Rheological Experimental Analysis Suspensions Based on Glucose Syrup: Characterization of an Apparent Rheo-Thickening Mixture

Benoît Fanou Zinsou FAGLA
Christophe AWANTO
Akanho Chakirou TOUKOUROU
Laboratoire d'Energétique et de Mécanique Appliquée (LEMA)
Ecole Polytechnique d'Abomey, Calavi/Université d'Abomey-Calavi
01 B.P. 2009 Cotonou
Bénin

Michel GRADECK
Christophe BARAVIAN
Michel LEBOUCHE
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

This paper examines the characterization of the carrier fluid in solid-liquid Newtonian suspensions isothermal laminar flow in a horizontal pipe. In Food industry, new products are developed and placed on the consumer market. Many of them are loaded fluids (suspensions) whose flow poses a certain number of problems for researchers. Thus, the current state of knowledge on the hydrodynamics of these Newtonian and Non-Newtonian suspensions does not fully understand the problems related to it, especially if the fluid is loaded with "large spherical hard particles". Currently problems related mainly to loaded flows made of the spherical hard particles of large dimensions (diameter D = 4.4 mm) are complex. The influence of the solid phase made of hard alginate spheres on this flow is critical to the rheology of the carrier fluid. And a rheological experimental analysis of glucose syrup (carrier fluid) showed a change in the behavior of the mixture related to the law of modification of rheology and in the same manner, its hydrodynamics. The study showed that the lateral migration of the particles toward the axis of the pipe in the flow, contributed to this change in the law of behavior of this mixture; this change of Newtonian rheology of suspensions generates the pseudo Non-Newtonian character(the apparent rheo-thickening type) observed in the carrier fluid.

Keywords: Behaviour, Rheology, Solid-liquid, Suspensions, Particles and Hydrodynamics.

Nomenclatura

$Re_{mono} = \frac{\rho U_d D}{\eta_0}$: Reynolds number calculated on the basis of the viscosity of the carrier fluid

$Re_{eff} = \frac{\rho U_d D}{\eta_{eff}}$: Reynolds number calculated using the effective viscosity suspensions

$C_f = \frac{16}{Re_{mono}}$: Laminar friction coefficient monophasic continuous medium

$C_f = \frac{16}{Re_{eff}}$: Laminar friction coefficient effective biphasic medium

$C_f = 0{,}079\, Re_{mono}^{-0{,}25}$: Friction coefficient in turbulent single-phase in continuous medium

$C_f = 0{,}079\, Re_{eff}^{-0{,}25}$: Friction coefficient in turbulent two-phase medium (effective medium);

$q = [\eta]\phi_P = 2$: Exponent of the formula Quemada (1998) which is the product of ϕ_P with the intrinsic viscosity $[\eta]$;

L: Entire length of the vein measurement

$\dot{M}$: Mass flow of the carrier fluid;

Qv: Volume flow of the carrier fluid

Tu: Turbulence rates;

P: Pressure;

$u = U_d\left(1-\left(\frac{r}{R}\right)^2\right)$ Velocity of a sphere (m/s);

U_d: Flow velocity of the mixture;

R, r: Radius

U_{max}: Maximum velocity;

D: Diameter of the pipe;

Um: Average velocity;

z: Axial distance (or abscissa x along the axis of the tube);

V : Total volume;

Vp: Volume of the particles;

V_f : Volume of the suspending fluid;

ρ_f : Density of the suspending fluid;

ρ_p : Particle density;

$\dot{\gamma}$: Shear rate;

ϕ : Volume fraction;

ϕ_c : Critical volume fraction;

ϕ_i : Volume fraction of phase i;

ϕ_{local} : Local volume fraction of particle;

ϕ_P : Volume fraction of maximum stacking of particles;

η_0 : Viscosity of the suspending fluid;

η_a : Apparent dynamic viscosity of the mixture (Pas);

ρ : Density;

η_r : Relative viscosity [with $\eta_r = \frac{\eta_a}{\eta_0} = \eta_r(\phi, Pe, De)$];

τ_p : Wall shear stress (with $\tau_p = \frac{\Delta\hat{p}.D}{4.L}$) (Pa);

τ : Shear stress or shear stress, (with $\tau = K\dot{\gamma}^n$) (Pa);

De: Deborah number;
Re_p: Reynolds number of the particles;
Pe_{hydro}: Hydrodynamic Peclet number;
Re_0: Reynolds number monophasic;
Re: Reynolds number;
Re_{eff} : Effective Reynolds number calculated using the effective viscosity;
Re_a: Apparent Reynolds number calculated based on the apparent viscosity;

Introduction

In the food sector, manufacturers offer new products: milk desserts, sauces, soups, ready meals, these products often have a single rheological Newtonian behavior or a complex rheological behavior of Non Newtonian type. In addition, these fluids are often increasingly laden with solid particles (yogurt with fruit pieces, jams,..) that completely alter the hydrodynamics of the carrier fluid. All these fluids or mixtures produced by Agro-food industry have complex rheological properties. Knowing these properties is essential to model with precision all the phases of a process during which the product will undergo multiple physicochemical transformations during the phases of its transport. The mode of transport more or less viscous fluids charged particles or not accentuates the residence time and can lead to denaturation of the product in the parietal area (either through dirty wall or by burning the pore fluid). In 2005, through a study, Longo has examined the rationale behind the semi empirical formulation of a generalized viscoplastic fluid (GVF) model in the light of the Reiner-Rivlin constitutive theory and the viscoplastic theory, there by identifying the parameters that control the rheology of granular flow.

He shown that the shear-rate number (**N**) proves to be among the most significant parameters identified from the GVF model. As **N** → 0 and **N** →∞, the GVF model can reduce asymptotically to the theoretical stress versus shear-rate relations in the macroviscous and grain-inertia regimes, respectively, where the grain concentration (*C*) also plays a major role in the rheology of granular flow. Using available data obtained from the rotating-cylinder experiments of neutrally buoyant solid spheres dispersing in an interstitial fluid, the shear stress for granular flow in transition between the two regimes proves dependent on **N** and *C* in addition to some material constants, such as the coefficient of restitution. So he highlighted the insufficiency of data on rotating-cylinder experiments can not presently allow the GVF model to predict how a granular flow may behave in the entire range of **N**; however, the analyzed data provide an insight on the interrelation among the relevant dimensionless parameters.

Longo (2005) also worked on sediment transport models. Thus most models of sediment transport are based on the hypothesis of a weak interaction between the fluid and the sediment phase, where the main flow is subjected to the mass and momentum conservation of the fluid phase, with small corrections due to the presence of the sediments. These models usually give a correct answer for conditions where the concentration of sediment is really low. In the case of high sediment transport, some models analyze the two subdomains separately, the high and the low concentration, and employ different constitutive equations.

In this present model, Longo (2005) has shown that there is a two-phase description of the whole domain. The closure of the turbulence and the interaction between the sediments and the fluid introduce approximations, but results are consistent with experiments and previous models.

The authors Saintillan Shelley (2013) worked on active suspensions and nonlinear models. Indeed active suspensions, such as suspensions of self-propelled micro-organisms and related synthetic micro-swimmers, are known to undergo complex dynamics and pattern formation as a result of hydrodynamic interactions. In this review, they summarized recent efforts to model these systems using continuum kinetic theories. At first, they derived a basic kinetic model for a suspension of self-propelled rod like particles and discuss its stability and nonlinear dynamics. They have presented the extensions of this model to analyze the effective rheology of active suspensions in external flows, the effect of steric interactions in concentrated systems, and the dynamics of chemotactically responsive suspensions in chemical fields.

Studies of the hydrodynamic transport of solid particles allowed apprehending the problem of pressure drop in a horizontal pipe. This loss is strongly linked to the two-phase flow regime. According to numerous studies conducted by different authors, were highlighted four main flow regimes: symmetrical, asymmetrical, and circulating bed stationary bed (Chhabra, 1990; Kyokai, 1981. Other studies, also carried out on suspensions "solid - liquid", have characterized the pressure drop of a two-phase mixture (liquid and solid spheres rheofluidifying) depending on the concentration (Ayukawa, 1969; Ayukawa, 1970; Hoareau, 1996) and (Fagla & al., 2002).
But to date, the influence of the solid phase flow is still not very well known and yet it is what determines the rheology of the mixture and the pressure drop. The factors affecting the transport of slurry were identified. This is (Chong, 1971): Particle size, particle concentration, the flow regime of the suspension, the rheological characteristics of the carrier fluids, hydraulic diameter and the fluid density ratio - particle.
Furthermore, by using coarse particles of Carboxymethyl cellulose (CMC) in suspension in a Non-Newtonian fluid bearing, the sliding of the particles relative to the carrier fluid has been demonstrated (Antoine and Lebouché, 1998). These authors showed that, in a charge flow, the solid phase modifies the shape of the velocity profiles: for example, the measured velocity reflects both the braked particles by impact particles / particle and particle / wall. The expression of the apparent shears viscosity of the suspensions in hard spheres whereas an elementary volume containing a fluid (density ρ_f) and hard spheres (density ρ_p) in purely hydrodynamic interactions has been established (Mills et Snabre 1995). To this end, the authors used the expression of the averaged velocity field of the volume V to establish the relationship $V=\phi . V_p+(1-\phi).V_f$, where and are respectively the speed of the volume averaged particle, that of the carrier fluid and particle volume fraction. Similar results were obtained by Zarraga et al, (2000). Other authors such as Taghipour, Naoko and Wong (2005) investigated the hydrodynamics of a two-dimensional gas–solid fluidized bed reactor were studied experimentally and computationally. Computational fluid dynamics (CFD) simulation results from a commercial CFD software package, Fluent, were compared to those obtained by experiments conducted in a fluidized bed containing spherical glass beads of 250–300μm in diameter. A multifluid Eulerian model incorporating the kinetic theory for solid particles was applied in order to simulate the gas–solid flow. Taghipour, Naoko and Wong (2005) have shown that the modeling predictions compared reasonably well with experimental bed expansion ratio measurements and qualitative gas–solid flow patterns. They demonstrated that pressure drops predicted by the simulations were in relatively close agreement with experimental measurements at superficial gas velocities higher than the minimum fluidization velocity.

Researchers Murat and Gareth (2012) worked on the interactions between particles magneto-rheological fluids with the ferro-magnetic wall. The interaction between magneto-rheological (MR) fluid particles and the walls of the device that retain the field-responsive fluid is critical as this interaction provides the means for coupling the physical device to the field-controllable properties of the fluid. This interaction is often enhanced in actuators by the use of ferro-magnetic walls that generate an attractive force on the particles in the field-on state. The aggregation of the particles and the time-dependent evolution in the microstructure is studied in rectilinear, expansion and contraction channel geometries. The results obtained allowed help identify methods for improving MR actuator design and performance. Other authors such as Dingyi Pan, Nhan Phan-Thien and Boo Cheong Khoo (2014) used the dissipative particle dynamics (DPD) method to simulate droplet suspension. They analyzed the deformation of a single droplet is first studied to validate the method and a good agreement with previous theoretical, numerical and experimental results is obtained. They observed that a larger repulsion force is imposed between particles from different droplet to prevent two droplets from coalescing. Shear thinning and non-zero normal stress differences are captured in the simulations. These phenomena are related with the mean droplet deformation parameter and mean inclination angle. A good agreement is achieved between their zero shear viscosity results and previous model/experimental work. A study on hydrodynamic characteristics of the flow of a microbubble suspension in a surfactant solution through a pipe has been conducted by Parmar and Majumder (2014). They analyzed the microbubbles exhibit excellent gas-dissolution abilities owing to their larger gas–liquid interfacial areas and longer residence times compared to conventional larger bubbles.

Hence, it is expected that microbubbles should increase the efficiency of gas–liquid contact devices for various applications in chemical and biochemical processes. In most of these applications, it is necessary to understand the hydrodynamics, such as the rheology, pressure drop, and friction factor, associated with microbubble flow in devices. Their study investigates the hydrodynamic characteristics of the flow of a microbubble suspension in a surfactant solution through a pipe.. A correlation between the intensity factor of interfacial stress and the friction factor based on energy loss due to wettability has been developed. The functional form of the correlation appears to predict the hydrodynamics satisfactorily for the flow of a microbubble suspension in a pipe. Their study is helpful in further understanding multiphase flow for industrial applications.

Other authors such as Chiodi, Claudin and Andreotti (2014) conducted studies on transport. The transport of dense particles by a turbulent flow depends on two dimensionless numbers. Depending on the ratio of the shear velocity of the flow to the settling velocity of the particles (or the Rouse number), sediment transport takes place in a thin layer localized at the surface of the sediment bed (bedload) or over the whole water depth (suspended load). They have proposed here a two-phase flow model able to describe both viscous and turbulent shear flows.
They have shown that particle migration is described as resulting from normal stresses, but is limited by turbulent mixing and shear-induced diffusion of particles. Using this framework, they have theoretically investigated the transition between bedload and suspended load.

1. Materials and Methods

1.1 Experimental device and Techniques of measurements

1.1.1 Experimental

The experimental setup shown schematically in Figure (1) is essentially constituted by a test loop and an experience vein (5). The assembly consists of a pump unit (2), a tubular graphite exchanger (3), from an upstream container (4), a PVC tube (polyvinyl chloride) placed downstream of the tank upstream, a tube de polymethylmethacrylate transparent (P M M A), a measurement cell, a bypass line, an electromagnetic flowmeter (7) and a downstream container (1). The presence of a phase of solid particles sensitive to mechanical constraints determined the choice of the pump unit. The one we used, is powerful enough to allow the flow of highly viscous products at rates approaching 12 m^3/h (debiting velocity U_d = 4.6 m/s). It is a semi open centrifugal pump wheel and helical rotor in order not to degrade the solid phase too fast. The pump outlet, the mixture drawn from the downstream 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 stream is kept constant with an accuracy of 0.2 ° C.

Then, the mixture enters an upstream tray for damping pulsations in the flow induced by the pump to homogenize the solid-liquid mixture and the temperature. A polyvinyl chloride tube (PVC) with a length of 34.54 diameters (1.05 m), and another transparent tube of polymethylmethacrylate (P M M A) with a length of 39.87 diameters (either 1.212 m), arranged successively in series and of the same diameter (0.0304 m), allow to obtain the dynamic property of the flow. They are followed by the experience of vein is also P M M A. A bypass line connected in parallel to the experience of vein connects the output of the upstream tank to the downstream tank. it adapts the mixture flow rate to the desired handling conditions without causing the formation of a plug in the pipe. On leaving the zone of action, an electromagnetic flow meter (6), consisting of a cylindrical member made of Teflon and two platinum electrodes, measuring the real-time rate. A downstream tray, placed at the output of the vein of experience and the bypass, is intended to ease the flow of damping the pulsations from the pump unit, ensure a minimum load on the pump and introduce phases solid and liquid in the pipe. Pressure taps arranged at the entrance and exit of the test vein allow the measurement of the pressure drop with a differential pressure sensor. This study focuses on monodisperse suspensions, made of spherical hard particles in the corn syrup solution at concentrations of 1%, 3%, 5% 10% and 15% (Fagla & al., 2001).

Fig. 1: Scheme of the test loop

1.1.2 Technics of measurements

1.1.2.1 Rheometer and rheological measurements

To study the laws of flow and heat transfer of a fluid whatever it is, it is important to know beforehand its rheological properties. This knowledge is made by means of a number of rheological measuring devices using different methods. We used the rotational viscometer plan cone types (flow between a disc and a cone), is a type of rheometer that has similar benefits to those of the figure 2 which we used for the rheological characterization of our products. The measuring principle of the device is also based on the approximation of the little gap.

1.1.2.1.1 Operating principle of rotational rheometer plan-cone types

The test substance is trapped between a plate and a cone of revolution, of radius R, whose axis is perpendicular to the plate plane and whose apex is located on the plateau (Fig. 2). The angle ψ between the generatrix of the cone with the plate is small: it is always less than 5° and can go down to 0.3°. It may impose on the cone a known torque M; in this case, it measure then, the corresponding angular velocity ω_0 either an angular velocity of rotation ω_0; then we can measure the corresponding torque M.

1.1.2.1.2 Rheological measurements

We performed the characterization of thermo rheological tests. The determination of the behavior of the fluid requires knowledge of the distribution law of angular velocity and vice versa by placing themselves in the case of small gap. We do not know, a priori, how to solve this problem. But we can overcome this difficulty in being placed in the case of small gap. We demonstrate and for very small angles cone-plate, ($\psi \leq 5°$), it may be considered with a very good approximation that the stress τ and the shear rate $\dot{\gamma}$ are constant throughout the occupied space by the sample between the cone and the plate and they are expressed by relations

$$\tau = \frac{3}{2\pi}\frac{M}{R^3} \quad (1)$$

and $$\dot{\gamma} = \frac{\omega_0}{\tan(\psi)} \approx \frac{\omega_0}{\psi} \quad (2)$$

with corresponding values τ and $\dot{\gamma}$.

By varying M or ω_0, it is easy to deduce the flow curve $\tau = f(\dot{\gamma})$. The rheological characteristics of the studied fluids were determined using an imposed stress rheometer. The fluid is placed between a fixed plate and a cone of revolution, of radius R, whose axis is perpendicular to the plate plane and whose apex is situated on the tray. We used a stainless steel cone (which has a low coefficient of thermal expansion) of radius R = 0.03 m and angle $\alpha = 2{,}1°$ and an acrylic cone of radius 0.03 m to 48,4µm truncation at an angle $\alpha = 1{,}58°$. All testing was carried out with imposed constraint on the rheometer AR 1000 Rheolyst (Texas Instruments AR 1000 model ST-B) equipped with cone-tool controlled by a PC Elonex 5200 x. The PC is equipped with a control software and other software destine to analyze the results. This device allows to creep flow tests and oscillation of 0 à 500 s^{-1} ($\dot{\gamma} = \omega/\alpha$). By providing the cone, a constant rotational velocity ω, we get a steady shear at any point of the sample with $\dot{\gamma}$ varying from 0 to 500 s^{-1} ($\dot{\gamma} = \omega/\alpha$). The results are transmitted to a computer PC which stores and are then analyzed (Fig.2).

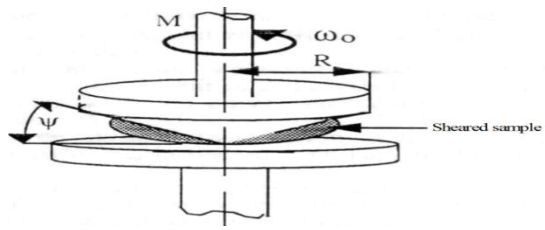

Fig. 2 : Diagram of rotational rheometer plane-cone (Fagla & al., 2002)

1.1.3 The used carrier fluid: Glucose syrup

1.1.3.1 Physical properties

Glucose syrup made from wheat, has a density of 1437.1 kg/m^3; it has a constant viscosity of 24.63 Pa.s at 20 ° C; Newtonian fluid is a highly viscous and thermodependent with a thermal conductivity (λ) equal to 0.404 W/ (m. ° C) (data provided by the manufacturer). Its viscosity being high, we diluted to various concentrations.

1.1.3.2 Preparation of the glucose syrup solution

We diluted glucose syrup in water at 11%, 20% and 35% by volume. The various tests we made allowed us to observe that the 89% glucose solution has a high viscosity and does not match the one we are looking at 65% while it is too diluted. After several tests, we chose the glucose solution at 80% whose density is 1141.3 kg/m^3. We added a few drops of formaldehyde solution to 150 liters of glucose solution against bacterial degradation. This solution has a Newtonian behavior with a viscosity of up to 0.069 Pa.s. at different temperatures (Fig. 3).

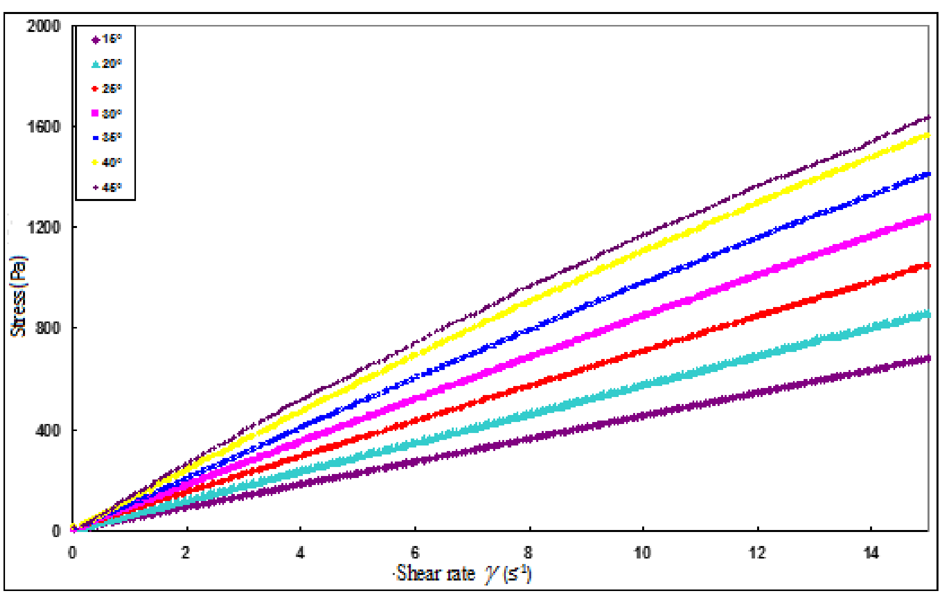

Fig. 3 : Rheogram glucose syrup at 80% with the evolution of the dynamic viscosity of glucose syrup as a function of shear rate at various temperatures.

Effects of temperature on the viscosity

The dynamic viscosity of the solution of glucose syrup varies depending on the temperature. It is highly thermodependent (Fig.4).

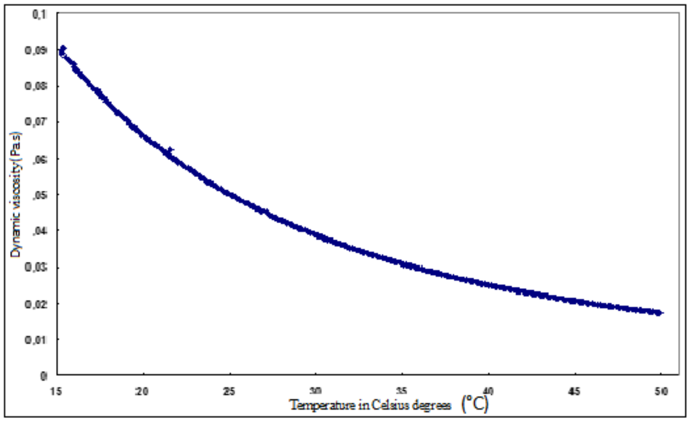

Fig.4 : Evolution of the dynamic viscosity of the glucose syrup solution as a function of temperature.

1.2 Methods

1. 2.1 The flow regimes suspensions

In the case of solid-liquid suspensions flow in a horizontal cylindrical conduit, there are four flow regimes namely suspension symmetric, asymmetric suspension, the circulating bed in suspension and the suspension stationary bed and each with its specificity (Fig. 5). Thus, Acrivos and Davis (1985), in their work, have shown that at low Reynolds number, the influence of surrounding particles is proportional to the volume fraction of particles.

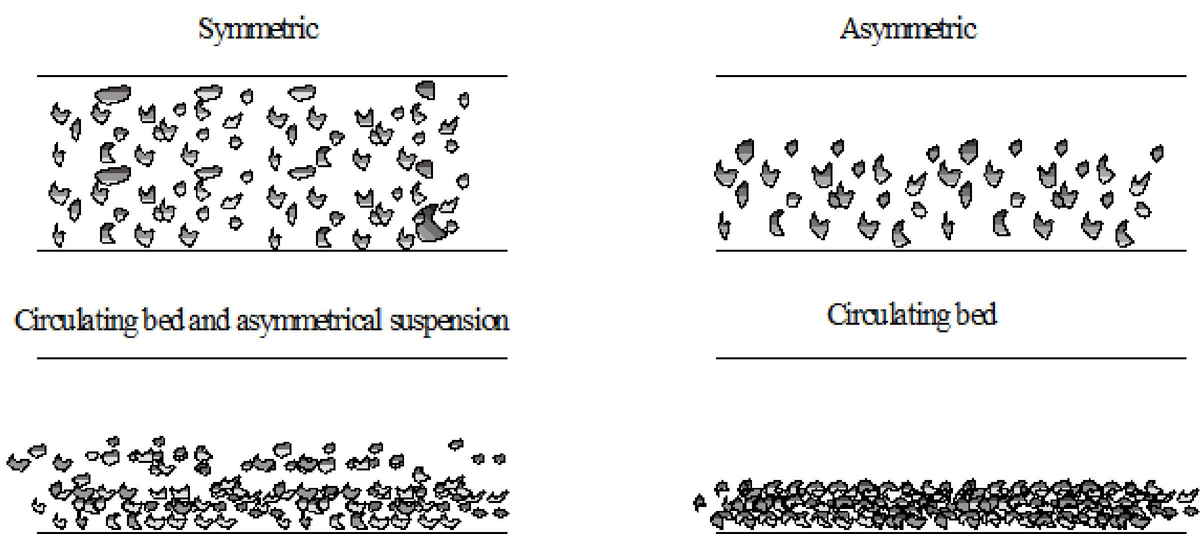

Fig. 5 : Various suspensions flow regimes

1. 2. 2 Established laminar flow of suspensions

In this case, the relationship between the pressure drop $\Delta\hat{p}$ in the wall shear τ_p stress is given by the following expression $\tau_p = \frac{\Delta\hat{p}.D}{4.L}$ (1) : with $\hat{p} = p + \rho g z$

From the expression of debit in the tube and the velocity gradient

$Q_v = 2\pi \int_0^R r u(r) dr$ (2) $\dot{\gamma} = -\frac{du}{dr} = f(\tau p, \frac{r}{R})$ (3)

We get Rabinowitch-Mooney's equation:

$$\frac{Q_v}{\pi R^3} = \frac{8.Q_v}{\pi D^3} = \frac{1}{\tau_p{}^3}\int_0^{\tau_p} \tau^2 f(\tau)d\tau \qquad (4)$$

The law of behavior, after integration, enable us to connect the pressure drop to debit, especially in the case of a suspension flowing in the tube:

$$\frac{\Delta\hat{p}.D}{4.L} = f\left(\frac{Q_v}{\pi R^3}\right) = f\left(\frac{8.Q_v}{\pi D^3}\right) \qquad (5)$$

For Newtonian fluids, the Poiseuille's equation establishes the relationship between the flow and the pressure drop in line. It is in the form:

$$Q_v = \frac{\pi D^3 \tau_p}{32\mu} = \frac{\pi D^4 \Delta\hat{p}}{128\mu L} \qquad (6)$$

By setting the flow velocity and the friction factor respectively by:

$$U_d = \frac{4Q_v}{\pi D^2} \quad \text{and} \quad Cf = \frac{\tau_p}{\rho \frac{U_d^2}{2}} \qquad (7)$$

Poiseuille's equation gives: $Cf = \frac{16}{\text{Re}}$ (8)

For fluids whose behavior is pseudoplastic (i.e Non-Newtonian fluid), the following relationships apply as well to liquid as suspensions. Taking the law of behavior $\tau = K\dot{\gamma}^n$ by applying the Rabinowitch-Mooney's relationship, we get:

$$\frac{8.Q_v}{\pi D_3} = \frac{n}{3n+1}\left(\frac{\tau_p}{K}\right)^{\left(1/n\right)} \qquad (9)$$

hence

$$\Delta p = 4KL\left(\frac{6n+2}{n}\right)^n \left(\frac{\bar{U}^n}{D^{n+1}}\right) \qquad (10)$$

and

$$\tau_P = K\left(\frac{3n+1}{4n}\right).\left(\frac{8U_d}{D}\right)^n \qquad (11)$$

These relationships also apply to suspensions, which will enable us, by measuring the pressure drop online access to the wall shear stress and define the rheological parameters of the suspension. The coefficient of friction can be put in the form:

$$Cf = \frac{16}{\text{Re}'} \qquad (12)$$

where Re' is the Metzner and Reed generalized Reynolds number.

1.2. 3. Flow of Newtonian fluids in cylindrical pipe

The flows in cylindrical pipe are governed by classical Navier-Stokes'equations. For concentrations below 0.5% of particles, we note, in a first step, the relative viscosity is linearly dependent of the volume concentration ϕ. And then very rapidly, with distance from this linear law and the viscosity increases to infinity as one approaches of a volume concentration limit called volume fraction of maximum stacking (Fig. 6). In this case, the particles are sufficiently distant from each other so that one can estimate the velocity field of the carrier fluid around each particle. The hydrodynamic interactions between particles are negligible for low concentrations. We note that the viscosity of the suspending fluid (η_{susp}) doesn't depend neither on the number of Deborah (De) nor how many hydrodynamic Peclet (Pe_{hydrod}); in the same way, η_{susp} does not depend on Brownian character (or not) of the particles. The distance over which the flow is disturbed is of the order of the particle.

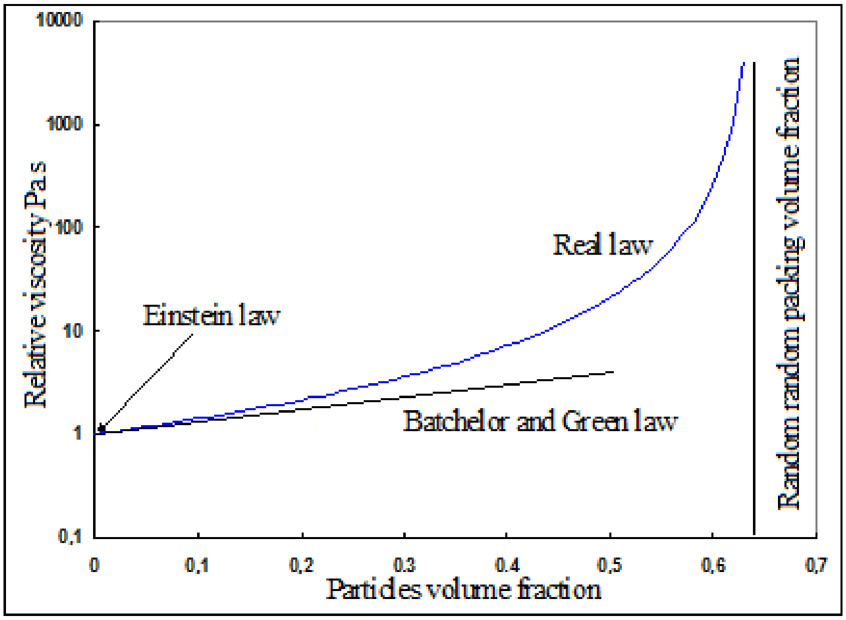

Fig. 6 : Example of viscosity change with the volume fraction.

2. Results and Discussion

2. 1. Study of drop pressure in suspensions isothermal flow

Assuming that the carrier fluid would behave as a non-mixed with particles glucose solution, we represent the evolution of the friction coefficient in function of the Reynolds number calculated with the viscosity of the carrier fluid and we find that there is no uniqueness of the friction law (Fig. 7).

To a volume fraction of solid particles (%), evolution is almost in agreement with the master curve ($16/Re_0$) with a gap of 0.17%; but increasing the volume fraction is significantly increase the coefficient of friction (Fig.7). The introduction of the particles in the flow affects the behavior of the mixture and particularly on the carrier fluid. We come to the findings that the Reynolds number calculated from the single-phase viscosity is not a good parameter to describe the pressure drop in suspensions of monodisperse particles of hard spheres (Fig. 7).

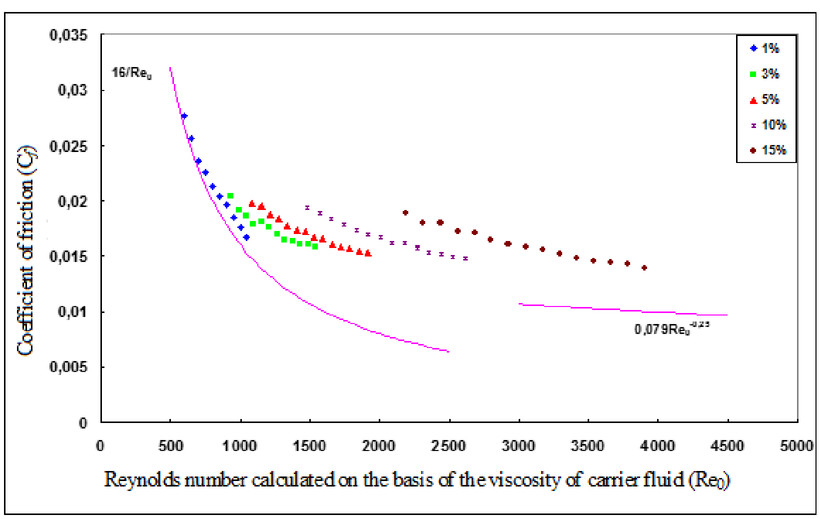

Fig. 7: Evolution of the friction coefficient as a function of Reynolds number (Re_0) determined by the viscosity of the fluid (η_0) in laminar and turbulent flow isothermal.

2.2. Hypothesis concentration Einstein

For a Newtonian fluid and carrier for weakly loaded suspensions, we made the assumption that the concentration of Einstein (1906) that a simple relationship binds the viscosity of the carrier fluid to the viscosity of the mixture (fluid-particles) (Fig. 8); Testing laminar flows suspensions were carried out with the Einstein law to verify the evolution of the friction coefficient in function of the Reynolds number calculated according to the Einstein law (13) is: $\eta_{susp}=\eta_0(1+2{,}5\phi)$ (13)

We note that there is a slight improvement but not sufficient; because the suspension is not sufficiently diluted ($\phi=$ 1% while Einstein's law is valid for a volume fraction $\phi\leq 0{,}5$) (Fig. 8).

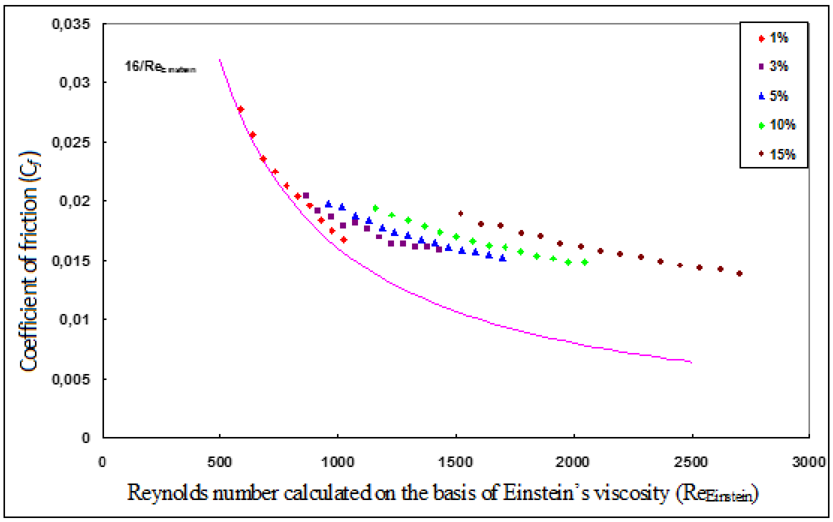

Fig. 8 : Evolution of the friction coefficient monodisperse suspensions isothermal Flow depending $Re_{Einstein}$ determined using laminar Einstein's viscosity

2.3. Hypothesis of "effective" medium

We propose to do, now, the hypothesis that the suspension behaves like an effective fluid; that is meaning a suspension of hard spheres considered as a continuous medium. Effective viscosity is then determined depending on the viscosity of the fluid suspending η_0 the volume fraction of particles ϕ and the maximum stack fraction $\phi_P \approx 0{,}64$ .This is the Quemada's law:

$$\eta_{eff}=\eta_0\left(1-\frac{\phi}{\phi_P}\right)^{-2} \quad (14)$$

We proceeded to compare the Quemada's law with the viscosity obtained by Poiseuille's law in the case of the flow of suspensions constant debiting velocity of 1.3 m/s. The results showed us a gap of 0.54%. We have shown in Figure 9, the changes in the relative viscosity ($\eta_r=\frac{\eta_{ap}}{\eta_0}$) as a function of the volume fraction of solid particles to a flow velocity of 1.3m / s (Fagla & al., 2002). The Quemada's law is consistent with that of Poiseuille's one. The comparison with experimental data of Quemada's model (1998) is quite satisfactory and seems to validate the approach effective medium.

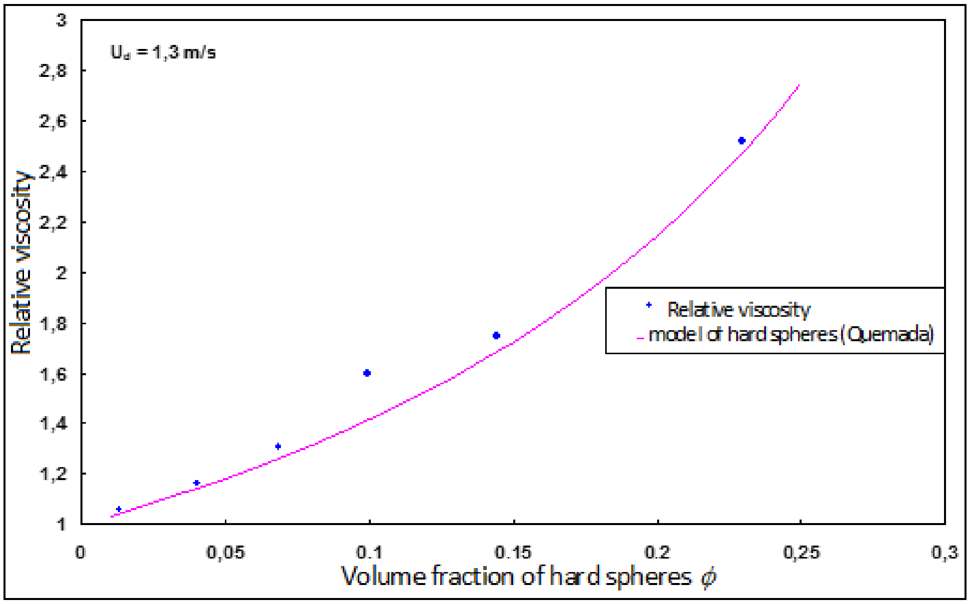

Fig. 9 : Demonstration of the approach effective medium in an isothermal flow suspensions:
the Quemada's law is consistent with the viscosity variation by Poiseuille's law (Fagla & al., 2002)

2.4. Pressure drop in isothermal laminar flow suspensions

With the concept of effective viscosity, we show that it is possible to find the general law of laminar friction where the effective Reynolds number from equation below is calculated taking into account the effective viscosity $\eta_{eff.}$ of the mixture.

$$Cf = \frac{16}{\mathrm{Re}_{eff.}} \qquad (15)$$

The experimental results are compared to the theoretical model (Fig. 10). There is one law that governs the curves of different volume fractions of solid particles. The consistency of the results is good. We note, however, that the transition comes at $Re_{eff.}$=800 (for all concentrations except 1%). It seems that the transition from laminar to turbulent occurs earlier, at an early stage for loaded fluids. We can conclude that the suspensions of particles destabilize the flow without inducing a transition on the scale of the overall flow. We note that it is from 2% that multiple hydrodynamic interactions are taken into account to describe the viscous dissipation.

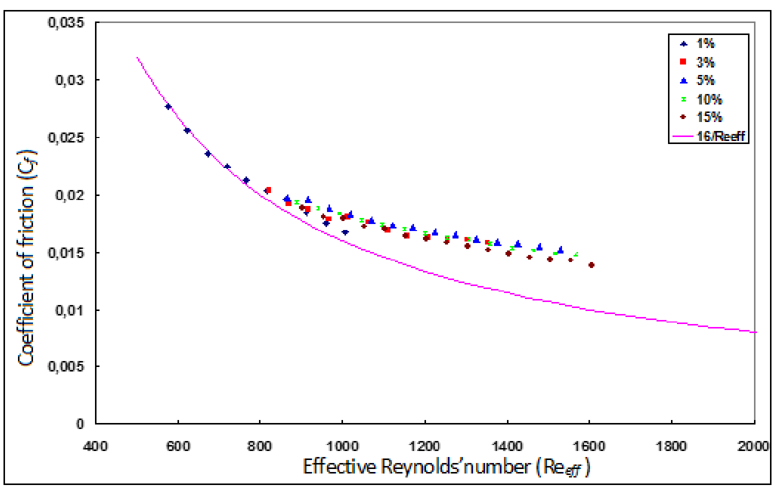

Fig.10: Evolution of the friction coefficient of isothermal suspensions depending on
the Reynolds number (Re_{eff}) determined using the effective viscosity in laminar flow.

2.5 Demonstration of the non-homogeneous nature of the studied suspensions

2.5.1. Hypothesis of "homogeneous" fluid

We worked with various concentrations (1%, 3%, 5%, 10% and 15%) of spherical particles in monodisperse suspensions in the glucose syrup solution doing the hypothesis of the "homogeneous" Fluid. If suspension (two-phase mixture) behaves as a homogeneous Newtonian fluid equivalent (in the case of a Newtonian fluid carrier), one can deduce the apparent viscosity of the suspensions from measurements of debit and pressure drop in a pipe flow. The longitudinal pressure gradient ($\Delta P / L$) is connected to the wall shear stress by the linear relationship (16):

$$\tau_p = \frac{\Delta P}{L} . \frac{D}{4} \qquad (16)$$

and $$\tau_P = \eta_{ap} \dot{\gamma}_P = \eta_{ap} \left(\frac{8 U_d}{D} \right) \qquad (17)$$

with η_{ap}, the apparent viscosity of the mixture.

2.5.2. Determining the relative viscosity and highlighting of the apparent rheo-thickening nature of the suspension.

We define the equivalent relative viscosity,

$$\eta_r = \frac{\eta_{ap}}{\eta_0} \qquad (18)$$

where η_0 is the viscosity of the carrier fluid.

We study the equivalent viscosity suspensions for several volume fractions of particles. The change of viscosity depends on the debiting velocity. We find that, regardless of the volume fraction, we observe an almost linear dependence between this equivalent viscosity and debiting velocity for each volume fraction and that there is no uniqueness of law (Fig.11). The relative viscosity increases with the volume fraction of particles. To a volume fraction greater than or equal to 3%, the curves have almost the same inclination; they are then governed by the same non-linear law (with the exception of the lowest volume fraction or 1%, for which the relative viscosity is close to 1).

At a low volume fraction ($\phi = 1\%$ with slope ≈ 1), the law is almost linear and in this case, the apparent viscosity can be compared to the viscosity of the carrier fluid (Fig. 11). The mixture behaves like a fluid apparently rheo-thickening (then Non Newtonian).

In fact this variation of the relative viscosity η_r is a consequence of variations in the volume fraction when the velocity changes. We consider, at first approximation, that the viscosity remains constant for a volume fraction. We obtain a viscosity as a function of the volume fraction. This variation of the volume fraction of particles with the flow rate is due to a settling effect, particularly in the areas of singularity (or dead zones) of the installation and in the downstream container. Increasing the debiting velocity induces a suspension, causing an increase in the effective viscosity of the mixture. We note, from experimentation, that the distribution of particles in the pipe is not made uniformly regardless of the value of the volume fraction. This could be the basis of the variation in the apparent viscosity of the mixture during the flow.

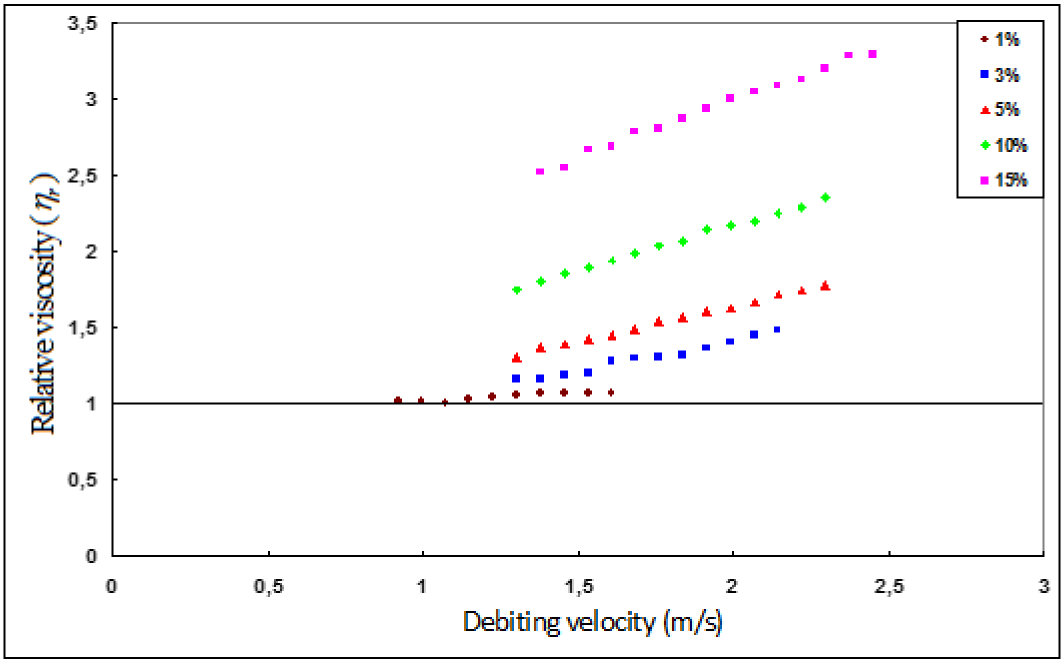

Fig. 11 *:* Highlighting the apparent thickening rheological nature of the suspension.

3. Conclusion

Experimental analysis conducted on suspensions made of syrup of glucose (Newtonian fluid) and large hard alginate spheres (D = 4.4 mm) in isothermal flow in a horizontal pipe produced results that highlight the different variations observed about the relative viscosity. This equivalent viscosity of the suspensions varied, proportionally to the volume fractions of particles; this is an almost linear dependence between this equivalent relative viscosity and the debiting velocity that regardless of the volume fraction of particles. This highlighted the non-uniqueness of the law of behavior and also the growth of the relative viscosity with the volume fraction of particles. The presence of these particles confirms their influence on the nature of the fluid and their contribution to the change in the rheology of the mixture and therefore that of interstitial fluid. This change of the nature of the rheology of the mixture fundamentally alters the hydrodynamics of the mixture; the interactions between the carrier fluid and the spherical particles are responsible for the inhomogeneity (irregular distribution of particles in the pipe) suspensions in an isothermal flow. The radial migration of particles nearby the center line and more precisely its part immediately above is the basis of the overall flow change. It is generated by the sedimentation of particles and their grouping in the heart of laminar flow. The obtained results showed that a Newtonian fluid loaded with particles of large dimensions give Non-Newtonian behavior of suspensions apparent rheo-thickening type. It should be noted that a high viscosity tends to decrease as one approaches the wall from the axis of the pipe, in most cases studied. This led to obtain a pseudo Non-Newtonian mixture from a single phase Newtonian fluid.

Bibliographic References

Longo, S., 2005, ‘‘Two-Phase Flow Modeling of Sediment Motion in Sheet-Flows above Plane Beds,’’*J. Hydraul. Eng.*, 131 (5), pp. 366–379.

Longo, S., 2005, ‘‘Granular-flow rheology: role of shear-rate number in transition regime,’’J. Hydraul. Eng. 131 (5) pp.366.

Saintillan D. et **Shelley** M. J., 2013, ‘’Active suspensions and their nonlinear models,’’ 14 (6) pp. 497–517, Académie des sciences. Elsevier Masson SAS.

Chhabra R. P., 1990, ‘‘Motion of spheres in power law (visciinelastic) fluids at intermediate Reynolds numbers: an unified approach’’ Chem. Eng. Process, 28, pp. 89-94.

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.

Takahashi I. 1978. Pressure drop of suspensions inheterogeneous flow. Hydrotransport V, 8-11 May, paper C5.

Kemblowski Z. and **Kolodziejski** J., 1973, ‘‘Flow resistance of Non-Newtonian fluids in transitional and turbulent flow,’’, Int. Chem. Eng. 13, pp. 265-279.

Cheng D. C. **-** H., 1970, ‘‘A design procedure for pipeline flow of Non Newtonian dispersed systems’’ Hydrotransport I, 1-4 September, paper J 5.

Durand R. D. 1953, Minnesota Int. Hydraulics Conv., Proc. Int. Ass. for Hydraulics Research, p. 89.

Ayukawa K., 1969. ‘‘Velocity profile in a horizontal duct in the hydraulic transport of solid’’. Proceedings of 47th Congress of japan Soc. Mech. Engrs.

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 solid in pipes.

Hoareau F., 1996, ‘‘Etude dynamique et thermique de suspensions solides-liquides non-newtoniennes en conduite’’. Thèse Mécanique-Energétique Université de Nancy I France.

Fagla F.Z.B., 2002, ‘‘Etude thermomécanique de suspensions solide-liquide newtonienne et non newtonienne en écoulement dans une conduite horizontale’’, Thèse en Mécanique-Energétique INPL Vandoeuvre-lès-Nancy France, p. 252.

Chong J., S., **Christiansen** E. B., **Baer** A D., 1971, ‘‘Rheology of Concentrated Suspensions,’’ Journal of Applied Polymer Science, **15**, pp. 2007-2021.

Antoine Y, et **Lebouché** M., 1998, ‘‘Détermination des vitesses de glissement lors de l’écoulement d’une suspension non newtonienne par l’utilisation de la vélocimétrie ultrasonore à effet Doppler’’. Comptes Rendus de l’Académie des Sciences de Paris, t.326 Série II b, 1998.

MetznerA. B.**,Reed** J. C., 1955, ‘‘Flow of Non-Newtonian fluids correlation of the laminar, transition and turbulent flow regions,’’ AICHE, 1, pp. 434.

Mills P.,**Snabre** P., 1995, ‘‘Rheology and Structure of Concentated Suspensions of Hard phères. Shear Induced Particle Migration,’’ J. Phys. 10 pp. 1597-1608.

Zarraga I. E., **Hill** D. A., **Leighton** Jr. D., T., 2000, ‘‘The characterisation of the total stress of concentrated suspensions of noncolloidal spheres in Newtonian fluids,’’ J. Rheol. 44, pp.185-220.

Taghipour F, **Naoko** and E, **Wong** C, 2005, Experimental and computational study of gas–solid fluidized bed hydrodynamics. Chemical Engineering Science 60, (24), pp. 6857-6867.

Murat O., **Gareth** H. Mc., 2012, ‘‘Rheology and microstructural evolution in pressure-driven flow of a magnetorheological fluid with strong particle–wall interactions,’’ *Journal of Intelligent Material Systems.*

Dingyi P., **Nhan** P.-T., et **Boo** C., K., 2014, ‘‘Dissipative particle dynamics simulation of droplet suspension in shear flow at low Capillary number,’’ Journal of Non Newtonian Fluid Mechanics 212, pp. 63–72.

Parmar R., **and Kumar Majumder S.,** 2014, ‘‘Hydrodynamics of Microbubble Suspension Flow in Pipes,’’*Ind. Eng. Chem. Res.*, 53 (9), pp. 3689–3701.

Chiodi F., **Claudin** P., and **Andreotti** B., 2014. ‘‘A two-phase flow model of sediment transport: transition from bed load to suspended load,’’ Journal of Fluid Mechanics, 755, pp.561- 581.

Fagla F. Z. B**, Gradeck** M**, Baravian** C.**, Lebouché** M., 2001, ‘‘ Ecoulement de suspensions solides-liquides, Rhéologie’’ soumis au XVème Congrès Français de Mécanique Nancy INPL France.

Metzner, A., B**.,** and **Reed**, J., C., 1955, ‘‘Flow of Non-Newtonian fluids correlation of the laminar, transition and turbulent flow regions,’’ AICHE, 1, pp. 434.

Einstein, A., 1956,‘‘In Investigation of the Brownian movement,’’ New York, Dover publication English translation of Ann.Physik, 19, p.286 (1906), et 34, p. 591, (1911).

Davis, R. H. and **Acrivos**, A., 1985, ‘‘Sedimentation of noncolloidal particles at low Reynolds’’A. Rev. Fluid Mech., 17, pp.91-118.

Quemada D., 1998, ‘‘Rheological modelling of complex fluid **I**. The concept of effective volume fraction revisited’’ Eur. Phys. J. AP 1, pp.119-127.