A review of the usage of highly viscous fluids in industrial applications

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Abstract. Highly viscous fluids (HVF) are used in food sector as raw materials (melted vegetable, animal fats) or finished products (chocolate, sorbets), in construction sector as liquid state of Phase Change Materials (PCM) used to store thermal energy inside building structure or building materials such as liquid concrete, bitumen and tar, in automotive industry as PCMs used to passively cool batteries, and many others. Some applications are rather new and lot of research has been done, in the last decade, to find mathematical models for predicting HVF behaviour, in heat and mass transfer processes in scraped surface heat exchangers, in vegetable fat melters and in waxy crude oil transport pipelines. Better results could be obtained by enhancing HVF thermal properties such as increasing the thermal conductivity of PCMs by adding metallic powders, or by finding new natural materials (vegetable fats) which can replace more expensive and harmful ones (waxes) for PCMs. This study was performed to shortly present the main applications in which HVFs are being used, the main advances and findings made in the last years and the current challenges and research possibilities which are likely to be explored in the future.

1. Introduction

The viscosity of a fluid represents its resistance to flow, seen as deformation, as a result of its high internal friction which is related to its molecular structure [1]. A highly viscous fluid is a fluid that requires the usage of a high quantity of energy to transport it through piping systems. These kinds of fluids can be single phase fluids such as melted PCMs [2], melted vegetable fats at a temperature close to their solidification point [3], tar, melted plastic polymers [4] etc., or multiphase fluids like ice slurries [5], vegetable and fruit juices [6], sorbets [7], jams, gums solutions, concrete, waxy crude oils [8], some types of nanofluids [9] etc. They can either be finished products or raw materials which are industrially processed to obtain saleable goods.

HVF\s are used in many industries such as the food and beverage [10], chemical and oil [11], energy storage in buildings [12], constructions and roads etc. Some of them have rather simple chemical structures and their thermo-fluid characteristics are easy to obtain but most are rheological (non-Newtonian) fluids which are difficult to be described and modelled [13].

Some of the applications in which HVFs are used, such as latent heat energy storage or heating/cooling using nanofluids, have become really interesting for researchers because a lot of attentions and funds has been given to them by the authorities or private companies. As a result, many research projects have been carried out and many scientific articles have been published [14].

2. Usage of HVFs in industrial applications
As mentioned above, HVFs are being used in many industrial sectors and for a varied array of applications. In the following, a summarized list of the main usages, grouped in industry types, is presented.

2.1. Food and beverage industry
Most of food products such as gels, suspensions of solids in liquids, emulsions, semi-solids etc., which are used to produce ready-to-eat foods have a complex physical structure. Based on their chemical composition, as well as on the temperature and pressure at which these materials are being processed, they can behave as HVFs. Some of the most known HVFs used in the food industry are presented in the following.

Chocolate and other cocoa based products are, in their fluid state, dispersions in which the melted cocoa butter is the liquid phase and cocoa mass, sugar crystals and other solid materials make up the solid phase. Because of its high viscosity (typical values of 5 to 20 Pa·s [15]) chocolate is being transported in jacketed pipes supplied with hot water, at low speeds in laminar flow regime. In order to decrease the viscosity of chocolate and to make it easier to flow, the content of fat (cocoa butter or normal butter) needs to be increased, because this leads to increasing the distances between the solid particles. The storage of chocolate is also made in jacketed stainless steel tanks which are equipped with a mixer which is started once every few minutes to prevent the separation of the chocolate ingredients. In recent studies chocolate has been found to help neurological and heart health [16].

Vegetable and fruit juices as well as purees are also dispersions made up of water as the liquid phase and mainly vegetable/fruit pulp as the solid phase. These are sold as finished products or can be used to obtain other foods, mainly desserts. In high concentration of pulp they can become quite viscous. In order to reduce the viscosity, the temperature of the dispersion should be increased. A review of literature data available on the rheological properties of fluid fruit and vegetable purees products can be found in [17].

Sorbets are mixtures of water and sucrose (from fruit concentrate of fruit pulp) which are cooled down below 0°C, temperatures at which ice crystals form. The viscosity of these products is very high, that is why scrapped surface heat exchangers are being used to cool them [18].

Gums mixture solutions have also high values of viscosity of tens to hundreds of Pa·s [19]. The main types of gums used in the industry are Accacia gum, guar gum, xanthan gum, locust bean gum. They can be used for the manufacture of chewing gums, as food thickeners, to control the viscosity, enhance consistency etc. [20].

Other food materials that exhibit high viscosities are jams, which can have viscosities of tens of thousands of Pa·s [21], ice cream [22], gelling agents which normally are made of polysaccharides and proteins [23].

The flow characteristics of these kinds of rheological fluids are very difficult to be measured and predicted due to their complex physical and chemical structure. A comprehensive review of the mathematical models which are currently used to model the flow of various types of fluid and fluid-like food materials, their accuracies and limitations, is found in M.A. Rao’s book [10]. As an example, for the flow of chocolate, for modelling the shear stress, \( \tau \) in Pa, as a function of the shear rate, \( \gamma \) in s\(^{-1}\), Casson model is widely recommended:

\[
\tau^{0.5} = K_{0c} + K_c (\gamma)^{0.5}
\]

in which \( \gamma \) is the shear rate in s\(^{-1}\) and the parameters \( K_{0c} \) and \( K_c \) represent the slope and the intercept, respectively, of a plot of the square root of the shear rate against the square root of the shear stress [24].

2.2. Chemical and oil industry
In oil industry, some of the most highly viscous fluids that need to be transported are heavy crude oil (viscosity < 10 Pa·s) and natural bitumen (viscosity > 10 Pa·s) [25]. In order to be economically feasible for transporting these fluids in piping systems, some methods are normally used to reduce their viscosity,
such as heating, dilution, oil water emulsion, core annulus etc. [26] Natural bitumen is used for road construction (as part of asphalts), producing paints, polish and insulation of tanks and others.

In chemical industry, one of the fluid types with high viscosity is the plastic polymer melt. The values of shear viscosity vary, based on the chemical structure of the polymers, from 10 to $10^7$ Pa·s [27]. These are used to obtain a lot of products as plastic containers, plastic foils and many others.

The flow of polymer melts and waxy crude oil are difficult to model as they are non-Newtonian fluids. Usually, the conservation equations of mass, momentum and energy are used to describe the flow and a power-law formula is used to describe the apparent viscosity, $\mu_a$ in Pa·s as a function of the shear rate, $\gamma$ in s$^{-1}$ [28]:

$$\mu_a = K \cdot \gamma^{n-1}$$

in which, $K$ is the consistency coefficient in Pa·s$^n$ and $n$ is the dimensionless index of the rheological fluid. Both $K$ and $n$ can be experimentally obtained.

2.3. Building and construction industry

In the construction sector, the highly viscous fluid-like materials are cements mortars [29] and self-consolidating concrete [30], the already mentioned bitumen in the structure of asphalts, some types of paints, polyurethane foams and others.

The rheological properties for concrete mixtures can be calculated according to the Bingham model [31]

$$\tau = \tau_0 + \eta \cdot \gamma$$

in which $\tau_0$ represents the yield stress in Pa and $\eta$ is the plastic viscosity in Pa·s. The shear stress at varying shear rates is being measured with viscometers.

The yield stress, $\tau_0$ for a concrete mixture can be calculated according to the following formula:

$$\tau_0 = 0.00815 \rho_m/((0.498/(30-\text{SL}))^{0.5}-0.024)^2$$

in which $\rho_m$ represents the density of the concrete mixture in kg/m$^3$ and SL is the slump of the concrete mixture in cm.

One of the topics which have been studied very much in the past years is the reduction in the energy consumption, for which in Europe and U.S. the buildings account for about 40% of the primary energy consumption [32]. That is why a class of viscous fluids (in the melted phase) which are being incorporated more and more in building are the phase change materials (PCM) which are used for the latent heat energy storage [33]. Most of the materials used as PCMs are paraffin waxes and salt hydrates but recently some vegetable fats and oils (coconut oil) have also started to be used for energy storage in buildings [34]. The viscosity of coconut butter decreases with temperature and has a value of 0.02877 Pa·s at 30°C [35].

An empirical formula was developed to estimate the dynamic viscosity, $\mu$ of paraffin waxes based on the actual temperature at which the melted wax is, and its melting temperature [36]

$$\mu=(3.7 \cdot 10^8 \cdot T^2+6.1 \cdot 10^6 \cdot T-4.4 \cdot 10^4 \cdot T+1.4 \cdot 10^2) \cdot c$$

$$c = 0.01 \cdot T_m^2 - 0.0215 \cdot T_m + 0.5815$$

in which $T_m$ is the melting temperature.

The melting and natural convective flow of PCMs can be modelled using the Stefan and Neumann problem approaches [37].

Because the thermal conductivity of most PCMs is low so the heat transfer inside the mass of the PCM is also quite low, several methods are normally used to enhance the performance of thermal storage systems such as the use of fins, filling materials, nanofluids and nanoparticles [38].

PCMs are not only used inside buildings to reduce the energy consumption but also to increase the performance of solar panel by reducing solar panel’s heat losses towards the environment [39], to
passively cool the batteries of electrical vehicles and thus severely increase their lifetime [40], for cold storage in air-conditioning systems [41] and others.

2.4. Refrigeration industry

One of the refrigerant types which are being used more and more are ice slurries which are dispersions of water and ice. The dynamic viscosity of the ice slurries, $\mu_{TP}$ (TP – two phase) in Pa·s, is a function of the volume fraction of ice according to the formula [42]:

$$\mu_{TP} = \mu_l \cdot (1 + 2.5 \cdot \varphi_s + 10.05 \cdot \varphi_s^2 + 0.00273 \cdot e^{16.6 \cdot \varphi_s})$$

(7)

in which $\mu_l$ is the dynamic viscosity of the liquid in Pa·s and $\varphi_s$ is the volume fraction of solid ice in the slurry.

For the modelling of both phase-change (melting of the ice crystals) and slurry flow through pipes, the multiphase Euler-Euler which is based on the kinetic theory of granular flow can be used [43]. This model is based on the conservation of mass, momentum and energy equations but it also uses elements from the granular flow theory.

Ice slurries are used as refrigerants, as storage mediums in the air-conditioning systems for buildings mostly in Japan (over 400 systems), in early stages for district cooling – a 5 years pilot project was started also in Japan, in breweries (replacing ammonia) and in large kitchens. They are also used for cooling foods from direct contact in bakeries, for produce packing and fisheries etc. Other applications are in the pharmaceutical industry for medical cooling of organs and some types of minimal invasive surgery [44].

2.5. The use of nanofluids in various industries

Nanofluids, which are colloidal suspensions of metallic and non-metallic nanoparticles in conventional base fluids, are used to increase the heat transfer capabilities. They can be used for cooling electronic components, industrial and nuclear systems cooling, heating of buildings, energy storage, friction reduction and many others. The viscosity also has a high impact on the transfer capabilities. High viscosity in nanofluids is not desired because it will increase the needed pumping power. The viscosity increases with increasing effective size of aggregates for a given primary nanoparticle size and by lowering the temperature [45]. At low shear rates the viscosity of some nanofluids (EG/Fe$_2$O$_3$ nanofluids at 25% concentration) can reach up to 7 Pa·s [46].

A brief description of the theoretical models used to predict the viscosity of a nanofluid as a function of the viscosity of the base fluid and volume/mass fraction of the particles in suspension can be found in [47]. A review on the experimental measurements made to determine the viscosity of nanofluids is found in [46].

One of the most used models to calculate the dynamic viscosity, $\mu_{nf}$ in Pa·s, of a nanofluid that is also accepted by researchers is the one developed by Brinkman [48] for particle concentrations of up to 4%:

$$\mu_{nf} = (1 - \omega)^2 \cdot \mu_f$$

(8)

in which, $\mu_f$ is the dynamic viscosity of the base fluid in Pa·s and $\omega$ is the mass fraction of particles in the suspension. Some correlations were developed to take into account the temperature dependency of the viscosity [49]:

$$\mu_{nf}/\mu_f = (2.1275 \cdot 0.0215 \cdot T + 0.00027 \cdot T^2)$$

(9)

in which $T$ is the temperature of the suspension in K.

3. Conclusions

Many industries use HVFs as either raw materials or finished products. Several such fluids are used in food industry, ranging from melted fats to jams, sorbets and chewing gum, in chemical industry, with natural bitumen and heavy waxy crude or processed paints and polymer melts, in the construction sector, in which cement mortars are used to create structural elements and PCMs, which in recent times include
also vegetable fats such as coconut oil, are part of energy storage systems, and in the refrigeration and pharmaceutical industries where ice slurries are being used in many different applications.

A newer type of rheological fluids, the nanofluids, are used in many different industries with many different applications which include the cooling electronic components, industrial and nuclear cooling systems, heating of buildings, energy storage, friction reduction. HVFs can be single phase fluids but most of them are complex multiphase rheological fluids which are difficult to be mathematically described and modelled. Different viscosity formulations apply to different fluid types and data obtained from experimental measurements are always needed to validate their accuracy. A lot of research has been done on this topic and new mathematical formulations and practical methods of improving the performance of HVFs are still being developed.

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