NON-NEWTONIAN HEAT TRANSFER

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Contents

Summary

This chapter is devoted to heat transfer of non-Newtonian fluids but given the vastness of this topic it focuses on pipe flow after the presentation of the required governing equations. Before presenting results and correlations for laminar and turbulent heat transfer of purely viscous and viscoelastic fluids the chapter introduces the relevant non-dimensional numbers and in particular presents the various definitions of characteristic viscosity currently used. The correlations and data are useful to design heat transfer systems based on confined flows for fully-developed and developing pipe flows and the data are based on experimental, theoretical and semi-theoretical investigations. This chapter also discusses other relevant issues such as scaling methods, the degradation of fluids and the analogy between heat and momentum for viscoelastic turbulent flows. For other flows the reader is referred to the literature and complete forms of the required governing equations are presented in Appendix 1.

1. Introduction

Previous chapters in this Encyclopedia have already conveyed the complex nature of non-Newtonian fluids, often leading to remarkable flow features that contrast to those of Newtonian fluids. In particular, the previous chapters have shown that such characteristics are typical of a wide variety of fluids: concentrated and dilute polymer solutions, polymer melts, suspensions of particles, suspensions of immiscible liquids and surfactant solutions, amongst others. With few exceptions, blood and other biofluids for instance, a common denominator to all these fluids is that they tend to be synthetic, and consequently transfer of thermal energy not only takes place when they are being used, but also manufactured. Examples are the manufacture of plastic products by injection and extrusion, the production of paints, food products, chemicals or the use of "intelligent" thermal fluids in district heating and cooling systems, amongst other cases.

Investigations on heat transfer and friction with non-Newtonian fluids are as old as the studies on their rheology and fluid dynamics, and over the years there have been several reviews on the topic. As with Newtonian fluids, research and the solution of engineering problems on heat transfer and flow friction of non-Newtonian fluids can be carried out experimentally, theoretically and analytically. However, there is an important difference between Newtonian and non-Newtonian studies rooted in the non-linear nature of the latter. It emphasizes the role of experimental and, more recently, numerical methods when dealing with non-Newtonian fluids: whereas the rheological constitutive equation is known *a priori* for Newtonian fluids, for non-Newtonian fluids the rheological equation of state cannot be anticipated prior to an extensive fluid characterization, which anyway is invariably more complex than its Newtonian counterpart.

Heat transfer with non-Newtonian fluids is a vast topic given the wide range of fluids and flows of interest, and it cannot be covered in its vastness in this chapter. Internal flows are quite relevant in the scope of non-Newtonian fluid flows and heat transfer, with the pipe flow playing a leading role. Given the limited space available, it was decided to cover extensively this flow, but not all the possible combinations of heat transfer boundary conditions, with the expectation that the extensive treatment of the pipe flow case guides the reader towards other problems in this and other geometries. The review will also emphasize recent advances, especially for viscoelastic fluids. A fundamental approach will be followed to help the interested reader on the use of existing data and correlations for engineering purposes and to introduce heat transfer calculations in complex industrial non-Newtonian flows, especially for viscoelastic fluids described by differential constitutive equations, which over the last ten to fifteen years has become a reliable method for engineering purposes. In this work, a few reviews in the field will be used to some extent to limit the scope of this chapter.

Non-isothermal flows of viscoelastic fluids have captured the attention of researchers and engineers due to their industrial relevance. In recent times, there have been significant contributions in the thermodynamics of viscoelastic fluid flows leading to the development of more accurate rheological constitutive and energy equations accounting for such effects as storage of mechanical energy by the molecules, thermodynamics of non-equilibrium processes, temperature dependent properties, fluid compressibility and deformation induced anisotropy of heat conduction. The proper quantification of some of these effects is still a matter of research, but in most applications they are small, or inexistent, and can be safely ignored. In a few situations they may have to be considered, but these are rather advanced issues for this text and will not be pursued here. The interested reader is invited to further their knowledge in some of the advanced texts in the bibliography.

This chapter starts with the presentation of the relevant governing equations stating their assumptions and validity range and then proceeds to describe the required thermal fluid properties and their specificities for non-Newtonian fluids prior to addressing the applications. The focus is on pipe flow, dealing first with fully-developed laminar flow, followed by developing flow and the issues on thermal entrance length and viscous dissipation. The treatment of turbulent flow comes next and here the issue of drag and heat transfer reduction by additives is quite important. New experimental results will be presented, dealing both with polymer solutions and surfactants to shed light onto flow and heat transfer characteristics in the various flow regimes. Issues of combined forced and free convection will be briefly addressed, together with problems related to fluid degradation, solvent chemistry, solute type and the coupling between friction and heat transfer under turbulent flow conditions. Before the end some brief comments are also made on the subject of heat transfer in other fully-developed confined flows to warn the reader to the danger of generalizations to non-Newtonian fluids of arguments and conclusions based on Newtonian fluid mechanics and heat transfer.

2. Governing Equations

The behavior of viscoelastic fluids undergoing heat transfer processes is governed by the momentum, continuity and energy equations in addition to constitutive equations for the stress and the heat flux. For non-isothermal flows the momentum and rheological constitutive equations are affected in two ways relative to an isothermal case: dependence of fluid properties on temperature, leading to the buoyancy term amongst others and, on thermodynamic arguments the existence of extra terms in the constitutive equation, which can be traced back to the effect of temperature on the mechanisms acting at microscopic level. Such microscopic level changes, together with considerations of second law of thermodynamics for irreversible processes also affect the classical thermal energy equation. However, as mentioned in Section 1, the treatment of these extra terms is an advanced topic still under investigation and given their limited role in many engineering processes, they will not be pursued here. Another simplification in this text is the consideration of a constant and isotropic thermal conductivity, even though some non-Newtonian fluids do exhibit deviations from such idealized characteristics. A brief reference on how to deal with this problem is made later in this chapter.

In general, the fluid dynamics and heat transfer problems are coupled and the whole set of equations has to be solved simultaneously. For a general flow problem this can only be done numerically. However, when thermal fluid properties are considered to be independent of temperature (for instance, if temperature variations are small) it is possible to solve for the flow without consideration for the thermal problem (although not the other way around). In some other cases, the solution can still be obtained assuming temperature-independent properties, but a correction is introduced to compensate for the neglected effect. This is a fairly successful approach for simple geometries and simple fluids (such as inelastic fluids), but for viscoelastic fluids a more exact approach may be required for accurate results.

The general form of the governing equations is presented in Appendix 1. Since the review concerns pipe flow, the governing equations of Section 2.1 are presented in simplified form for steady pipe flow of incompressible fluids.

2.1. Equations for Pipe Flow

The equations of motion for laminar pipe flow of incompressible fluids are written in cylindrical coordinates with x, r and θ denoting the streamwise, radial and tangential coordinates and u and v denoting the streamwise and radial velocity components. For turbulent flow the governing equations to be considered are either those in Appendix 1, where all quantities are instantaneous and a solution must be obtained by Direct Numerical Simulation (DNS), or time-average quantities are being considered and extra terms originating from the nonlinear terms must be added. These extra terms contain correlations between fluctuating terms. The equations in this section are only valid under laminar flow conditions.

- Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rv\right)+\frac{\partial u}{\partial x}=0 \tag{1}$$

- x-momentum equation:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}\right)=-\frac{\partial p}{\partial x}+\rho g_x+\left(\frac{\partial \tau_{xx}^{\mathrm{T}}}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rx}^{\mathrm{T}}\right)\right) \tag{2}$$

- r - momentum equation:

$$\rho\left(v\frac{\partial v}{\partial r}+u\frac{\partial v}{\partial x}\right)=-\frac{\partial p}{\partial r}+\rho g_r+\left(\frac{\partial \tau_{xr}^{\mathrm{T}}}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rr}^{T}\right)-\frac{\tau_{\theta\theta}^{\mathrm{T}}}{r}\right) \tag{3}$$

where ρ is the fluid density, g_x and g_r are components of the acceleration of gravity vector and p is the pressure. The fluid total extra stress (τ_{ij}^{T}) is the sum of a Newtonian solvent contribution having a solvent viscosity η_{s} and a polymer/additive stress contribution τ_{ij}^{p} as in Eq. (4).

Constitutive equation:

$$\tau_{xx}^{\mathrm{T}}=2\eta_{\mathrm{s}}\frac{\partial u}{\partial x}+\tau_{xx}^{\mathrm{p}};\tau_{xr}^{\mathrm{T}}=\eta_{\mathrm{s}}\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right)+\tau_{xr}^{\mathrm{p}};\tau_{rr}^{\mathrm{T}}=\eta_{\mathrm{s}}\frac{\partial v}{\partial r}+\tau_{rr}^{\mathrm{p}};\tau_{\theta\theta}^{\mathrm{T}}=\eta_{s}\frac{v}{r}+\tau_{\theta\theta}^{\mathrm{p}} \tag{4-a}$$

$$\tau_{kk}=\tau_{xx}^{\mathrm{p}}+\tau_{rr}^{\mathrm{p}}+\tau_{\theta\theta}^{\mathrm{p}} \tag{4-b}$$

If an inelastic non-Newtonian fluid described by the Generalized Newtonian Fluid model is being considered, the above equations remain valid, with $\tau_{ij}^{\mathrm{p}}=0$ and the solvent viscosity no longer is a constant, but is given by a function $\eta_{\mathrm{s}}=\eta_{\mathrm{s}}\left(\dot{\gamma}\right)$ that depends on the second invariant of the rate of deformation tensor defined as $\dot{\gamma}\equiv\sqrt{2D_{ij}D_{ij}}$. The polymer/ additive stress contributions to the total stress are given by the remaining Eqs. (4).

- xx component

$$P\left(\tau_{kk}\right)\tau_{xx}+\frac{\lambda}{F\left(\tau_{kk},L^2\right)}\overset{\square}{\tau}_{xx}-\alpha\left(\tau_{xx}^2+\tau_{xr}^2\right)=\eta_{\mathrm{p}}\frac{\partial u}{\partial x}\text{ with}$$

$$\overset{\square}{\tau}_{xx}=v\frac{\partial \tau_{xx}}{\partial r}+u\frac{\partial \tau_{xx}}{\partial x}-2\tau_{rx}\frac{\partial u}{\partial r}-2\tau_{xx}\frac{\partial u}{\partial x}+2\xi\left[\tau_{xx}\frac{\partial u}{\partial x}+\tau_{rx}\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right)\right] \tag{4-c}$$

- xr component

$$P\left(\tau_{kk}\right)\tau_{xr}+\frac{\lambda}{F\left(\tau_{kk},L^2\right)}\overset{\square}{\tau}_{xr}-\alpha\left[\tau_{xr}\left(\tau_{xx}+\tau_{rr}\right)\right]=\eta_{\mathrm{p}}\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right)\text{with}$$

$$\overset{\square}{\tau}_{xr}=v\frac{\partial \tau_{xr}}{\partial r}+u\frac{\partial \tau_{xr}}{\partial x}-\tau_{rr}\frac{\partial u}{\partial r}-\tau_{xx}\frac{\partial v}{\partial x}-\tau_{xr}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}\right)+\xi\left[\frac{1}{2}\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right)\left(\tau_{xx}+\tau_{rr}\right)+\tau_{xr}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}\right)\right] \tag{4-d}$$

- rr component

$$P\left(\tau_{kk}\right)\tau_{rr}+\frac{\lambda}{F\left(\tau_{kk},L^{2}\right)}\overset{\square}{\tau}_{rr}-\alpha\left(\tau_{xr}^{2}+\tau_{rr}^{2}\right)=2\eta_{\mathrm{p}}\frac{\partial v}{\partial r}\text{ with}$$

$$\overset{\square}{\tau}_{rr}=v\frac{\partial\tau_{rr}}{\partial r}+u\frac{\partial\tau_{rr}}{\partial x}-2\tau_{rr}\frac{\partial v}{\partial r}-2\tau_{xr}\frac{\partial v}{\partial x}+2\xi\left[\frac{1}{2}\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right)\tau_{xr}+\tau_{rr}\frac{\partial v}{\partial r}\right] \quad (4\text{-e})$$

- $\theta\theta$ component

$$P\left(\tau_{kk}\right)\tau_{\theta\theta}+\frac{\lambda}{F\left(\tau_{kk},L^{2}\right)}\overset{\square}{\tau}_{\theta\theta}-\alpha\tau_{\theta\theta}^{2}=0\text{ with}$$

$$\overset{\square}{\tau}_{\theta\theta}=v\frac{\partial\tau_{\theta\theta}}{\partial r}+u\frac{\partial\tau_{\theta\theta}}{\partial x}-2\tau_{\theta\theta}\frac{v}{r} \quad (4\text{-f})$$

Equation (4) is a generalized equation for pipe flow containing several viscoelastic constitutive models depending on the numerical values of the parameters and on the specific forms of functions $F(\tau_{kk}, L^2)$ and $P(\tau_{kk})$. The reader is referred to Appendix 1 for the form of these functions, a brief explanation of the various viscoelastic models and to Table A01-1 for the corresponding numerical values of the parameters.

Energy equation

$$\rho cu\frac{\partial T}{\partial x}+\rho cv\frac{\partial T}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\tau_{rx}\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial x}\right), \quad (5\text{-a})$$

where k is the fluid thermal conductivity, T is the temperature and c is the specific heat of the fluid. These equations are valid for developing and fully-developed pipe flow in the absence of swirl. They are complex and coupled in a complex manner, but for fully-developed conditions, they can be further simplified because $v=0$ and all $\partial/\partial x$ =0, except for the pressure. This set of simplifications allows some analytical solutions, even though the equations remain coupled and provided fluid properties are constant. The energy Eq. (5-a) is also used in a simplified form, even for developing flow, after realization that $\partial v/\partial x << \partial u/\partial r$, i.e., that axial diffusion is far less important that radial diffusion and that radial heat convection is much weaker than axial heat convection, leading to Eq. (5-b)

$$\rho cu\frac{\partial T}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\tau_{rx}\frac{\partial u}{\partial r} \quad (5\text{-b})$$

Further simplification is possible after normalization of the temperature in a manner that is problem dependent, as will be seen later. These equations will be used in subsequent Sections to obtain some relevant heat transfer solutions. When an analytical solution is not possible then the problem must be solved numerically or experimentally.

3. Boundary and Initial Conditions

The solution of differential equations requires adequate boundary and initial conditions. For the velocity at a wall the no-slip condition is imposed whereby the velocity of fluid particles in contact with the wall is equal to the wall velocity. Most commonly this velocity is null ($u_i = 0$ at walls) unless the wall is porous with flow across. For unsteady flows it is also necessary to define the initial condition for the velocity, which is a prescribed velocity profile at some location, usually at the inlet. Symmetry conditions may also be imposed if the geometry is symmetric and it is known *a priori* that the flow is symmetric. This may seem trivial, but there are many situations where geometry and boundary conditions are symmetric and steady, whereas the flow is not, in which case the full domain must be used to obtain a solution to the problem. In numerical calculations there is also a problem of setting boundary conditions at outlets. This is usually solved by putting the outlet sufficiently far from the region of interest to allow setting there a fully-developed condition, which does not affect the flow in the latter region.

For pipe flow the main boundary condition is no-slip at the wall and symmetry on axis. If the flow is fully-developed it is not necessary to consider the radial component of velocity and these conditions are enough providing the axial pressure gradient is known. Alternatively, the flow rate is given and the constant pressure gradient is calculated as a function of the flow rate after integration of the velocity profile. For developing flow it is also necessary to impose an inlet condition, which very often is a plug profile (at $x = 0$, $u = cte$ and $v = 0$). Again, a solution is obtained for a specific value of the pressure gradient or a flow rate is given which determines dp/dx. Note that in a developing region dp/dx is not constant.

For the temperature equation a similar problem exists, but now this is complicated by the infinite number of possible combinations of wall temperature and wall heat flux conditions. In general terms, the problem of the boundary conditions for temperature are similar to those for velocity, but compounded by the wider number of possibilities. It is necessary to provide also inlet and outlet conditions for steady flows and initial conditions for unsteady heat transfer. The issue of symmetry is also made more complex, because it is possible to have a symmetric flow with an asymmetric heat transfer problem, provided the velocity field is decoupled from the temperature field (a possibility if temperature differences are small). Some of the simpler more commonly used boundary conditions, for which there are analytical solutions in pipe flow, are presented below. The thermal solution is very much dependent on the boundary condition for laminar flow and less so for turbulent flow due to improved mixing of the fluid. Fluids possessing large values of the ratio between momentum and heat diffusivities, denoted Prandtl number, are also less sensitive to the type of thermal boundary condition.

For flows in pipes, the main focus in this review, the main boundary conditions are:

1. T condition: constant wall temperature;
2. H2 condition: constant wall heat flux imposed both axially and peripherally.

In all cases it is also necessary to impose an inlet temperature profile.

For other geometries, these conditions equally apply. If not all the walls are heated, then the boundary condition combines with the number of heated walls. Obviously, more complex thermal boundary conditions can also be used, such as a prescribed variable wall temperature or wall heat flux or combinations of all these.

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Bibliography

Aguilar, G., Gasljevic, K. and Matthys E. F. (2001). Asymptotes of maximum friction and heat transfer reductions for drag-reducing surfactant solutions. *Int. J. Heat Mass Transfer* 44, 2835–2843. [A new maximum drag reduction asymptote for surfactant solutions is presented based on experiments with a wide variety of solutions. This work also shows that the use of the solvent viscosity to compute the Reynolds and Prandtl numbers underestimates the friction coefficient].

Aguilar, G., Gasljevic, K. and Matthys, E. F. (1999). Coupling between heat and momentum transfer mechanisms for drag-reducing polymer and surfactant solutions. *ASME Journal of heat transfer* 121, 796-802. [Investigation on heat and momentum transfer of drag-reducing pipe flows aimed at assessing the existence of an analogy in both the asymptotic and non-asymptotic regimes. This experimental work shows drag and heat transfer reductions to be coupled and related by a constant turbulent Prandtl number, which assumes different numerical values for polymer and surfactant solutions]

Barletta, A. (1997). Fully developed laminar forced convection in circular ducts for power-law fluids with viscous dissipation. *Int. J. Heat Mass Transfer* 40, 15–26. [An analytical investigation to determine the temperature field and heat transfer for laminar fully-developed forced convection of a power-law fluid in a pipe taking into account viscous dissipation, while neglecting axial heat conduction.]

Choi, U. S., Cho, Y I. and Kasza, K. E. (1992). Degradation effects of dilute polymer solutions on turbulent friction and heat transfer behavior. *J. Non-Newtonian Fluid Mech.* 41, 289-307. [Experimental investigation on long-term degradation for dilute polymer solutions (Polyox WSR-301 and Separan AP-273 at 200 wppm) in turbulent pipe flow using a closed loop flow system, and quantifying the impact on drag and heat transfer coefficients.]

Coelho, P.M. and Pinho, F.T. (2009). A generalized Brinkman number for non-Newtonian duct flows, *J. Non-Newtonian Fluid Mech*. 156, 202–206.[In this work a generalized Brinkman number is proposed, based on an energy balance for the power dissipated by friction]

Coelho, P. M., Pinho, F. T. and Oliveira, P. J. (2003). Thermal entry flow for a viscoelastic fluid: the

Graetz problem for the PTT model. *Int. J. Heat Mass Transfer* 46, 3865–3880. [A theoretical study of the entrance thermal flow problem in pipes and channels for fluids obeying the simplified Phan-Thien and Tanner (PTT) constitutive equation].

Coelho, P.M., Pinho, F.T. and Oliveira, P.J (2002). Fully developed forced convection of the Phan-Thien –Tanner fluid in ducts with a constant wall temperature. *Int. J. Heat Mass Transfer* 45, 1413-1423. [Analytical solutions for fully-developed laminar pipe and channel flows of Phan-Thien—Tanner fluids under an imposed constant wall temperature.]

Gasljevic, K. and Matthys E. F. (1997). Experimental investigation of thermal and hydrodynamic development regions for drag-reducing surfactant solutions. *ASME Journal of Heat Transfer* 119, 80-88. [Investigation on drag and heat transfer reduction for turbulent pipe flows of surfactant solutions in the thermal entrance region.]

Gasljevic, K., Aguilar, G. and Matthys E. F. (2001). On two distinct types of drag-reducing fluids, diameter scaling and turbulent profiles. *J. Non-Newtonian Fluid Mech*. 96, 405-425. [Investigation on scaling methods for drag and heat transfer reduction pipe flows of polymer and surfactant solutions. Two distinct scaling procedures are reported: one procedure correlates the relative drag reduction with flow bulk velocity and appears applicable to fluids that comply with the 3-layers velocity model, namely many polymer solutions and some surfactants. The second scaling procedure relates the wall shear stress with the flow bulk velocity and is applicable to fluids for which the slope of temperature increase with bulk velocity in a fan-type manner, the case of many surfactant solutions and some polymer solutions.]

Gasljevic, K., Aguilar, G. and Matthys E. F. (2000). Buoyancy effects on heat transfer and temperature profiles in horizontal pipe flow of drag-reducing fluids. *Int. J. Heat Mass Transfer* 43, 4267–4274.[Experimental investigation on buoyancy effects in horizontal laminar and turbulent pipe flows of drag-reducing fluids. In laminar flow distortions of the temperature field by buoyancy lead to variations in Nusselt number that are larger than for the corresponding Newtonian flow. In turbulent flow buoyancy effects can also be large and should be properly accounted for, but no quantification is presented.]

Hartnett, J. P. and Cho, Y. I. (1998). *Non-Newtonian fluids*. Handbook of heat transfer chap. 10, (3rd ed. W. Rohsenow, J. Hartnett and Y. Cho), 10.1–10.53. New York: McGraw-Hill. [Late 1990's review of fluid mechanics and forced convection heat transfer of non-Newtonian duct flows].

Hoyt, J. W. and Sellin, R. H. J. (1993). Scale effects in polymer solution pipe flow. *Experiments in Fluids* 15, 70-74. [Presents a new scaling method for the non-asymptotic regime of polymer solution drag reduction in pipes. This method is based on the use of a modified Colebrook-White equation where the drag reduction is made equivalent to a negative relative roughness. This method also allows the determination of the *f-Re* relation for a pipe of diameter D_2, provided the same information is available for a pipe of diameter D_1.]

Irvine, T. F. and Karni J. (1987). *Non-Newtonian fluid flow and heat transfer*. Handbook of single-phase heat transfer, chap. 20 (Kakac S., Shah, R. H. and Aung, W.) John Wiley & sons New York [A 1987 review of some aspects of non-Newtonian fluid mechanics, fluid rheology and heat transfer for flows of power-law fluids with relevance to engineering practice].

Lee, D.-L. and Irvine, T. F. (1997). Shear dependent thermal conductivity measurements of non-Newtonian fluids. *Experimental Thermal and Fluid Science* 15, 16-24. [Experimental determination of thermal conductivities of non-Newtonian purely viscous and viscoelastic fluids in steady shear flow using a coaxial cylinder apparatus.]

Matthys, E. F. (1991). Heat transfer, drag reduction and fluid characterization for turbulent flow of polymer solutions: recent results and research needs. *J. Non-Newtonian Fluid Mech*. 38, 313-342 [Some results of investigations on heat transfer and drag reductions for pipe flows of viscoelastic polymer solutions discussing also the effects of polymer concentration and mechanical degradation.]

Matthys, E. F. (2005). *Heat transfer to Non-Newtonian fluids*. The engineering handbook, chap. 56, (2nd ed.): CRC Press. [Summary of the 2005 state of the art on heat transfer in non-Newtonian duct flows including bibliographic references about the latest developments in the field].

Poole, R. J. and Ridley, B. S. (2007). Development-length requirements for fully developed laminar pipe flow of Inelastic non-Newtonian liquids. *ASME Journal of Fluids Engineering ASME* 129, 1281-1287. [Detailed systematic numerical investigation of dynamic pipe flow development of inelastic non-

Newtonian power-law fluids. A judicious choice of the Reynolds number collapses data for the development length at high Reynolds number onto a single curve whereas at low Reynolds numbers the development length is always finite and a function of the power-law index]

Virk, P. S., Mickley, H. S. and Smith, K. A. (1970). The ultimate asymptote and mean flow structure in Toms' phenomenon. *ASME Journal of Applied Mechanics*, 37, June 488-493 [Compilation of experimental data at maximum drag reduction leading to Virk's ultimate asymptote for maximum drag reduction. Formulation of the three-zone-layer model for the law of the wall.]

Wapperom P. (1995). Non-isothermal flows of viscoelastic fluids. Thermodynamics, analysis and numerical simulation. PhD thesis, Delft University of Technology, Holland. [This thesis derives the general forms of the thermodynamic, momentum and energy equations for viscoelastic fluids, discussing in particular the new contributions from viscoelasticity that modify the classical forms of the equations. Then it implements the energy equation into an existing finite-element code for viscoelastic fluid flows and performs numerical investigation of polymer melt flows in a variety of geometries to assess the relevance of the various new terms of the balance equations.]

Biographical Sketches

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