# THERMAL STUDY OF THE NON NEWTONIAN << SOLID - LIQUID >> SUSPENSIONS BASED ON CARBOXYMETHYLCELLULOSE IN THE FLOW OF A HORIZONTAL DUCT

Benoît Fanou Z. **FAGLA***, Michel **GRADECK****, **Christophe BARAVIAN****, Michel **LEBOUCHE****

*** Laboratoire d'Energétique et de Mécanique Appliquée (LEMA),** Ecole Polytechnique d'Abomey-Calavi/Université d'Abomey-Calavi 01 B.P. 2009 Cotonou (Bénin).

**** Laboratoire d'Energétique et de Mécanique Théorique et Appliquée (LEMTA)** CNRS/ INPL / UHP1, avenue de la forêt de Haye - BP 160 54504 Vandoeuvre-lès-Nancy cedex (France).

## Abstract

On this paper we present the results of an experimental study of heat and hydrodynamical treatment of Non Newtonian solid-liquid suspensions in a horizontal pipe. Aseptic and organoleptic quality of these products depends primarily on the continuous heating in food industry. The presence of particles in the solution containing Carboxymethylcellulose (C.M.C.) changes the rheology of the carrier fluid. Heat sterilization, continuous way of food fluid loaded in spherical hard particles of large dimensions (diameter D ≈ 4.4 mm and aspect d / D ≈ 0.13) without denaturation of the carrier fluid is a major problem for industry and researchers. It is necessary to provide answers to these concerns; the present non isothermal study was conducted from measurements of temperature at the wall. It is also made with the velocity field measurements to demonstrate the influence of hard spherical particles on the heat.

**Keys-words:** Thermal, Suspensions, Solid-liquid, Particle, food-industry.

## Nomenclature

### Latin notation

$Cf$ : coefficient of friction

$c_p$ : Specific heat at 20 ° C

u : velocity

$U_d$ : flow velocity

r : radius

$T$ : temperature

z : length

d : average diameter of a particle

D : diameter of the pipe

$h$ : heat transfer coefficient

$h(z)$ : local exchange coefficient

$t_c$ : displacement characteristic time of a particle with avec $t_c = \frac{1}{\dot{\gamma}_c}$

$\dot{\gamma}_c$ : critical shear rate with $\dot{\gamma}_c = kT / \eta . a^3$

$T_m(z)$ : average temperature

ISSN 2229-5518

$T_P$ : wall temperature

z : length

$\dot{M}$ : mass rate

$Te$ : inlet temperature

**Greek Notation**

$\rho$ : density at room temperature

$\varphi_p$ : heat flux of parietal density

$\lambda$ : thermal conductivity

$\dot{\gamma}_P$ : shear rate at the wall.

$\eta$ : viscosity

$\eta_0$ : viscosity of the suspending fluid,

$\eta_{eff}$ : effective viscosity

$\eta_m$ : viscosity of the mixture

$\eta_p$ : viscosity of the mixture

$\phi_p$ : fraction with maximum stacking with $\phi_p \approx 0{,}64$.

$\phi$ : volume fraction of particles

$\rho$ : density

$\varepsilon$ : coefficient showing the temperature dependence of CarboxyMethylCellulose (CMC)

such as $\varepsilon = \left[\left(-\frac{1}{\eta}\frac{d\eta}{dT}\right)\frac{\varphi_p.D}{2.\lambda}\right]^{\alpha}$

b : coefficient showing the temperature dependence of CarboxyMethylCellulose (CMC)

such as b = $\left[-\frac{\partial\eta}{\eta\partial T}\right]$

$\xi$ : it is the coefficient, resulting from following product, $\xi = \varepsilon.\Delta^{1/3}$

$\Delta$ : it is the ratio of parietal velocity gradient for Non-Newtonian fluid to that obtained for Newtonian fluid

**Dimensionless numbers**

$G_Z$ : Number of Graetz

$X^+$ : Cameron number

$Nu$ : Nusselt number

$Nu(z)$ : local Nusselt number

$Nu_{nn}(z)$ : local Nusselt number in a Non-Newtonian fluid

$Nu_{n}(z)$ : local Nusselt number in a Newtonian fluid

## Introduction

The industrialists of the agro-food sector show evidence of imagination by proposing more and more new products to consumers. This raises new problems to solve notably to guarantee some organoleptic and sterile properties of these products destined to consumption on a big scale. It is to bring the necessary answers to their preoccupations that the present study is undertaken from measures of the temperatures in the partition. These new products as the milky desserts, sauces,… often have a complex rheological behavior, Non-Newtonian. Besides, these fluids are more and more loaded in solid particles as the yogurts with pieces of fruits, jams,... that completely modify the hydrodynamics and the heat sciences of the out-flow of the carrier fluid. Most fluids and mixtures produced by the agroalimentary industries present some complex rheological properties, possibly dependent on the temperature. The knowledge of these properties is primordial in order to model, with precision, all phases of a process during which the product is going to undergo multiple physico-chemical transformations at the time of the transportation phases, heating, cooling and conditioning. In the case of the very viscous fluids or at threshold, loaded with particles or not, the thermal transfer essentially takes place by conduction of the partition of the intersection toward the heart of the flow. This transfer mode accentuates the times of stay and can lead to denaturations of the product in the wall zone (wall fouling, burning) without guaranteeing the complete aseptisation of the fluid and the particles. Processes permitting a correct brewing of the very viscous fluids loaded already exist (scraped surface exchangers, chaotic heat exchangers). The use of plate heat exchangers is delicate or even impossible in the case of the solid-liquid suspensions because they can cause a denaturation of the particles and their hydraulic diameter is too weak to permit the flowing of the suspension. The mechanisms of transfer between the loaded liquid and the wall, between the liquid and the particles are problems still less mastered. Important issues they arouse, deserve theoretical and experimental studies to in order to palliate lack of knowledge The factors influencing on the transportation and the heat transfer of the loaded liquids are the size of the particles, the concentration in particles, the regime of the suspension flow, the rheological characteristics of the carriers fluids, the hydraulic diameter and the report of fluid-particle density. The hydrodynamics of these fluids loaded of particles is sometimes governed by a behavior law that undergoes some variations according to the conditions of transportation and heating in which the flowing of this mixture takes place. Authors Kono and al. (1979) established transfer laws for the suspensions of spheres of resin or glass in water, in a vertical tube where the aspect ratios of the diameters (d / D) range vary from $7{,}910^{-3}$ to $12{,}510^{-3}$. They calculated, for the mixture, the Nusselt number ($Nu = h.D/\lambda$) while making the hypothesis that the spheres and the fluid are at the same temperature. The temperatures are measured at the wall by thermocouples. The heating of the mixture is assured by a device of heated water circulation giving a constant wall temperature. Kono and al., took in account the correction of viscosity by the factor $\left(\frac{\eta_P}{\eta_m}\right)$. Most of the authors propose a Graetz type of solution in which Non-Newtonian character is taken into account in the svelocity profile. Lyche and Bird (1956) worked on pseudoplastic fluid. So for the first time, a dimensional analysis has been applied to the simplest case by Krieger (1963). The author used suspensions of small hard monodisperse spheres of radius a, suspended in a Newtonian fluid, with viscosity, of the same specific mass as the solid particles with only hydrodynamic interactions. Studies on the hydraulic transport of solid particles permit now fully understand the problem of drop, in horizontal tube, which is strongly related to two-phase flow regime: Chhabra (1990), Cheng, (1970), Kemblowski and Kolodziejski (1973), Takahashi (1978). Durand (1953) as well as Kyokai (1981) and Ayukawa (1970) put in evidence four main regimes of flow as the symmetrical, asymmetric flows, in circulating bed and in stationary bed which essentially depend on the average velocity of the suspension and on the limit velocity of the fall of the particles.

In the case of a Non-Newtonian fluid, the rheological characteristic of the fluid can be very dependent on the temperature. This rheological evolution influences the parietal gradient of velocity; it acts therefore on the temperature profile of the mixture zone.

Scirocco (1985) took again the expression introduced by Joshi and Bergles (1982) that translates the temperature dependency of the flux consistency of imposed heat. El Ouardighi (1990), in a numeric and experimental study of the flow and the transfer of heat for Non-Newtonian thermodependent fluids in industrial conducts, showed the factor of pseudoplaticity at the third power. As for the Sastries and al (1990), they used a sphere joined to a thermocouple moving within a water flow at 45°C. The authors made different parameters vary to show their influence as the report d/D, the volumic mass of the spheres and the rate of flow of the monophasic fluid. The measure of the velocities of the monophasic fluid and of the particles permitted to control the velocity of sliding. The comparison of the coefficient of heat transfer by convection $h$ with the previous studies, showed a growth of the coefficient $h$ in relation to the Lee and Singh's study (1990) and a partial recovery of the values of Sastry and al (1990), of Heppell (1985) and of Stoforos and al (1991). Balasubramamian and Sastry (1996) implanted a miniaturized thermocouple transmitter in a spherical and cylindrical particle. The temperature of the free particle within the fluid is transmitted to a receiver that records its temporal evolution. The coefficients of exchange in relation with the number of Nusselt which are ($Nu$ = 3,6 to 17,3) measured with this non intrusive technique are extensively superior to the limit value 2. Farbar and Depews's works (1963) put in evidence the influence of the particle sizes on the thermal transfer. They showed that while combining a strong ratio in weight with the small particles in suspensions, one notes a meaningful increase of the heat transfer. With the help of the measures done on the distribution of the concentration of particles and on the velocities of slip, Soos and al., (1964) noted that the concentration is slightly bigger close to the partition than everywhere else. Which allowed them to show that the particles influence the thermal transfer that occur between the wall and the fluid that is to say the transfer of heat particule/fluide, the transfer of heat particule/particule and the transfer of heat particule/particule according to Saxena (1978). Kaviany (1988) studied numerically the movement of a unique particle during a flow in a bidimensional channel with as an objective to understand the increase of the convection due to the presence of particle and to estimate the phenomenon of the conduction during the impact of the particle on the wall of the channel. To better analyze the phenomenon, the author made simplifying hypotheses while taking a particle of square geometric shape, and the length of the impact is determined by assuming an elastic collision of the equivalent of a sphere.

Terekov et al. (2008) has developed a mathematical model to simulate two-phase gas-dispersed flow moving through a pipe with axisymmetric sudden expansion. The model is based on solving Reynolds-averaged Navier - Stokes equations for a two-phase stream. In calculating the fluctuating characteristics of the dispersed phase, equations borrowed from the models by Simonin (1991), Zaichik et al. (1994), and Derevich (2002) were used. Results of a comparative analysis with previously reported experimental and numerical data on two-phase flows with separation past sudden expansion in a plane channel and in a pipe are given.

Pan et al. (2010) study a model for the relative velocity of inertial particles in turbulent flows. They found that their model with a two-phase separation behavior, an early ballistic phase and a later tracer-like phase, as found by recent simulations for the forward (in time) dispersion of inertial particle pairs, gives good fits to the measured relative velocities from simulations at low Reynolds numbers. Their calculations for the bidisperse case show that, with the friction timescale of one particle fixed, the relative velocity as a function of the other particle's friction time has a dip when the two timescales are similar. They found that the primary contribution at the dip is from the generalized shear term, while the generalized acceleration term is dominant for particles of very different sizes.

## 1. Material and methods

### 1.1. Material

The experimental setup shown schematically in figure 1 below is essentially composed of a loop testing and experience a vein (5). The installation is comprised of a pump unit (2), a tubular heat exchanger made of graphite (3), upstream of a tank, a tube of PVC (polyvinyl chloride) located downstream of tank (4), a tube of PMMA (poly methyl methacrylate) transparent, a measuring vein, a derivation conduct, an electromagnetic flow meter and a downstream of tank (1). The presence of a solid phase particles sensitive to mechanical stresses determined the choice of the pump unit. That we used is powerful enough to allow the flow of highly viscous products at flow rates approaching 12 m3 / h (flow velocity Ud = 4.6 m / s). This is a centrifugal pump with semi-open impeller and rotor helicoidal order not to degrade too quickly the solid phase. At the pump output, the mixture sucked from the downstream of tank is pumped into a tubular heat exchanger made of graphite, for regulating the temperature of the mixture. The inlet temperature of the suspension in the test section is kept constant with an accuracy of 0.2 ° C. Then the mixture comes in a upstream tank for damping the pulsations in the flow induced by the pump to homogenize the liquid-solid mixture and temperature. A tube of polyvinyl chloride (PVC) with a length of 34.54 diameters (or 1.05 m), and one transparent tube of polymethyl methacrylate (PMMA) with a length of 39.87 diameters (either 1.212 m), successively arranged in series and of the same diameter (0.0304 m), allow to obtain the dynamic establishment of flow. The pressure taps at the input and at the output of the test vein allow the measurement of pressure drop by using a differential pressure sensor (6). Tubes and veins of Experience: To measure the pressure drop in a pipe, we used a tube of P. M. M. A. Two pressure taps located at each end of the tube P. M. M. A. allow you to perform the measurement of pressure drop over a length of 2.225. m. The tubes are suitable for the implementation of various technics of measurements such as the use of ultrasonic Doppler velocimetry and laser Doppler velocimetry (LDA). For tests in isothermal conditions, using a test vein of copper (total length 2.16 m) around which a heating wire (Thermocoax) is wound (5). This allows electric heating vein parietal at flux density constant (Maximum power is 4126 W), 55 thermocouples inserted into the wall permit to measure the temperature along the parietal local copper tube. The measured temperatures are recorded with a central data type AOIP SA 70, piloted using a Personal Computer with a software operating AOIP"" Instrumentation.

### 1.1.1 Carboxymethylcellulose fluids and suspension

The fluid used for this study is a Non-Newtonian fluid; it is the Carboxymethylcellulose solution (C.M.C.). The Carboxymethylcellulose at low degree of substitution is water-soluble. In fact, this fluid is a colloidal suspension composed of very fine particles. In order to eliminate the bacterial degradation, we added a few grams of copper sulfate. It is transparent. Some authors such as Shaver et al (1959), Ernst (1965) and Bassett et al (1975) used the C.M.C. because of his pseudoplastic nature, non-reducing friction to sufficient concentrations (higher than 0.05%). We found that this fluid deteriorates quickly under the effect of thermo mechanical treatment. At more than 65°C it is damaged and appears as a precipitate. Its volumic mass at the ambient temperature is $\rho$ = 888,25 kg/m$^3$At 65 ° C it is degraded and it appears as a precipitate. Its density at room temperature is $\rho$ = 888.25 kg/m3. We also adopted the specific heat of water to the C.M.C. solution (Scirocco, 1985). Thus the specific

ISSN 2229-5518

heats of the C.M.C. are $c_p = 4180\,JKg^{-1}K^{-1}$ at 20°C and $c_p = 4184\,J.Kg^{-1}K^{-1}$ at 60°C. Lee, Cho and Hartnett (1981) carried out systematic measurements of thermal conductivity of Non-Newtonian solutions. They obtained for concentrations of products lower than 1%, $\lambda$ is identical to the value of the water with an accuracy of 5%.

### 1.1.2 Preparation of spheres of alginates

The fluid used for our study was a Non Newtonian fluid; it is the solution of the carboxymethyl-cellulose (C.M.C.) which chemical formula is CH2COONa. It was a cellulosique ether that is obtained in the form of sodium salt by having the monochloracetate of sodium to act on the sodicocellulose. The solid phase, it was constituted of hard spheres of alginates with an average diameter d = 4.4 mm. It was obtained by making fall, drop after drop, a liquid solution of alginate in a bath of calcium chloride (CaCl2) where the formed spheres during their fall polymerized once in contact with this solution. A 3% solution of alginate (Protanal L F 10/60 or Protanal S F 120) corresponding to 600 grams of Protanal for 20 liters of demineralized water. The chemical formula of sodium alginate or polymannuronate sodium is (NaC6H7O6) n. A device permitted to pour this solution drops by drops in a tray containing a solution of calcium chloride (CaCl2) at the rate of 20 grams by liter. The drop, taking the shape of a sphere during the free fall, polymerized in surface when it was in contact with the saline solution.

## 1.2 Methods

### 1.2.1 Hydrodynamics – pressure drop in suspensions based on carboxymethylcellulose

In a recent study, we did the rheological characterization of the C.M.C. solution. The analyses **with** the help of a rheometre allowed us to elaborate a model of the viscosity behavior of the fluid carrier with the model of behavior defined by the relation (1).

$$\eta = \frac{\eta_0}{\left(1+\left(t_c \cdot \dot{\gamma}_p\right)^{0,5}\right)} \tag{1}$$

with the viscosity with " no shearing at 20°C", in other words $\eta_0 = 0,3149$ Pa.s (Fagla et al., 2011).

We study the pressure drop of the suspensions (fluid carrier C.M.C.). We propose to analyze the influence of particles on the pressure drop and give correlations for the various studied cases.
We conducted an experimental study of coefficient of friction in each case considered law of behavior (Ostwald model and full model).
This study is conducted the inlet constant temperature (Te) of 20 ° C. The results of these analyzes have revealed us that the Ostwald theory is consistent with the experimental results with a deviation of 7.22%. However, the Ostwald model is easily transposable to the case of suspensions. In contrast, the model we developed, the change in viscosity by addition of solid particles is taken into account by the correction factor of the form Quemada's form (2):

$$\left(1 - \frac{\Phi}{\Phi_p}\right)^{-2} \tag{2}$$

It is this model that we keep for the rest of our work. This is the hypothesis of Quemada effective medium (1995) for a non-Newtonian fluid. An effective viscosity is then determined according to the viscosity of the fluid suspending, the volume fraction of particles and the fraction of maximum stacking. This is the Quemada law according to followingexpression (3):

$$\eta_{eff} = \eta_0 \left(1 - \frac{\phi}{\phi_P}\right)^{-2} \tag{3}$$

In analyzing the pressure drop of carboxymethylcellulose (CMC) monophasic flow in isothermal , the application of Poiseuille $Cf = \frac{16}{\mathrm{Re}\, g}$ and Blasius laws $Cf = 0{,}079\,\mathrm{Re}\, g^{-0{,}25}$ respectively for laminar and turbulent regimes has permit to determine the coefficient of friction from the generalized Reynolds number . The viscosity $\eta$ of the carrier fluid is of the form:

$$\eta = \frac{0{,}3149}{1 + (0{,}032.\dot{\gamma}_p)^{0{,}5}} \tag{4}$$

### 1.2.2 Pressure drop of the monodisperse suspensions

Make the assumption of homogeneous medium the monodisperses suspensions applicable to monodisperse suspensions ( $\eta_{mélange}=\eta_{eff}$ ) for several volumetric fraction (0%, 1%, 5%, 7%) and compute the friction coefficient taking into account the generalized effective Reynolds number based on the apparent viscosity of the carrier fluid. We find that there is no single law independently of the volume fraction. But the introduction of Quemada model (considering the monodisperses suspensions as an effective medium ) makes a significant difference. The presence of particles in the mixture led us to the hypothesis of effective medium that we apply to the monodisperses suspensions ( $\eta_{mélange}=\eta_{eff}$ ). Like Newtonian fluids, we also checked whether it is possible to apply the concept of effective medium suspensions at large particles which the carrier fluid is non-Newtonian. We calculated the effective viscosity derived from the Quemada's model of hard spheres Quemada's and compared with the viscosity calculated from the experimental data. The results allow us to say that there is a good agreement between the model of hard spheres and Quemada's model that we have developed with a constant flow velocity of 2, 49 m/s (fig. 2) .

### 1.2.3 Thermal study of a Carboxymethylcellulose (C.M.C.) solution and the suspensions in laminaire and turbulent flows

This study consists in determining the laws of thermal transfer between the fluid (or the suspension) and the wall, for the different regimes of flow. The determination of the exchange coefficient ***h*** suppose the knowledge of the dynamic and thermal fields, and therefore, the resolution of the three equations (of continuity, movement and heating). By making the hypothesis of constant physical properties, one can uncouple the equations and can enter the isotherm velocity field in the equation of energy. We conduct the experimental study of heat transfer here in a flow of suspensions with the solution of Carboxymethylcellulose (C.M.C.). This study allows us to put in evidence the influences of particles on the convection. Graetz (1883) solved this equation in the newtonian case by disregarding the viscous dissipation and the radial diffusion (problem of Graetz). The equation that governs this behavior is the form represented by the expression(5): $\rho Cpu \frac{\partial T}{\partial z} = \frac{\lambda}{r} \frac{\partial}{\partial r}\left( r \frac{\partial T}{\partial r} \right)$

(5) The adimensionnal numbers and the variables that intervene in the determination of the transfer laws are the local Nusselt number Nu(z) defined by the relation (6):

$$Nu(z) = \frac{h(z).D}{\lambda} = \frac{\varphi_p.D}{[T_p(z) - T_m(z)].\lambda} \tag{6}$$

The temperature of the solid/liquid mixture is obtained from the balance of an element heated on the z length according to the expression (7): $T_m(z) = Te + \frac{\pi.D.\varphi_p.z}{\dot{M}.C_p}$ (7)

The axial position z is often presented under an adimensional form. Cameron's number is defined by the relation (8):

$$X^{+} = \frac{2\left(z/D\right)}{\mathrm{Re}.\mathrm{Pr}} \tag{8}$$

and Cameron's number is inversely proportional to Graetz's (Gz) number expressed by equation (9):

$$Gz = \frac{\pi\, \boldsymbol{Re}\, \boldsymbol{Pr}}{4z/D} \tag{9}$$

or Graetz number given by the relation (10): $$Gz = \frac{\pi}{2X^{+}} \tag{10}$$

In the case of the C.M.C., the thermodependance is taken into account by the coefficient such as

$$\varepsilon = \left[\left(-\frac{1}{\eta}\frac{d\eta}{dT}\right)\frac{\varphi_p.D}{2.\lambda}\right]^{\alpha} = \left[\frac{b.\varphi_p.D}{2.\lambda}\right]^{\alpha} \tag{11}$$

In the formula (11) showed the thermorheological parameter $b = -\frac{1}{\eta}\frac{d\eta}{dT}$ of the fluid. The value of b for the used carboxyméthylcellulose is 0,043 obtained from the thermorheological characterization of the fluid done on a rheometre to imposed stress.

The author El Ouardighi El (1990) obtained numerically from equation of newtonian fluids as follows:

$$Nu(X^{+}) = 2{,}8.\left(\frac{b.\varphi_p.D}{2\lambda}\right)^{0{,}14} (X^{+})^{-0{,}26} \tag{12}$$

The suspensions for which the carrier fluid is Newtonian laminar flow, we used the law established by Leveque (1928), El Ouarghidi (1990), Moudachirou (1992) and Laï (1998) (Fig. 3). Thus, thermal regime none established, and in the case of an increasing thermal boundary layer for effective fluids as suspension based C.M.C., we obtain:

$$Nu_{nn}(z) = 1{,}64.\left(-\left(\frac{d\eta}{\eta dT}\right)\frac{b.\varphi_p.D}{2\lambda}\right)^{0{,}14} (X^{+})^{-\frac{1}{3}} \tag{13}$$

The experimental results we obtained are in agreement with the model we have chosen (Moudachirou model, 1992). These results show a great difference with the model of El Ouardighi. These observations allowed us to choose the model Moudachirou model for further work (Fig. 3) on the basis of C.M.C. suspensions.

### 1.2.3.1 Longitudinal profiles of temperature

The analysis of the longitudinal profiles of measured temperatures at the heated wall for the Non Newtonian suspensions (solution of C.M.C.+ particles) is made. The distribution of the thermocouples along the heated tube allowed us to get profiles of the wall temperature as those presented according to in the

Figure 4.These experimental measurements confirm the well-known results relative to the theory of boundary layers. Indeed, for the weak values of z/D, we observed a fast increase of the temperature, followed by a less marked increase. These evolutions correspond well to the birth and to the development of a thermal boundary layer. For a generalyzed Reynolds Number Reg = 2007, the parietal temperature is always more elevated in the monophasic case than in the case of the

suspensions à 1% (at the temperature Te = 20 °C with a constant flow velocity). The parietal temperature decreases as the volumic fraction of the particles increases (Cf. Fig. 4).

#### 1.2.3.2 Transfer laws

The convective particle effects (disturbance of the boundary layer) led to an increase in the exchange coefficient thus a decrease in temperature and a parietal faster establishment of the thermal regime known for the turbulence. By relying on previous work, it seems appropriate to us to take as a reference the laws such as in none established thermal regime for a newtonian fluid and in the case of a heating with a constant density flux, the number of local Nusselt is given by Graetz (1885) and Works led by Scirocco (1985) permitted to get the relation.

$$Nu_{nn}(z) = \varepsilon.\left(X^{+}\right)^{-1/3}$$

$$\varepsilon = 1{,}64\left[\frac{b.\varphi_p.D}{2\lambda}\right]^{0.14}$$

with: $Nu(z) = Cte.\left(X^{+}\right)^{-1/3}$

with analytic solutions that have been proposed for the heat transfer in the case of non thermodependant newtonian fluid. It means:

$$Nu_{nn}(z) = \varepsilon.\left(X^{+}\right)^{-1/3} \quad \text{with} \quad \varepsilon = 1{,}64\left[\frac{b.\varphi_p.D}{2\lambda}\right]^{0.14} \quad \text{accordind to the expression (13)}$$

Taking into account the effect of the pseudo-plasticity for a Ostwald fluid was a new modification of the law of exchange law that results in the expression (14):

$$Nu_n(z) = \xi\left(X^{+}\right)^{-1/3} \qquad (14)$$

avec $\xi = \varepsilon.\Delta^{1/3}$ et $\Delta$ est rapport du gradient pariétal de vitesse pour le fluide non newtonien à celui obtenu pour le fluide newtonien. En effet, le coefficient d'échange est proportionnel à la puissance 1/3 du gradient pariétal de vitesse. Dans un écoulement en conduite cylindrique $\Delta$ est égal à $(3n+1)/4n$ . Cette corrélation est surtout valable pour des faibles valeurs du nombre de Cameron $\left(X^{+} < 10^{-3}\right)$ dans la zone d'établissement du régime thermique.

## 2. Results and discussion

### 2.1 Thermodependence of the fluid

The temperature dependence of the solution is highlighted in Figure 5. In fact we have traced the evolution of the local Nusselt number for various heat flux densities. There is the effect of the temperature dependence of the fluid by a translation of curves. More flux density, the higher the local Nusselt number is large. Similarly it was found that the thermal regime is not established regardless of the used power . With the exception of the heat flux density equal to 1000 W / m², the results begin early the establishment for $X^{+} \geq 0{,}007$ (Fig. 5).
Following the example glucose, the experimental results from the heating of the C.M.C. in the laminar regime is consistent with the chosen model. The effect of the temperature dependence is visible.

### 2.2 Heating of the diphasic flow - Non Newtonian fluid carrier

#### 2.2.1 Influence of rate flow

On Figure 6, we plot the evolution of the local Nusselt number based on the Cameron number for different values of flow for a given volume concentration (5%). We find that the higher the flow rate (Reynolds number growing), plus the Nusselt number increases.

### 2.2.2 Influence of particles concentration

We conducted the study of heat transfer in a solution of charged particles at different volume fractions (monophasic, 1% and 5%).

We find that the addition of particles significantly affect the heat transfer. As in the case of Newtonian fluid, the thermal regime seems be established very quickly.. Nusselt number is almost constant for all studied concentrations and it increases as the concentration increases (Fig. 7).

Thus in general, the analysis of flow in horizontal pipe heated suspensions of large particles provides the answers to the coupling between the thermal and dynamic fields. The main results show that the addition of particles is beneficial to the transfer and wall-fluid transition between laminar and turbulent regime is much earlier than the particle concentration is high. In addition, the particles limit the radial extent of the thermal boundary layer in destabilizing the flow. This translates into a Nusselt number becomes constant at a given axial position. The heat transfer is then performed only by diffusion to the heart of the fluid. This study shows the problems of continuous sterilization. Far from being bought, it has a better understanding of heat transfer and it opens up a field of investigation about the influence of thermo rheology on the velocity field and distribution of thermal field. But it does not mention the influence of physico-chemical transformations that intervene during sterilization of the << real >> products and must have a considerable influence on the pressure drop and heat transfer.

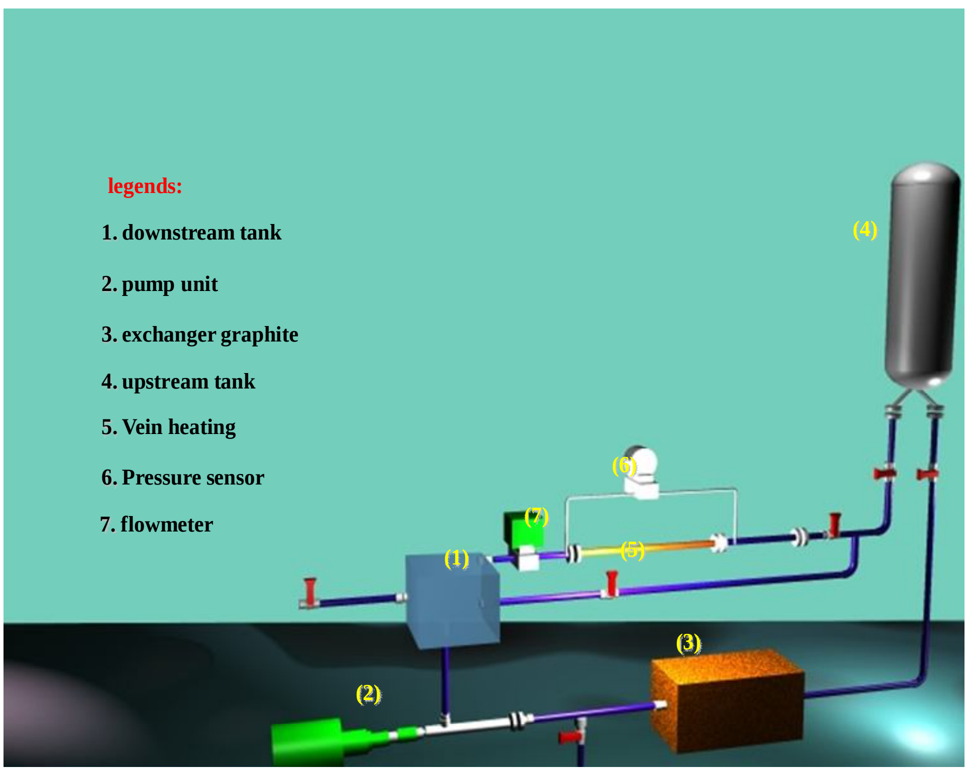


**Fig. 1**: Schematic of test loop

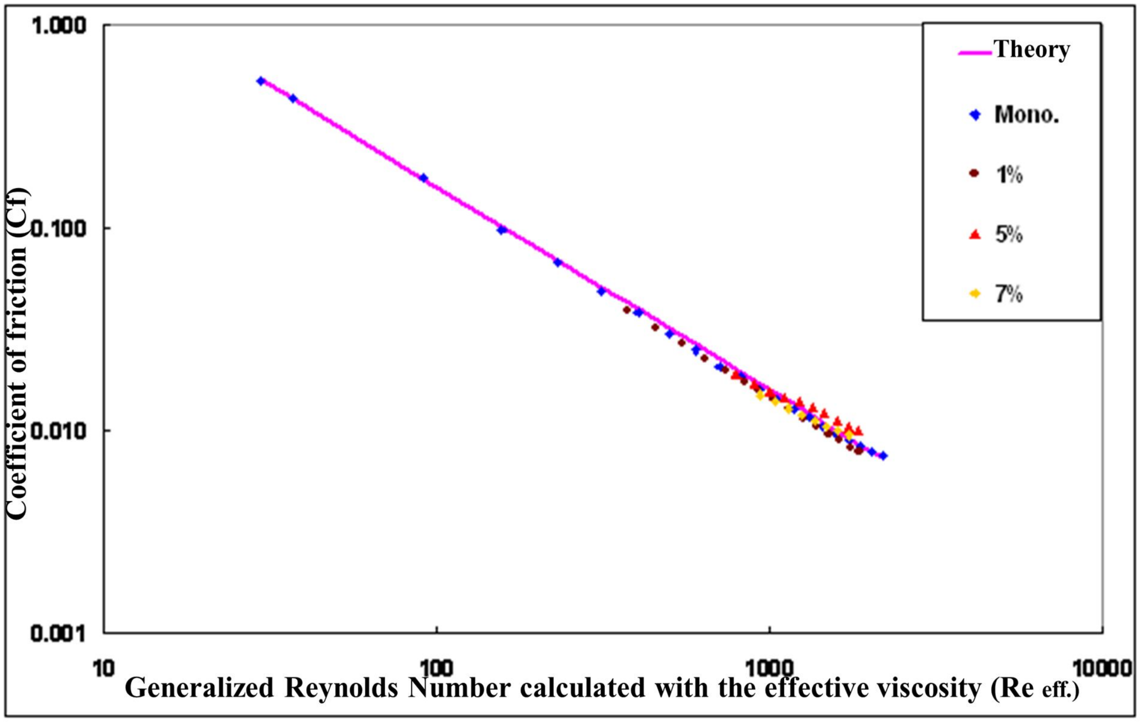


**Fig. 2: Determination of the coefficient of friction of suspension flow (based on C.M.C.) at different volumetric fraction (0%, 1%, 5%, 7%) depending on the generalyzed effective Reynolds number of the corrected carrier fluid (Quemada's model; FAGLA et al., 2011).**

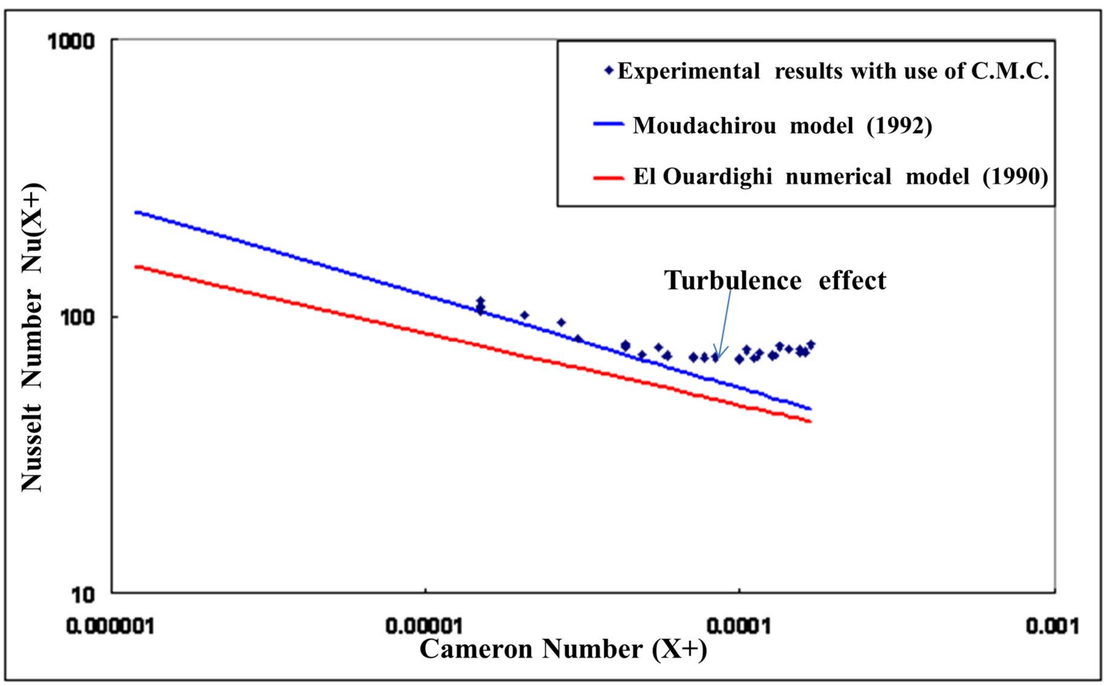


**Fig. 3: Comparison of Moudachirou's model (1992) and El Ouardighi 's model (1990) with the experimental data of the C.M.C. solution (at flow velocity Ud = 1.91 m / s with the Reynolds Number Re = 2787 and density heat flux $\varphi p =$ 15 000 W / m²).**

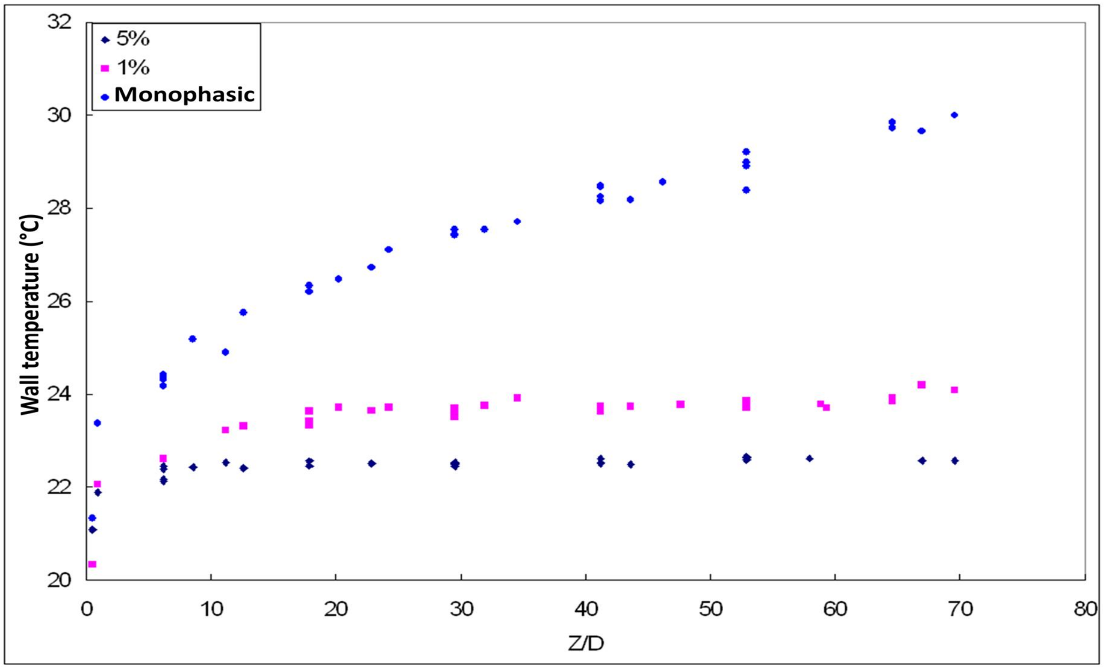


**Fig. 4 : Evolution of the longitudinal wall temperature in Non-Newtonian suspensions and Non Newtonian C.M.C. monophasic solution ; Ud = 2.11 m / s, $\varphi_p$ = 5000 W / m².**

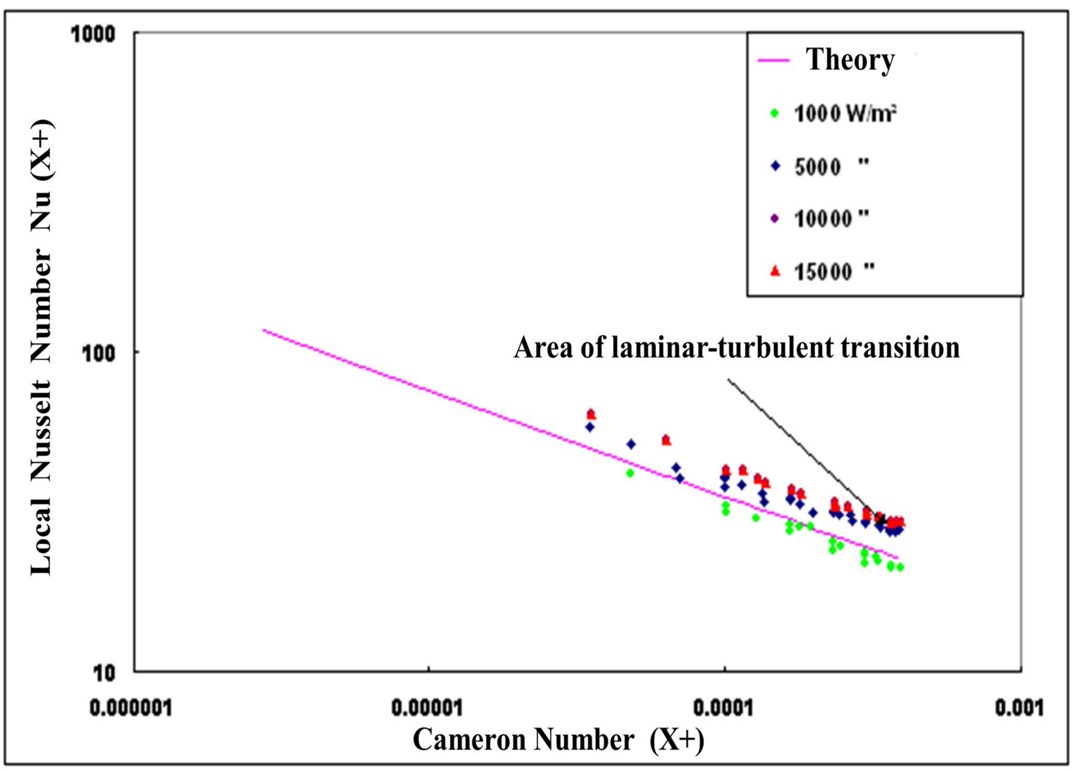


**Fig.5 : Evolution of carboxymethylcellulose (C.M.C.) in monophasic flow based on the number of Cameron for different heat flux densities at Reynolds Number Re = 1126.**

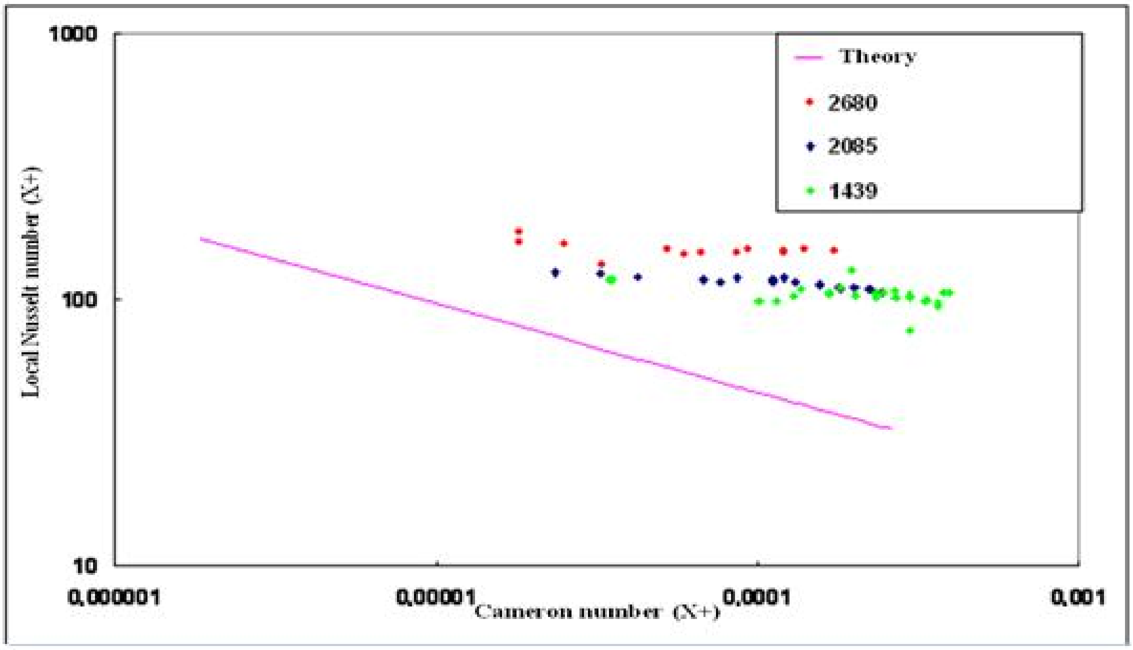


**Fig. 6** : Evolution of local Nusselt number based on the Cameron number for different values of rate flow, the Reynolds number is calculated from the apparent viscosity of C.M.C. with a 5% charge on particles and the density of heat flux $\varphi_p = 5000$ W / m².

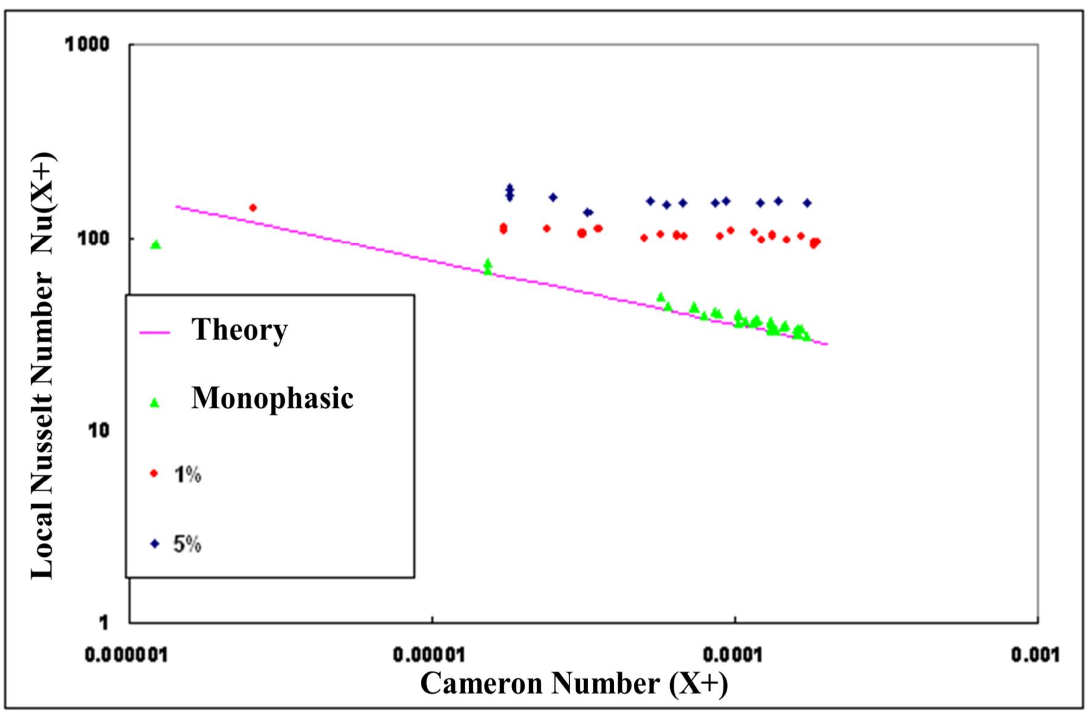


**Fig. 7** : Evolution of local Nusselt number based on the Cameron number for different volume fractions to $\varphi_p = 5000$ W / m² and Ud = 3.44 m / s. Influence of particles concentrations on the heating.

## 3. Conclusion

The present anisothermal study has allowed allowed us to understand the hydrodynamics of suspensions and also highlight the influence of hard spheres on the flow and modification of the rheology of the mixture. Migration of the particles towards the axis of the pipe has also contributed to the global change in the flow. The hydrodynamic study suspensions situation uniform parietal heating showed the interest of approach "effective medium" that is not applicable to the heat transfer of suspensions. In contrast, the Quemada effective medium approach applied in the case of hydrodynamic suspensions, despite the large size of the particles is validated. The thermal regime is established nearest the entrance of the vein heated with the increase of the particle volume fraction. Depending on the nature of the carrier fluid, the thermal regime is not established with a dynamic laminar regime. The present anisothermal study shows that the heat transfer is better in turbulent than in laminar regime and that this transfer is influenced by the presence of particles.

## Bibliographical references

Kono, H., Harada, E., Toda, M., Kuriyama, M. and Asano, M., 1979. Heat transfer of solid liquid mixtures in vertical downward flow. Dept. Of Cem. Eng.,Yamagata Univ., Yonezawa 992.
Lyche B. C. and Bird R. B., 1956. The Graetz Nusselt problem for a power law non newtonian fluid. Chem. Eng. Sci.,Vol.6, pp. 35.
Krieger, I. M., 1963, Trans.Soc.Rheol. vol.7 p.101.
Chhabra R.. P. , 1990. Motion of spheres in power law (visciinelastic) fluids at intermediate Reynolds numbers: an unified approach. Chem. Eng. Process, Vol.28, pp. 89-94.
Cheng D. C. - H. , 1970. A design procedure for pipeline flow of non-newtonian dispersed systems. Hydrotransport I, 1-4 September, paper J5.
Kemblowski, Z. and Kolodziejski, J.. ; 1973. Flow resistance of non-newtonian fluids in transitional and turbulent flow. Int. Chem. Eng. , Vol. 13, pp 265-279.
Takahashi, I., 1978. Pressure drop of suspensions in heterogeneous flow. Hydrotransport V, 8-11 May, paper C5.
Durand, R., 1953. Minnesota Int. Hydraulics Conv., Proc.Int. Ass.for hydraulics Research, pp. 89
Kyokai O., 1981. Trajectory and Diffusion of Particles in Liquid-Solid Flow of Slurry Pipeline. Journal of Pipelines, 1, 211-223, Elsevier Scientific Publishing Company,Amsterdam- Printed in The Netherlands.
Hoareau, F., 1996. Etude dynamique et thermique de suspensions solides-liquides non-newtoniennes en conduite. Thèse Université de Nancy I.
Ayukawa, K., 1970. Velocity distribution and pressure drop of heterogeneously suspended flow in hydraulic transport through a horizontal pipe, First International Conference on the hydraulic transport of solids in pipes.
Scirocco, V., 1985. Convection thermique pour un fluiude pseudoplastique en conduite cylindrique. Thèse de doctorat-Ingénieur, Université de Nancy I.
Joshi, S. D. and Bergles, A. E.,1982. Heat transfer laminar flow of non newtonian pseudoplastic fluids in tubes. Heat Transfer Vol.3 pp.51.56.
Balasubramaniam, V. M. et Sastry, S. K., 1996. Liuid-to-particle heat transfer in continuous tube flow : Comparison between experimental techniques, International Journal of Food Science and Technology, Vol.31, pp.177-187
Lee, W.Y., Cho, Y. I. and Hartnett, J. P., 1981. Thermal conductivity measurements on non newtonians fluids. Letters in heat and mass transfer, Vol. 8, pp. 255.
El Ouardighi, A., 1988. Etude numérique et expérimentale de l'écoulement et du transfert de chaleur pour des fluides non-newtoniens thermodépendants en conduites industrielles.
Lee, J. H. and Singh, R. K., 1990. Particle residence time distribution in scraped surface heat exchanger. Paper N° 90-6522. Presented at the International Winter Meeting of American Society of Agricultural Engineers, Dec 18-21, Chicago, Il.
Sastry, S. K. and Bhasar, D.,1990. Velocity distributions of food particles suspensions in holding tube flow. J. Food Sci. Vol.55,pp.1148-1453.

ISSN 2229-5518

Heppell, N. J., 1985. Measurement of the liquid-solid heat transfer coefficient durin continuous stabilization of foodstuffs containing particles. IuFoST Symposium on aseptic processing and packing of foods : proceedings. Pp. 108-114. Sep. 9-12. Tylosand, Sweden.

Stoforos, N. G., and Merson, R. L. 1991. Measurement of heat transfer coefficients in rotating liquide/particulate systems. Biotechnology Progress, Vol. 7, pp. 267-271.

Fagla FZB., Gradeck M., Baravian C., Lebouché M. étude expérimentale de l'hydrodynamique des suspensions non-newtoniennes de «grosses » particules dans une conduite horizontale, annales des sciences agronomiques 15 (1) : 139-157, 2011 issn 1659-5009.

Quemada, D., 1995. modélisation structurelle du comportement rhéoépaississant des fluides complexes en application aux dispersions colloïdales, 30$^{ième}$ coll. Gr. Franç. Rheol., les Cahiers de Rhéologie XIV-1 pp.1-10.

Soo, S. L., Trezek, G. J. Dimick, R. C., Hohnstreiter, G. F., 1964. Concentration and Mass Flow Distributions in a Gas-Solid Suspension. Ind. Eng.Chem. Fundam., vol.3, pp.96-106

Ernst, W. D., 1965. Investigation of turbulent shear flow of dilute aqueous C.M.C. solutions. AICHE Journal 12, n° 3, 581-586.

Depew, C. A. et Farbar, L., 1963.Heat transfer to pneumatically conveyed glass particles of fixed size. J. Heat Transfer 85c, pp.164-172.

Saxena, S. C., et al., 1978. Heat Transfer between a Gas Fluidized Bed and Immersed Tubes. Adv.Heat transfer, vol. 14, pp. 149-247.

Kaviany M., 1988. Effect of moving particle on wall heat transfer in a channel flow. Numerical Heat Transfer, vol. 13, pp. 111-124

Shaver, R. G. and Merril, E. W., 1959. Turbulent flow of pseudoplastic polymer solutions in straight cylindrical tubes. *AICHE Journal*, Vol.5, n°2, pp.181-188.

Bassett, C. E. and Welty, J. R., 1975. Non newtonian heat transfer in the thermal entrance region of uniformly heated horizontal pipes, *AICHE Journal* Vol. 21, p.699.

Terekhov V. I., Pakhomov M. A., 2008. Turbulent gas-dispersed flow in a pipe with sudden expansion: numerical simulation, Thermophysics and Aeromechanics, Vol. 15, N° 4, pp. 589 - 601

Pan L., Padoan P., Relative Velocity of Inertial Particles in Turbulent Flows, Journal of Fluid Mechanics, 2010, Vol. 661, N° 1, Pages: 35