Computational Analysis of a Microfluidic Viscometer and Its Application in the Rapid and Automated Measurement of Biodiesel Blending Under Pressure Driven Flow

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The fossil fuels are depleting with time, hence the research work in the area of alternate energy is growing; thereby providing an abundant scope for Biofuel production and deployment. The various physical properties that govern the fuel mixture are viscosity, concentration, additives, boiling point, melting point, etc. Hence, developing a sensor, based on such physical properties, can provide a reliable and effective solution to detect and monitor the biodiesel blending. This research paper describes the computational analysis of a Y-shaped microfluidic device which performs various fluidic operations by analyzing physical properties and their variations. The idea behind this study is to find out the adherence of the device to the Hagen-Poiseuille flow equation. The working principle in this case is concentration dependent width capture by the fluids flowing in the channels based on the pressure difference in the inlet and outlet ports. The different physical characteristics with their test results for various blending ratios of diesel with biodiesel have been shown in this study. Such microfluidic devices also have other viscosity based sensing and monitoring applications such as hemoglobin detection, food adulteration etc.

Keywords: Biodiesel Blending, Comsol Multiphysics, Kinematic Viscosity, Laminar Flow, Microfluidics.

1. INTRODUCTION

Alternate energy has come a long way since its gain in importance due to the depleting fossil fuel reserves and the need to conserve global resources for the future generations.1 The usage of alternate fuels in automobiles mark a significant progress in this field enabling the reduction of emissions and also supporting the cause of depleting resources.2 Biofuels are of many types ranging from ethanol or methanol based ones to the blended ones where certain quantity of biofuel is mixed with the existing fuels such as diesel and petrol.3 Biodiesel is an alternative for diesel. It can be obtained by trans-esterification of vegetable oils that are largely composed of tri-glycerols.4 The non-edible oil plants like Jatropha, Karanja, and Putranjiva etc. are used for the production of biodiesel as they are found to be very economical.5 The emissions such as smoke, CO, and other particulates of the combustion process for producing the energy in the engines that use biodiesels are lesser than the conventional fuel based engines.6,7 This has a lower impact on the environment and living organisms.8

The blending of biofuels is an important function because the level of blend determines the advancement in engine research.4 It was initially difficult to exactly specify the percentage of biodiesel that could be blended with diesel because of the co-related factor with the uncertainty of the availability of biodiesel in the initial stages.9 The Ministry of New and Renewable Energy-Government of India has proposed that 20% blending of biofuels for both biodiesel and bio-ethanol by the end of 2017.10 They have proposed to make blending recommendatory up to certain prescribed levels and then subsequently would be made as a mandate. Biodiesel usage has several advantages over conventional fuels like reduced emissions, improved combustion and high biodegradability.11,12 The increase in viscosity of biodiesel w.r.t to the slight variation in the production method makes this a very complicated proposition13 as it would directly affect the engine
performance and durability. The present day engines are expected to be modified to use not more than 20% blended biodiesel. Fractions more than that requires a redesigned injector which works in higher viscosity ranges.\textsuperscript{16, 17}

Viscosity is an important rheological property that can be defined as resistance to fluid flow.\textsuperscript{18} In simple terms, viscosity is the thickness or the internal resistance between layers of the flowing fluid. Viscosity measurement is of great importance both in research and industrial applications.\textsuperscript{16, 18--22} The viscosity of biodiesel is slightly greater than petro diesel but less than that of parent vegetable oils.\textsuperscript{15, 21, 23, 24} There is a misconception that density is directly related to viscosity but equally dense substance may have a wide range of viscosities. A viscometer is a measuring instrument which is used to measure the viscosity of the fluid whose surroundings are constant throughout the experiment. A rheometer is a device that is used to measure the viscosity of those fluids whose viscosity varies with flow conditions.\textsuperscript{25, 26} The blended amount of bio-fuel in diesel can be monitored by measuring the viscosity. There are some standard laboratory viscometers which are used to measure the viscosity of fluids. Most commonly used viscometers are U-shape glass viscometer, Rotational and vibrational viscometer.\textsuperscript{27} The major limitations of these viscometers are that they require large sample amounts, controlled surroundings and expensive instrumentation for measurements.\textsuperscript{29}

Microfluidics have emerged as a promising technology for a wide range of applications from micro-chemistry to bio-engineering.\textsuperscript{28} It provides a pathway to address many issues related to the dimensions of devices and miniaturized sensors for various applications. Microfluidic devices offer several advantages over large scale processes such as small sample requirement, improved analysis time, real time monitoring, and high aspect ratio etc.\textsuperscript{28--30} The usage of micro-viscometer to do the viscosity testing has been in research work for quite some time.\textsuperscript{31} But, a real-time monitoring of the viscosity variations w.r.t to blending of bio-fuel or adulterations is still an emerging field of research. The prime aim of this paper is the analysis of a y-shaped microfluidic device that can do the measurement of viscosity of an unknown sample when it is allowed to mix with a reference sample of a known viscosity in a microfluidic channel.

In this paper we report the computational analysis of a y-shaped lab-on-a-chip microfluidic device\textsuperscript{32} that can be used to know the biodiesel blending ratio in diesel, in real-time by way of monitoring their viscosity.\textsuperscript{33} The device records the interface position of the blended fuel and the immiscible reference fluid in a common channel. Further, the device can also be used for the purpose of automobile fuel adulteration and food adulteration\textsuperscript{34} wherein the reference can be mixed with the unknown quantity of fluid and reports can be generated. This miniaturized viscometer\textsuperscript{35} would offer many advantages like low cost, excellent insulation, transparent, available in different thicknesses and many more. The simple and versatile device design offers the advantage of being compatible for many applications.\textsuperscript{36}

The blending of diesel with biodiesel for different mixing ratios was successfully tested in the computational study and the results have been explained with detailed analysis.

2. MICROFLUIDIC DEVICE SIMULATION

2.1. Simulation Considerations Based on Hagen Poiseuille Flow Equation

The growing interest in investigating the flow of fluids through micro-tubes and micro-channels has risen because of the wide range of potential industrial and medical applications.\textsuperscript{37} Many researchers and investigators have used the Navier–Stokes equations to describe the laminar flow in micro-channels.\textsuperscript{38} The usual assumptions include thermally and hydro-dynamically fully developed flow, constant fluid properties, and no slip at the wall. This approach has been suitable for laminar flows in macro-tubes or macro-channels.\textsuperscript{39} In these flows, viscosity of the fluids is one of the major factors as it takes into the account the width of the channel. The heat dissipation from the walls of the channels is negligible and the rise in temperature because of this is practically immeasurable and hence, the pressure loss measurements are also negligible as the input parameter is restricted to the fluid input per minute.\textsuperscript{40, 41}

The Hagen Poiseuille flow equation given below is the basis of determining the viscosity by considering all the other variables in the equation as a constant excepting the width of the channel which would differ based on the two different fluids flowing inside the microfluidic channel.\textsuperscript{36}

\[ \mu = \frac{w^2 \Delta P}{2 \nu m L} \] (1)

Here ‘\( \mu \)’ is the viscosity of the fluid, ‘\( w \)’ is the width of the channel in mm, ‘\( \Delta P \)’ is the difference in pressure between the inlet and outlet in Pascals, ‘\( \nu m \)’ is the fluid velocity inside the channel and ‘\( L \)’ is the length of the channel. The version of the model solved involves the viscosity being dependent linearly on the distance of separation between the two fluids flowing in, taking one of the fluids as a reference. Thereby the equation would thus become as

\[ \mu \propto w^2 \] (2)

Here ‘\( w \)’ is a dimension quantity and in this model it is the width of the entire channel. The width has been considered as 3 \( \mu m \). The width occupied by each fluid while flowing inside the channel and ‘\( \nu m \)’ is the fluid velocity.

The proportionality factor \( \Delta P/2 \nu m L \) is dependent on the microfluidic environment and is considered to be constant for the present study. Therefore

\[ \frac{\mu_1}{\mu_2} = \frac{w_1^2}{w_2^2} \] (3)

Hence if we know the viscosity of one reference fluid and with the help of dynamic measurement we can determine the width occupied by the two fluids in the channel, we can determine the viscosity of the unknown fluid. Such a relationship between width of the channel and viscosity is usually observed in solutions of larger molecules. For solving the Navier-Stokes equation and the convention-diffusion physics the mesh applied to the channel is extremely fine with a maximum element size of 0.359 mm and the minimum element size of 0.00359 mm. The mesh is made to flow through the channel with an element growth rate of 1.3 (No Unit).42

2.2. Design and Pre-Assumptions for the Y-Shaped Microfluidic Device

To analyze the interface shift, when kinematic viscosity of the sample fluid is changed with respect to the immiscible reference fluid, the simulation tool COMSOL 4.2a was used. As shown in Figures 1(a) and (b), the device is a Y-shaped microfluidic device made of acrylic for controlled mixing through diffusion.43 It was designed with two input channels and a common channel. In a typically device, the width of the input channels were 25 μm and the width of the common channel was 30 μm wide. The length of the common channel was chosen to be as large as possible to allow the flow to be laminar. The length was taken as 20 μm long as shown in the same figure. The design was aimed to maintain a laminar flow in the field when the two streams, A and B, are united and thus prevent uncontrolled convective mixing.20

The transport of species between streams A and B was such that it took place only by diffusion in order to make the species with low diffusion coefficients stay in their respective streams.44 To avoid any type of convective mixing, the design was allowed to smoothly let both streams come in contact with each other.45 The flow rate at the inlet was approximately 7.5 × 10^{-8} m^3/s. The Reynolds number,45 which is important for characterizing the flow, is given by:

\[
Re = \frac{\rho UL}{\mu}
\]  

(4)

where ‘\(\rho\)’ is the fluid density (assuming water as the benchmark the value is 1000 kg/m^3), ‘\(U\)’ is a characteristic velocity of the flow (7.5 × 10^{-8} m/s), ‘\(\mu\)’ is the fluid viscosity i.e., in this case we consider the kinematic viscosity which is dependent on the concentration of the fluids flowing in the channel. Inserting the known numbers we can calculate the Reynolds number. When the Reynolds number is less than 1, as in this example, the Laminar Flow interface can be used.46 The problematic convective term in the Navier-Stokes equations can be dropped, leaving the incompressible Stokes equations as:

\[
\nabla \cdot (-p I + \mu (\nabla u + (\nabla u)\mathbf{^T})) = 0
\]

(5)

\[
\nabla \cdot u = 0
\]

(6)

Here ‘\(u\)’ is the local velocity (m/s) and ‘\(p\)’ is the pressure (Pa). In this model, the parametric solver is used to solve Hagen Poiseuille flow equation for the two different fluids that flow inside the channel.47 One can be water and the other can be a higher concentration fluid. The flow rate is given a value of 7.5 × 10^{-8} m^3/sec and the entrance length before going into the channel was set as 1 meter. This is considered because the flow of the fluid in the channel requires a certain length for it to get a stabilized Reynolds number.46 COMSOL does the computation stability by default, as found in most of the problems solved using the Finite Element Analysis techniques particularly for such solid-liquid interfaces.48-49 Hence no explicit user settings was manually required to be added.

2.3. Velocity Field and Pressure Flow Characteristics

The velocity field for this case, where viscosity varies with the concentration of the fluid given as input is based on the type of fluid which is made to flow through the channel. According to Eq. (2), the flow is not symmetric and influenced by the concentration field.45 This is because of the different viscosities of the fluids sent into the channel. The Figure 2(a) shows the variation in the concentrations of the fluids flowing in. The Inlet 1 is considered to be carrying Fluid 1 with a concentration of 3.75 mol/m^3 and the Inlet 2 is considered to be carrying another Fluid 2 with a concentration of 5.2 mol/m^3. Now the laminar flow input value is used and when computing the values of velocity field, 0.018 m/sec was obtained at the center of the Inlet 2.

![Diagram](image-url)
and 0.008 m/sec at the center of the Inlet 1. This shows that the heavier Fluid 2 flows in a bit slowly due to its higher density as shown in the Figure 2(b) (lower portion of y channel). It is difficult to see the differences in this figure but careful inspection reveals a slight change in the velocity profile.

The corresponding pressure distribution on the walls of the channel for the fluid flow is shown in Figure 3. These results depict that the pressure at the inlet is high (in the range of 30–35 Pascal’s) because of the flow rate which is fixed during calculation. The density of the fluid going into the channel also plays a major part in the pressure at the inlet ports.

There are significant differences between the inlet and outlet pressures. The pressure gradually reduces to a bare minimum near the outlet. The reason behind keeping such values is attributed to the fact that the flow would occur only if there is a pressure difference. If the pressures at the outlet and inlets are kept the same then it would result in no flow across the channel according to Bernoulli’s principle of liquid flow. The viscosity varies with the concentration and hence the width occupied by the fluids in the channel varies. Based on the ratios of the width occupied the viscosity of the unknown fluid can be determined.

2.4. Concentration and Viscosity Based Characteristics

In cases involving solutions of macromolecules, the macromolecule concentration has a large influence on the fluid’s viscosity. In such situations, the Navier-Stokes and the convection-diffusion equations become coupled, and so they must be solved simultaneously. Figure 4 show the result of such a simulation, in which the Navier Stokes equations are solved with a concentration dependent viscosity. In this case, the species with diffusivity $5 \times 10^{-11} \text{ m}^2/\text{s}$ is shown. The velocity field is altered slightly by the concentration dependent viscosity but this has little effect on the mean stream outlet concentration, which changes only slightly from 0.450 to 0.451 (No Unit). The more serious effect is that of the non-uniform viscosity on the pressure distribution required to maintain the two streams at the same flow rate.

A larger pressure is required at the inlet of stream B to drive the higher viscosity fluid through the system. This asymmetry in the pressure distribution makes placing
several devices in series much more difficult. Hence the consideration of stacking many such channels for more efficiency is a difficult proposition. The velocity field for the uncoupled flow simulation showing the difference between the velocity profiles from the outer edge to the inner surface of the channel is shown in the iso-surface plot of Figure 5. The diagram shows the fluid viscosity as a function of concentration. The higher the velocity, the lesser is the concentration dependent viscosity of the fluid that is flowing in which are indicated by the blue and dark blue lines.

2.5. Biodiesel Blending Comparison Using Simulation

The microfluidic device was initially tested using water and a slightly denser liquid like honey in the software by inserting their physical properties. The major test was done between Biodiesel at various blending ratios and 20 wt.% Glycerol solution. For biodiesel testing glycerin was taken as reference fluid. The values of viscosity used in the fluids are based on standard temperature (20°C) and pressure (1 atmosphere). The computation involved the use of two different viscosity fluids for their interaction in the channel. The basic idea was to introduce two immiscible fluids through the two inputs channels and observe the interface in the common channel. In the real-time model the flow will be initiated using peristaltic pumps whereby we can control the flow rate based on the requirements. When two fluids flowing through the channel have different viscosities, the more viscous fluid will have higher resistance than the other fluid. The less viscous counter-part will have better flow dynamics and hence it will take the wider path initially. But after a few minutes the more viscous fluid goes in stabilizes, there after showing that the higher viscous fluid taking the wider path.

The Figures 6(a)–(c) show the comparison of the various blends of biodiesel with 20 wt.% Glycerol solution. The results clearly indicate that as the test sample of different viscosity is selected there is an interface shift i.e., the test sample with higher viscosity tends to take broader path in the common channel thereby pushing the less viscous reference fluid. The comparison results were confirmed for various biodiesel blends with Glycerin as the reference fluid.

The simulation was also run with other oils including the hair oils, machine oils etc. with different densities and miscibility factor to confirm the interface shifting phenomenon. The results of those will be put up in a separate module. Interface spreading for different oils was compared at a specific position in the channel to ensure the systematic and reliable measurement. All the computations were carried out using the simulation tool. The interface position of the fluids in the microfluidic channel was then used to find out the viscosity of the biodiesel blends. After considering all the parameters as constant in the Hagen-Poiseuille equation, five sets of data readings for each of the blended biodiesel samples were taken and the average was calculated based after repeating the simulation ten times. The interface position was measured with the help of the data from the software. The variations in the widths occupied by the fluids in the microfluidic channel are shown in Figure 7. This graph can be used to derive that as the viscosity of fluid 1 going in through the inlet 1 increases the width occupied by the fluid in the microfluidic channel also increases in a linear fashion.

The values of the biodiesel was found to be virtually matching with the experimental values at the standard temperature.
temperature (20° Celsius) and pressure (1 Atmosphere). The graph (Fig. 8) shows the match-ability of the measured viscosities of the biodiesel blends with the experimental kinematic viscosity values.

Thus the above curves can be used to find the viscosity of unknown fuel samples when they are mixed with the reference fluid (in this case 20 wt.% Glycerol solution). The viscosity value can be then be used to find out the biodiesel fraction present in the fuel sample. If viscosity of the reference fluid is known then the viscosity of the unknown fuel sample can be easily calculated. Thus, the viscosity of the various blends of biodiesels can be found using the value of the viscosity of the reference fluid and the widths occupied by the fluids in the channel.

Therefore if the values of the various parameters in the Hagen-Poiseuille equation are considered to be constant then by using the data related to the width occupied by the fluids flowing into the microfluidic channel, the unknown viscosity of one of the fluids can be found. The above graphs also signify the linear relationship between the width occupied by the fluids inside the microfluidic channel and the biodiesel viscosity. Hence if the reference fluid is made to be pure diesel and the second fluid is taken as biodiesel then the blending ratio can also be determined using the same phenomenon.

3. CONCLUSION

This analysis provides a unique method of calculating viscosity of test samples on a simple y-shaped microfluidic device. The simulation data indicates that real-time detection and monitoring of biodiesel blending can be done. According to the width taken by the test sample in the viscometer one can easily calculate its respective viscosity by calculating the width value occupied by the individual fluid streams in the microfluidic channel using the Hagen Poiseuille equation. The simulation study clearly indicates that when there is a pressure difference between the inlet and outlet ports the fluid flows through the channel. The concentration dependent viscosity of biodiesel can be found out based on the increase in the occupancy of the microfluidic channel. This indicates that the ratios of the squares of the widths occupied by the fluids increases linearly with the viscosity of the biodiesel blend introduced into the channel. Moreover the device can be manufactured for a low cost and will have high durability. The device is re-usable, can be re-calibrated and made into a plug-n-play device as well so that it can be readily plugged into automobiles. The computational processes have been optimized for efficient viscosity analysis for various biodiesel blending.

In the future scope, a pilot model of the optical version of the device will be made and tested real-time for the identification of viscosity of unknown fluids. An electronic version of the micro-viscometer can also be explored which will work on the similar principle i.e., for any fluid time required to travel a unit distance in a micro-channel, of a given cross-section, will be inversely proportional to its viscosity. There will be no reference fluid required for such a device and its electrical output can have higher possibilities of integration with other electric controls. This can further contribute to the measurement of fuel adulteration based on the electrical signals obtained from the device. This micro-viscometer can also be modified for other applications like food adulteration and hemoglobin detection in blood.

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