Study on the suitability of a new method for in-situ viscosity measurement in industrial practice

FELICIA SYRÉN
Abstract

In this work cold model experiments in combination with Comsol modeling have been carried out to investigate the possibilities of a new method for industrial inline measurements of slag viscosities. The method aims at measuring the mass of the drag force as a sphere is dragged upwards in a liquid. The sphere was connected to a balance that was elevated at constant velocity. The liquids used were silicon oils of two different viscosities; 0.1 Pa*s and 0.5 Pa*s. A computer logged the mass from which the viscosity was calculated. Comsol modeling was used to show approximately at which time the drag force is constant, and to investigate the wall effect. The importance of laminar flow is discussed. The results show that the method is more suitable for liquids of higher viscosities. The reason is that the drag force is one order of magnitude lower than the other forces in the system. Since the drag force is directly proportional to the viscosity, it becomes larger with higher viscosity. The Comsol model shows that the drag force becomes constant in a few seconds from start of the movement. Comsol gives approximately the same values for the drag force as can be calculated by hand. The viscosities calculated from the experimental data are between two and five times too large for the higher viscosity tested, and between two and ten times too large for the lower viscosity tested. There is a wall effect for the two containers used in the experiments that can be seen both experimentally and by Comsol. Further work and development of the model has to be done before this method possibly could work for industrial purposes.

Keywords: Viscosity, Drag force, Sphere, Comsol model, Cold model experiments

Sammandrag


Nyckelord: Viskositet, dragkraft, sfär, Comsol simulering, modellexperiment
Contents
Abstract ........................................................................................................................................... 0
Sammandrag ...................................................................................................................................... 0
Contents ........................................................................................................................................... 1
1. Introduction ................................................................................................................................... 2
   1.1. Background viscosity measurements ...................................................................................... 2
   1.2. Motivation and brief explanation of this work .......................................................................... 2
2. Theoretical background .................................................................................................................. 3
   2.1. Forces of the system .................................................................................................................. 4
   2.2. Turbulent vs. laminar flow ....................................................................................................... 4
   2.3. Wall effect ................................................................................................................................. 5
3. Comsol model .................................................................................................................................. 5
   3.1. Mathematical background ......................................................................................................... 6
   3.2. Simplifications and assumptions ............................................................................................... 6
   3.3. Initial conditions ....................................................................................................................... 6
   3.4. Boundary and domain conditions ............................................................................................. 6
   3.5. Experimental conditions studied in the simulation ................................................................. 7
   3.6. Calculation ............................................................................................................................... 7
4. Cold model experiments .................................................................................................................. 8
5. Results from Comsol ....................................................................................................................... 10
   5.1. Time for constant drag force .................................................................................................... 10
   5.2. The wall effect .......................................................................................................................... 11
6. Results from cold model experiments .......................................................................................... 13
7. Discussion ...................................................................................................................................... 18
   7.1. Wall effect ................................................................................................................................. 18
   7.2. Force magnitudes ...................................................................................................................... 19
   7.3. Turbulence ............................................................................................................................... 20
8. Summary ....................................................................................................................................... 20
References ....................................................................................................................................... 21
1. Introduction

1.1. Background viscosity measurements

Viscosity of liquid in chemical processes plays an important role. It also gives a record of how the process varies with time, instead of giving one value of viscosity at one time. Industry often use modeling as a tool of understanding and controlling processes.

There are several methods for measuring the viscosity of slags, metals and oxides. The capillary method measures the time that it takes for a certain amount of liquid to flow through a narrow tube. The falling body method measures the time for a body to fall in the liquid, or to be dragged upwards in it. Rotation methods measure the torque on a cylinder rotating in the liquid. Oscillating methods measure the liquid response to oscillating movements. There are different categories depending on the oscillating object: cylinder, plate, and crucible. The Herty viscometer consists of a tube in which the liquid is gathered. The Herty viscosity is given by the length the liquid has moved in the tube. In the inclined plane method, viscosity is given by the length of the slag ribbon resulting from pouring the liquid at the top of a v-shaped plate held at a specific angle. For the Krabiell immersion viscometer a heated vessel is immersed into the liquid and the viscosity is given by the amount of liquid entering it. The use of a constant, achieved through calibration, prevent measurements of the absolute viscosity in the rotational, oscillating, Herty, and Krabiell immersion methods.

Industrially measurements can be made with rotational, vibrating, and falling object methods. The suitability of a method depends on the process and purpose. Parameters such as flow velocity, temperature, and material will put restrictions to the methods that can be used. When it comes to measuring the viscosity of slags there are difficulties since the slags often are very reactive, and the temperatures very high. Most methods for viscosity measurements are not developed for these high temperatures. This increases the uncertainty of the measurements as the methods are modified.

Measurements performed in a process usually don’t give the same results as those performed in a laboratory environment since the conditions for the measurements vary. However, if the inline measurements show the same trend as the laboratory ones, they can be helpful in getting better understanding of the process and keeping the quality of the product consistent.

1.2. Motivation and brief explanation of this work

When industrially measuring the viscosity of slags factors that limit the choice of methods are: temperature, bubbles, particles, and flow. This makes most methods unsuitable. For example, the turning and vibrational methods involve a lot of uncertainties when used in situ. Therefore there is an interest in developing a new simple method that allows measurements of a reactive slag at high temperatures during the process.

The method investigated in this report is similar to the dragging of an object in the falling sphere method. However, instead of measuring the time of the movement, the drag force on the object will be measured. For simplification the measurements will be performed with a balance, where the mass of the force is measured. A computer will be used in order to control the movement parameters and to log the measured mass during the measurements. In Figure 1 a schematic of the setup can be seen.
Since the purpose is for industrial use, the method needs to be simple. The aim of the method is to measure changes of viscosity for comparison, rather than to measure absolute values. It would give the industry knowledge and understanding about the process. The resulting values could be used in models and to better control the process in order to enhance the quality of the product. In reality the conditions when measuring will be complicated and possibly varying. This report is only a first step towards a new method helping industry to measure the viscosity in a simple way. Heat transfer, gas bubbles and solid phases are not considered in this work, though will affect the possibilities of the method. Another simplification is that the flow will be assumed laminar. The theoretical background is followed by a COMSOL Multiphysics model, and some cold model experiments.

The goal of this work is to show if this method for viscosity measurements could work for the industry.

2. Theoretical background
The idea of this method is to measure the mass of the drag force and to relate this to the viscosity of the liquid. Two important factors that must be considered are: (1) when the force becomes constant (constant velocity), and (2) is the wall effect negligible? These conditions are necessary for the used relationship to give correct results. Otherwise there is a need for a correction factor. Another important factor for the validity is the character of the flow, which has to be laminar.
2.1. Forces of the system

In the system studied there are forces in two directions: upwards and downwards, as can be seen by the following force balance:

The upward forces are:
- The balance force: \( F_b = m_{balance} \times g \)
- The Buoyancy force: \( F_B = \rho V g \)

The downward forces are:
- The gravity force: \( F_g = mg \)
- The drag force: \( F_D \)

The drag force is given by eq. (1):
\[
F_D = 6\pi r \mu v
\]  
(1)

In eq. (1) \( r \) is the radius of the sphere, \( \mu \) is the viscosity of the liquid, and \( v \) is the velocity. The expression is called Stokes drag. It includes the pressure differences and is the sum of form drag and friction drag (that is the sum of normal and tangential forces). The drag force is a reaction force from the movement of the object in a fluid. Or more precise from the friction of fluid against the moving surface of the object. It is the relative velocity between the object and the liquid that matters therefore, the result will be the same if the sphere is standing still in liquid flow or if the sphere is moving in stagnant liquid. For Stokes law to be used the flow has to be laminar. A correction factor is needed if there are any inertial forces, end-, or wall effects.9

In the experiments, the balance used to measure the mass is zeroed when the sphere is in the liquid, removing the Buoyancy force and the weight of the sphere from consideration. Since the velocity is constant the acceleration is zero, giving according to Newton II: \( F = ma = 0 \). This result in that only two forces are left to consider: the drag force, \( F_D \), and the balance force, \( m_{balance} \times g \). Using eq. (1) and solving for the viscosity gives eq. (2):
\[
\mu = \frac{m_{balance} \times g}{6\pi r v + v}
\]  
(2)

2.2. Turbulent vs. laminar flow

For a sphere standing still in a stream of a fluid with constant velocity, there is an unsteady eddy motion behind the sphere for Reynolds numbers above about 1.10 Re<0.1 is called “creping flow” or “Stokes flow” and is characterized by absence of eddy currents.10 The equation for the drag force is only valid for these Stokes flows. Reynolds number is given by eq. (3):
\[
Re = \frac{D v \rho}{\mu}
\]  
(3)

where \( D \) is the tube diameter, \( v \) is the velocity, \( \rho \) the density of the liquid, and \( \mu \) its viscosity. It should be pointed out that the theoretical analysis of laminar vs. turbulent flow is highly complicated and the result depends on initial assumptions. Therefore, experimental analysis is very important in the field of fluid dynamics.10
2.3. Wall effect

Viscosity measurements can be sensitive to the shape and size of container for the liquid. This is called the “wall effect”. There are different correction factors for the wall effect; one of them is the Ladenburg’s correction. The validity of the Ladenburg’s correction is determined by the ratio between sphere and container radii \( r/R \). It is only valid for ratios less than 0.09.\(^1\)

There are, as mentioned, various ways of expressing the wall effect. The factor can, as the Ladenburg’s, be a function of the ratio between sphere and container. It can also depend on a second variable, the Reynolds number. The different expressions all have different limits for where they are valid. For very high and very low Reynolds numbers, it is not affecting the wall effect. There is a lot of research done on the subject that can be found elsewhere. It seems most common to investigate spheres settling in fluid.\(^2\)

3. Comsol model

Comsol 4.4 was used to create a model and to simulate the experiments. The model was created in the fluid-structure-interaction interface (fsi) of Comsol and the geometry can be seen in Figure 2. For simplification it was made axisymmetric. It consisted of half a circle representing the sphere and a rectangle representing the cylindrical container. The fluid-structure interaction interface is used for modeling effects between a fluid and a solid. Both domains are modeled and there is a built in condition for the boundary between fluid and solid. For the geometrical changes of the fluid domain there is an ALE (Arbitrary Lagrangian-Eulerian) formulation. The ALE method makes it possible to have moving boundaries where the moving mesh does not have to follow the material.

![Figure 2: The geometry setup used for the Comsol model.](image)

One reason for simulating was to see if a constant value of the drag force (in Comsol called reaction force) could be found when moving the sphere, at constant velocity, upwards in the liquid. If a constant force were found, the time to reach it was to be used to determine when the measurements for the viscosity calculations could be started. That is the time when there is no acceleration of the sphere. The drag force on the sphere was calculated.

Another reason for simulating was to investigate the wall effect. This was done by changing the dimension of the container and comparing the resulting drag forces. When the drag force does not change for different container dimensions it means that there is no wall effect.
3.1. Mathematical background
The Navier-Stokes equations are used to describe the fluid flow. There is a solution for the velocity field. The force that the fluid exerts on the solid boundary is the negative of the reaction force on the fluid. The single phase flow of the fluid and the solid mechanics of the solid are solved in different reference frames, therefore there is a transformation between them. These frames are automatically included in the Fluid-Solid Interface boundary condition.

The ALE method makes it possible for the fluid mesh to move freely in the fluid domain and makes it possible for it to follow the changes of the solid boundaries. The fluid fills up the areas left by the solid. This is possible since ALE is a combination of a Lagrangian and an Eulerian equation.

3.2. Simplifications and assumptions
Assuming that the drag force on the connection between sphere and balance is much smaller than the drag force on the sphere, the connection between the sphere and the balance pulling it upwards was neglected.

The flow was assumed to be laminar.

The axisymmetric geometry simplifies the calculations.

3.3. Initial conditions
All initial values were set to zero. The initial values are: the velocity field, the pressure, the displacement field, and the structural velocity field. Since the velocity initially is set to zero all movement comes from the sphere as it is lifted upwards. A step function started the movement at 0.1 s.

3.4. Boundary and domain conditions
Since the model is axisymmetric the middle boundary was set to have axial symmetry. A Pressure point constraint was added to set the pressure as constant zero in one point. The point was chosen arbitrary. The pressure level must be set in some way; an alternative is to use a boundary condition.

The boundary condition Free means that the boundary is free from loads and constraints. It was overridden by the Fluid-Solid Interface Boundary. It gives the load of the fluid on the solid and how movements of the solid affect the fluid velocity. It was applied on the sphere surface boundary with a time dependent equation. The equations for this type of boundary are included in the fsi interface.

Linear elastic material was applied to the sphere domain. Isotropic material was chosen meaning that the properties are the same in all directions. The box for nearly incompressible material was ticked, and the global coordinate system was used.

A Prescribed velocity was added, it is either a boundary or a domain condition where the velocity is given in some direction. It was used for the sphere domain setting the velocity in z direction to $v*\text{step1}$, where $v$ is the velocity that was changed between calculations and step1 is the step function going from zero to one at t=0.1 s. The velocity in r direction was set to zero. The global coordinate system is default and was used for this work.

The walls of the container had a no slip condition meaning that the liquid velocity was the same as the velocity of the solid, which was zero.

The Prescribed mesh displacement condition is used on boundaries of domains with free deformation, for choosing the directions in which movement will be possible, and also restricting it if necessary. The default Prescribed mesh displacement was zero in r and z directions. It was used on
the walls of the container, and on top of the liquid to prevent it from leaving the container. An added
Prescribed mesh displacement only restricted the movement to zero in the r direction, leaving the z
direction unticked. This condition was used at the liquid boundary of axial symmetry. The default
global coordinate system was used.

The liquid density was set to 970kg/m^3 and the viscosity to 0.1Pa*s or 0.5Pa*s since the silicone oils
used for the cold model experiments had these properties.

3.5. Experimental conditions studied in the simulation
Time for constant drag force – At the beginning of the movement there will be acceleration affecting
the drag force. The drag force should be constant when the velocity is constant. To see at which time
from start the drag force is constant the force was plotted against time for the different containers
and viscosities. The experimental measurements can start at the time of constant drag force.

The wall effect – A wall effect will affect the drag force measurements depending on the ratio
between the sphere and container radii. The effect was investigated by changing the container radius
and calculating the drag force to see at which radius the drag force becomes independent of the
container size.

3.6. Calculation
For calculating the drag force a Global Variable Probe was added under Definitions. The expression
intop1(fsi.T_stressz) was used. Intop1 was an integration over the sphere surface, also added under
Definitions. Since the movement of the sphere is in z direction, the forces in z direction were chosen.
A free triangular mesh was added and automatic remeshing was activated. The remeshing was
needed to prevent the mesh from stretching out too much as the sphere moves during the
simulation. After calculating the results were analyzed by creating plots.
4. Cold model experiments

A hollow stainless steel sphere of radius 15 mm was filled with the liquid to be measured. It was connected to a balance and lowered into a cylindrical container filled with the liquid. The balance was then set to zero meaning that the forces $mg$ and $F_B$ were neglected. The detection limit of the balance was 0.01 g with a labeled minimum of 0.5 g. The sphere was dragged upwards by a compact module from Boschrexroth controlling the movement of the balance and hence, also the sphere. The module had a ball screw and a maximum distance of 1264mm for movement. Velocity and target position were set to control the movement (within an accuracy of 1 mm) dragging the sphere through the liquid. The balance logged the mass every second. The balance log was started before the movement. In Figure 3 a picture of the setup can be seen.

![Figure 3: The setup for the cold model experiments. The holding of the balance is lifted by a computer-controlled motor. As the balance is lifted the sphere in the container with liquid is dragged upwards and the measured mass is logged in the computer.](image)

At first the experimental setup included a rod screwed on to the hollow sphere and hanged in the balance with a hook. This setup was changed, as can be seen in Figure 4, to a screw and a 0.2 mm thin silver wire which lead to constant measurements on the balance. From these measurements the viscosity was calculated. The calculated values were compared to the value given on the bottles of the oils.
Two containers were used, as can be seen in Table 1, with the radii 4 cm (called the long container) and 7 cm (called the short container) respectively in order to detect a possible wall effect. Two liquids were used; silicone oils with viscosities of 0.5 Pa*s and 0.1 Pa*s respectively, that can be seen in Table 2. The velocity was changed between runs; 50mm/min, 100mm/min, 300mm/min, and 600mm/min were chosen for comparison.

**Figure 4:** The changed setup with a silver wire connected to the sphere by a screw.

**Table 1** The containers used for the cold model experiments

<table>
<thead>
<tr>
<th>Name</th>
<th>Radius [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td>0.04</td>
</tr>
<tr>
<td>Short</td>
<td>0.07</td>
</tr>
</tbody>
</table>

**Table 2** The liquids used for the cold model experiments

<table>
<thead>
<tr>
<th>Name</th>
<th>Viscosity [Pa*s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodorsil silicone oil 47 V 100</td>
<td>0.1</td>
</tr>
<tr>
<td>Rhodorsil silicone oil 47 V 500</td>
<td>0.5</td>
</tr>
</tbody>
</table>
5. Results from Comsol

5.1. Time for constant drag force

When using Comsol to see if the reaction force becomes constant, it was found that the reaction forces become fairly constant in less than four seconds from start of the movement. At lower velocities and at higher viscosities the constant value is achieved earlier. This can be seen in Figure 5-8. The higher viscosity also gives a more even curve.

**Figure 5:** Short container 0.5Pa*s viscosity, reaction force stable at about 1s.

**Figure 6:** Short container 0.1Pa*s viscosity, reaction force stable at about 3s.
5.2. The wall effect

The radius of the container was increased with 0.01 m for each calculation. When changing the radius from 0.04 m (long container) to 0.07 m (short container) it was found that the drag force decreases with increasing radius.

At 0.07 m and at 0.08 m the drag forces become the same for both the long and the short container. This was seen for both the viscosities at the lowest velocity investigated, 50 mm/min. Therefore only the short container was used to calculate the drag force for the different velocities and viscosities.

Table 3 shows, for the 0.1 Pa*s and 0.5 Pa*s viscosities respectively, the lowest radius where the drag force becomes constant for the four velocities. The drag force values are taken from graphs. It can be seen that the drag force increases with increasing velocity, and that the drag force is higher
for the higher viscosity. For the 0.5 Pa*s viscosity the necessary container radius increases with increased velocity. For the lower viscosity the radius is between 0.1 m and 0.17 m not following the change of velocity. The higher viscosity needs a radius between 0.9 m and 0.16 m for the drag force to be independent of the ratio between sphere and container radii.

Table 3 The smallest container radii for which the drag force is independent of the ratio between sphere and container radii.

<table>
<thead>
<tr>
<th>Velocity [mm/min]</th>
<th>Radius [m]</th>
<th>Drag force [N]</th>
<th>Velocity [mm/min]</th>
<th>Radius [m]</th>
<th>Drag force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.15</td>
<td>2.60E-05</td>
<td>50</td>
<td>0.09</td>
<td>1.5E-04</td>
</tr>
<tr>
<td>100</td>
<td>0.17</td>
<td>5.20E-05</td>
<td>100</td>
<td>0.13</td>
<td>2.7E-04</td>
</tr>
<tr>
<td>300</td>
<td>0.13</td>
<td>1.70E-04</td>
<td>300</td>
<td>0.15</td>
<td>7.8E-04</td>
</tr>
<tr>
<td>600</td>
<td>0.1</td>
<td>3.70E-04</td>
<td>600</td>
<td>0.16</td>
<td>1.55E-03</td>
</tr>
</tbody>
</table>
6. Results from cold model experiments

The setup with a rod connecting the sphere to the balance gave a linear change in measured mass as the rod was gradually leaving the water which decreases the lifting force and adds gravity force. To simplify the calculations, and to easier find the measured mass of the drag force, the setup was changed to a screw and silver wire.

When the results from the experiments are plotted the graphs show a remarkable resemblance between measurements with the same velocity and viscosity. Figure 9 shows one example where the velocity, viscosity, and container are the same for two experiments plotted in one graph. This plot is also used to exemplify the beginning and end measurements. It can be seen that when the movement starts much higher masses are measured. The same effect is observed when the movement of the sphere stops.

![Graph showing mass vs time for different conditions.](image)

**Figure 9:** Shows the reproducibility of the method. Almost identical values of the mass are achieved for two experiments with same conditions. At the beginning and at the end of the sphere movement the mass is much higher. The zero values at the beginning are before the movement starts.

The viscosities were calculated using the average from the measurements. The values at the beginning and at stopping the sphere movement were not included. The calculated viscosities can be seen in Table 4 and Table 5 for the 0.1Pa*s oil and the 0.5Pa*s oil respectively.
Table 4 Calculated viscosities in [Pa*s] for the two containers. It should be 0.1 Pa*s

<table>
<thead>
<tr>
<th>Velocity [mm/min]</th>
<th>Short container (r &lt; 7 cm)</th>
<th>Long container (r = 4 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>100</td>
<td>0.3-0.4</td>
<td>0.7-0.8</td>
</tr>
<tr>
<td>300</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>600</td>
<td>0.2-0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 5 Calculated viscosities in [Pa*s] for the two containers. It should be 0.5 Pa*s

<table>
<thead>
<tr>
<th>Velocity [mm/min]</th>
<th>Short container (r &lt; 7 cm)</th>
<th>Long container (r = 4 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>100</td>
<td>1.3</td>
<td>2.2</td>
</tr>
<tr>
<td>300</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>600</td>
<td>1.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

The values are between two to ten times too large for the 0.1 Pa*s liquid, and between two and five times too large for the 0.5 Pa*s liquid.

Figure 10-17 show the difference between the two containers. There is one plot for each combination of the four velocities and two viscosities. It can be seen that the difference is more pronounced for the higher viscosity in all different velocities. To facilitate the comparison, the scaling of the y-axis is equal for the same velocity; this also means that some data points are cut out from the plot. Those points are from the start- and end effects and therefore not interesting for this study. A higher velocity give higher mass, also the long container gives higher mass than the short. A higher viscosity gives higher mass. Naturally the long container give more data points since the amount of liquid did not vary.

Figure 10: The difference between long and short container for the velocity 50mm/min and viscosity 0.1Pa*s.
Figure 11: The difference between long and short container for the velocity 50mm/min and viscosity 0.5Pa*s.

Figure 12: The difference between long and short container for the velocity 100mm/min and viscosity 0.1Pa*s.
Figure 13: The difference between long and short container for the velocity 100mm/min and viscosity 0.5Pa*s.

Figure 14: The difference between long and short container for the velocity 300mm/min and viscosity 0.1Pa*s.
**Figure 15:** The difference between long and short container for the velocity 300mm/min and viscosity 0.5Pa*s.

**Figure 16:** The difference between long and short container for the velocity 600mm/min and viscosity 0.1Pa*s.
Figure 17: The difference between long and short container for the velocity 600mm/min and viscosity 0.5Pa*s.

To summarize the results from the cold model experiments:

- A high velocity gives a high mass
- A high viscosity gives a high mass
- The long container gives higher mass compared to the short
- A high viscosity gives a larger difference in mass between the two containers

7. Discussion

It is positive to see the repeatability of this method. For two experiments with the same conditions the mass is almost identical. Unfortunately the resulting viscosities from the measurements are not very exact. This method gives more constant values when the viscosity is higher, implying that the method is suitable for liquids of high viscosity. There is a need for a correction factor in order to get a more precise value. Since most research done regarding correction factors is on settling of spheres, it is difficult to appreciate the validity for dragging the sphere at constant velocity.

In the Comsol model heat transfer was neglected, and was not needed in order to compare with the cold model experiments performed at room temperature. For the industrial application it could be interesting to further develop the model adding bubbles, particles, heat transfer, and movement of the liquid. The discussion is divided in three main areas from this work.

7.1. Wall effect

The cold model experiments gave different results depending on the size of the container. The long container gave higher mass, which led to higher viscosities. This is due to the wall effect giving a higher viscosity at smaller radius. In this work the ratios between sphere and container are 15/70=0.214 and 15/40=0.375 respectively. This limits what correction factors that can be valid for these ratios.
Table 6 show the average difference in mass between the long and the short container. The higher viscosity always show a larger difference compared to the lower viscosity at same velocity, the importance of that can be questioned since the values are so small and therefore almost the same. However, it can be seen that for the higher viscosity the average difference is larger by one order of magnitude for the two higher velocities. This gives reason to believe that the wall effect is higher for higher viscosities. Perhaps it should not be called the wall effect in that case, since the correction factor will depend on the viscosity as well as the wall. Considering that the purpose of the method is to measure the viscosity, a need for correction depending on the viscosity is problematic.

<table>
<thead>
<tr>
<th>Viscosity</th>
<th>50 mm/min</th>
<th>100 mm/min</th>
<th>300 mm/min</th>
<th>600 mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 Pa*s</td>
<td>1E-5</td>
<td>2E-5</td>
<td>4E-5</td>
<td>7E-5</td>
</tr>
<tr>
<td>0.5 Pa*s</td>
<td>2E-5</td>
<td>4E-5</td>
<td>2E-4</td>
<td>3E-4</td>
</tr>
</tbody>
</table>

The wall effect was also investigated with Comsol by increasing the container radius with 0.1 m between the simulations. For the two viscosities and two containers the resulting drag force became the same at equal radius of 0.07 m and 0.08 m. This means that there is no effect coming from the height of liquid. For the experimental case there could be such an effect since the liquid volume was the same in both containers which increases the height of liquid at smaller radius.

In Comsol the drag force decreases when increasing the radius from 0.04 m to 0.07 m, and then increases when increasing the radius further. As if there is a minimum for the drag force at about 0.07 m radius. This was not further investigated in this work. The Comsol calculations also show that for a sphere of 15 mm radius, a container radius between 0.09 m and 0.17 m is needed to achieve constant values of the drag force. The simulations confirm the experimental results that the needed container radius depends on viscosity and velocity.

As theory predicts the drag force increases with increasing velocity, and is higher for the higher viscosity. If looking only to the high viscosity, it seems that the container has to be larger the higher the velocity is in order to achieve a constant drag force. This conclusion is not supported by the simulations with lower viscosity. The two viscosities both need approximately the same radius to show drag forces that are independent of radius. This could mean that it is easier to investigate the wall effect using a liquid of high viscosity as those forces will become larger. These investigations show on the importance of correct dimensions of the measuring equipment. It could be meaningful to further investigate how different conditions affect the results in order to find a suitable correction factor.

7.2. Force magnitudes
In Table 7, the forces in the system have been calculated. The interesting part of this table is the third column where it can be seen that the gravity and buoyancy forces are of the magnitude E-1 and the drag forces in this work varies between E-5 and E-3. It means that comparing them can be difficult. It is like comparing a molecular scale to a macroscopic one; changes in the molecular scale has to be very large in order to be visible at the macroscopic level. In addition to this, the balance used in this work had a detection limit of 0.01 g, but was labeled with minimum 0.5 g. That is at the limit of being able to measure the drag force. Therefore it also becomes more difficult to separate the drag force from experimental variations in the measurements. The result is that the measured values are uncertain. However, they can still be used to investigate if this method could work. Which was the goal of this work.
Table 7 The magnitude of different forces with different conditions.

<table>
<thead>
<tr>
<th>Force type</th>
<th>Specification of conditions</th>
<th>Force magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity (mg)</td>
<td>m=49 g, g=9.81 m/s^2</td>
<td>4.8E-1 N</td>
</tr>
<tr>
<td>Buoyancy (ρVg)</td>
<td>ρ=970kg/m^3, V=1.4*10^-5 m^3, g=9.81 m/s^2</td>
<td>1.3E-1 N</td>
</tr>
<tr>
<td>Drag (6πρμν)</td>
<td>r=0.015 m, μ=0.5 Pa*s, v=600 mm/min</td>
<td>1.4E-3 N</td>
</tr>
<tr>
<td>Drag (6πρμν)</td>
<td>r=0.015 m, μ=0.1 Pa*s, v=50 mm/min</td>
<td>2.3E-5 N</td>
</tr>
</tbody>
</table>

It is interesting to note that the drag force values taken from graphs when investigating the wall effect in Comsol are between 2.6E-5 N and 1.55E-3 N. The order of magnitude is the same for the values calculated by hand. This is positive and supports the reliability of the simulations.

Since the drag force becomes larger with higher viscosities, it should be easier to measure liquids of higher viscosity. The viscosity needs to be high enough to make the drag force comparable to the macroscopic forces, such as mg and buoyancy, and to make changes visible on the balance. A balance of higher accuracy could also be beneficial. Increasing the velocity should also increase the measured mass of the drag force. This is not seen in these experiments where increasing velocity lead to decreased calculated viscosity. The explanation is that the mass does not increase enough to compensate for the increased velocity. However, why it does not compensate is not understood.

7.3. Turbulence

It has to be considered that a high velocity will increase the risk of a turbulent flow. If the flow becomes turbulent the equations will not be valid and a new expression for the force balance has to be found. As mentioned earlier it is very difficult to analyze fluid flows theoretically and experiments to investigate the flow might be necessary. Another option is to model and simulate the flow. The Comsol model in this work did, however not include the attachment of the sphere to the balance. This might have an effect on the result. In the experimental situation of this work, the flow pattern could be affected by the screw attaching the silver wire from the balance to the sphere. The screw was quite large compared to the sphere, which possibly creates turbulence or some other flow effect.

One way of investigating the flow character is by Reynolds number, but it is not always true that a low Reynolds is only for laminar flows. Since the equation used for finding Reynolds is based on a sphere in a cylinder, it might not be valid in this case where the sphere is dragged by a wire. For the Comsol model there is something called the cell Reynolds number that can be calculated, unfortunately it is not related to the flow character. These are the reasons why the Reynolds number was not investigated in this work. Therefore it could be of interest to further investigate the flow and its effect on the measurements.

8. Summary

The possibilities of a new method for industrial inline viscosity measurements have been investigated. The theory of the method is based upon Stokes drag. Comsol modeling was carried out to determine at which time the measurements could start (constant velocity), and to investigate the wall effect. Cold model experiments were performed dragging a sphere upwards in two silicone oils of different viscosity, and using two containers of different radius. The results suggest that:

- Corrections need to be added
- This method is more suitable for liquids of high viscosity
- Further development of the method is needed before it could work
References


