes the form (cf Bilgen (1973); Zahorski (1978))

$$\boldsymbol{\sigma} = -p\mathbf{I} + \alpha_1\mathbf{A}_1 + \alpha_2\mathbf{A}_1^2 + \alpha_3\mathbf{A}_2 \tag{3.2}$$

For isotropic incompressible fluids $\mathbf{A}_1$ and $\mathbf{A}_2$ are defined as

$$\begin{aligned} \mathbf{A}_1 &= (\mathrm{grad}v) + (\mathrm{grad}v)^\top \\ \mathbf{A}_2 &= \frac{d}{dt}\mathbf{A}_1 + \mathbf{A}_1(\mathrm{grad}v) + (\mathrm{grad}v)^\top\mathbf{A}_1 \end{aligned} \tag{3.3}$$

The material constans α_1, α_2 and α_3 are only functions of the second invariant of the rate of deformation tensor (cf Bilgen (1973); Zahorski (1978)). For the type of boundary layer flow discussed here, it is not necessary to specify the function form of the material constant α_2. It has been shown (cf Shenoy and Mashelkar (1978)) … result of the order magnitude analysis, that the terms in which α_2 appears in the stress equations vanish. Following the boundary layer approximation the stress components in Eq (3.2) reduce to

$$\sigma_{xy} = \alpha_1 \frac{\partial u}{\partial y} + \alpha_3 \Big(\frac{\partial^2 u}{\partial \tau \partial y} + u \frac{\partial^2 u}{\partial x \partial y} + v \frac{\partial^2 u}{\partial y^2} + 2 \frac{\partial u}{\partial x} \frac{\partial u}{\partial y} \Big) + \mathcal{O}(\delta)$$

$$\sigma_{xx} - \sigma_{yy} = -2\alpha_3 \Big(\frac{\partial u}{\partial y} \Big)^2 + \mathcal{O}(\delta) \tag{3.4}$$

Assuming that $\alpha_3 = -\alpha_1 \Theta$ (where Θ is the material constant of time-dependent (cf Zahorski (1978)) and taking the results of experimental evidence that $\Theta \approx 0.01\,\mathrm{s}$ (cf Bilgen (1973)) for dilute polymer solutions, the second term of Eq $(3.4)_1$ can be simplified. The corresponding stress components include only the terms of the same order of magnitude $\mathcal{O}(\delta)$. For the dilute polymer it has been found experimentally that the material constants α_1 and $\alpha_3 = -\alpha_1 \Theta$ can be approximated by power functions of the second invariant II

$$\alpha_1(II) = k \sqrt{\Big(\frac{1}{2} II\Big)^{n-1}} \qquad \alpha_3(II) = -m \sqrt{\Big(\frac{1}{2} II\Big)^{s-2}} \tag{3.5}$$

where the values of n, s, k and m are constant.

Following the boundary layer approximation, and making use of the power functions, given by Eqs (3.5), the stress components in Eqs (3.4) reduce to

$$\sigma_{xy} = k \Big(\frac{\partial u}{\partial y} \Big)^n \qquad \sigma_{xx} - \sigma_{yy} = 2m \Big(\frac{\partial u}{\partial y} \Big)^s \tag{3.6}$$

4. Dimensionless form of balance equations and their numerical model

The final differential equations are recast in dimensionless form by introducing

$$U = \frac{u}{U_c} \qquad V = \frac{v}{U_c} \qquad U_c = \sqrt[n+2]{\frac{k}{\rho} [g\beta(t_w - t_\infty)]} \tag{4.1}$$

$$X = x \sqrt[n]{\frac{\rho}{k} U_c^{2-n}} \qquad Y = y \sqrt[n]{\frac{\rho}{k} U_c^{2-n}} \tag{4.2}$$

$$\bar{\tau} = \tau \sqrt[n]{\frac{\rho}{k} U_c^2} \qquad T = \frac{t - t_\infty}{t_w - t_\infty} \tag{4.3}$$

$$\mathrm{Ws} = \frac{2m}{\rho} \sqrt[n+2]{\left(\frac{\rho}{k}\right)^{s+2} [g\beta(t_w - t_\infty)]^{2(s-n)}} \tag{4.4}$$

$$\mathrm{Pr} = \frac{c_p \rho}{\lambda} \sqrt[n+2]{\left(\frac{k}{\rho}\right)^{3} [g\beta(t_w - t_\infty)]^{2(n-1)}} \tag{4.5}$$

The dimensionless numbers of Weissenberg Ws and Prandtl Pr are defined here similarly as by Shenoy and Mashelkar (1978).

The simultaneous differential equations are then

$$\begin{aligned} &\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \\ &\frac{\partial U}{\partial \bar{\tau}} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = \frac{\partial}{\partial Y}\Big[\Big(\frac{\partial U}{\partial Y}\Big)^{n-1}\frac{\partial U}{\partial Y}\Big] + \mathrm{Ws}\frac{\partial}{\partial X}\Big[\Big(\frac{\partial U}{\partial Y}\Big)^{s-1}\frac{\partial U}{\partial Y}\Big] + T \\ &\frac{\partial T}{\partial \bar{\tau}} + U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 T}{\partial Y^2} \end{aligned} \tag{4.6}$$

The dimensionless boundary conditions on velocity and temperature are

— for $\bar{\tau} < 0$

$$U = V = T = 0 \tag{4.7}$$

— for $\bar{\tau} \geq 0$

$$\begin{array}{lll} X = 0 & U = V = T = 0 & \\ Y = 0 & U = V = 0 & T = 1 \\ Y \to \infty & U = V = 0 & T = 0 \end{array} \tag{4.8}$$

The system of differential equations (4.6) together with the boundary conditions (4.7) ÷ (4.8) has been solved using the method of finite differences (cf Crochet et al. (1984); Rup (1986) and (1994)). The numerical scheme used for solving the natural convection problem was also an explicit finite difference scheme. The solution started at the instant $\bar{\tau} = 0$, at which the temperature of vertical surface suddenly rises. At every time step temporary temperature and velocity fields were computed. The solution was marched on in time until a steady-state has been reached, for which the temperature and velocity fields remain constant. According to the method applied, differential equations resulting from balance of mass, momentum and energy have been replaced by corresponding difference equations. Spatial division network has been buit up of $M \times N$ points and a time step $\Delta\bar{\tau}$ has been assumed. Taking into account that intensive heat, momentum and mass transfer occurs only in the close vicinity of discussed vertical surface, the following maximum values of dimensionless coordinates $X = 110$, $Y = 43$ have been assumed. Nonlinear terms containing the higher order derivatives have been approximated by central differences, characterized by the second degree of accuracy. Forward differences were used for the first order derivatives with respect $\bar{\tau}$ and Y, and a backward difference was used for X derivatives.

The parameters of the problem are: Weissenberg number, Prandtl number, exponent in shear stress exponential formula and exponent in normal stress exponential formula, respectively. FORTRAN computer code has been produced to integrate numerically the system of equations (4.6) ÷ (4.8).

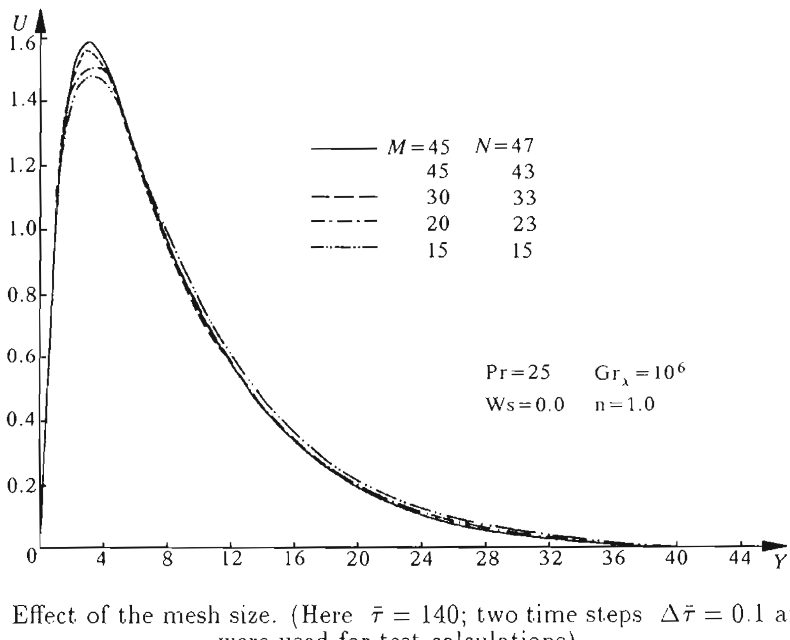

Fig. 2. Effect of the mesh size. (Here $\bar{\tau} = 140$; two time steps $\Delta\bar{\tau} = 0.1$ and 0.05 were used for test calculations)

In Fig.2 are plotted predictions of the U velocity variation for various mesh sizes. As can be expected, the succesive refinement of the mesh tends asymptotically towards the correct solution. From a series of calculations with different mesh sizes and time steps, it was concluded that $M = 45$, $N = 47$ and $\Delta\bar{\tau} = 0.1$ would yield acceptable accuracy.

5. Discussion of results

Transient fields of temperature and velocity have been calculated for various values of the parameters Ws, Pr, n and s. On the basis of defined transient field of temperature in fluid, time changes in the local Nusselt number Nu_x, characterizing the intensity of heat transfer between a vertical surface heated by a sudden temperature rise and viscoelastic fluid, have been also given. Nu_x number is determined by the following expression

$$\mathrm{Nu}_x = \frac{\alpha x}{\lambda} = \frac{q}{t_w - t_\infty}\frac{x}{\lambda} \tag{5.1}$$

where the convective heat transfer coefficient α refers to the difference between the temperature of vertical surface and t_∞ temperature. Substituting dimensionless expressions (4.2) and (4.3) into Eq (5.1) one gets

$$\frac{\mathrm{Nu}_x}{\sqrt[4]{\mathrm{Gr}_x}} = \sqrt[4]{X^{2-n}}\frac{\partial T}{\partial Y} \tag{5.2}$$

where

$$\mathrm{Gr}_x = X^{n+2} = x^{n+2}\Big(\frac{\rho}{k}\Big)^2[g\beta(t_w - t_\infty)]^{2-n} \tag{5.3}$$

is the Grashof number, characteristic dimensionless parameter for the process of natural convection.

In order to compare the the numerical results obtained the following correlation formula, received from the experimental study of Newtonian fluid and given by Petukhov and Polakov (1986) is taken into account

$$\frac{\mathrm{Nu}_x}{\sqrt[4]{\mathrm{Gr}_x}} = K_1(\mathrm{Pr})\sqrt[4]{\mathrm{Pr}} \tag{5.4}$$

where

$$\begin{aligned} K_1(\mathrm{Pr}) &= \frac{3}{5}\sqrt[4]{\frac{\mathrm{Pr}}{1 + 2\sqrt{\mathrm{Pr}} + 2\mathrm{Pr}}} \\ 10^5 &\leq \mathrm{Pr}\mathrm{Gr}_x \leq 10^8 \end{aligned} \tag{5.5}$$

Eqs (5.4) and (5.5) are valid for a vertical surface of a constant temperature within the range of parameter changes. Table 1 collects values of dimensionless ratios (5.2) and (5.4) for selected values of Ws, Pr, n and s parameters in the steady-state case.

Table 1. Ratio $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ in the steady-state case ($\bar{\tau} = 140$) for the Prandtl number Pr=25

Ws	n	s	$\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ (5.2)	$\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ (5.4)
0.0	1.0	0.0	1.0815	1.0735
0.0	0.8	0.0	1.3217	–
1.0	0.8	1.25	1.2859	–
1.0	0.8	1.50	1.2938	–
5.0	0.8	1.25	1.1903	–
5.0	0.8	1.50	1.2222	–

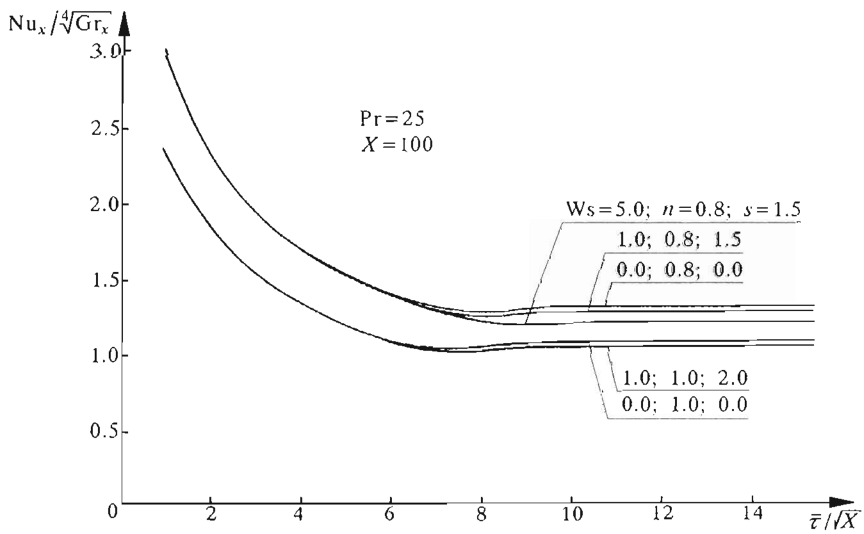

Fig. 3. Effect of n and s on the local Nusselt number

Time changes of Eq (5.2) are presented in Fig.3 and Fig.4. They show that the increase in Weissenberg number Ws is accompanied by the decrease in $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$. That means that the intensity of heat transfer between vertical surface and fluid is diminished. Decrease in the value of ratio $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ is particularly visible for higer values of time coordinate, where the convective heat transfer dominates. At initial moments of the process, i.e., till the ratio $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ reaches its minimum values, conduction is a dominant form of heat transfer between fluid and the vertical surface. Fig.3 also shows that the region of variation of dimensionless time coordinate $\bar{\tau}$, characteristic for domination of conductive heat transfer, enlarges with the Ws number. Further, thorough analysis of the results given in Fig.3 reveals that the value of index

n exerts the most significant influence on $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ within the whole range of time coordinate $\bar{\tau}$ analysed. Relative variation of ratio $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ for the Newtonian fluid and for the non-Newtonian fluid (Ws=0.0, $n = 0.8$) reaches its maximum value of about 22%.

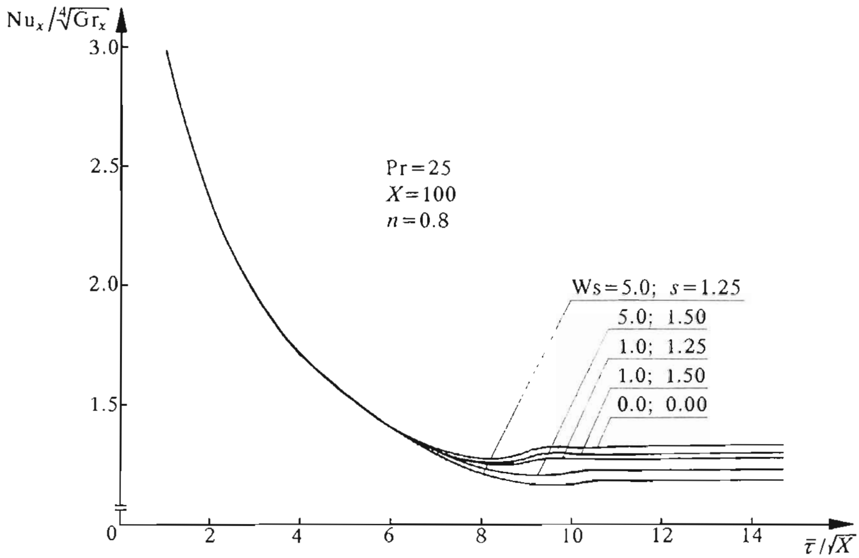

Fig. 4. Effect of s on the local Nusselt number

Analysis of curves presented in Fig.4 makes it possible to estimate the influence of the value of index s on time changes of the ratio $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$. It leads to the conclusion that the increase in index s, causes the increase in $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ for fluids represented by the Weissenberg numbers Ws=1.0 and Ws=5.0. Relative variation of $\mathrm{Nu}_x/\sqrt[4]{\mathrm{Gr}_x}$ in the case of the steady-state process is higher for fluid characterized by the value of number Ws=5.0 ($s = 1.5$ and $s = 1.25$) and reaches about 3%.

Fig.5 presents transient changes of the dimensionless shear stress on the vertical surface heated by a sudden temperature rise. Corresponding relation for the dimensionless shear stress has been obtained from Eq $(3.6)_1$ along with Eqs (4.1) and (4.2)

$$\frac{\sigma_{xy}}{\rho U_c^2} = \left(\frac{\partial U}{\partial Y}\right)^n \tag{5.6}$$

Fig.5 shows clearly that together with the increase in values of indices n and s, the dimensionless shear stress on the vertical surface also increases. Moreover, Fig.5 reveals that while the value of number Ws rises, the dimen-

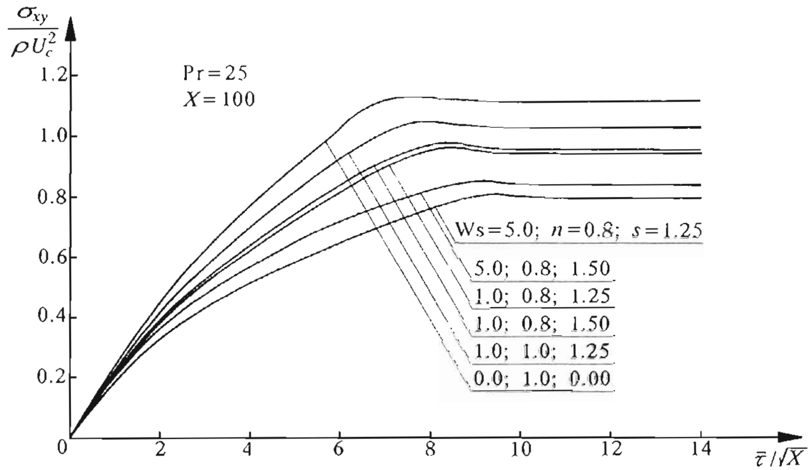

Fig. 5. Transient run of the dimensionless shear stress on vertical surface

sionless shear stress drops. Relative drop in dimensionless shear stress between fluids described by parameter values Ws=1.0, $n = 1.0$, $s = 1.5$, and Ws=5.0, $n = 0.8$, $s = 1.5$, reaches 16.8%.

One of the most important quantities describing behaviour of viscoelastic fluid is the difference of normal stresses $\sigma_{xx} - \sigma_{yy}$. Dimensionless form of this difference is obtained by including Eqs (4.1), (4.2) and (4.4) to Eq $(3.6)_2$

$$\frac{\sigma_{xx} - \sigma_{yy}}{\rho U_c^2} = \mathrm{Ws}\Big(\frac{\partial U}{\partial Y}\Big)^s \tag{5.7}$$

Next dividing by sides Eqs (5.7) and (5.6) one obtains the relative, referred to the shear stress, difference of normal stresses on the discussed vertical surface

$$\frac{\sigma_{xx} - \sigma_{yy}}{\sigma_{xy}} = \mathrm{Ws}\Big(\frac{\partial U}{\partial Y}\Big)^{s-n} \tag{5.8}$$

Fig.6 presents the transient changes of the relative difference of normal stresses in fluid, heated by the vertical surface temperature of which suddenly rises at $\bar{\tau} = 0$. Visible mutual intersections of the curves within the range of small values of time coordinate $\bar{\tau}$, i.e., the range of heat conduction dominance, may be explained by the presence of small gradients of velocity component $(\partial U/\partial Y < 1)$ within this region of time.

It is worth while to notice that local extremes of curves given in Fig.3 ÷ Fig.6, occur within the same periods of time, defined by approximate values of parameters Gr_x, Pr, Ws, n, s.

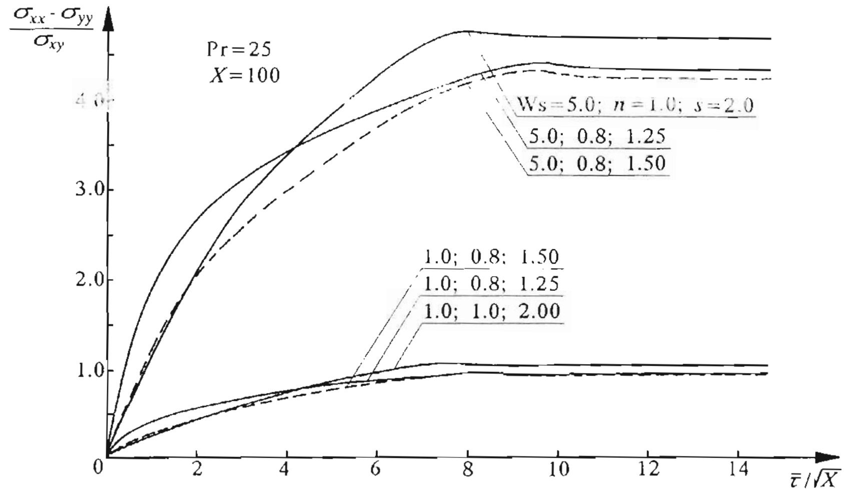

Fig. 6. Transient run of the relative difference of normal stresses on vertical surface

6. Conclusions

On the basis of numerical calculations of the natural convection in viscoelastic fluids with the assumed values of local Grashof number $Gr_x = 10^6$ and Prandtl number Pr=25 it comes out that the value of Nusselt number Nu_x actually depends on such parameters as Ws, n and s. It can be observed that the number Nu_x decreases while the Ws increases. whereas drop in values of indices n and s from $n = 1$ to $n = 0.8$ and from $s = 1.5$ to $s = 1.25$, respectively, makes Nu_x rise. Relative increase in $Nu_x/\sqrt[4]{Gr_x}$ in the Newtonian fluid $(n = 1)$ in comparison with the viscous fluid $(n = 0.8)$ reaches 22%. The influence of changes of parameters Ws, n and s on the number Nu_x is especially visible for longer time of the process $(\bar{\tau} > 70)$, where the convective heat transfer dominates. Moreover for the dimensionless time $\bar{\tau} > 70$ the rise in the number Ws causes the decrease of dimensionless shear stress on the vertical surface. Its relative value for the fluid defined by parameters $Ws = 1.0$, $n = 1.0$, $s = 1.5$ in relation to the corresponding shear stress in the Newtonian fluid reaches 7.7%.

Process of forming temperature and velocity gradients in discussed fluid in direction normal to the vertical surface heated by a sudden rise of temperature exists for the same values of time coordinate $\bar{\tau}$ which points to the analogy of processes of heat and momentum transfer. Values of the dimensionless time coordinate $\bar{\tau}$ which show local extremes of courses the number Nu_x visible and dimensionless stress σ_{xy} and relative difference of stresses $\sigma_{xx} - \sigma_{yy}$ occur within the interval $70 < \bar{\tau} < 100$ for the discussed fluid.

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Nieustalona konwekcja naturalna w płynie nienewtonowskim wykazującym własności lepkosprężyste

Streszczenie

W pracy rozwiązano zagadnienie nieustalonej konwekcji naturalnej w płynie lepkosprężystym rzędu drugiego znajdującym się w pobliżu pionowej powierzchni, której temperatura zwiększa się skokowo. Do rozwiązania równań różniczkowych bilansu masy, pędu i energii zastosowano metodę różnic skończonych. W rezultacie wyznaczono nieustalone pola temperatury i prędkości oraz nieustalone przebiegi zmian liczby Nusselta, bezwymiarowego naprężenia stycznego i względnej różnicy naprężeń normalnych. Otrzymane przebiegi porównano z dostępnymi w literaturze wynikami eksperymentów dla cieczy newtonowskiej w przypadku ustalonym.

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