

# Experimental Study of Heating of the Newtonian Suspensions made of Large Hard Spheres Based on the Glucose & Water Solutions Flowing in a Horizontal Duct

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**Abstract** – In this paper, we present the results of our research work. The current state of knowledge of Newtonian suspensions of heat flux does not fully understand the problems of flow of charged particles in the Agro-Food Industry. The influence of the hard spheres on the flow was studied. That determines the heat transfer in the mixture. This study highlights the interdependence of the dynamics and thermal of the suspensions of particles with an average diameter ( $D= 4, 4$  mm). Analyses of longitudinal and radial profiles of measured wall temperature permit to verify the convective effects of particles (perturbations of the boundary layer) in flows. Analysis of the heating of these suspensions show that the heat transfer increases with the concentration of particles. The organization of the carrier fluid in monophasic ring surrounding the area of the particles in the center of the pipe is relevant. This fluid ring is linked to the monophasic layer substantially free of particle ("monophasic" layer). It is harmful because the particles migrate to the cold zone where sterilization is difficult and this layer due to a layer quasi-free particle ("monophasic" layer) that appears on the wall. This phenomenon raises the problem of regular sterilization of the solid-liquid suspensions in the Agro-Food Industries (AFI). The "effective medium" approach is validated for suspensions of large sized particles. This essential result served to validate the laws of heat transfer typically used for monophasic phase flow and show their implementation in case the two-phase approach is made.

**Keywords:** Mixture, Suspensions, Solid - liquid, Particles, Thermal, Hydrodynamics, Agro-Food Industry.

## 1 INTRODUCTION

The industrial food industry (I.F.A.) show imagination to offer new products to consumers. This raises constantly, new problems to solve particularly to ensure sterile and organoleptic properties of these products for a large-scale consumption. These new products (desserts, sauces, soups, ready meals...) often have a complex rheological Newtonian behavior. Moreover, these fluids are more often charged with solid particles (yogurt with pieces of fruit, jams, ..) that completely modify (alter) the hydrodynamics and heat flow of the carrier fluid. All fluids and mixtures produced by agribusiness have rheological properties of complex, possibly time-dependent. The knowledge of these properties is essential to model, accurately all phases of a procedure during which the product will undergo multiple physicochemical transformations during phases of transport and heating.

In the case of highly viscous fluids, the particle charged or not, the heat transfer takes place mainly by conduction from the wall of the vein to the heart of the flow. This mode of transfer increases the residence time and can lead to denaturation (alteration) of the product in the parietal area (wall fouling, burning) without ensuring complete

sanitization of the fluid and particles Chong [1]. There are already methods for proper mixing

highly viscous fluids. The use of plate heat exchangers is difficult or even impossible in the case of solid-liquid suspensions because they can cause denaturation of the particles and their hydraulic diameter is too small to allow the passage of the suspension. Mechanisms of heat transfer between the charged liquid and the wall, between the liquid and the particles are still poorly understood problems. Important issues they raise deserve theoretical and experimental studies. Factors affecting the transport and heat transfer charged fluids have been identified. It is the particle size, the particle concentration, the flow regime of the suspension, the rheological characteristics of the carrier fluid, and the hydraulic diameter of the density ratio of fluid-particle. Studies on the hydraulic transport of hard particles allow now fully understand the problem of drop in horizontal pipe, which is strongly linked to the regime of two-phase flow and heat. Authors such as Einstein [2], Batchelor [3] Batchelor [4] have worked on diluted suspensions and determined the viscosity. The calculation of the viscosity of a suspension at a concentration higher than a few percent poses enormous problems

because hydrodynamic interactions develop effectively; disturbance induced velocity field by the presence of a particle are no longer negligible around neighboring particles. The velocity field in the fluid can be complex. Many theoretical, semi-empirical or empirical approaches have been proposed to estimate the viscosity of a suspension of rigid particles when the particle concentration  $\phi$  is higher than a few percent according to Kamal [5], Utracki [6]. Most of the formulas obtained predict viscosity values close enough and have two main characteristics: they are identical to Einstein's formula when  $\phi$  it tends to zero, possibly with some assumptions about the value of the maximum concentration  $\phi_m$  used in the heap model and predict, as a first approximation confirms the experimental observations that the viscosity tends to infinity when the concentration tends to a critical concentration, which is often referred to  $\phi_m$ , but which turns out to be only a reference concentration for suspensions particles of arbitrary shapes. Thomas [7] proposed an expression of the relative viscosity of fine particles dissolved in water. Coussot [8] established an empirical expression for the viscosity of the mixture and Chong et al. [1], has established semi-empirical formulas calibration of the results obtained with a large number of monodisperse suspensions and polydisperse. For dependencies  $\eta(\phi)$ , Krieger and Dougherty [9] and Krieger [10], gave a correct solution to the theoretical approach of Mooney [11]. Quemada [12] worked on the maximum volume fraction (fraction of maximum particle stacking. Studies on the hydraulic transport of hard particles allow to understand the problem of drop, in horizontal tube, which is strongly linked to the two-phase flow regime: Chhabra [13], Cheng [14], and Kolodziejki Kembrowski [15], Takahashi [16], Durand [17], as well as Kyokai [18], and Ayukawa [19] have identified four main flow regimes (symmetrical, asymmetrical, circulating bed and stationary bed) which are essentially functions of the average velocity of the suspension and the setting velocity of the particles. The work done by Hoareau [20] on the solid-liquid suspensions allowed the characterization of the pressure drop of a two-phase mixture (liquid and solid spheres rheofluidifying) depending on the concentration. It showed the influence of the spheres on the heat transfer. Heat transfer has been quantified, in general, an equation developed by Newton [21]. Graetz [22] solved the heat equation using method of separation of variables. Leveque [23] and Bird [24] have demonstrated the expression of average

Nusselt number. Other values of local Nusselt number were calculated using numerical methods of finite differences by Kays [25], and asymptotic methods by Sellars [26] and Eckert and Drake [27]. Kono [28] Chandarana [29] Sastry [30], Heppell [31] and Stoforos [32], and Balasubramanian and Sastry [33] have established transfer laws in suspensions. Barigou [34] studied the heat transfer in a two-phase flow (solid-liquid) food of a fluid to ensure the sterilization process in the solid particles of food. The results are to reduce energy requirements and improve process control. The authors have shown, through fluid mechanics Agro-food Industry (AFI) loaded (solid-liquid) flow, heat transfer and fluid-particle and wall-fluid. In this study, measurement techniques and mathematical models to estimate them are reviewed, the application of existing knowledge to the design of continuous aseptic processing is discussed, and research needs are highlighted. Through this study, they have allowed manufacturers to produce better quality food by sterilization processes continuously. The determination of the coefficient of heat transfer at the wall is insufficient. Responses were made to the problems related to the heat transfer between the particles and the carrier fluid Fagla [35]. The organization of the carrier fluid monophasic layer ring surrounding the area of the particles in the center of the pipe is highlighted. This monophasic ring constituted by the carrier fluid, is bonded to the layer of quasi-free particle ("monophasic layer") that appears on the wall. This problem is based on continuous sterilization of solid-liquid suspensions in the Agro-Food Industry (A.F.I.). This organization is harmful because the particles migrate to the cold zone where sterilization is difficult according to Fagla [36] and Fagla [37]. Other authors have also worked on solid-liquid two-phase flows Rhafiki [38]. They studied the storage and distribution of cold latent heat treating, in a manner essentially numerical, two-phase flows with solid-liquid phase change in an exchanger. Two types of the phase change materials were tested: ice slurry and stabilized grout. The ice slurry is a suspension composed of a carrier phase. To model the flows of ice slurry, they chose a coupled approach: temperature, ice fraction, based on the assumption of a thermodynamic equilibrium between the solid and liquid phases. The results from the model and the experiment are

in good agreement. They are used to estimate a precise way the local heat exchange coefficient along the exchanger. In the case of stabilized grout, they proposed a physical and homogeneous 2D model describing the flow taking into account the heat transfers with phase change in a warming (melting of a pure substance and a binary solution (or cooling (crystallization of a pure substance). the model allows to determine the coefficient of heat exchange between the two-phase mixture and the wall of the exchanger. Finally, they developed a model based on two phases Eulerian approach. This one introduces coupling between the two phases to describe the various mechanisms of mass transfer, the amount of movement and energy. It offers large possibilities for, in particular, to study the effect of interactions between the liquid and solid phases, on the flow and heat transfer into the suspension.

## 2. MATERIAL AND METHODS

### 2.1. Material

#### 2.1.1. Test loop experimental setup

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  $12 \text{ m}^3 / \text{h}$  (flow velocity  $U_d = 4.6 \text{ m} / \text{s}$ ). 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  $0.2 \text{ }^\circ \text{C}$ . 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 PMMA. Two pressure taps located at each end of the tube PMMA. 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.

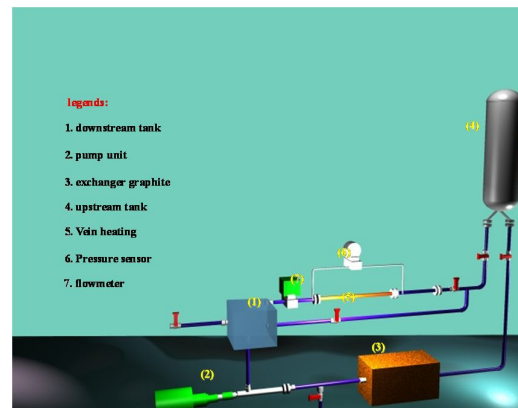


Fig. 1: Schematic of test loop

#### 2.1.2. Fluids and mixtures

Newtonian carrier fluids, objects of our study is glucose syrup and water. Glucose syrup used for the present study, is made from wheat; it has a density of  $1437.1 \text{ kg/m}^3$ , we study its physical properties. It has a constant viscosity of  $24.63 \text{ Pa}$  at  $20 \text{ }^\circ \text{C}$ , it is a highly viscous thermodependent

Newtonian fluid with a thermal conductivity ( $\lambda$ ) equal to 0.404 W / m . ° C (data provided by the manufacturer). Its viscosity is high, we diluted at different concentrations. We diluted glucose syrup in water at various concentrations of 11%, 20%, 35% and 89% by volume. The various tests that we have made, have revealed that the glucose solution has a viscosity of 89% is too high and does not correspond to what we seek. But concentrated to 65%, it is too diluted. After several tests, we chose, finally, the glucose solution with a concentration of 80% with a density of 1141.3 kg/m<sup>3</sup>. The made measurements have allowed to establish the rheogram of this solution (Fig. 2). The preservation of the solution against bacterial degradation is carried out by adding a few drops of formaldehyde solution to the 150 liters of glucose solution. Verifications of the effects of temperature on the viscosity of the solution of glucose syrup made confirmed its Newtonian behavior with a viscosity up of 0.069 Pa.s at the temperature of 20 ° C. (Fig. 3). The dynamic viscosity of the solution of glucose syrup varies with temperature. It is highly thermodépendante (Fig. 4). We also adopted the specific heat of water to the glucose solution, Thus the specific heats of the C.M.C. are  $C_p = 4180 JKg^{-1} K^{-1}$  at 20°C Scirocco [39].

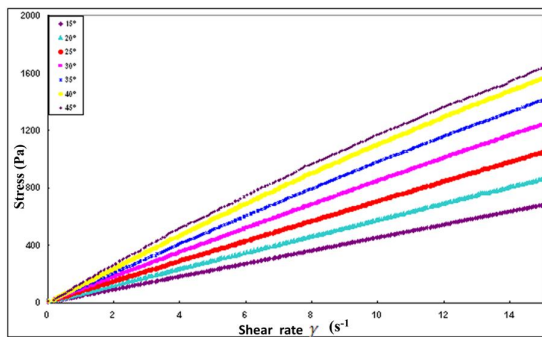


Fig. 2: Rheogram concentrated glucose syrup at 80%.

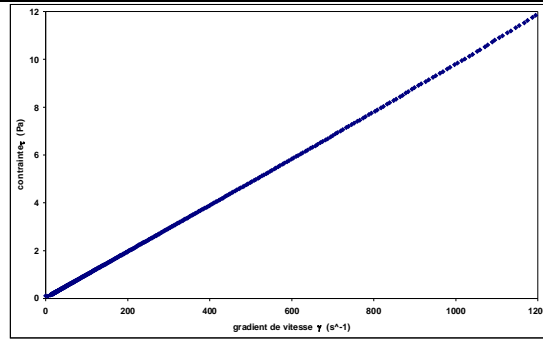


Fig. 3: Evolution of the dynamic viscosity of the syrup glucose as a function of shear rate at the temperature of 20 ° C.

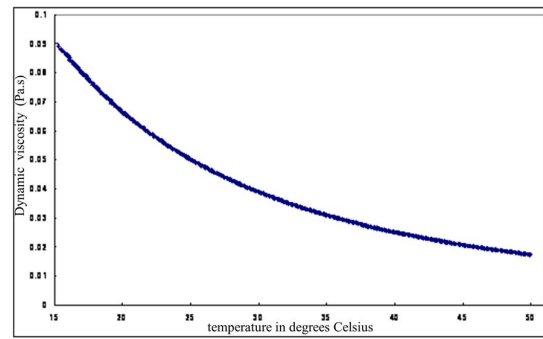


Fig. 4: Highlighting of the temperature dependence of the viscosity of the solution of glucose syrup

### 2.1.3. Production of alginate spheres and problems of flow of the solid phase in suspension (mixture)

The solid phase consists of hard spheres of alginate with an average diameter of about 4.4 mm. They are obtained by drop, drop by drop, a liquid solution of alginate into a bath of calcium chloride (CaCl<sub>2</sub>) where the spheres formed during fall polymerize upon contact with this solution. The manufacturing method of alginate spheres has been provided by the CERIA Brussels. The thesis of Hoare (1996) allowed us to know the method of manufacture of alginate spheres. A 3% solution alginate (Protanal LF 10/60 or Protanal SF 120) or 600 grams of Protanal for 20 liters of demineralized water. The chemical formula of sodium alginate is sodium or polymannuronate (NaC<sub>6</sub>H<sub>7</sub>O<sub>6</sub>) n. The solution was brewed until complete homogenization. A device can run this solution drips into a tank containing a solution of calcium chloride (CaCl<sub>2</sub>) at a rate of 20 grams per liter. Gout, taking the form of a sphere during free fall,

polymerized on the surface in contact with the saline solution. It takes about one hour to ensure complete polymerization spheres but their mechanical strength is better as time spent in the solution is long.

## 2.2. METHODS

### 2.2.1 Hydrodynamical Study - Study of drop pressure in the suspensions based on Newtonian fluids such as water and glucose solution

Several concentrations (1%, 3%, 5%, 10% and 15%) monodisperse spherical particles in suspension in the solution of glucose syrup were studied. It is proposed to study, in laminar and turbulent regimes, the pressure drops of suspensions of solid particles in isothermal flow according to several assumptions. We made the assumption of "homogeneous" fluid is made considering that the suspension (two-phase mixture) behaves like a equivalent homogeneous Newtonians fluid , we can deduce the apparent viscosity of the suspension from measurements of flow rate and drop pressure for a duct flow. The longitudinal pressure gradient ( $\frac{\Delta P}{L}$ ) is connected to the wall stress by the linear law (1) and equation (2):

$$\tau_p = \frac{\Delta P}{L} \cdot \frac{D}{4} \quad (1)$$

$$\tau_p = \eta_{ap} \dot{\gamma}_p = \eta_{ap} \left( \frac{8U_d}{D} \right) \quad (2)$$

with is  $\eta_{ap}$  the apparent viscosity of the mixture. We assume that the mixture is considered as a homogeneous medium  $\eta_{ap} = \eta_0$ . In this case, we analyzed the evolution of the friction coefficient of a suspension of particles in isothermal flow depending on the Reynolds number obtained from the viscosity  $\eta_0$  for laminar regime as well as turbulent. These results led us to say that the evolution of the friction coefficient increases with the volume fraction. This is consistent with the work previously carried out by other authors on suspensions of fine particles. We now assume of the "effective" middle. We assume that the suspension behaves like a effective fluid, that means, a suspension of hard spheres considered as a continuous medium. An effective viscosity is

then determined as a function of viscosity of the suspending fluid  $\eta_0$ , the volume fraction of particles  $\phi$  and the fraction of maximum stacking  $\phi_p \approx 0,64$ . This is the Quemada's law (3):

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

We then proceeded to compare the Quemada' s law viscosity obtained by Poiseuille's law in the case of the flow of suspensions to constant flow velocity of 1.3 m / s. The results have shown a difference of 0.54%. We have represented in Figure 5 the evolution of the relative viscosity (4) as a function of the volume fraction of solid particles for a flow velocity of 1.3 m / s.

$$\eta_r = \frac{\eta_{ap}}{\eta_0} \quad (4)$$

Quemada's law is consistent with that of Poiseuille. The comparison with experimental data of Quemada's model (1998) is quite good and seems to validate the effective medium approach. We assume that the mixture is considered an effective medium expressed by the equation (5).

$$\eta_{ap} = \eta_{eff} \quad (5)$$

This time, we have represented the evolution of the friction coefficient of a suspension of particles in isothermal flow depending on the Reynolds number obtained from the viscosity  $\eta_{eff}$  for laminar regime as well as turbulent (Fig. 5).

We get practically uniformity of the laws of friction. For  $Re_{eff} \approx 900$  the friction coefficient for curve 3% is about the same as 1% or 0.002. We make the same conclusion by comparing the coefficients of friction of the two following volume fractions: 5% to 10% and we obtain (5%) (10%), the value of 0.015 for a constant Reynolds number of about 1900. The results obtained with both the glucose solution with water then appear to validate the hypothesis of suspensions of hard spheres Quemada, regardless of the carrier fluid (Newtonian) used and the flow regime. All the laws of friction (whatever the regime) are close to the Poiseuille law (6) for the laminar

$$Cf = \frac{16}{Re_{eff}} \quad (6)$$



and Blasius law expressed by the equation (7) for the turbulent

$$C_f = 0.079 \text{Re}_{eff}^{-0.25} \quad (7)$$

This allows us to say that there are also unique law coefficient of friction. The increase in the coefficient of friction is proportional to the volume fraction (Fig. 5). It should be noted that there is a loss of energy due to the velocity gradient near the wall where heating and a decrease in the apparent viscosity therefore the stress (4).

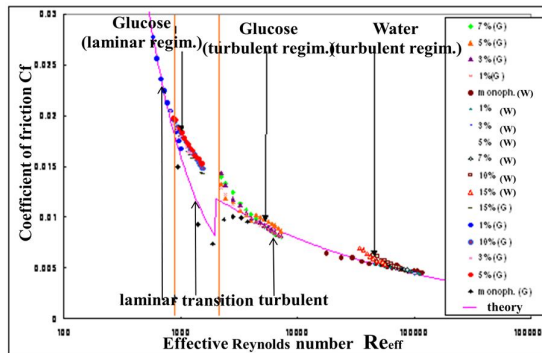


Fig. 5: Evolution of the friction coefficient of the suspensions as a function of Reynolds number determined using the effective viscosity  $\eta_{eff}$  for different volume fractions of particles in laminar and turbulent regimes with isotherms legend: G put for the suspension which is the carrier fluid glucose syrup and E put for the suspension based on of the water.

### 2.2.2 Study of heat transfer in suspensions

It is necessary to determine the laws of heat transfer between the fluid (or suspension) and the wall for the different flow regimes. Here we proceed to the experimental study of heat transfer in a flow of suspensions with Newtonian carrier fluids (glucose syrup and water). This study will highlight the influence of particles on convection in determining the exchange coefficient  $h$  assuming knowledge of dynamic and thermal fields, therefore, in solving the three equations continuity, momentum and heat). Assuming constant thermophysical characteristics, we can decouple the equations and enter the velocity field in isothermal equation of energy. This analysis is done using dimensionless numbers and variables which involved in the determination of transfer laws.

### 3. EQUATIONS

It is the case of the local Nusselt number defined by equation (8):

$$Nu(z) = \frac{h(z) \cdot D}{\lambda} = \frac{\phi_p \cdot D}{[T_p(z) - T_m(z)] \cdot \lambda} \quad (8)$$

The axial position  $z$  is often presented in dimensionless form. The number of Cameron ( $X^+$ ) is defined by the expression (9):

$$X^+ = \frac{2(z/D)}{\text{Re} \cdot \text{Pr}} \quad (9)$$

This dimensionless number is the axial position  $z$ . The number of Cameron is inversely proportional to the Graetz number ( $Gz$ ) described by the relations (10) and (11):

$$Gz = \frac{\pi \text{Re} \text{Pr}}{4z/D} \quad (10)$$

$$Gz = \frac{\pi}{2X^+} \quad (11)$$

The Nusselt number is a thermal characteristic. Its expression (12):

$$Nu = h \cdot \frac{D}{\lambda} = \frac{\phi_p \cdot D}{T_p - T_m} \quad (12)$$

with  $\phi_p$ , the density of heat flux to the wall. It is calculated from Fourier's law (13) is

$$\phi_p = -\lambda \left( \frac{\partial T}{\partial r} \right)_{r=R} \quad (13)$$

with  $\lambda$ , the thermal conductivity of the fluid;  $T_p$  temperature at the wall;  $D$  diameter of the duct;  $h$  heat exchange coefficient;  $T_m$  temperature of the mixture.

The temperature of the solid-liquid [ $T_m(z)$ ] expressed by the equation (14) which is obtained from the balance of a heated member along the length  $z$  is:

$$T_m(z) = T_e + \frac{\pi \cdot D \cdot \phi_p \cdot z}{\dot{M} \cdot C_p} \quad (14)$$

We present here the laws of heat transfer which we will compare our experimental results with the results of previous work. In thermal regime is not established for a Newtonian fluid and in the case of heating at imposed constant flux density, the local

Nusselt number is given by Graetz (1885) the relation (15).

$$Nu(z) = Cte.(X^+)^{-\frac{1}{3}} \quad (15)$$

We developed two laws of heat transfer, one in a suspension containing the glucose solution, which is given by the relation (16) follows (see Fig. 6):

$$Nu(z) = 1,04 \left[ \frac{\varphi_p \cdot D}{2.\lambda} \right]^{0,14} . (X^+)^{\frac{1}{3}} \quad (16)$$

and the other in a suspensions made of water, which is given by the relation (17) follows (See the relation 7):

$$Nu(z) = 0,94. \left[ \frac{\varphi_p \cdot D}{2.\lambda} \right]^{0,14} . (X^+)^{\frac{1}{3}} \quad (17)$$

## 4. RESULTS AND DISCUSSION

### 4.1 Study of pressure drop in a solution of glucose syrup isothermal flow

All the laws of friction (whatever the regime) superimposed Poiseuille's law ( $\frac{16}{Re_{eff}}$ ) for the

laminar regime and the law of Blasius ( $0.079. Re_{eff}^{-0,25}$ ) for the turbulent regime, which allows us

to say that there are also unicity of law of coefficient of friction. The increase in the coefficient of friction is proportional to the volume fraction (Fig. 5). We note that there is a loss of energy due to the velocity gradient near the wall. This is due to heating and a decrease in the apparent viscosity so the stress. Experiments are performed on the isothermal flow of a solution of glucose syrup in monophasic cylindrical duct (laminar and turbulent regimes). We plot the curve of coefficient of friction in different flow regimes (Fig. 5). We measured the longitudinal pressure drop of fluid in steady state, isothermal, laminar and turbulent (Fig.5) and verified if our measures are consistent with the theory. We could observe that for Re between 1000 and 2200, the flow is laminar and the friction coefficient (Cf) and decreases as the Reynolds number increases. For a Reynolds number between 2200 and 2700, we reached the transitional regime. Turbulent flow is observed at a Reynolds number  $Re \approx 2800$  (undeveloped turbulent) and a Reynolds number  $Re \geq 3000$ , turbulence is developed. The experimental values are slightly lower than the theoretical values. The

discrepancy is probably due to a change in the viscosity of the fluid at the wall, that is to say, the heat is caused by viscous dissipation, which is a phenomenon known for this type of fluid (Fig. 4).

This time, we represent the evolution of the coefficient of friction of a suspension of particles in isothermal flow depending on the Reynolds number obtained from the viscosity  $\eta_{eff}$ . for laminar regime as well as turbulent (Fig. 5). We get practically a unicity of the laws of friction. For  $Re_{eff} \approx 900$ , the obtained results show that the hypothesis of effective medium is confirmed for both glucose syrup solution and water (Fig. 5). We find that the behavior of the isothermal flow of the suspension seems more related to the concentration of particles which approximates the master curve. The obtained results with both the glucose solution with water then appear to validate the hypothesis of suspensions of Quemada's hard spheres, regardless of the Newtonian carrier fluid used and of the flow regime.

### 4.2 Study thermal

We analyze the longitudinal and radial profiles of temperature. We present in this section the analysis of longitudinal profiles of temperature measured at the heated wall for Newtonian suspensions. The radial profiles of temperature, measured at the outlet of the heating zone, are also analyzed.

#### 4.2.1 Heating of monophasic flow in laminar and turbulent regimes - Newtonian carrier fluids: glucose and water

##### 3.2.1.1 Case of glucose

In Figure 6, we present the results for the single-phase Newtonian fluid in laminar flow ( $Re = 1115$ ) flow and transition to turbulence ( $Re = 2787$ ). The obtained results allow us to say that experimental evolution of local Nusselt number based on the number of Cameron is in agreement with the theoretical laminar (equation 16).

In case  $Re = 2787$ , we observe a transition to turbulence: indeed, for lower values of  $X^+ < 8.10^{-5}$ , the Nusselt number follows the theoretical law as the boundary layer does not reach the core turbulent. When it reaches the Nusselt number stays constant, the thermal regime is established

and the Nusselt number does not vary into function of  $X^+$ .

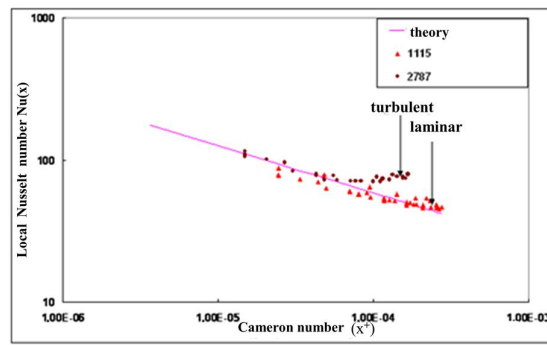


Fig. 6: Evolution of the local Nusselt number according to the Cameron number at different regimes of a solution of glucose at  $\Phi p = 15000 \text{ W/m}^2$ .

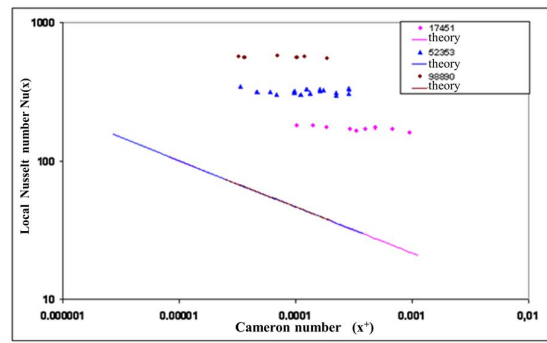


Fig. 7: Evolution of the local Nusselt number according to the Cameron number at different regimes with solution of glucose with  $\Phi p = 15,000 \text{ W/m}^2$ .

#### 4.2.1.2 Case of water

To obtain a developed turbulent regime, we used water as the carrier fluid. The results presented here show the development of the local Nusselt number according to the Cameron number. We note that the Nusselt number increases with the flow and the thermal regime is constantly drawn (Fig. 7). For different heat flux densities, evolving between  $5000 \text{ W/m}^2$  and  $15000 \text{ W/m}^2$ , and for a constant flow velocity ( $U_d = 3.25 \text{ m/s}$ ,  $Re = 98,890$ ) thermal regime is established and the Nusselt number is constant ( $Nu = 850$ ).

In Figure 7, we plot the curve of evolution of the Nusselt number according to the Cameron number at ( $X^+$ ) at different Reynolds numbers, we find that the thermal regime is established for these different Reynolds numbers ( $Re$ ). This is explained in that the development of the thermal boundary layer is blocked by the turbulent kernel.

#### 4.2.1.3 Influence of flow rate in suspensions based on glucose

In Figures 8 and 9, we present results for a suspension of 1% (low concentration) we heat at different densities at heat flow. At low volume fraction (1%), the thermal regime is not established first few Cameron numbers and then it establishes more quickly as the flow increases (Fig. 8 and 9). It is noted that the presence of particles (1%), the turbulent thermal regime is observed from  $Re_{eff} = 1023$  () and it is obtained in a manner more early (lower values) when the Reynolds number grows. For  $Re_{eff} = 2456$  and  $3070$ , the critical value is the same:

- For a flux density equal to  $1000 \text{ W/m}^2$ , we find that the thermal regime is not established in  $X^+ > 10^{-4}$  in the laminar regime ( $Re_{eff} = 1023$ ), whereas in turbulent flow ( $3070 = Re_{eff}$ ) thermal regime is established with a small number of Cameron (or  $X^+ \leq 10^{-5}$ ) (Fig. 8).
- For a flux density equal to  $15000 \text{ W/m}^2$ , the thermal regime is not established  $X^+ > 10^{-4}$  for the laminar regime ( $Re_{eff} \leq 1459$ ) while for the turbulent ( $Re_{eff} = 3127$ ) the thermal regime is not established small number of Cameron ( $X^+ < 10^{-5}$ ). He then moved from ( $X^+ \geq 4 \cdot 10^{-5}$ ) (Fig. 9).

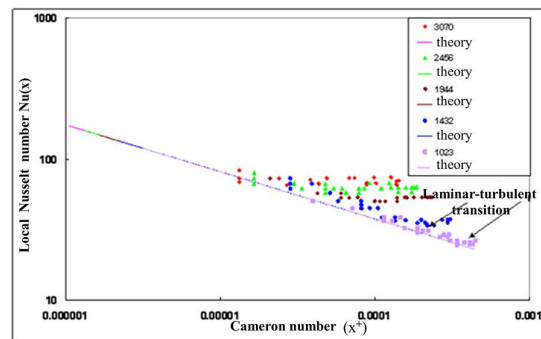
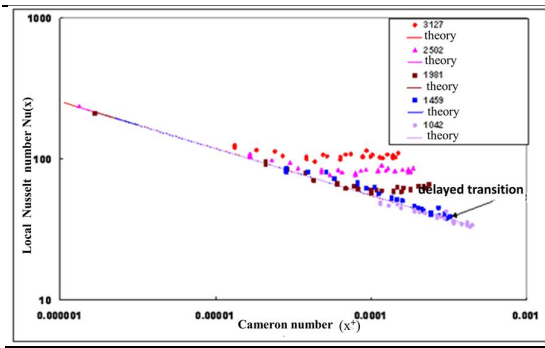


Fig. 8: Evolution of the local Nusselt number depending on the Cameron number of Cameron in suspensions flow at different Reynolds numbers at  $\Phi p = 1000 \text{ W/m}^2$  with volume fraction = 1%.





**Fig. 9:** Evolution du nombre de Nusselt local en fonction du nombre de Cameron . écoulement de suspensions à différents nombre de Reynolds.  $\Phi_p = 15000 \text{ W/m}^2$  - fraction volumique = 1%

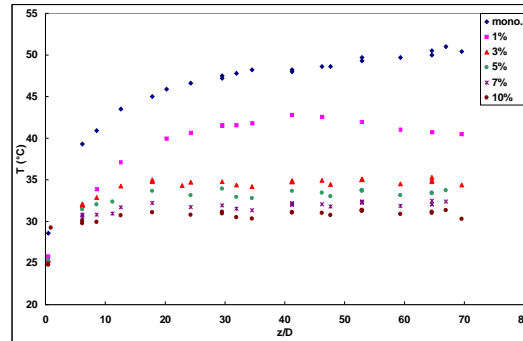
#### 4.2.1.4 Longitudinal Profiles

The distribution of thermocouples along the heated tube allows us to obtain profiles of the wall temperature, such as those shown in Figures 10 and 11. The suspensions are considered Newtonian suspensions (water or glucose + particles). These experimental measurements confirm the well-known results on the theory of boundary layers. Indeed, for small values of  $z / D$ , we observe a rapid increase in temperature, followed by a less marked increase. These changes correspond to the birth and development of a thermal boundary layer. We can notice that for the same Reynolds number  $Re = 2007$ , the wall temperature is always higher in the case of single phase than in the case of suspensions ( $T_e = 20 \text{ }^\circ\text{C}$ , constant flow velocity). The wall temperature at decreases as the volume fraction of particles increases (Fig. 10 and 11). The temperature reached a limit parietal constant in case of the fully developed turbulent flow (Fig. 11) and in any case suspensions having a concentration higher than 1%.

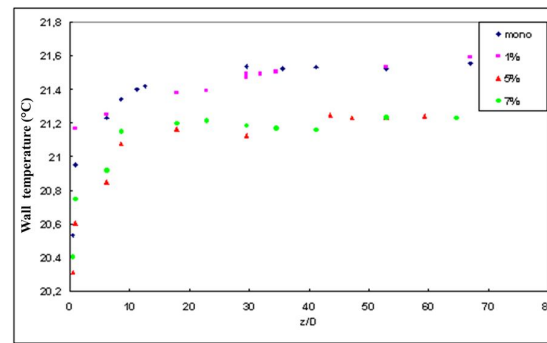
#### 4.2.1.5. Radial temperature profiles

In Figure 12, we show the evolution of the temperature in the case of monophasic radial (or water) and in the case two-phase (1% suspension). Temperature close to the wall, the seat of heat transfer is high and it drops quickly (thermal boundary layer) to a value close to the inlet temperature ( $20 \text{ }^\circ\text{C}$ ) in the heart of the flow. We interpret these two previous cases that the boundary layer remains thin and the heart of the flow is practically not heated. The presence of the particles, even in low volume fraction, leads to a significant decrease of thickness of the thermal

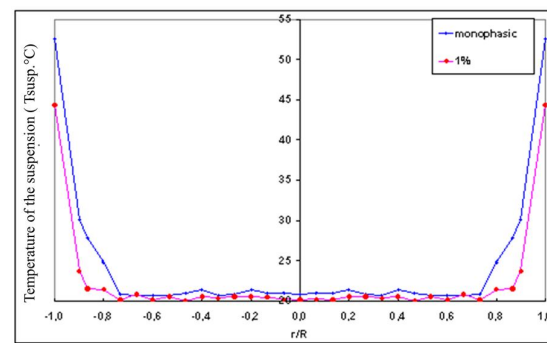
boundary layer (Fig. 12). It is shown that the thermal boundary layer is less developed in the case of diphase. So it is clear that the convective effects of particles (perturbation of the boundary layer) leads to an increase in the exchange coefficient thus a decrease in temperature at wall and a faster establishment of the known thermal regime for turbulence.



**Fig. 10 :** Longitudinal evolution of the temperature wall with solution of glucose  $U_d = 1.38 \text{ m/s}$ ; à  $\Phi_p = 15000 \text{ W/m}^2$  à  $Re = 2007$ .



**Fig. 11:** Longitudinal evolution of the wall temperature with solution of water  $U_d = 3.25 \text{ m/s}$  with  $\Phi_p = 15000 \text{ W/m}^2$  à  $Re = 98890$ .



**Fig. 12:** Radial temperature distribution outlet heated zone glucose syrup at 1% suspension with the velocity  $U_d = 1.5 \text{ m/s}$ , at heat density  $\Phi_p = 10000 \text{ W/m}^2$  and at  $z/D = 71$ .

## 5. CONCLUSION

The main results show that in hydrodynamic Newtonian suspensions, the validity of the model of "effective medium" for the analysis of pressure drop for Newtonian carrier fluids such as water and glucose solution. We find that the transition from laminar to turbulent flow occurs gradually for the Newtonian carrier fluid we leaves the laws to join the classical laminar and turbulent law without a transient well marked. This is due to the effects of hydrodynamic particle-particle interactions and particle-wall which dissipate more energy. The curves diverge from laminar at a Reynolds number about 1000 and tend to continuously without a turbulent flow regime abrupt change appears. The same results into thermal suspensions 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. Particles, although they tend to favor heat transfer vorticity transport (improved mixture), limit the radial extent of the thermal boundary layer into 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 limitations of sterilizing of the food fluid in the presence of particles and raises the problem of continuous sterilization. Far from being completed, it allows a better understanding of heat transfer and mechanical coupling in the flow of Newtonian fluids.

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## NOMENCLATURE

### Latin notation

$C_D$	drag coefficient
$C_f$	friction coefficient
$C_f^*$	friction coefficient normalized by the $C_{f_{iso}}$
$C_{f_{iso}}$	friction coefficient in a isothermal flow
$C_{f_p}$	friction coefficient of the particle
$C_{p_i}$	specific heat at constant pressure
$D$	diameter of the conduit
$D_c$	heating vein diameter
$g$	gravity of
$h$	heat exchange coefficient

$L_D$	total length of the stream of measurement
$L_{Therm}$	heating length of the vein
$\dot{M}$	mass flow rate
$p$	pressure
$P$	dissipated electric power
$Q_v$	volume flow rate of the fluid
$S_{latérale}$	total lateral surface of the heating duct (m <sup>2</sup> )
$T^+$	normalized temperature (with $T^+ = \frac{T - T_e}{\left(\frac{\varphi_p}{\rho C_p u^*}\right)}$ )
$T_\infty$	temperature of the medium beyond the thermal boundary layer
$T_e$	temperature at the inlet of the duct
$T_f$	film temperature (with $T_f = \frac{1}{2}(T_p - T_m)$ )
$T_m$	temperature of the mixture
$T_p$	temperature at the wall
$Tu$	turbulence ratio
$U$	velocity of a sphere (m / s)
$U_d$	flow velocity of the mixture
$U_{max}$	maximum velocity
$z$	axial distance (or x: abscissa along the axis of the duct)

**Greek notation**

$\dot{\gamma}$	shear rate
$\dot{\gamma}_c$	critical shear rate (with $\dot{\gamma}_c = \frac{kT}{\eta \cdot a^3}$ )
$\tau$	stress tensor
$\chi$	term that designates the thermodependent group
$\delta_t(z)$	dimension of the thermal boundary layer at the abscissa z
$b$	term taking into account the group thermodependent
$\Phi$	volume fraction
$\Phi_i$	volume fraction of phase i
$\Phi_{local}$	local volume fraction of particle
$\Phi_m$	maximum volume fraction of particles stacking
$\mu_0$	suspending fluid viscosity
$\mu_a$	apparent dynamic viscosity of the mixture (Pa.s)
$\Phi_p$	density of heat flux to the wall (with $\varphi_p = -\lambda \left(\frac{\partial T}{\partial r}\right)_{r=R}$ )
$\lambda$	thermal conductivity
$\rho$	density
$\bar{\tau}$	shear stress or shear stress (with $\tau = K\dot{\gamma}^n$ ) (Pa)
$\bar{\tau}_p$	wall stress (with) (Pa)
$\mu_{eff}$	effective viscosity of the suspension (Pa.s)
$\lambda_p$	thermal conductivity of the particle

$\tau$  shear stress or shear stress (with  $\tau = K\dot{\gamma}^n$ ) (Pa)

$\tau_p$  wall stress (with  $\tau_p = \frac{\Delta\bar{p} \cdot D}{4 \cdot L}$ ) (Pa)

**dimensionless numbers**

Gr Grashof number

Gz Graetz number  
 $G_z = mC_p / \lambda \cdot L$

Nu (z) local Nusselt number

Nu\* asymptotic Nusselt number

Nu<sub>max</sub> maximum Nusselt number

Pe<sub>hydro</sub> Péclet number hydrodynamics

Pe<sub>therm</sub> thermal Péclet number (with  $Pe_{therm} = Re \cdot Pr$ )

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Pr Prandtl number

$$Pr = \frac{\eta C_p}{\lambda}$$

Pra apparent Prandtl number, calculated by using the apparent viscosity

Re Reynolds number

$$Re = \rho U_d D / \eta$$

Re0 monophasic

$$Re_0 = \rho U_d D / \eta_o$$

Re<sub>eff</sub> effective Reynolds number calculated using the effective viscosity

$$Re_{eff} = \rho \frac{U_d D}{\eta_{eff}}$$

X<sup>+</sup> Cameron number

with  $X^+ = 2 \cdot (\frac{z}{D}) \cdot Re \cdot Pr$



