論文の内容の要旨

Thesis Summary

Dampening mechanism of fluid flow under shear in different physical phenomena－analytical and experimental approach

(異なる物理現象における剪断下の流体の流れの減衰メカニズム－分析的および実験的アプローチ)

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Fluid flow majorly occurs due to the application of shear forces on the fluid. Fluids deform when a shear force is applied and resist when they are in motion. Flow in a fluid can be induced by a pressure difference or the shear stress over a distance in a thin-walled structure. Shear forces are developed in these channels due to the motion of fluid particles. Fluids at rest do not resist any applied shear force and they deform continuously under the shear forces; however small they are. The applied shear stress is a function of the rate of shear strain in the case of fluids. The resistance to the shear force appears only when the fluid is under motion. This property of the fluid to resist the growth of shear deformation is called viscosity. Viscosity is caused due to the interchange of momentum between the layers of fluid moving with different velocities due to the random motions. Examples of shear flows occurring in the fluid are Couette flow (by applied shear force), flow in pipes (pressure-driven flow). Here, we are considering the shear flow of water in the microchannel to study the water flow rate reduction mechanism based on experimental work and understand the shear rate attenuation mechanism in Non-Newtonian flows based on analytical analysis of velocity profiles obtained from Couette flows.

Flows in microchannel devices differ from their macroscopic counterparts for two reasons: the small scale makes molecular effects such as wall slip more important, and it amplifies the magnitudes of certain ordinary continuum effects to extreme levels. Fluids that are Newtonian at ordinary rates of shear can become non-Newtonian at very high rates at the microscale level. Several experiments have shown general agreement with the macroscale theoretical predictions for the flow of a Newtonian fluid in at least certain parameter ranges in circular microtubes and rectangular microchannels. Good agreement between conventional Poiseuille theory and

experimental results has been reported for other microscale flows including square microtubes with a diameter or hydraulic diameter of 15 to 150 microns and Reynolds numbers of 8–2300 [Judy et al., 2002]; and rectangular channels with hydraulic diameters from 244–974microns [Liu and Garimella, 2004].

Water flow in narrow gaps is a most intriguing study in recent times, especially when there is a presence of two different phases, due to the observations of interesting mechanisms. For example, two-phase flow patterns of air and water flow in microchannels studied based on surface contamination and wettability between tube wall and fluids show different flow patterns. If the wettability of the surface increases the apparent viscosity also increases and deviates more from theory and experimental. Moreover, the effect of the wettability decreases with an increase in hydraulic diameter. However, in some cases, a significant change in the flow behavior of microchannels is observed as the flows are unpredictable because of the variations in viscosity, size effect, surface roughness. Interface wettability has a different effect on the apparent viscosity and liquid flow in smooth microchannels.

The flow rate of the fluid in microchannels is least focused by researchers. Initial investigation on the effect of water flow rate due to slip was carried out by Chang-Hwan Choi et al. (2003). The water flow experiences drag resistance due to friction of the solid surfaces and no-slip boundary condition. The drag force reduces the water flow rate because of the adhesion between the surface and the water in hydrophilic surfaces. However, some micro and nano air bubbles help in reducing the friction on the hydrophobic wall surfaces mentioned by Hajime Tanaka et al. (2020). This kind of phenomenon is most utilized in ship propulsion, in which microbubbles are formed due to cavitation near the propeller and helps in moving forward. In this case, the micro air bubbles are continuously formed and destroyed due to the water flow near the propeller surface. The air bubbles in the propulsion have very less lifetime but help in propulsion. In the current research, air bubbles are held at the crevices (bubble forming locations) to know its effect on the water flow rate over time in microchannels. The air-water interface is responsible for the water braking effect is confirmed based on the findings of Kayondo et al. (2017). The water flow rate is reduced due to the interface effect. If the supersaturated water is used the air bubbles grow larger and block the entire microchannel resulting in the water blocking effect.

The effect of large air bubbles blocking the entire path, by reducing the flow area, of the microchannel can be easily and clearly understood. The water braking effect is novel and difficult to interpret. The presence of small micro air bubbles in the path of the water flow takes time to show its effect on the water flow rate. By conducting continuous observations and water flow measurements, the water flow reduction is observed continuously. The formation of small size micro and nano air bubbles on crevices are responsible for the water flow reduction. This is experimentally observed by a microscope and analytically understood. The braking effect of the air-water interface, formed by the small micro air bubbles, is responsible for the water flow reduction. Thus, the Newtonian fluid like water behaves differently in micro scales in the presence of the air-water interface. Water flow tests are also conducted to know the condition for water flow reduction by using a different type of water, varying the type of surface, changing the number of crevices present to know their dependency on the water flow rate. Bubble formation was observed on both hydrophobic and hydrophilic surfaces, but the water flow reduction was observed in the case of the hydrophilic surface when equilibrated water is used. This water flow reduction was observed even when there were no visible air bubbles. The probable formation of air bubbles on the surface of the microchannel leads to the reduction in the water flow rate. The flow behavior of water near the interface is indifferent and is responsible for the water flow reduction.

The flow behavior of 'complex fluids' which includes all types of materials like pastes, emulsions, colloids, suspensions, and anatomy like plasma, blood, etc. is of practical and fundamental interest. The flow field of these fluids is responsible for the structural, rheological behavior of the material and in deciding the type, usage of material. A flow curve is determined by applying a shear rate to the materials by different viscometric flows like Couette flow, parallel disks flow, cone-plate flow. A flow curve (shear stress vs shear strain graph) generally represents the rheological behavior of the fluid. The main properties of shear flow of fluids include viscosity, shear rate, and shear stress, which help determine the flow behavior.

In rheology, apart from knowing the shear stress and viscosity to understand the flow behavior, velocity profile also plays a prominent role in deriving the constitutive laws. Many researchers have focused on the velocity profiles of the material in Couette flow due to the observation of viscosity bifurcation near the critical stress. The velocity profiles are obtained by using techniques MRI, NMR studies by considering the Couette flow. Most of the materials like emulsions, foams, cornstarch, and cement paste exhibit different behavior at low and high shear rates in Couette flow as suggested in the literature. At low shear rates, the materials get localized near the rotor but for high shear rates, we can observe sheared and un-sheared zones visualizing the two different regions in the velocity profile observed by Cussot et al. (2002). The profile closer to the moving cylinder has a constant slope and far away the profile has zero slope. The Power-law model can be fitted easily for low shear rate velocity profiles and are validated with the shear flow curves.

Based on the obtained velocity profiles, individual material behavior like the colloidal formation, jamming of fluids locally and others were discussed. Many different shear flow equations were used to define the shear flow as well as velocity behavior. These equations could not exactly define the velocity behavior and regularity of flow of the material in Couette flow. In this study, various velocity profiles of different materials and different RPM values are considered to understand the shear rate mechanism and the flow regularity of the fluid in Couette flow. Partially sheared Couette flows are only considered to avoid the boundary effects, to consider the actual fluid behavior of the material. The velocity profiles of these flows are considered and analytically analyzed using theoretical cubic and quadratic equations to find the regularity of the fluids in Couette flows.

The analysis of the velocity profiles is started by separating the Newtonian and Non-Newtonian regions. Initially, the Newtonian velocity equation is applied to a limited portion of velocity profiles always starting from the rotor end and the Non-Newtonian analysis started from flow stop end. The corresponding residual is calculated and compared. The analysis which give the least residual variance is identified and the velocity profile is fit based on that Non-Newtonian equation (Cubic or Quadratic). Almost 50 velocity profiles have been analyzed and they can be either fitted with the quadratic or cubic equation. This piece wise analysis of the velocity profile shows either a linear or non-linear rate of reduction in the shear rate. The type of material behavior is distinguished based on the shift of the velocity profiles, the material parameter alpha (α). The macroscopic behavior of the materials is identified as either Pseudoplastic or Dilatant or Bingham fluids. These materials have different characteristic behavior based on the fluid particle behavior and is explained based on the new hypothesis.

A new understanding of the behavior of the fluid particles is proposed to understand the phenomena of water braking mechanism and shear rate attenuation behavior in Couette flows. The behavior of the fluid particles in the flow of the fluid is based on the consideration of forces between them. Consideration of cohesive forces in static condition is common but this cohesive force consideration is absent in the dynamic condition of flow of fluids. So, in this new theory considering the cohesive forces and the rotation of the particle's behavior in Newtonian and Non-Newtonian fluids the mechanisms are clearly explained. In Newtonian fluids, particles are restrained to rotation in a specific direction due to which there is no energy loss mechanism between the fluid layers. However, there will be energy losses due to friction between the fluid layers. But, in Non-Newtonian fluids at low shear rate, fluid particles rotate due to the influence of cohesive between the particles. So, the energy loss takes place not only due to frictional forces but also due to the rotation of particles. For the water flow in hydrophobic channels, the water molecules are restrained to rotation but molecules at surface are solidified due to non-isotropic nature of cohesive force. These solidified molecules form a continuous sheet of layer causing the slip behavior in the hydrophobic channels (as hydrophobic surface and air-water interface are similar in behavior). However, in hydrophilic surfaces, these solidified molecules form an anchorage layer around the air-water interface causing the braking mechanism of the fluid and hence decreasing the water flow rate.

The shear flow behavior mechanism of the Newtonian and Non-Newtonian fluids is different in different physical phenomenon and depends on various factors. But the basic behavior of the fluids is understood based on the fluid particle behavior in shear flow. The flow rate of water in the narrow channels is modified due to the air-water interface in the path of the flow. In the Couette flow, fluids exhibit continuous decrease in the shear rate along the radius. The mechanism of the water flow reduction due to the interface and the shear rate reduction mechanism along the radius in Couette flow is understood rotation of particles in the fluid flow due to cohesive force. Thus, two different phenomena are understood based on the new hypothesis of fluid particle behavior considering the rotation and cohesive forces between the particles.