Flows of Viscous Fluids in Food Processing Industries: A review

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Abstract: The process of fluid movement is involved in a majority of food industries around the world. Viscous fluids are often used in such industries to make useful food products in bulk. These industries need to ensure that concerned equipment such as pipes are kept clean as well as are clear for the smooth transport of viscous liquids. The fluids are pumped in these pipes which results in friction over the walls of the pipe. Flow characteristics are the fundamental basis of the mass transfers taking place in food industries. The resulting qualities of the products are mainly reliant on these fluid flow properties. The design as well as control of the properties of a food in terms of its rheology is a big factor for the commercial success of a product. Therefore, to better understand this complex problem, it is crucial to first comprehend the rheological properties of different materials and fluids, which are widely present in the food industry. Thus, understanding the properties of fluids and overall the rheology of these is important. This paper discusses the fluid movements in food processing industries and discusses the concepts of fluids in motion. Concepts of viscosity and different flow regimes along with flow phenomena are also discussed in terms of rheology. Finally, as a case study example, the rheology of a complex fluid, honey, is reviewed in this paper.

Keywords: Newtonian and non-Newtonian flow; Viscosity; laminar and turbulent flow; Reynolds Number; Rheology; Honey.

1. Introduction
Food industries around the world involve several requirements for processing which demand material transport during operations. Food processing industries often makes use of viscous liquids which require the procedure of fluids movement to take place adequately [1, 2]. Food products such as spreads and sauces are commonly produced and marketed. These products are usually non-Newtonian, viscous liquids (White et al., 2008). In addition, solid food products such as chocolates and ice creams are also marketed but are originally non-Newtonian fluids [3]. Moreover, some products involve the use of viscous liquids as a main component to their assemblies. These can for example include syrups as well as jams for fillings or chocolates for coatings [4, 5].

Industries concerning operations of food processing need to ensure that the pipes are kept clean as well as are clear for the smooth transport of viscous liquids. Overall, foods which are liquid in nature, for instance, juices and milk, need to be pumped through equipment such as pipes with the aid of differential pressure from one batch or container to another [1, 6]. To elaborate, proper designed pipelines are mainly needed for the adequate distribution of service utilities (for example, gases, steam and water) around the
plant. However, it must be noted that pumping results in friction over the walls of the pipe. This could obstruct the smooth transportation of ingredients. Fluid flow applications in food processing industries often involve several essential unit operations. These include procedures such as mixing, pressing as well as filtration. Flow characteristics are the fundamental basis of the mass transfers. In fact, the overall resulting qualities of the products are mainly reliant on the fluid flow properties [1, 7]. This may result in rheologists facing various key challenges in the food industries. It must be noted that the design as well as control of the properties of food in terms of its rheology is a big factor for the commercial success of a product.

As discussed above, manufacturing, distribution, handiness and sensory feel of a product may be affected by the product’s rheological properties [8-12]. Therefore, to better understand this complex problem, it is essential to first comprehend the rheological properties of different materials and fluids, which are widely present in the food industry. The study of fluids which are transported in industry falls under the discipline of fluid mechanics. Thus, understanding the properties of fluids and overall the rheology of these is important.

2. Literature Review

2.1. Flow Regime

In the field of fluid mechanics, fluid mixing and fluid flow characteristics can be explained by the Reynolds number, Re. This number is a ratio of inertial forces to viscous forces and is described as:

\[ Re = \frac{\rho u L}{\mu} = \frac{u L}{v} \]  

(1)

Here \( \mu \) is the fluid dynamic viscosity, \( v \) is the kinematic viscosity, \( L \) is the characteristic length and \( \rho \) is the density. It must be noted that Re is a dimensionless number [13, 14].

The viscosity is not constant in Non-Newtonian fluids and therefore viscosity decreases as shear rate enhances in shear thinning materials [15]. The power law can explain the behaviour of these non-Newtonian liquids in a rheological manner by the following equation:

\[ \tau = k \gamma^n \]  

(2)

Here \( n \) refers to the flow behaviour index and \( k \) is the consistency factor. \( \tau \) is the shear stress while \( \gamma \) is the shear rate[13, 15]

The fluid thickness is measured by the aid of the consistency factor. Whereas, the strength of a non-Newtonian liquid is measured by \( n \). For Newtonian fluids, \( n = 1 \) and lies between 0 to 1 for shear thinning fluids. When the viscosity of material is not constant, the Reynolds number correlation described above is not useful. For calculating average shear rates in a stirred vessel, Metzner and Otto correlation is used and its very useful. It also helps calculate the Re by the power law model:

\[ Re = \frac{\rho N^2 - n D^2}{k s^{n-1}} \]  

(3)

Here \( k_s \) is the Metzner and Otto constant. This value is based on the pitched blade turbine and on the impeller type. \( \rho \) is the density, \( N \) is the rotation frequency, \( D \) is the impeller diameter, \( k \) is the consistency factor [15, 16].

The shear thickening material also shows non-Newtonian behaviour and its behaviour is opposite to shear thinning fluids. The shear rate and viscosity both increases simultaneously in shear thickening materials. The power law model can also be used to represent their rheological behaviour where the flow behaviour index is usually greater than 1 [15, 17].

2.1.1. Laminar and Transitional Flow Regimes: Laminar regimes are usually related to fluids with increased viscosities. For a fluid of laminar flow at typical energy input, the viscosity is above 10 Pas.
For such high viscosity fluids, their rheology is usually very complicated. Flow regimes mainly prevail in situations where effective agitation of highly viscous fluids is complex and not easy to achieve. Creams, pastes and paints are examples of high viscosity fluids. In laminar flows, the inertial forces tend to wipe out quickly. This is usually because of the action of increased viscosities in such cases. Hence, for enough motion, it is usually recommended to ensure that the impellers which rotate are able to cover significant vessel areas [13, 18-21].

2.1.2. **Turbulent Regimes**: Fluid flow is called turbulent when viscosity is less than 10 Pas in mixed vessels. The inertial force developed by the moveable impeller is able to distribute the fluid in the vessel and move it backwards to the impeller. Turbulent eddy diffusion takes place in this circulation. The mixing is enhanced due to eddy diffusion in turbulent flow. This mixing is larger as compared to laminar flows. The lack of eddy diffusion in laminar flows and in transition regions is the main cause of inefficient mixing. The fluid mixing rate increases due to motion of turbulent eddies therefore turbulent regime is a region of efficient mixing in a vessel [22].

Works done on the characteristics of mixing showed that the flow field often illustrates 3D fluctuations in velocity for turbulent regimes [23]. This was explained further by researchers who stated that under turbulent regimes, the fluids exhibit periodic hydrodynamics as well as anisotropic turbulent dissipations [24].

2.2. **Newtonian and Non-Newtonian Fluids**

Fluids can be classified as “Newtonian or non-Newtonian””. A Newtonian fluid at all shear rates has same viscosity at constant pressure and temperature and is explained by a single parameter rheological model:

\[ \tau = \mu \dot{\gamma} \]  

(4)

Here \( \tau \) denotes shear stress, \( \mu \) refers to the Newtonian fluid’s viscosity and \( \dot{\gamma} \) denotes the shear rate. Using this correlation, a Newtonian material can be described by a straight line if shear rate is plotted against shear stress.

To elaborate, Newton observed and analysed that normal liquids have constant viscosity. He also pointed out that viscosity only varies with pressure and temperature changes. A non-Newtonian fluid viscosity changes and is dependent upon the applied force and stress. A non-Newtonian fluid behaves in a different way under applied stress. With the application of stress, some fluids become more liquid and some become solid. Therefore, the quantity of applied stress and duration of stress plays a key role in the responses of non-Newtonian fluids [25, 26].

The relation is linear between the rate of deformation and shear stress in case of non-Newtonian fluids. The most interesting example of a non-Newtonian fluid is corn starch mixed with water. The properties of Newtonian fluids like water depend upon pressure and temperature. However, non-Newtonian fluid behaviour depends upon forces which can vary from time to time. Works carried on this have shown that water changes into gas at 100°C and changes into ice at 0°C. However, viscosity remains constant and shows properties of a normal liquid.

It is worth mentioning that the rate of flow cannot change the viscosity of a fluid in case of Newtonian fluids. Newtonian fluids adopt the shape of vessel in which they are transferred but non-Newtonian fluids do not follow this rule. Overall, non-Newtonian fluids are highly viscous fluids. They have complex rheologies and thus this results in complications with their mixing. In the various industries in operation worldwide, most fluids show properties of non-Newtonian fluids. For example, properties such as thixotropy, yield stress as well as plasticity are shown by fluids employed in industries such as mining, oil and food [27].

Non-Newtonian fluids can be mainly characterised into 3 classes. This is based on their shear rates as well as fluid viscosities [28]:

- Time independent fluids;
- Time dependent fluids;
- Viscoelastic fluids
Figure 1 shows a plot of the shear stress vs shear rate for different types of Newtonian and non-Newtonian fluids.

![Figure 1: Plot of shear stress vs shear rate for various Newtonian and non-Newtonian fluids (adapted from [29]).](image)

2.2.1. **Time independent fluids:** As the name suggests, there is no role of time in the behaviour of time independent fluids. The material has no memory and its current state is independent of deformation history. Figure 2a below shows shear stress vs shear rate plots for different fluids. A straight line through the origin is used to represent a Newtonian fluid and viscosity remains same at all shear rates. However, for non-Newtonian fluids, the flow curves are shown for fluids with different constitutive equations. Figure 2b shows the viscosity versus shear rate plots for the shear thinning, shear thickening and Newtonian materials.

Both shear thinning and shear thickening materials are explained by power law equation:

\[
\tau = K\dot{\gamma}^n
\]  

Here, \(n\) is the power-law exponent and \(K\) is the consistency index. For shear thinning materials, the exponent \(n\) lies typically between 0.2 to 1. For shear thickening, \(n\) is greater than 1.

![Figure 2: Plot of (a) shear stress vs shear rate and (b) viscosity vs shear rate for various Newtonian and non-Newtonian fluids (adapted from Liu et al., 2018).](image)
2.2.2. Time dependent fluids: Contrary to time independent fluids, these fluids have a long memory. Their viscosity changes with time during shearing of a material. These types of material can be classified as Thixotropic material and Rheopctic materials. In Thixotropic materials, the shear is thin over extended time. Self-assembling surfactant and block co-polymers are examples of Thixotropic materials. The opposite of Thixotropic material is Rheopctic materials. In these, shear thickens over extended time and they are not of a common type. The highly filled fibre and wood pulp are examples of Rheopctic materials. Time dependent fluids have a long memory as compared to experiments. The physical structure changes due to applied stress on fluids and therefore viscosity of material changes with passage of time. These are time dependent fluids and they show thin shear over an extended time period. When shear stress is applied, the viscosity decreases till stress is removed and recovery phase starts gradually. Rheopctic materials’ viscosity increases by addition of stress and strain. The fluid regains its shape after removal of stress. Such materials are very complex and difficult to analyse. A structural fluid changes the viscoelasticity in the system due to stress or strain addition. The microstructure behaves in a linear way and no changes are apparent and sometimes in a nonlinear way where changes are apparent but are reversibly. There are too many complications as recovery of microstructural changes are noticeable after a very long time. The thixotropic studies become a challenge for rheologists due to extended time response of microstructure as exact experimentation results and sufficient explanation is complex and difficult to achieve [27].

In several cases, thixotropy is developed in products to make ease for nonprofessional members to use the product easily. As per research, this type of development is required where maximum shear thinning is needed [27]. To do so, unwanted thixotropy is introduced in system. The thixotropy phenomena must be explained for early researchers and it should be up to date. The early researchers provided information about thixotropy materials stating some examples of thixotropic materials [30]. The most common examples are flour dough, clays, soil suspensions creams, paints as well as starch pastes. The instruments used to classify thixotropy are known as thixotrometers. Another point also raised about thixotropy in these studies is based on constant shear rate or constant shear input. The break down and recovery process in 3D thixotropic material is shown in figure 3.

2.2.3. Viscoelastic fluids: The most common type of non-Newtonian fluids is Viscoelastic fluids. These are a viscous liquid and possess elastic solid properties. Newtonian and Hookean show rapid action upon addition of strain and stress. On the other hand, no action is visible in viscoelastic
materials by increasing stress. After removal of shear stress these fluids try to partially recover their shape slowly and gradually. This type of recovery is known as creep. Yield stresses of different fluid are studied by creep and recovery tests which are performed at different stress levels and helps determine yield stresses. The molecular weight of a viscoelastic fluid is high as they are macromolecular in nature. The viscoelastic fluids including polymeric fluids are usually used in food systems and plastic products. They are used in making dough for breads as well as in biological liquids in parts like joints [31]. Dynamic testing method is useful in fluids for measuring viscoelastic changes. These tests are beneficial to solve problems of products and are also helpful in assessment of such products. The behaviour of viscoelastic fluids shows complexity and rheometers are often used to measure responses of fluid.

2.2.4. Viscoplastic fluids: These fluids are a kind of non-Newtonian fluids where describing these fluids is done by apparent yield stress. These fluids flow under the condition that the material’s shear stress is higher than the apparent yield stress. However, if this condition is not followed then the material may behave like a solid. Overall, such fluids can be described by Bingham plastic model:

\[ \tau = \tau_y + \eta_B \dot{\gamma} \quad \text{for } \tau > \tau_y \]
\[ \dot{\gamma} = 0 \quad \text{for } \tau < \tau_y \]

Here \( \eta_B \) is the plastic viscosity and \( \tau_y \) represents the fluid yield stress.

It is found that by increase in shear rate, the apparent viscosity of Bingham plastic material reduces. This also happens in shear thinning fluids. That is why measurement of shear stresses is impossible at small shear rates. The yield stresses are determined by the extrapolation of the shear stress vs shear rate plot backward to zero. This yield stress is called apparent yield stress.

One more viscoplastic model is made by joining Bingham plastic model and power law and is known as the Herschel-Bulkley model:

\[ \tau = \tau_y + k \dot{\gamma}^n \quad \text{for } \tau > \tau_y \]
\[ \dot{\gamma} = 0 \quad \text{for } \tau < \tau_y \]

This model involves index \( (n) \) for flow behaviour, comparatively. Also, the fluid is known to be Bingham, if \( n = 1 \). However, if \( n \) is less than 1, it is referred to as Herschel-Bulkley. Adams [32, 33] explained that mixing near impeller shows similar mixing properties in shear thinning fluids and viscoelastic fluids. However, because of the apparent yield stresses, no fluid motion takes place beyond the cave boundary in viscoplastic fluids. Also, fluid motion takes place in fixed boundaries [33-35].

3. Complex Fluids

Complex fluids have the arrangement of molecules and atoms at smallest scales. Conventional solids as well liquids also have similar arrangements. Bulk fluid is also made by the arrangement of these molecules and atoms in a larger structure. Deshpande and Krishnan [36] defined that, “in complex fluids, the atoms and molecules are organized in a hierarchy of structures from nanoscopic to mesoscopic scales, which in turn makes up the bulk material”.

Mayonnaise is an emulsion of oils, egg and vinegar. It is a good example of complex fluid. All reactants are liquids, but the end-product is a solid-like. The ingredients develop micro size structure called micelles and the mixing process has no chemical changes. Modelling of complex fluids is different due to complex structure. The behaviour changes and lot of interfaces are present. It is easy to describe simple fluid by density as well as viscosity but in complex fluid orientation, composition and history is must to describe therefore modelling of all molecules is arduous.

3.1. Importance of honey in food industries

Honey is used in medicine and foods all over the world. This is because it is a natural product obtained from nectar. People use this biological product regularly in all seasons. Honey contains fructose, glucose and water. Moreover, vitamins, proteins and minerals are also part of honey. In the field of medicine,
honey has been used as a food biomaterial. It helps against infections by acting as a natural therapeutic agent. In addition, it can also help in the process of wound healing. Therefore, the flow behaviour of honey has always been an interesting topic. This is because it can have an influence on the processing as well as consumption of honey [37].

Honey is extensively used as a food additive and food ingredient as well. The honey obtained from apiaries and combs has beeswax, pollen and other undesirable materials. The removal of these items is important for an overall good quality product along with improving shelf life. In food industries, honey is passed through different processes before being packed into containers and bottles. In these processes, honey passes through different stages like heating and filtration. The process of straining and pressure filtration is used to remove beeswax, pollen and other waste materials. The microorganisms are removed by thermal processes as honey may be spoiled by the influence of microorganisms. In addition, the moisture content should be controlled to eliminate the chances of fermentation [37].

3.2. Production, collection and processing of honey

Honey is obtained from nectar and is collected, digested and dehydrated by honeybees from the flower nectar. Honeybees fly from flowers to flowers and move on plants to get pollen and nectar. Honeybees use tube like tongues and suck honey from flowers and store in their stomachs. Finally, these honeybees reach the beehive. At this moment, 80% of water is present. In their stomachs, nectar reacts with protein and enzymes present. This results in the production of honey.

Hypopharyngeal gland of bees changes the sucrose into fructose and glucose. In this process, a number of molecules double, which contribute to the osmotic potential. The honey is dropped in beeswax comb made by bees. The honeybees continue to drop honey until the comb is filled completely. In the process of fanning, honeybees use wings to evaporate extra water and thicken the honey. The storage life lengthens in this way. The bees fully cover the comb and move towards empty combs to repeat the entire process.

In conventional processing, heat plays a vital role to dissolve large sugar granules and maintain the quality of honey. First, liquefaction is used in industries to maintain the honey in a liquid form for a long time. The second process is pasteurisation to kill microorganisms and avoid fermentation [38]. These processes require minimum temperature of a 50 °C, which extends to 70 °C. Figure 4 below shows an illustration of a conventional method used for processing honey.

![Figure 4: Processing of honey by a conventional method (Adapted from [38]).](image)
Another procedure to treat honey is the thermal treatment. This involves microwave heating and infrared heating. In nonthermal treatment, ultrasound and ultraviolet filters are involved [39]. These help ensure the quality and safety aspect of honey is maintained. These food processing methods provide fresh, tasty and nutritive food, which can satisfy the consumers and users’ demands [40]. Figure 5 shows an illustration of a typical honey processing plant used in India while Figure 6 shows a much detailed honey production line demonstrating the name of each equipment used.

![Figure 5: Typical honey processing plant (Adapted from [41]).](image)

![Figure 6: Typical honey processing plant (Adapted from [42]).](image)

3.3. **Rheological Properties of honey**

As Steffé [6] mentioned, the properties of honey in terms of its rheology can have a huge influence on its processing, handling as well as the experience. It must be noted that the behaviour of honey is dependent on its composition and its temperature. Therefore, the moisture and sugar content in honey
play a key role. To describe the temperature dependence, researchers often use the Arrhenius model [43-48]. In such studies, it was often concluded that the viscosity of honey decreases with an increase in the temperature. This was mainly because of the decrease in hydrodynamic forces as well as molecular friction. Also, viscosity can be lowered due to an increase in water content. One interesting finding concluded that changes in moisture content of 1% can have the same effect on the viscosity as a temperature change of 3.5 °C.

Around the world, honeys with reduced calories are becoming quite popular. This is influenced by the recent trend, which involves sugar reduction in food contents. Honeys produced with reduced calories comprise of lower natural sugar percentages. This is done by replacing these sugars with slow, non-metabolising molecules. This allows for preserving the taste as well as texture of honeys. However, it is highly likely that the rheology of these honeys is influenced by the decrease in sugar contents. Also, due to the insertion of additives, some changes may be observed in these honeys [37]. It must be noted that the rheological properties of a food product can be affected by the local, structural heterogeneities. These included properties such as local viscosity, which is known to have an effect on the interactions with the material transport, microenvironment as well as sensory feel. In addition, rheology is useful in characterising changes in the composition of honey. Such changes are expected to occur over time in a natural manner. For instance, sugar crystallization or moisture absorption may take place in honey [37].

3.3.1. Flow of honey in pipes: It must be noted that the rheological properties of a food product can be affected by the local, structural heterogeneities. These included properties such as local viscosity, which is known to have an effect on the interactions with the material transport, microenvironment as well as sensory feel. In addition, rheology is useful in characterising changes in the composition of honey. Such changes are expected to occur over time in a natural manner. For instance, sugar crystallization or moisture absorption may take place in honey [37].

In general, honey has been reported to be a Newtonian fluid. However, it behaves like a non-Newtonian fluid. This has been discussed for some of the varieties of honey [49, 50]. Therefore, honey can be classified as a power-law material, for pumping analysis. To do so, equation 5 can be used. Next, to define the flow of a power-law material like honey in a pipe, it is possible to use the dimensionless generalised Re number. This is given as [6, 51]:

\[
Re_{PL} = \left( \frac{D^n \nu^{2-n}}{8^{n-1}K} \right) \left[ \frac{4n}{3n + 1} \right]^n
\]  

(8)

The flow rate’s average velocity can be provided as:

\[
\nu = \frac{4Q}{\pi D^2}
\]  

(9)

As discussed in Section 2, Re helps in defining the characteristics of a flow. In a pipeline, the transitional flow is based on the material properties and the properties of the pipe. Therefore, as Sopade et al. [6] discuss, these values in the transitional region can be in the range of 2000 to 4000. Further, the critical Re was defined by Steffe, [6]. In cases, when the dimensionless generalised Re of a flow in a pipe is less than the critical Re, the flow is regarded as laminar. Rabinowitsch-Mooney equation can be applied in laminar conditions for estimating the shear rate at the walls of the pipe. This equation is [6]:

\[
\gamma_w = \left( \frac{3n' + 1}{4n'} \right) \left( \frac{32Q}{\pi D^3} \right)^n
\]  

(10)

Shear stress at the wall can be described as:

\[
\tau_w = \frac{\Delta P}{4 \left( \frac{L}{D} \right)}
\]  

(11)
In equation (10), the $n'$ refers to the point slope of the log-log plot of shear stress against apparent wall shear rate. $n'$ is equal to the power-law index for most fluids. However, the real power law index can be achieved with the application of the power law model (equation 5) to the shear stress – shear rate data.

Since friction factors play a key role in the adequate fluid flow of materials such as honey in pipes [32]:

$$f = \frac{2\tau_w}{\rho v^2}$$  \hspace{1cm} (12)

Combining equations (11) and (12) results in:

$$\Delta P = 2f\rho v^2 \left(\frac{L}{D}\right)$$  \hspace{1cm} (13)

Equation (13) can assist with calculating pressure loss in a pipeline [52].

In general, a fanning friction factor is used in the laminar flow region. This is related to the Re as:

$$f = \frac{16}{Re_{pl}}$$  \hspace{1cm} (14)

However, it is worth mentioning that for some foods, the constant of 16 in equation (14) is different [53].

Moreover, Darcy friction factor (4f) is also amongst the other friction factors employed in designs of pipelines [52]. It must also be noted that equation (14) holds irrespective of the roughness of the pipe. However, for turbulent region flows, the relation between friction factor and Re is rather complex and is based on the surface nature [6]. As honey is a viscous fluid, it is usually pumped under laminar conditions. Therefore, to understand and investigate its rheological performance in a pipe flow, the Rabinowitsch-Mooney equation can be employed successfully [51].

4. Conclusions

The process of fluid transport in food industries around the world is of great significance. Most food processing industries use viscous fluids to make useful food products in bulk. However, such industries need to ensure that concerned equipment such as pipes are kept clean as well as are clear for the smooth transport of viscous liquids. The fluids are pumped in these pipes which results in friction over the walls of the pipe. Flow characteristics are the fundamental basis of the mass transfers taking place in food industries. The resulting qualities of the products are mainly reliant on these fluid flow properties. The design as well as control of the properties of a food in terms of its rheology is a big factor for the commercial success of a product. Therefore, to better understand this complex problem, it is important to first comprehend the rheological properties of different materials and fluids, which are commonly present in the food industry. Thus, understanding the properties of fluids and overall the rheology of these is important. The fluid movements in food processing industries are discussed along with the concepts of fluids in motion. Moreover, concepts of viscosity and different flow regimes along with flow phenomena are also discussed in terms of rheology. Finally, as a case study example, the rheology of a complex fluid, honey, is reviewed in this study. Generally, honey has been reported to be a Newtonian fluid. However, it behaves like a non-Newtonian fluid. As honey is a viscous fluid, it is usually pumped under laminar conditions. Therefore, to understand and investigate its rheological performance in a pipe flow, the Rabinowitsch-Mooney equation can be employed successfully. These are explained in this study.

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