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Efficient heat transfer in a regime of elastic turbulence

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Résumé :

La conception d'échangeurs performants doit aboutir à un compromis entre une augmentation des performances thermiques et une minimisation des pertes de charge. Depuis une dizaine d'années, de nombreux systèmes miniaturisés ont été étudiés. Dans ce cas, les nombres de Reynolds atteignent de très faibles valeurs et l'utilisation du régime d'advection chaotique classique requiert un design particulier de microcanaux tridimensionnels, design impossible à réaliser à cette taille. Un moyen alternatif est d'introduire une source de non-linéarité dans les équations hydrodynamiques, autrement que par le terme d'inertie en utilisant des fluides complexes. L'objectif de cette étude est de comprendre comment le mouvement aléatoire d'un fluide en régime de turbulence élastique peut augmenter le transfert thermique.

Abstract :

The design of efficient heat exchangers requires a judicious compromise between the thermal performance and the minimisation of the heat losses. For over fifteen years, various microscopic heat exchanger devices have been studied. Each of such devices is constrained to operate at low Reynolds number. The use of the classical laminar chaotic advection in order to efficiently transfer the heat requires particular tridimensional designs which are often difficult to implement at a microscopic scale. An alternative solution for an efficient heat transfer is to introduce an extra nonlinearity (other than the inertia) in the hydrodynamic equations by using complex fluids. The global aim of this study is to illustrate how the random fluid motion in a regime of Elastic Turbulence can enhance the transfer of heat in the absence of any relevant inertial contribution.

Mots clefs : elastic turbulence ; rheology ; heat transfer

1 Introduction

The intensification of mass and heat transfer is of great practical importance to many industrial and laboratory applications (mechanical and thermal processing of food products, manufacturing of pharmaceutical and cosmetic products, etc). A more specific example comes from the industry of semiconductors and microprocessors. Indeed, the increase in the processor (CPU) power for small electronic systems such as smartphones and tablets requires an effective method of cooling in order to efficiently evacuate the heat released by the device. A classical and efficient cooling method employs the turbulent circulation of fluids around the device. In the case of newtonian fluid, such as water, the flow is likely to be turbulent when the Reynolds number, $Re = \rho V L / \eta$, is high, *i.e.* the nonlinear inertial term $(\vec{V} \cdot \nabla) \vec{V}$ in the Navier-Stokes equation (1), overcomes the viscous dissipative term $\nu \Delta \vec{V}$, [1].

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla) \vec{V} = -\frac{\nabla p}{\rho} + \nu \Delta \vec{V} \quad (1)$$

Here \vec{V} is the fluid velocity, p the pressure, ρ the fluid density and ν the kinematic viscosity. However, there exist a number of cases when working at high Reynolds numbers is highly unpractical or even impossible. That is the case of flow microchannels where the small spatial scales seriously limit the

values of the Re . The chaotic advection, which is the production of Lagrangian chaotic trajectories, is an effective mean for efficient heat transfer in the absence of unpractically high pressure drops. Since the first work of Aref [2] on the time-periodic flows (2D), many authors have studied the increase of mass and heat transfer of chaotic advection regime in different configurations [3, 4, 5]. Nevertheless, even if the laminar chaotic advection can be obtained at very low Reynolds numbers (of the order of 1)[6, 7], this requires a complex design of three-dimensional microchannel, which is often challenging. An alternative way to generate a chaotic flow that solves the problem is to introduce a source of non-linearity in the hydrodynamic equations other than that induced by inertia. This source of non-linearity is introduced by the non-linear dependence between stress and shear rate. This can be achieved by using complex fluids, consisting of blocks long molecular chains that can interact, in a nonlinear fashion, with the flow. An example of this type of chaotic flow is *Elastic Turbulence*. Elastic turbulence is a chaotic hydrodynamic state observed in the curvilinear flows of diluted solutions of flexible high-molecular-weight polymers [8]. It can be observed at arbitrarily small Re , since the elastic instability is solely driven by the non linear elastic stresses. Indeed, long polymer molecules added to a fluid make it elastic and capable of storing stresses that depend on the history of deformation, thereby providing the fluid with a memory [9]. Many properties of the polymer solution flows (especially dilute ones) can be understood on the basis of single polymer dynamics, since a polymer chain experiences the combined action of the stretching by the flow and the elastic relaxation. The elastic stress generated by the polymer stretching in the flow becomes the main source of nonlinearity in the polymer solution flow at low Re . Thus, the equation of motion (2) becomes more complicated.

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla) \vec{V} = -\frac{\vec{\nabla} p}{\rho} + \left(\frac{\eta_s}{\rho}\right) \Delta \vec{V} + \frac{\nabla \tau_p}{\rho} \quad (2)$$

Here τ_p stands for the elastic stress tensor which is due to the presence of stretched polymer molecules and η_s is the viscosity of the newtonian solvent. An elastic instability emerges when the elastic energy overcomes the dissipation due to polymer relaxation. The ratio of the nonlinear elastic term to the linear relaxation is defined by the Weissenberg number which is defined by $Wi = \lambda \dot{\gamma}$, where λ is polymer relaxation time and $\dot{\gamma}$ the rate of shear. The mixing efficiency in a elastic turbulence regime has been demonstrated experimentally for the first time in a macroscopic curvilinear channel [10]. The mixing experiments were carried out by injecting two identical polymer solutions, one on each side of the channel (one of them contained a low concentration of fluorescein). This study revealed a higher mixing efficiency (nearly two orders of magnitude) than that achieved by molecular diffusion alone. This mixing method at low Reynolds number has already been patented [11]. More recently, many studies have focused on the mixing properties in microfluidic systems [12, 13, 14]. The aim of the present study is to understand how the random fluid motion in a elastic turbulence regime can increase the efficiency of the heat transfer.

2 Experimental set-up and procedure

The experimental apparatus is schematically shown in Figure 1. The polymer solution was held in a stationary cylindrical cup (CC) with a flat bottom (lower plate). The cup radius was, $R_c = 80mm$, the length, $l_c = 80mm$. The cup was mounted on a commercial rheometer, HAAKE MARS (Modular Advanced Rheometer System). The upper plate (P) (with as radius $R_p = 78mm$) which just touches the free surface of the polymeric fluid was attached to the shaft of the rheometer. This allows a precise control of the upper plate velocity, Ω and the measurements of motor torque, T_m , which gives the average shear stress at the upper plate, τ , using the expression $\tau = 3T_m/2\pi R_p^3$. The shear rate, $\dot{\gamma}$, is given by the relation $\dot{\gamma} = \Omega R_p/d$, with d the distance between plates. The bottom of the cylindrical cup is placed on the top of a second cup (PC) in which water at constant temperature is circulated for heating or cooling the polymeric fluid. The water flow is maintained and thermally stabilised by thermostatic bath (Lauda). To measure the temperature fluctuations and distribution along the vertical direction, six mobile thermocouples that can move along the radial direction are placed on the side face of the cylindrical cup (see Figure 1). The two cups are made from Plexiglas so that the fluid can be illuminated with view of a characterization of the flow field by PIV. A mirror oriented at 45° is positioned below the cups for flow visualization and measuring velocity fields.

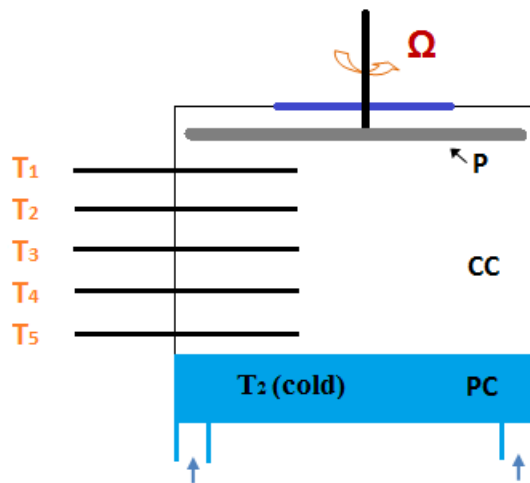


FIGURE 1 – Overview of the swirling flow apparatus : CC-cylindrical cup, PC-parallelepipedic cup, P-top disc, Ω -rotation velocity, $T_{c1, 2, 3, 4, 5}$ -mobile thermocouples.

The polymer used was polyacrylamide (PAAM) with the molecular weight $Mw = 18 \times 10^6 Da$. The polyacrylamide is a model viscoelastic fluid for this kind of experience, since it is possible to control its properties (concentration, viscosity, etc..), and its laboratory handling is easier than, for example, a molten plastic. It also proves to be remarkably stable with respect to mechanical degradation [9, 15], which allows to reach high values of Wi and to explore strongly non-linear flow regimes. The high molecular weight of polymer translates into a large characteristic relaxation time [9]. The preparation of the solution is done in two stages. First, we prepare highly concentrated aqueous solution, $1500 ppm$ (0.15%, by dissolving the polymer powder in water. We add to it sodium azide (in very small amounts, 0.025%) to prevent the bacterial growth, and isopropanol (0.01%), in order to preserve the solution from ageing. Next, the solution was diluted to a concentration of $100 ppm$ using as solvent highly concentrated sugar solution (around 66% which close to the solubility limit), in order to maximise the relaxation time of the solution and also minimise the Reynolds numbers ($Re < 1$) in order to separate the elastic non-linearity from the inertia. The polymer relaxation time, λ , was measured in oscillatory tests [15] at different shear rates, $\dot{\gamma}$, ranging from $0.2s^{-1}$ to $1.2s^{-1}$ (Figure 2).

3 Results

3.1 Observation of the elastic turbulence

The remarkable work of Groisman and Steinberg, [2, 3] has already captured one of the main features of the elastic turbulence manifested by a substantial growth of flow resistance above the onset of the instability. In the case of a von Karman swirling flow, a measure of the flow resistance is the power needed to spin the upper plate a constant angular speed [16, 17], $P = T_m \Omega = (2\pi R^3/3)\tau\Omega$. In first experiment, the shear rate, $\dot{\gamma} = \Omega R_p/d$, was gradually increased in time very slowly, then decreased at the same speed. The stress values thus measured allow one to obtain the evolution of the injected power. The dependence of P/P_{lam} on the Weissenberg number $Wi = \lambda(\dot{\gamma})\dot{\gamma}$ is shown in figure 3. P_{lam} stands for the injected power measured in a laminar regime and scales as $P_{lam} \propto Wi^{3.1}$. One can note a sharp transition in Fig. 3 which occurs at $Wi_c \approx 6$. The Reynolds number at the transition point is about 0.16 , so that the instability can not be inertial. The transition has pronounced hysteresis, which is rather typical for the purely elastic flow instability [18]. The data presented in Figure 3 reveal three distinct flow regimes : laminar (L), transitional (T) and turbulent regime (ET). These results will allow us to choose our control parameters to be in the range of elastic turbulence regime.

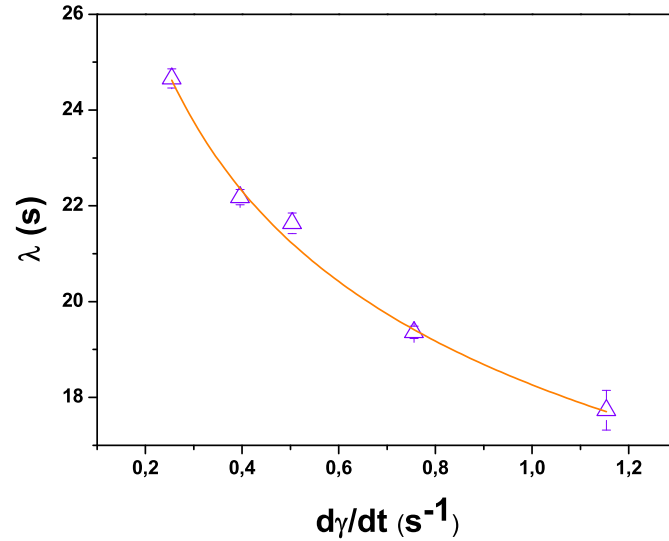


FIGURE 2 – Polymer relaxation time, obtained from oscillation measurements (frequencies ranging from $0.1Hz$ to $1Hz$), as a function of $\dot{\gamma} = d\gamma/dt$. The full line is a fit $18.26\dot{\gamma}^{-0.22}$

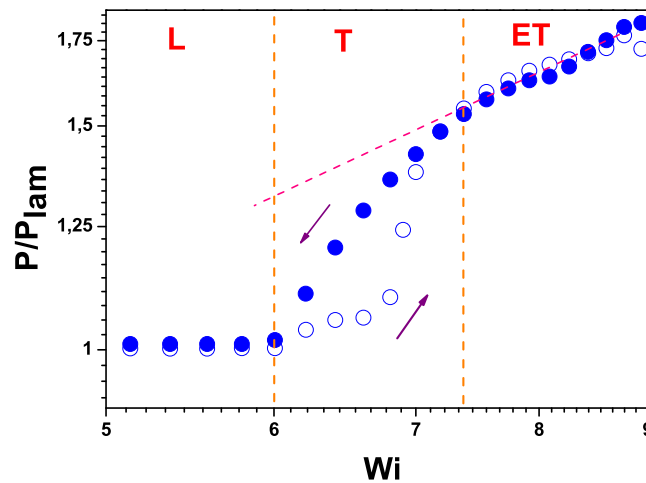


FIGURE 3 – The ratio of the power P to the power $P_{lam} \propto Wi^{3.1}$ measured in laminar shear flow as a function of the control parameter Wi . Empty circles : increasing Wi ; full circles : decreasing Wi . L-laminar, T-transition, ET-elastic turbulence. The dotted line is $Wi^{3.9}$

3.2 Efficiency of the heat transfer

In order to quantitatively assess the efficiency of the heat transfer in a regime of elastic turbulence, we combine the rheological measurements with measurements of the temperature distribution and fluctuations within the cel. The fluid is cooled from $23^{\circ}C$ to $16^{\circ}C$, while the top plate rotates at a constant speed. The measurements were repeated for different values of angular plate speed in order to monitor the temperature evolution versus time for various Wi numbers. The goal of these tests is to observe and compare the dynamics of the time series of temperature within each flow regime : E, T and ET. Figure 4 illustrates the signals from a single thermocouple placed at $d = 35mm$ (measured from the bottom plate) and at $r = 0$ (the center of the cup). It can be clearly seen that the heat transfer is intensified by the elastic turbulence at $Wi = 11.07$. To quantify the efficiency of the heat transfer, we monitor two quantities : the temperature homogenization time, t_h (Figure 6) and the rate of cooling, $|b|$ (Figure 5) obtained via a power fit ($y = ax^{-b}$) of the upper part of the temperature time series. One

can see in Fig. 5 that the cooling rate $|b|$ is nearly three times higher in the elastic turbulence regime than laminar regime. Consistently with this, the time needed for the temperature homogenisation t_h is two times smaller.

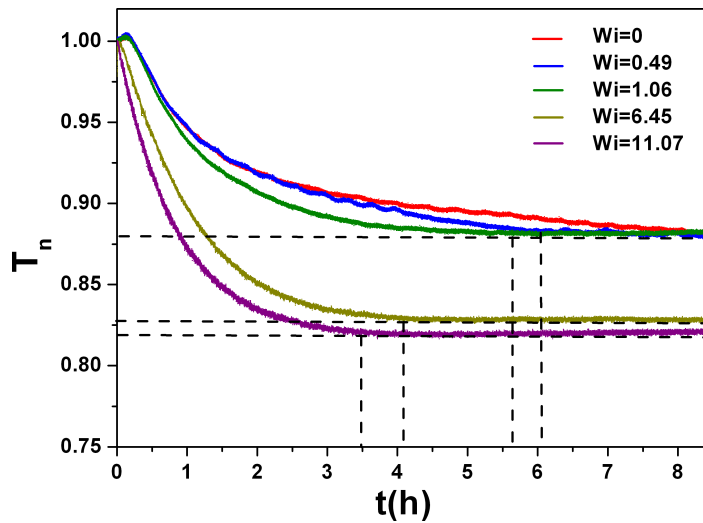


FIGURE 4 – Times series of temperature of the fluid for different values of the Weissenberg number Wi indicated in the insert. The initial temperature is $T_0 = 23^\circ C$ and the final temperature is $T_1 = 16^\circ C$. The normalised temperature is defined as $T_n = T/T_0$.

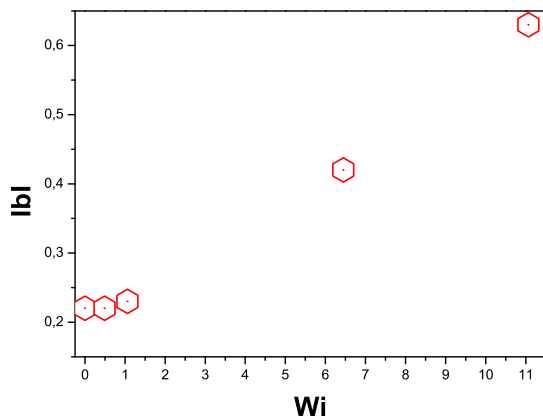


FIGURE 5 – Dependence of absolute value of the exponent, $|b|$ from fit $y = ax^{-b}$, on the Weissenberg number Wi .

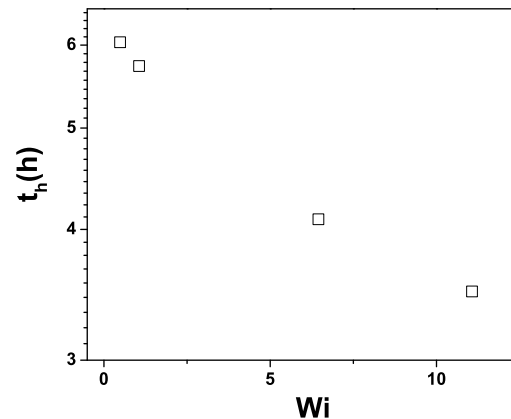


FIGURE 6 – Dependence of time needed for the temperature homogenisation t_h on the Weissenberg number Wi .

4 Conclusions

An experimental study of the efficiency of the heat transfer in a random von Karman flow in a regime of elastic turbulence is presented. High viscosity of the solvent and large relaxation time of the polymer molecules ensured an elasticity-dominated-flow regime where the effect of the non-linear constitutive relation between polymer stress and the rate of deformation are significantly more pronounced than the inertia-related non-linearity in the Navier-Stokes equation. The preliminary assessment indicates a clear increase of the efficiency of the heat transfer within a regime of elastic turbulence. Thus, the cooling rate increases three fold and the time of homogenisation of the local temperature is twice smaller. Our experimental investigation clearly demonstrates that the elastic turbulence can be successfully used

to efficiently transport heat in fluid media in situations where achieving large values of the Reynolds numbers is either unpractical or impossible.

Future studies will focus on the topology of the temperature field (especially within the boundary layer of the elastic stresses) and possible changes in the velocity field compared to the isothermal regime. These studies will be carried out by combining particle image velocimetry (PIV) and measurements of the temperature field by non-intrusive methods (liquid crystals, or temperature LIF).

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