NUMERICAL STUDIES OF THE ENHANCEMENT OF PARTICLE MOTION AND DRAINAGE OF A FALLING FILM BY MECHANICAL VIBRATION OF NON-NEWTONIAN FLUIDS

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Abstract

The fluidity of non-Newtonian fluids can be enhanced by vibrational motion. This phenomenon is well known in some industries such as the building and confectionery industries and has been exploited for many years, but mainly on an empirical basis. In this paper, we report on two studies: (i) the effects of vibration on the motion of particles in fluids of non-Newtonian rheology, which is relevant to problems of solid-liquid flow, particle settling and disengagement of entrapped bubbles in complex fluids; and (ii) the drainage of a non-Newtonian liquid film on an oscillating wall, which is relevant to applications such as dip coating and the emptying of complex liquids from hoppers and vessels.

The two problems have been studied numerically by Computational Fluid Dynamics. Inelastic time-independent fluids of the power law, Herschel-Bulkley, and Newtonian types have been investigated. Newtonian flow is unchanged by any superimposed oscillations but the flow of non-Newtonian fluids is greatly affected. The flow of shear-thinning fluids is enhanced whilst the flow of shear-thickening fluids is retarded. These effects are reflected in the motion of particles and falling films as they are, in turn, either accelerated or retarded. A detailed analysis of the influence of the various rheological as well as vibration parameters is presented.

Keywords: CFD, vibration, oscillation, flow enhancement, particle motion, falling film.

Introduction

(i) A knowledge of particle or bubble's motion in both stationary and moving fluid plays a very important role in wide range of engineering applications, including viscometry, transport of particulate substance (Chhabra et al., 1985), solid-liquid or air-liquid separation, e.g. solid-liquid fluidized beds (Richardson et al., 1971), bubbles' disengaging system in food industry, etc. Considerable work on terminal falling velocity of rigid particles in various non-Newtonian fluids has been reported in last fifty years. Slattery (1972) gave rigorous upper and lower bounds on the drag of a sphere under creeping flow conditions for both Newtonian and power law fluids. Numerical method started to be engaged since around thirty years ago. Gu et al. (1985) investigated spheres motion in power law fluids in low Reynolds number regime. Anubhav et al. (1994) obtained numerically velocity around a spherical solid particle for incompressible shear-thinning power law fluids in infinite region and extended this work for shear-thickening fluids (1995). Great interest also has been shown in wall retardation effects for particle and bubble's motion in a bounded region in recent years. Missirlis et al. (2000) investigated wall effects for motion of spheres in shear-thinning power law fluids numerically and experimentally. Song et al. (2009) reported the effects of moving wall on the momentum and heat transfer characteristics of confined spheres. Reddy et al. (2012) presented the work concerning to wall retardation effects on motion of confined spheres in shear-thickening fluids. However most of previous work is based on a stationary fluid, rare work related to oscillating fluids reported in past fifty years. Houghton et al. (1966) solved nonlinear Langevin equation analytically and numerically and obtained solution of terminal velocities of particles in vertically oscillating fluids. Also, retardation effect of vertically vibration was studied (Houghton et al., 1968). The aims of this work is to investigate the effects of vibration on motion of particles and bubbles in non-Newtonian rheology with Computational Fluid Dynamics (CFD).

(ii) The flows of thin liquid films are very essential models in our daily lives and engineering applications for a number of phenomena including stability of foams and the structure of biological membranes (Mysels, 1959, Weaire, 1999). Even a small action such as the blink of eyes even involves a motion over a thin corneal fluid film (Craster, 2009).

We focus on the difficulty in the drainage of pasty materials. As we known, under its own weight of fluid in the case of drainage, long duration is needed for some viscous fluids. Furthermore, drainage will stop for some yield-stress fluids due to their low gravity. In our work, we imposed vertical vibration on the wall and revealed the acceleration effects for shear-thinning fluids, and retardation effects for shear-thickening fluids,

CFX on BLUEBEAR was engaged in both of these two works.

Theory

Power law fluids

Shear thinning fluids, also known as pseudoplastic fluids, are characterised by an apparent viscosity which decreases with increasing shear rate. In contrast, shear-thickening fluids have an apparent viscosity which increases with increasing shear rate. The expression used to describe the relationship between shear rate and shear stress for both shear-thinning and shear-thickening power law fluids in our work is:

$$\tau = k\dot{\gamma}^{n}$$

where n<1 for shear-thinning fluids, and n>1 for shear-thickening fluids

Forced vibration

The mechanical vibration is imposed by specifying velocity function at the boundary. The velocity can be represented as follows:

$$\mathrm{u} = \mathrm{A}\omega\cos(\omega \mathrm{t})$$

where $\omega = 2\pi f$.

Method and results

(i) Effect of mechanical vibration on motion of rigid particles

A rigid particle was placed at the axis of a cylinder container and began to settle down along the axis driven by the gravity.

Model was built and validated by comparing the free settling terminal velocities obtained by our simulation with theoretical results for Newtonian fluids and published work for power law fluids. Then mechanical vibration was added on the wall of the container. Vertical positions were recorded and used to calculate the settling velocities. Comparison of terminal velocities with mechanical vibration and without vibration indicated its effects on motion of particles in various fluids.

Geometry and mesh

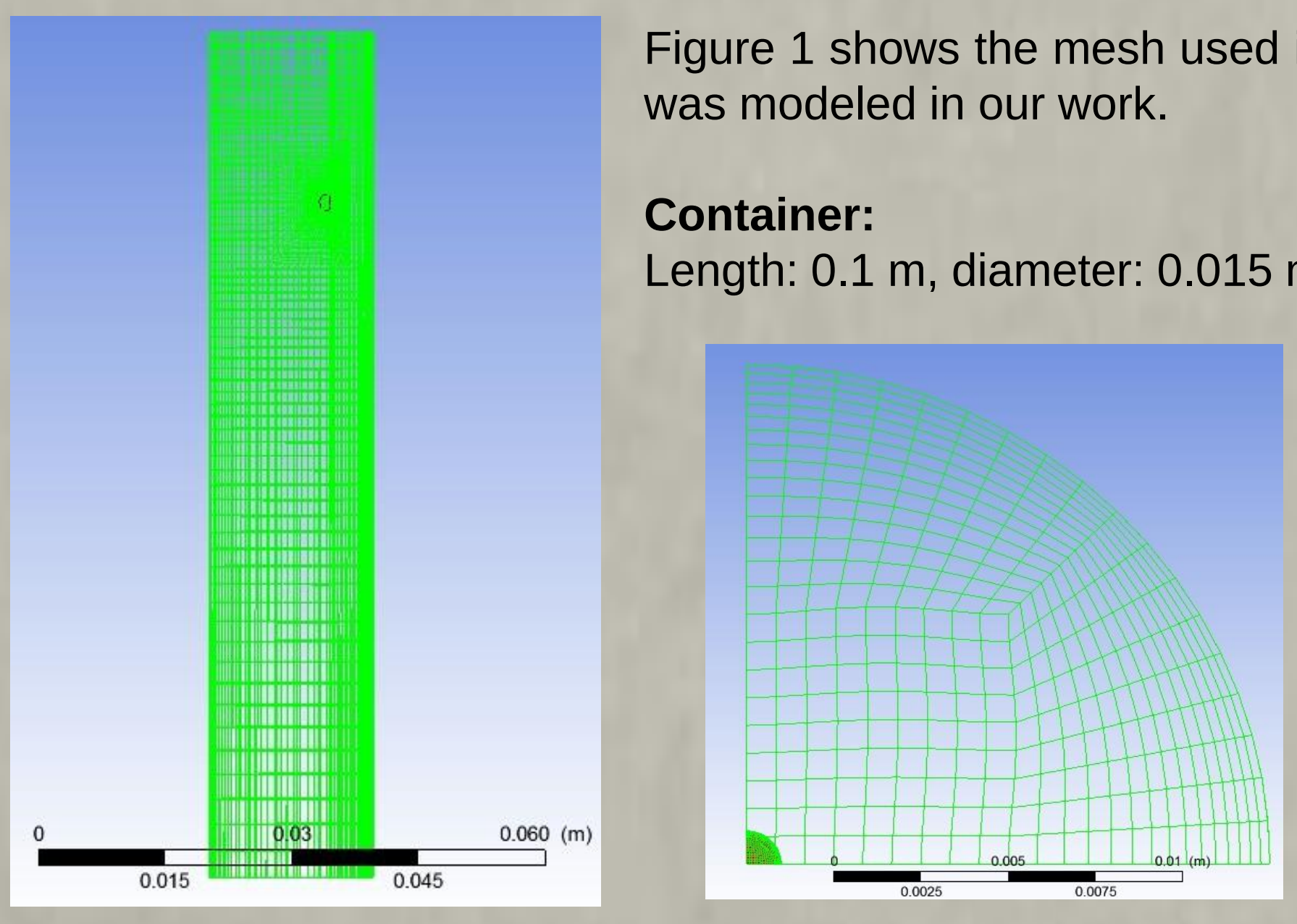

Figure 1 shows the mesh used in this simulation. ¼ of a cylinder container was modeled in our work.

Container:
Length: 0.1 m, diameter: 0.015 m

Rigid particle:
Density: 2500 kg/m^3,
Diameter: 0.002 m

Vibration properties:

Mechanical vibration was imposed on the wall of the container in the axial direction:

Amplitude: 0.002 m
Frequency: 50 Hz

Fig. 1: Meshed geometry for (i)

Validation of our model

Tab. 1: Comparison of our CFD results and Missirlis's (2000)

	Missirlis (unbounded) *(mm/s)*	Wall effect factor *(-)*	Missirlis (confined) *(mm/s)*	CFD result *(mm/s)*	Error *(%)*
n=1	3.252	0.858	2.790	2.842	1.85
n=0.9	2.994	0.895	2.680	2.739	2.20
n=0.8	2.781	0.929	2.584	2.616	1.24
n=0.7	2.614	0.958	2.504	2.516	0.48
n=0.6	2.494	0.982	2.449	2.428	-0.86

We are doing this simulation in a confined region, so the boundary, including wall and closed end, will retard the motion of particles. However, because that combined boundary factor for both wall effect and closed end effect is unavailable, also because that the ratio of distance from the center of particle to the bottom and the wall of container is over 2, we neglected the closed end effect in this comparison (Chhabra, 2007).

Tab. 1 shows the comparison of terminal velocities with Missirlis's. It can be concluded that our CFD model is quite reliable because that the present error is within ± 2.20%

Results

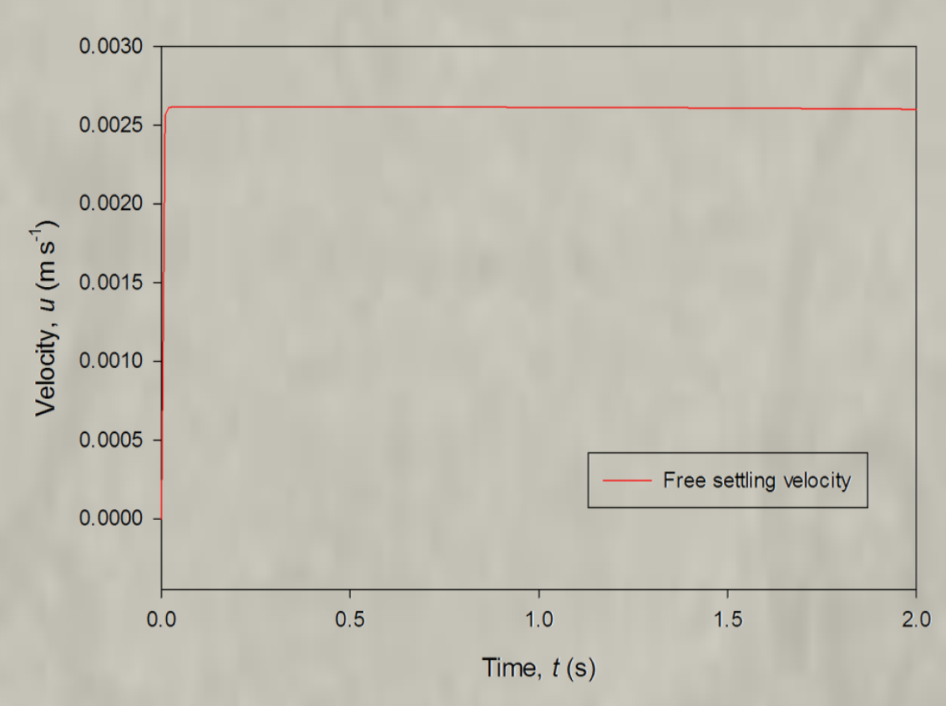

Fig. 2: Change of terminal velocity with time for power law fluid: $k = 1\ \mathrm{Pa\ s}^{0.7}$, $\mathrm{n} = 0.7$

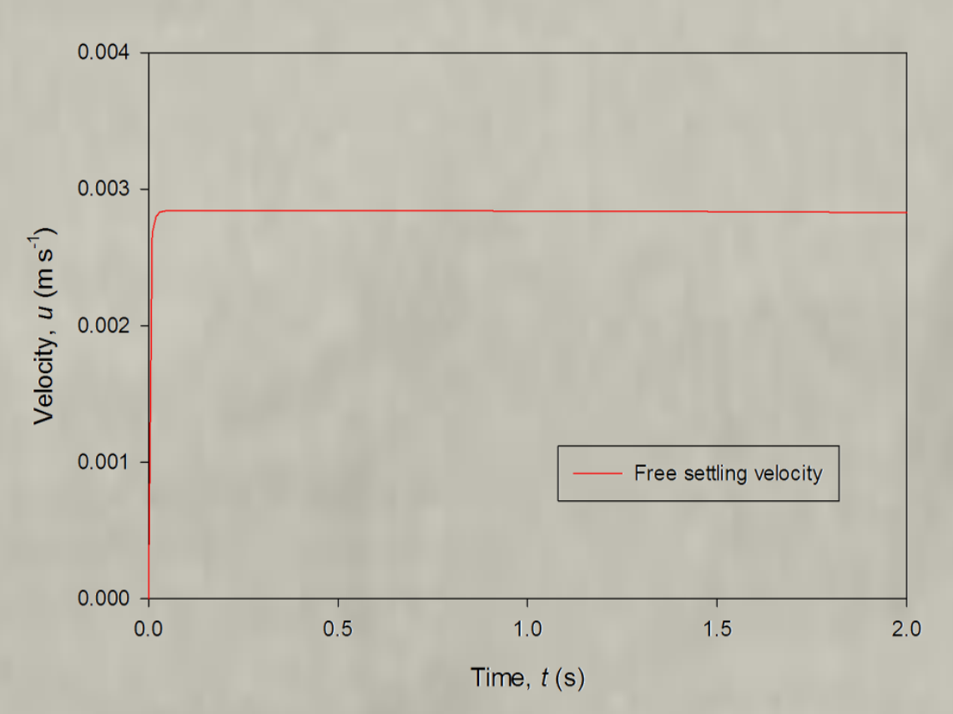

Fig. 3: Change of terminal velocity with time for Newtonian fluid: $k = 1\ \mathrm{Pa\ s}$

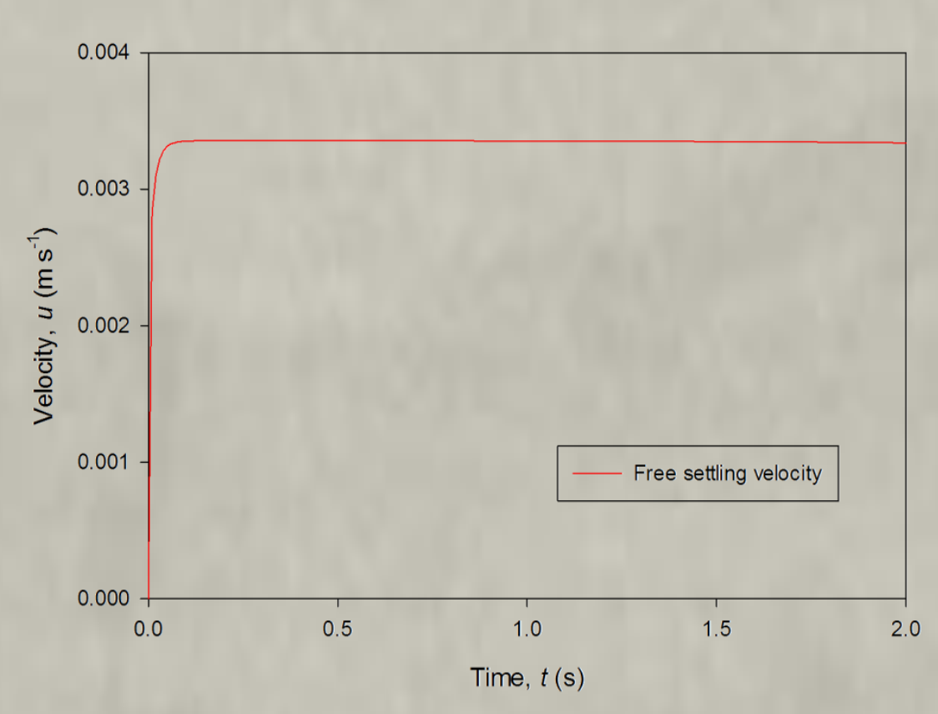

Fig. 4: Change of terminal velocity with time for power law fluid: $k = 1\ \mathrm{Pa\ s}^{1.4}$, $\mathrm{n} = 1.4$

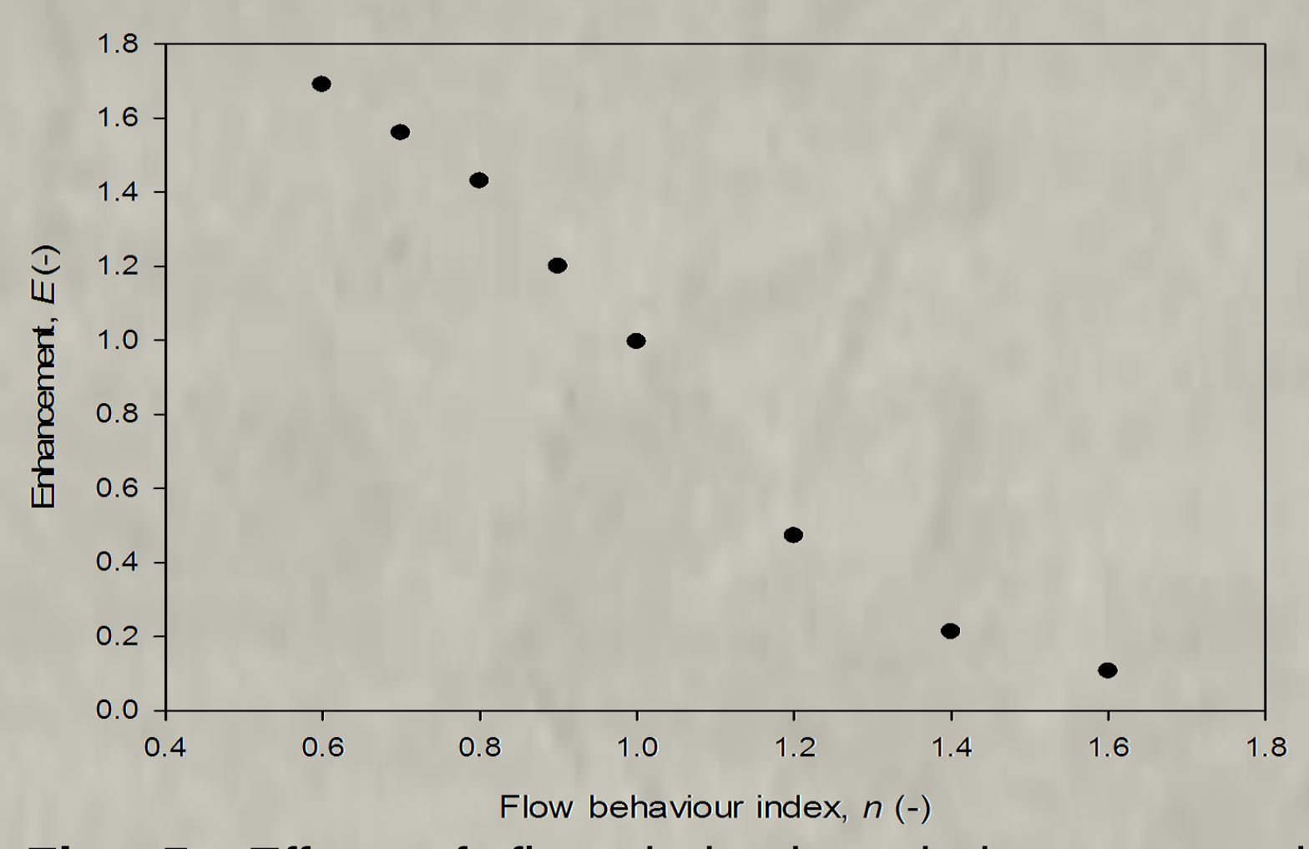

Fig. 5: Effect of flow behaviour index on terminal velocities enhancement in power law fluids subjected to vibration: $k = 1\ \mathrm{Pa\ s}^{\mathrm{n}}$, $\mathrm{A} = 2\ mm$, $f = 50\ \mathrm{Hz}$

As changing of settling velocity with time in shear-thinning, shear-thickening and Newtonian fluids shown in Fig. 2-4, settling velocity increases suddenly and reach a constant value after a very short duration of acceleration. It is in accordance with published work (Chhabra, 2007).

From Fig. 5, it can be concluded that particle's motion in Newtonian fluid cannot be changed by superimposed vibration. But it can be accelerated in shear-thinning fluids and retarded in shear-thickening fluids. With the increase in flow behaviour index for shear-thickening fluids and decrease in shear-thinning fluids, the acceleration and retardation effects are less and less obvious.

(ii) Effect of mechanical vibration on drainage of liquid film

A 2D rectangular model was built and three of its boundaries were specified as opening expect one as wall. Initially, the whole region was full with fluids, and free drainage driven by gravity was modeled. The profile comparison of thin liquid film with theory was used to validate this model. Then mechanical vibration was imposed on the wall. Difference in profiles between free drainage and drainage subjected to vibration reveals the effects of vibration on drainage of liquid.

Geometry and mesh

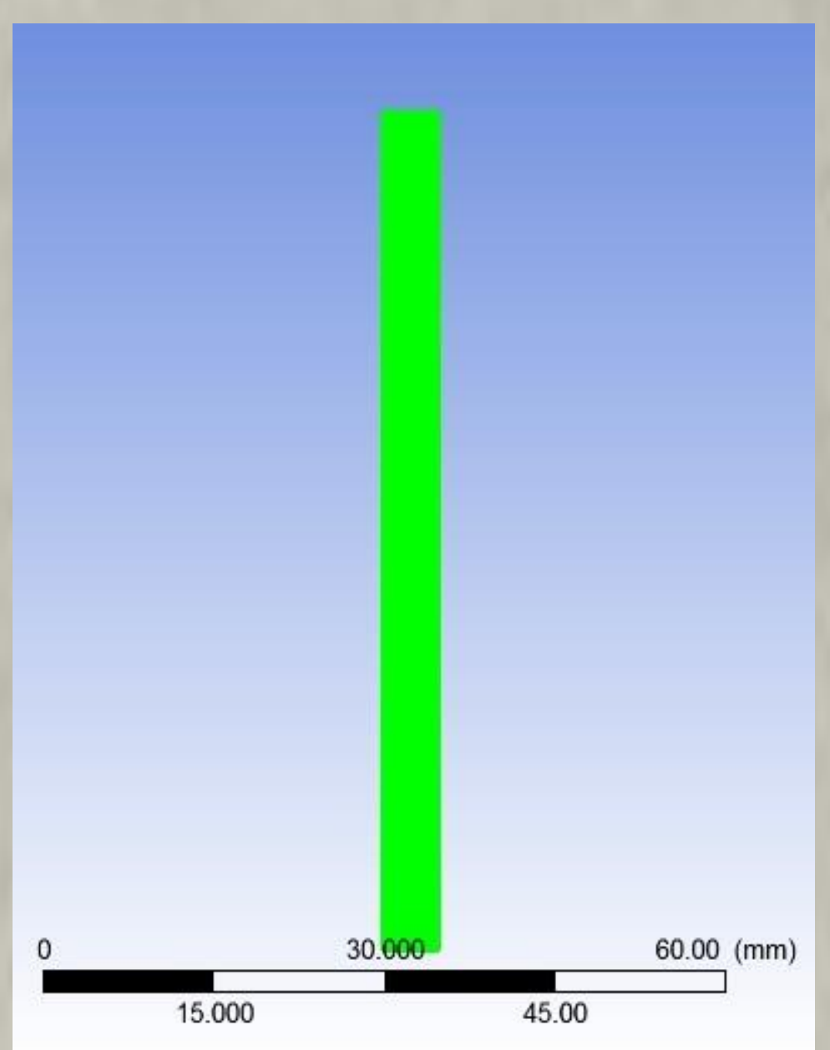

Fig. 6: Meshed geometry for (ii)

In order to get a distinct interface between different phases: liquid and gas, a very fine mesh was used in this simulation.

Length: 0.07 m. Width: 0.005 m

Nomenclature

A	Amplitude of vibration, mm
t	Time, s
u	Velocity, m /s
n	Flow behaviour index, dimensionless
f	Frequency of vibration, Hz
$\dot{\gamma}$	Shear rate, s^-1
τ	Shear stress, Pa
k	Flow consistence index, Pa s^n

Validation of our model

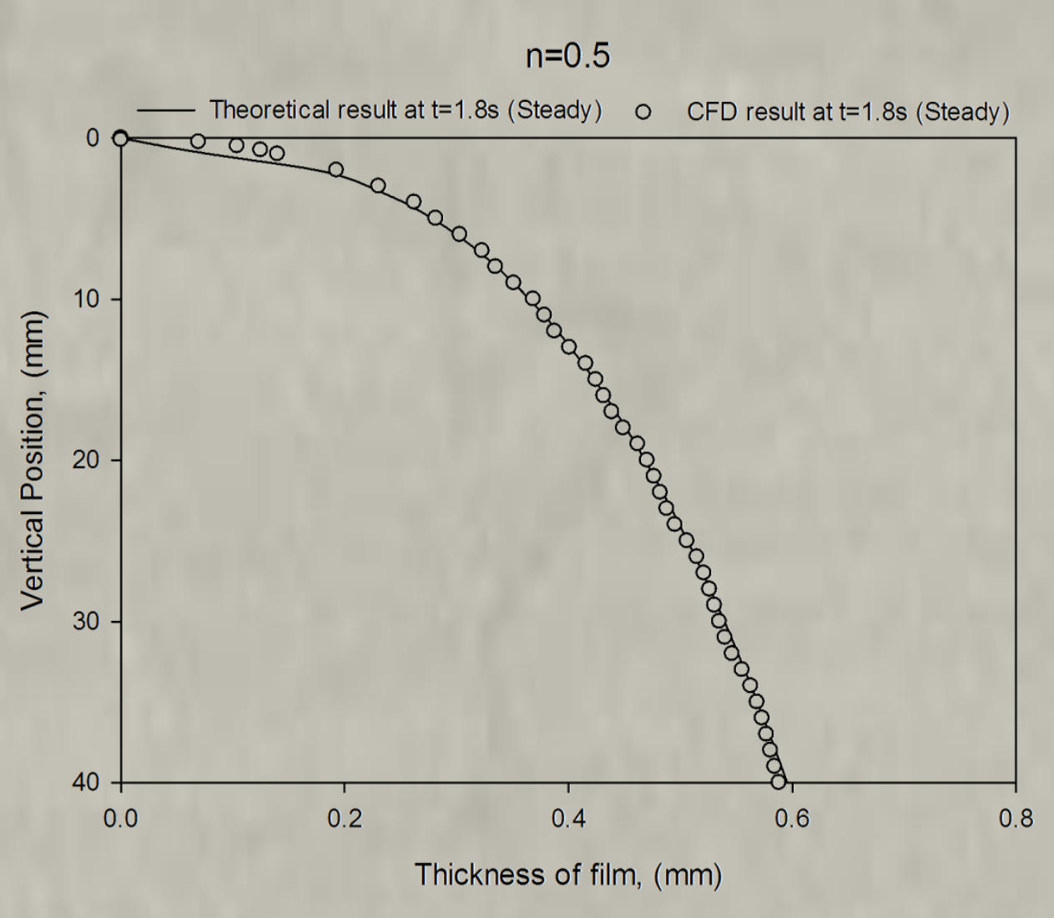

Fig. 7: Thickness of film at different vertical positions for power law fluid: $k = 1\ \mathrm{Pa\ s}^{0.5}$ $n = 0.5$

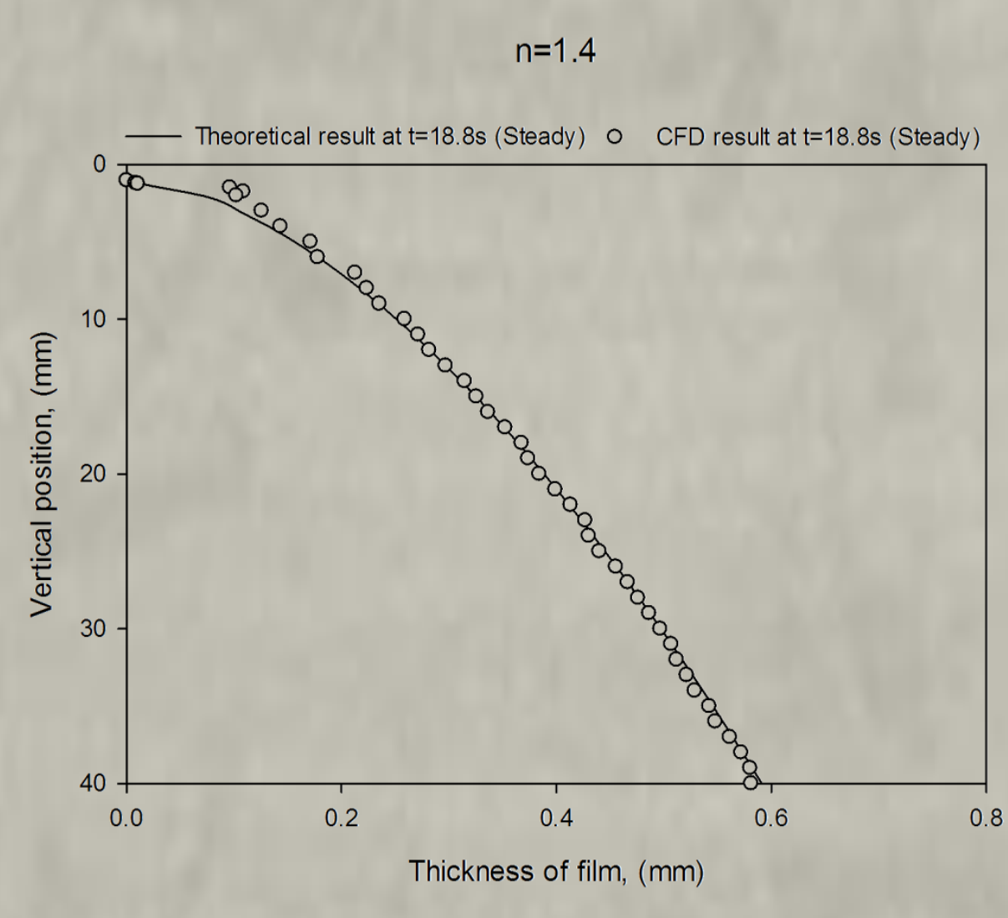

Fig. 8: Thickness of film at different vertical positions for power law fluid: $k = 1\ \mathrm{Pa\ s}^{1.4}$ $\mathrm{n} = 1.4$

From Fig. 7-8, it can be concluded that current CFD model shows excellent agreement with theory. So simulation about drainage of liquid film based on this model is reasonable and robust.

Results

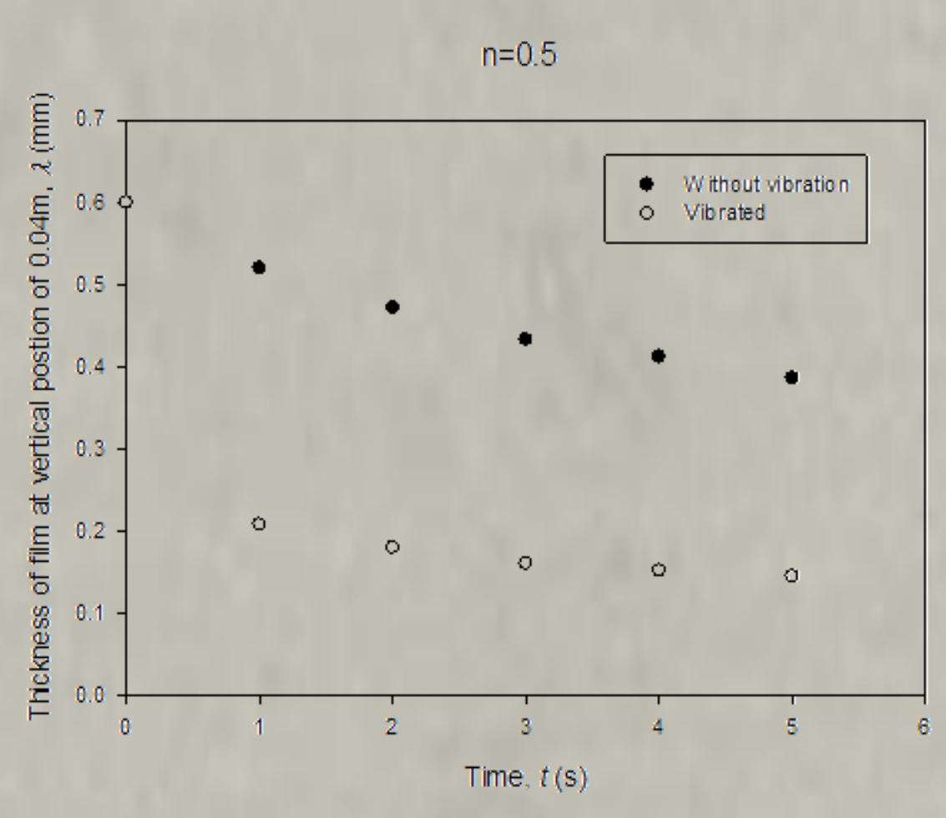

Fig. 9: Thickness of film at vertical position z=0.004m for power law fluid: $k = 1\ \mathrm{Pa\ s}^{0.5}$, $n = 0.5$

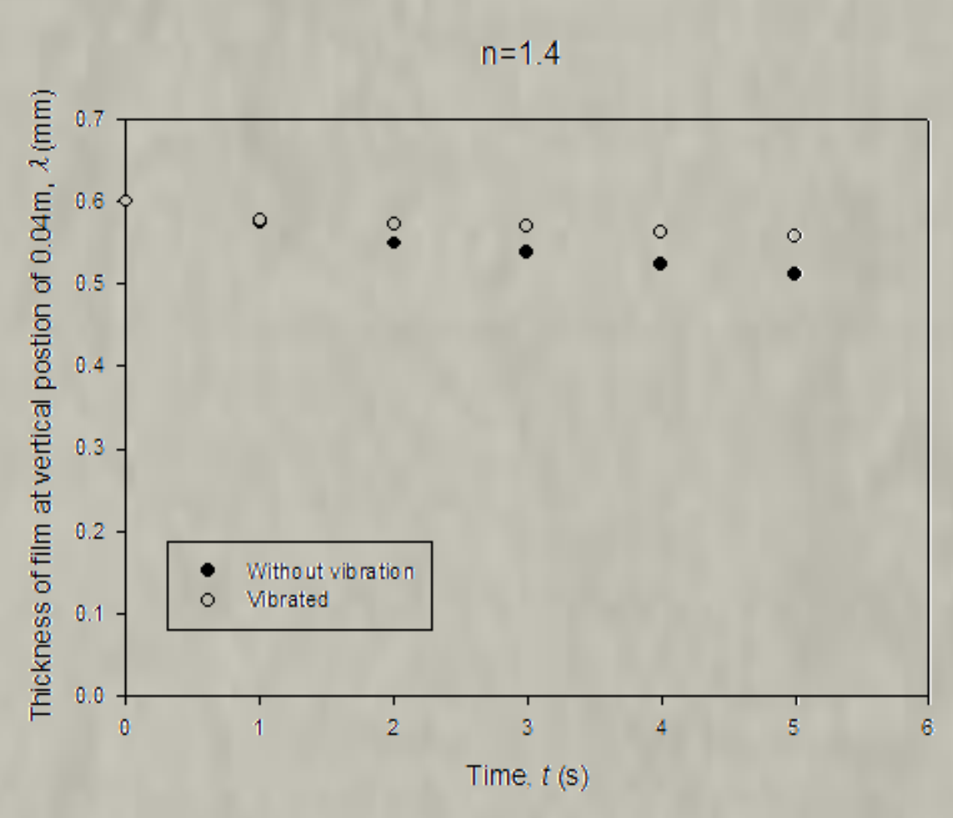

Fig. 10: Thickness of film at vertical position z=0.004m for power law fluid: $k = 1\ \mathrm{Pa\ s}^{1.4}$, $\mathrm{n} = 1.4$

From Fig. 9-10, it is apparent that superimposed vibration on the wall accelerates the drainage of liquid film for shear-thinning fluids, and retards that for shear-thickening fluids. For power law fluids which n=0.5, acceleration is very obvious at the beginning of vibration, and weaken while the profile of film is approaching the wall.

Conclusion

Mechanical vibration can affect flow of non-Newtonian fluids. Motion of particle can be accelerated for shear-thinning fluids and retarded for shear-thickening fluids by imposing vibration on the container. However, no influence is generated for motion of particles that in Newtonian fluid. Enhancement of terminal settling velocity depends on rheological parameters. Drainage of liquid film also can be affected on an oscillating wall. For shear-thinning fluids, it can be drained faster subject to imposed vibration than just driven by gravity. In contrast, for shear-thickening rheologies, more fluids will be left in the case of vibration than free settling.

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