

Generation of a model for the description of the viscosity of bio-oil produced by fast pyrolysis of wheat straw

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Abstract:

Bio-oil is a major product of biomass fast pyrolysis that could potentially be used in motor engines, boilers, furnaces and turbines for heat and power. However bio-oil of bioliq[®] is not intended for direct use in motor engines. It will be gasified to produce synthesis gas. Bioliq[®] Process analytics provides bio-oil characterization and rheological characterization is a key process parameter in this analysis. The aim of this work is to evaluate the role of viscosity of organic condensate obtained from wheat straw. This has to be done by means of a model that is able to adequately describe the viscosity as a function of relevant process parameters. The developed model of temperature is helpful to investigate the drop of heat transfer in the heat exchangers of the organic condensate cycle when glycol is replaced by an organic condensate. Glycol is used as preliminary material during start-up of the plant and has a different viscosity than the organic condensate. Temperature, solid contents and water contents play a significant role in affecting the viscosity of bio-oil. As temperature increases, the viscosity of oil reduces rapidly. Viscosity-temperature profile follows an Arrhenius-type-relationship, where the viscosity of the bio-oil decreases exponentially with increasing temperature. As solid content increases, exponential increase of viscosity takes place. By increasing water content, decrease of viscosity takes place on logarithmic scale.. The range of water addition in organic condensate is possible up to a certain limit, after that limit it starts to separate out in two phases. Investigation of drop of heat transfer in heat exchanger shows that Nusselt number decreases with the increase of viscosity. Therefore, the overall heat transfer coefficient will decrease in case of organic condensate as compared to glycol. Overall, from this study, it can be concluded that viscosity is influenced by the key parameters determining the organic condensate cycle through intrinsic relationships as mentioned above.

Key words: Rheology, temperature, solid content, water content, Nusselt number

Introduction

Bio-oil is a liquid product of fast pyrolysis that results from thermal decomposition of natural organic feedstock (crop waste, municipal waste and manure etc.) in an absence of oxygen. The bioliq[®] concept developed by KIT is a three step conversion process for the production of 2nd generation drop-in biofuels from biomass waste such as e.g. wheat straw. First, biomass is converted by fast pyrolysis to yield energy dense biosyncrude, a mixture of bio-oil and char. This slurry is the feed for subsequent pressurized entrained flow gasification at 8 MPa to yield producer gas free of tars. The gas is finally converted by Fischer-Tropsch synthesis to yield designer fuels. The given task is set in the first step, fast pyrolysis. This initial conversion is performed in a twin-screw mixing reactor at 500 °C. The comminuted biomass feed is thermo-chemically converted to hot pyrolysis vapors, gas, and char fines within seconds. Solid particles are separated by cyclones prior to a two-step condensation of the vapors to yield an organic and an aqueous condensate as shown in figure 1.1a. The organic condensate is recycled, cooled down and used for quenching the incoming hot vapors in order to assure rapid cooling. The technical feasibility of the organic condensate has not been evaluated yet. One major aspect of the technical feasibility is the viscosity of the organic condensate because viscosity is an important parameter for the determination of pipeline size and the power required to pump fluids through it.

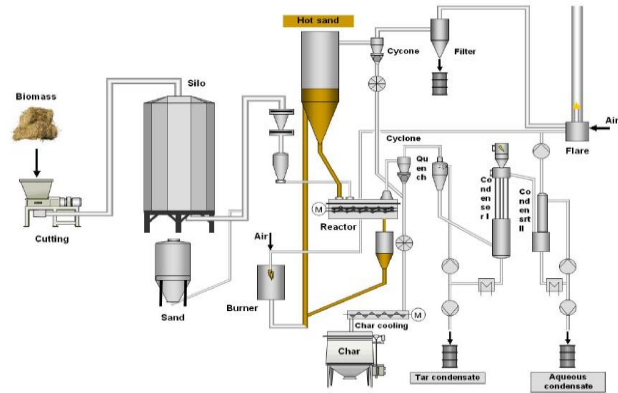


Figure 1.1a: Overall plant view

Literature

Bio-oil

Bio-oil is a liquid product of fast pyrolysis. Bio-oil can be recognized by different names like organic condensate, pyrolysis liquid. Bio-oil can separate in two phases: a heavier organic tar fraction with little water and a lighter aqueous phase with dissolved organics. Pyrolysis water consists of 50-80% water with 20-50% dissolved organics [1]. Bio-oils, the main constituent of bioslurries, are a dark brown to black liquid [2]. Scientists are trying to overcome the problems related to bio-oil and provide a suitable way to make it commercially available. Viscosity of bio-oils is an imperative parameter to make it commercially available because it is affected by number of parameters such as quenching temperature, fluid temperature, residence time/ age, water and solids content.

Significance of bio-oil viscosity

Viscosity of a fluid (either water or pyrolysis tar) is a measure of its resistance to gradually deform under shear stress or tensile stress [3]. Viscosity of bio-oil is an imperative fuel property that should be considered in designing, processing, handling and transportation. Viscosity of bio-oil during operation

of fuel injection equipment particularly affects the fluidity of fuel at low temperatures. However, the quality and practical application of bio-oil as fuel is intimately dependent on its viscosity and the elemental compositions so lower viscosity is desirable [4].

Model 1: Effect of temperature on biooil viscosity

The variation of viscosity with temperature follows an Arrhenius-type relationship. From literature, the variation of viscosity with temperature was studied in the range 20 °C to 80 °C. The natural log of dynamic viscosity versus reciprocal of temperature shows that the Arrhenius-type relation holds for wood samples [5]. The effect of temperature is normally fitted with the Arrhenius-type relationship is represented by equation (1) and (2).

$$\eta = a * e^{\frac{-E_a}{R*T}} \quad (1)$$

$$\eta = a * e^{\frac{b}{T}} \quad (2)$$

Whereas, η = Dynamic viscosity in Pa.s, a = Pre-exponential factor (Pa.s), T = Temperature in Kelvin, E_a = Exponential constant that is known as activation energy (J/mol) and R = Gas constant (J/mol/K). Equation (1) is in the form of equation (2) and it is widely accepted that natural logarithmic viscosity is directly proportional to the reciprocal value of the temperature. $\ln(a)$ is the intercept at the $\ln(\eta)$ -axis and 'b' is the slope of the linear graph [6].

$$\ln(\eta) = \ln(a) + \frac{b}{T} \quad (3)$$

Model 2: Effect of solid content on bio-oil viscosity:

Solids [char] are important due to requirements of the combustion system in different applications with respect to clogging of nozzles, valves and filters. Suspensions are generally solid-liquid mixtures, in which solid particles are dispersed in liquid phase. In the suspension rheology, viscosity of suspension (η_s) is based on the viscosity of liquid (η_L) present in suspension. This ratio is called the relative viscosity.

$$\eta_r = \frac{\eta_s}{\eta_L} \quad (4)$$

General influence on the relative viscosity is by the concentration of the solid, solid particle shape, and particle size distribution [7].

Krieger-Dougherty:

$$\eta_r = \left(1 - \frac{C_v}{C_{max}}\right)^{-\eta * C_{max}} \quad (5)$$

A model for describing the effect of particle on viscosity is given by equation (5), where C_v is the particle volume fraction and C_{max} is a parameter representing the maximum packing fraction, and η is the intrinsic viscosity. For ideal spherical particles $\eta=2.5$ (i.e., the Einstein coefficient). Non-spherical or highly charged particles will exhibit values for η exceeding 2.5. The value of η is also affected by the particle size distribution. The parameter C_{max} is a function of particle shape, particle size distribution and shear rate. Both η and C_{max} may be treated as adjustable model parameters [8].

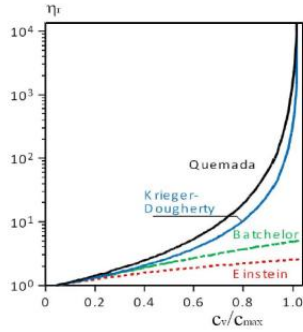


Figure 1.1b: Concentration dependence of the relative viscosity [7]

Effect of water:

Water affects physical properties of bio-oils. The density, viscosity, and heating value increase, when water content decreases. The increase in water content improves the stability of the bio-oil until it starts to separate out, typically at above 30% by weight [9]. It was already explained that the density, viscosity and surface tension strongly varies with the variation of water content. Oasmaa has explained the variation of viscosity with water that is considered to be important for upcoming experiments [9].

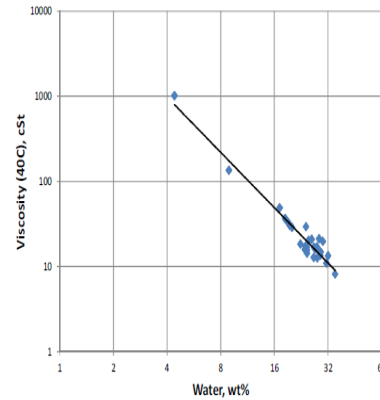
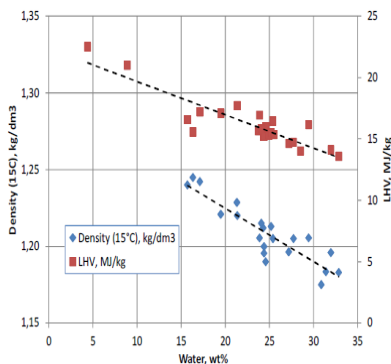


Figure 2: Density, heating value and viscosity of pine and forest residue pyrolysis bio-oils as a function of water content [9]

Heat exchanger:

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures. In heat exchangers, there are usually no external heat and work interactions.

There are different types of heat exchangers. Heat exchangers can be classified according to: Heat process, number of fluids, surface compactness, flow arrangements and construction [10].

Nusselt number:

The Nusselt number (Nu) is the ratio of convective to conductive heat transfer across (normal to) the boundary of the fluid [11].

For Internal Flow: Laminar pipe flow, $Re < 2300$ equation (6) and turbulent pipe flow, $Re > 2300$ equation (7) will be used.

$$\overline{Nu} = \left\{ 3.66^3 + \left[1.62^3 + 0.293 \left(Re \frac{d}{L} \right)^{\frac{1}{2}} \right] Re \cdot Pr \cdot \frac{d}{L} \right\}^{\frac{1}{3}} \quad (6)$$

$$\overline{Nu} = \left[\frac{\xi}{8} \cdot \frac{(Re-1000)Pr}{1+12.7\sqrt{\frac{\xi}{8}}(Pr^{\frac{2}{3}}-1)} \right] \left[1 + \left(\frac{d}{L} \right)^{\frac{2}{3}} \right] \quad (7)$$

$$\xi = (1.82 \cdot \log Re - 1.64)^{-2}$$

Material and material properties:

1) Wheat straw biomass and organic condensate of wheat straw: Dry lignocellulosic biomass like wood or straw below 15 wt. % moisture can be stored without biological degradation. The dry biomaterials are diminished into small particles of < 3 mm in size and biomass particles with a characteristic length of < 0.5 mm. Organic condensate of wheat straw obtained after bioliq[®] process was used in all experiments.

2) Modular Compact Rheometer MCR 102 Fa Anton Paar: a) Helix-spindle, ST24-2HR-37/120 SN29240, Fa. Anton Paar. b) Cylinder-spindle, CC27-SN27965, Fa Anton Paar



Figure 3: a) Cylindrical spindle b) Helical spindle

3) Char: The solid particles, used for analyzing the effect of solid on viscosity, are unmilled straw char with particle sizes given in Table 4.1. Unmilled

char so called bioliq[®] char obtained from the fast pyrolysis step of bioliq[®] process.

Table 1: Particle diameters of un-milled wheat straw char

Char	X ₅	X ₅₀	X ₉₅
Unmilled straw	10 μm	20 μm	70 μm

Methodology and experimental setup:



Figure 4: Experimental setup: A=mounting, B= computer with rheoplus software, C= sample from bioliq plant, D=spindle covering, E=pneumatic system for air pressure, F= methanol for cleaning, G= display of rheometer, H= covering to protect rheometer casing where spindle is attached

The experimental setup used in this study is shown in figure 4. All experiments are carried with this rheometer and samples have to be taken in the measuring beaker (up to the yellow mark on the top of the beaker). Place the beaker in the holder of the rheometer and screw it tightly. In case of a missing mark, it should be drawn with a paint stick 70 mm from the surface of the beaker. This instrument is connected to a computer by electrical wire signals which transform the mechanical action into electrical signals and show us in a graphical form using software called “rheoplus”. We fix the spindle with the above coupling attached just below the side of mounting, which can slide up and

down. Check that the mark on the coupling is in line with the spindle.

Experimental strategy:

This study aims to get a model for viscosity as a function of different parameters like fluid temperature, water content and solid content. In order to accomplish this goal, viscosity is measured by rheometer and the parameters are varied as:

- Solid loading: solid concentration of 10, 10.5, 11, 11.5, 12, 12.5, 13, 13.5 and 14 percent by weight
- Water content addition: water is added in 12.6, 13, 13.5, 14, 14.5, 15, 15.5, 16, 16.5, 17 percent by weight
- Fluid temperature: temperature range discussed in this study is 20°C, 40°C, 60°C and 80°C
- Beaker filling level: 70mm which is mentioned by yellow line in beaker
- Helical spindle with correction factor of 88 is used and variation of speed is from 1 to 500 rpm.

The different range of water content was selected from the studies of literature used for wood and forest residue, the maximum value of water is up to 30%. For wheat straw this value is up to 20 to 25% as investigated in bioliq[®] plant but from experiments as illustrated in the thesis, the range is 12.6 to 17 wt.%. Temperature range is selected from previous studies and the range from 20°C to 80°C is suitable for investigation. As far as the solid content is concerned, the Krieger-Dougherty model was selected since it is valid for solid contents higher than 10 wt.%. Higher values of solid contents could be selected as well but at higher values of solid content, the deviation increases.

For that reason, the lower range of solid content is selected.

Procedure technique:

Dynamic viscosities of sampled fluid are determined by the rheometer MCR 102 from Anton Paar which has helical spindle system as mentioned earlier in the material section. For all measurements, helical spindle was used due to its high accuracy of viscosity values and to avoid turbulent rheological regime. The measurement of viscosity is very important for the characterization and determination of the flow behavior of the bio-oil. The rheometer was equipped with a stirrer spindle (also called helical spindle) as a measurement system. The spindle has a structure like a small spiral agitator with a length of about 150 mm. The dynamic viscosities obtained by measurements of helical spindle cannot be considered as absolute values but only relative ones. This was due to the fact that geometry of the helical spindle is not well-defined in comparison with cylindrical spindle.

All samples 2012-1313 from the same campaign and same material (wheat straw) were stored at room temperature in glass or plastic jars and mixed thoroughly by shaking the respective sample vessel/jar before filling the rheometer measuring cup. Then the spindle was inserted and is automatically detected by the software of the rheometer/viscometer. Organic condensate 2014-1313 has less sedimentation and weak turbulent flow behavior at high shear rates and elevated temperatures as compared to bio-slurries. Speed of helical spindle is chosen 50 rpm to avoid the turbulent flow regimes otherwise temperature

increase consequently increases the viscosity which is explained well in the results section.

All rheological profiles shown in the results section were generated in accordance with the current standard operating procedure test routine. The measurement method is divided into the following four sections

Section 1: The speed $n = 500$ rpm was kept high to achieve better mixing. After the stabilization phase, for 2 minutes hold time at the desired test temperature ± 0.1 ° C pre-heating of the sample is done. 10-minute pre-heating for homogeneous mixing of the sample takes place.

Section 2: For the elimination of initial shear strains that were developed in section1, it is necessary to give 3-minute rest period.

Section3: This section is for elimination of a start up shear strain when the rotation starts again.

Section 4: There are 40 measured values depending on the speed ($n = 1 \dots 500$ rpm) generated. This is a section in which original viscosity values were measured.

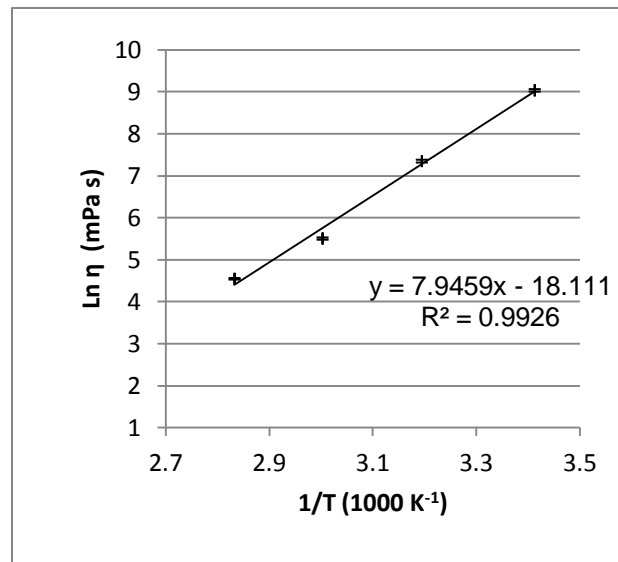
Results:

Rheological measurements were performed with a rheometric system. They were restricted to uni-directional shear flows (steady and unsteady) because of the practical importance of kinematics (in flow through tubes for example) and also because the shear viscosity remains the most important rheological function. It was observed that the use of a cylindrical spindle for viscosity determination should be the method of choice only for homogeneous samples with low solid content [12]. The use of a measuring system such as the

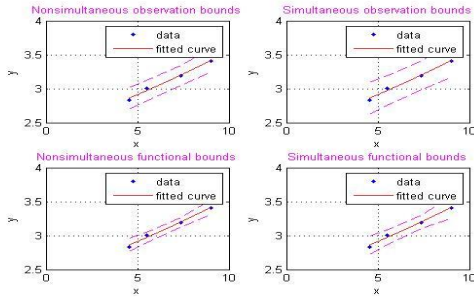
helical spindle enables the determination of viscosity for fluids with a high solid content with more accuracy. Due to the exertion of a turbulent flow profile at higher speeds, the helical spindle should not be used at higher rotational speeds because the increase of viscosity occurs at higher speeds as shown in figure 7a&b. Approximately at 400 rpm the turbulent effect is prominent.

Model 1: viscosity at different temperatures:

Temperature plays a significant role in changing the viscosity of bio-oil. As temperature increases, the viscosity of sampled fluid (wheat straw organic condensate) reduces rapidly as shown in the Figure 5. The applied temperature not only provides sufficient energy to break down the internal structure within the bio-oil very rapidly by reducing attraction forces between molecules; however, it also endorses molecular interchange.



a



b

Figure 5: (a): Temperature dependency of wheat straw bio-oil (b): Arrhenius plot with confidence interval of 95%

The $\ln \eta$ versus $1/T$ representation shows that, in the temperature range studied, the Arrhenius-type relation holds for sample 2014-1313. It can be observed from figure 5, when the temperature reaches from 20°C to 80°C the internal structure of molecules is going to allow the sampled fluid to reduce its dynamic viscosity. This pattern of temperature profile is similar as observed from previous studies of IKFT Karlsruhe as shown in figure [6].

The model equation as shown in figure 5a is given below with a relative value of standard deviation of 3% for all data points of viscosity. R^2 through curving fitting on Excel 2007 and MATLAB is shown in figure 5 a&b. So the actual model is given in Arrhenius formation is

$$\eta = 3 \times 10^{-3} * e^{\frac{7945.9}{T}} \quad (7)$$

When the developed model is compared with other models, for example the model of viscosity and temperature whose R^2 is 1 or the models which can be seen in Figure 6, it can be observed that wheat straw shows similar behavior of Arrhenius plot to beach wood.

R^2 is the first indication of the goodness of the curve fitting. But statistical analysis of regression like confidence interval of a model is important and better indicators to describe the precision of a model and evaluate its validity. Mean values of viscosity with confidence interval of 95% have been plotted by using Predint function of MATLAB as shown in the Figure 5b.

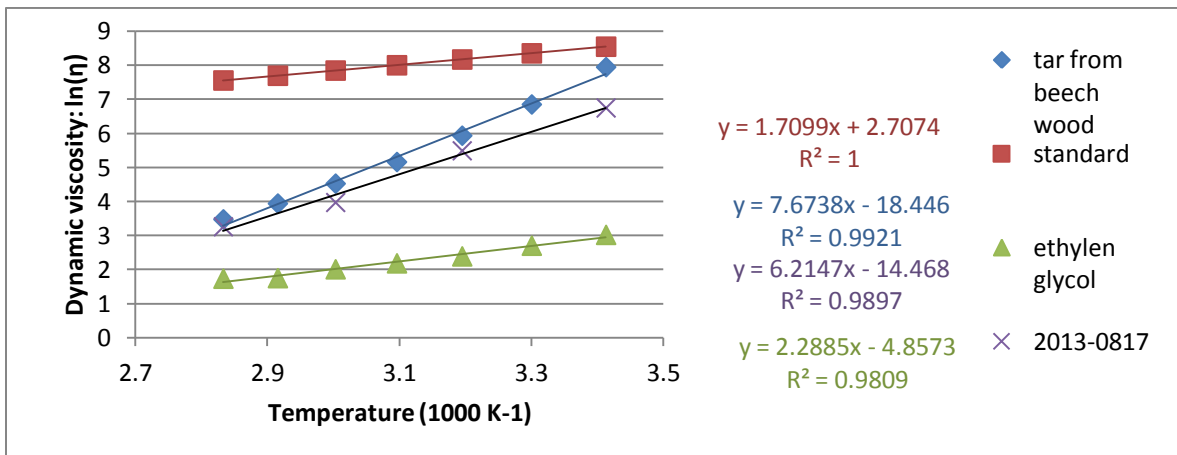
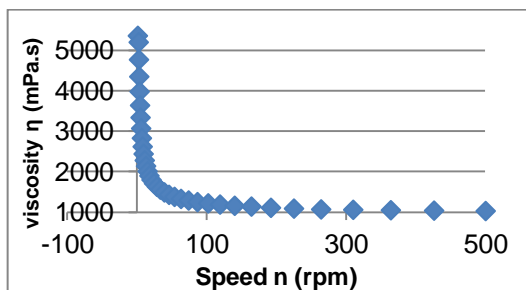


Figure 6: model of different sample of pyrolysis oil [88]

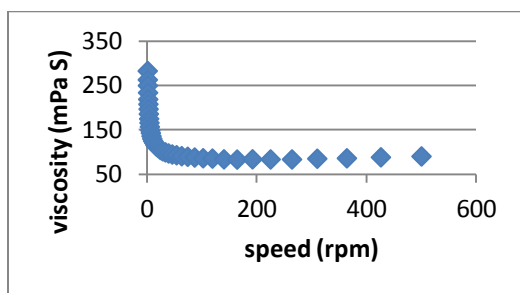
To analyze the behaviour of speed on pyrolysis oil of wheat straw, a plot of viscosity vs. spindle speed

is constructed automatically by rheoplus software. Viscosity is plotted along the y-axis and speed

(RPM) along the x-axis. The slope and shape of the curve indicate the type and degree of flow behavior, steeper slope as it is from 0 to 50 rpm shows more deviation from Newtonian behaviour than from 50 to 500 rpm as shown in the figure 7a&b. The profile of viscosity with speed shows that bio-oil follows non-Newtonian behaviour. In non-Newtonian fluid categories, figure 7a&b follows pseudo-plastic fluid behaviour in which shear thinning takes place. At high speed and high temperature, turbulent flow regimes occur which cause the increase of viscosity as shown in the figure 7b. It is can be observed that after 50 rpm there is small deviation of viscosity with speed but before 50 rpm, fluctuations are high.



a)



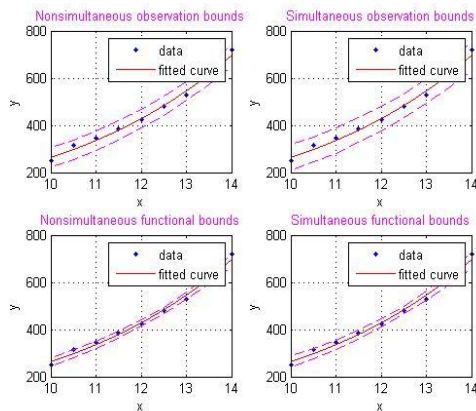
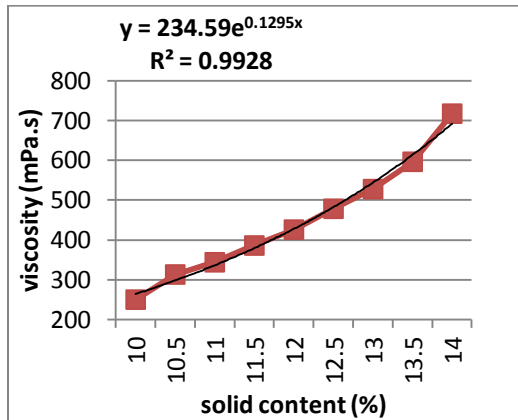
b)

Figure 7: Viscosity profile with speed a) without turbulent flow around 500rpm and 80 °C b) with the indication of turbulent flow around 500 rpm and 80 °C

Model 2: viscosity at different solid mass fraction:

Solid content is one of the key parameters to describe the viscosity of organic condensate because when the percentage of solids in the sample increases, the viscosity increases as shown in the Figures 8a&b and 9a&b. The range of solid content for the experiments is assumed to be 14%. It was observed that the higher range can be considered but deviation of viscosity is high at higher solid contents. Experiments at 60 and 80°C show that the viscosity gradually increases and it follows an exponential behavior when the solid contents rises as shown in the Figure 8 and 9. The increase of viscosity with the addition of solid contents is due to the resistance to flow of organic condensate. The frictional effect increases and mobility of organic condensate is affected by the addition of solids in sampled fluid 2014-1313. When the frictional effect increases, due to solids, the motion of flowing liquid is hindered by these particles of solids. The size and distribution of particles and homogeneity of solids with sample fluid is important in motion of any fluid. The smaller is the particle size, the better is the distribution of particles, smoother is the increase of viscosity. It is clear from Figures 8 and 9 that viscosity will increase. Better homogeneity provides better results and the same is for particle size distribution. As temperature has its own effect, when temperature increases, the percentage of water and volatiles, which are already present in the sample, were evaporated. The evaporation of volatiles and water, at higher temperatures is higher. So when temperature increases, evaporation will increase and it will give more

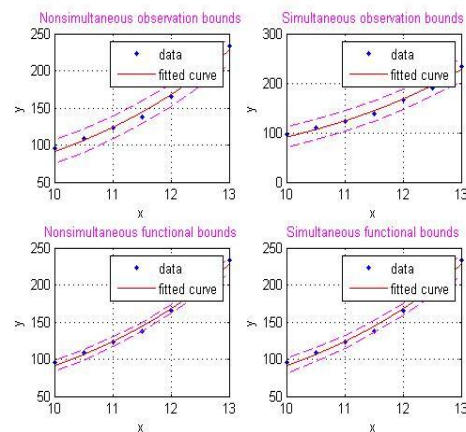
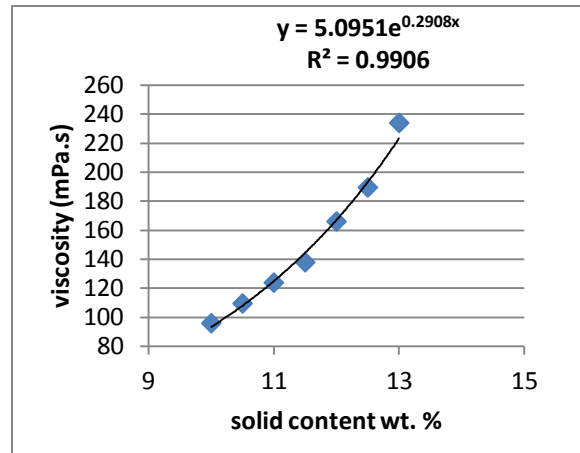
solids. The solid contents, which were added externally and those which were obtained through evaporation at higher temperatures, are responsible for the increase of dynamic viscosity of sampled fluid 2014-1313.



**Figure8: a) Variation of viscosity with solid contents
b)Confidence interval of 95% at 60°C**

The developed model is valid in between the values of solid content from 10 to 14 wt. %. The maximum relative value of standard deviation experimentally concluded is 16%, which is at 13% of solid content. Mean values of viscosity with confidence interval of 95% have been plotted by using Predint function of MATLAB as shown in the Figure 8.

At 80°C, the model which we get from the graph is represented below:



**Figure 9: a) Variation of viscosity with solid contents
b)Confidence interval of 95% at 80°C**

The developed model at 80°C is between the values of solid content from 10 to 13 wt. %. The relative value of standard deviation is 7%. At 80°C the viscosity is low in the range of 100 to 250 mPa s but at 60 °C the viscosity is high in the range of 200 to 700mPa.s, this effect is due to temperature as we have explained in previous model. Mean values of viscosity with confidence interval of 95% has been plotted by using Predint function of MATLAB as shown in the Figure 9.

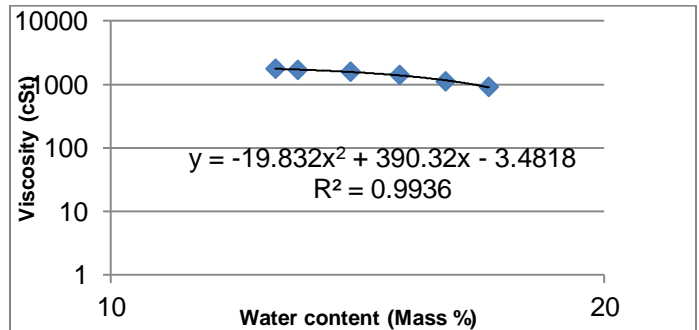
The developed models can be compared with Krieger Dougherty model only when the solid

particles are converted from mass fraction to volume fraction. The trend line for Krieger Dougherty is same with the model as shown in the Figure 8a&b and 9a&b. There are different models but the best suitable model for the developed models is Krieger Dougherty because it is more similar to the developed models as shown in Figure 8a&b and 9a&b. The main reason to choose Krieger Dougherty is the percentage of solid content which is higher than 10% and the trend line has similarity with the developed models.

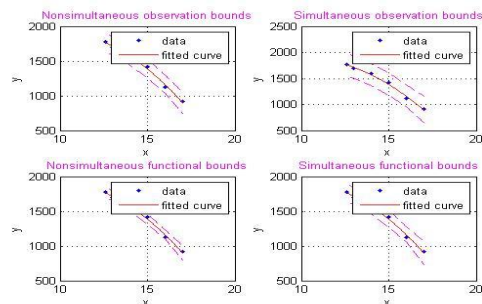
Model 3: Effect of viscosity with water mass fraction:

In fast pyrolysis bio-oils, the amount of water in bio-fuels is regulated because it forms a separate phase that can cause corrosion, emulsion formation and problems in burners. The developed model obtained from the measurements through experiments is shown in the figure 10a&b. The scale used here is logarithmic scale and the fitting accuracy of the model from Microsoft Excel and MATLAB is a polynomial fit. One important thing is that viscosity measurement is carried out at constant temperature of 40°C. The selected temperature is an intermediate temperature where the viscosity of bio-oil is not so much high and also the effects of temperature is not so much dominant such as loss of volatiles and water is less. It can also be observed through analytical analysis of sample which was experimented with different percentage of water and after that it was tested in KIT analytical lab to make sure the original percentage of water in the sample and the results are mentioned in the thesis. There are number of parameters which affect the analysis of viscosity with mass percentage of water such as density,

heating values and phase stability of organic condensate/Tar. Mean values of viscosity with confidence interval of 95% have been plotted by using Predint function of MATLAB as shown in the figure 10a&b.



a



b

Figure 10: a) Variation of viscosity with water contents b) Confidence interval of 95%

It can be observed from figure 10a&b that viscosity decreases when the water is added. The increase in water content improves the stability of the bio-oil until it starts to separate out, typically at above 30 wt. % water content [9]. However, in case of wheat straw, we observed the phase separation approximately when water content is reached by 17 wt. %.

The developed model 3 can be compared with Oasmaa's model as shown in the figure 2 Oasmaa

studied the influence of water content on viscosity extensively for different biomass feedstocks which is more important to be understood in order to compare the trend developed for wheat straw with different water content. The range of water content is more dependent on the nature of the feedstock considered, in the case of wheat straw consumed in bioliq pilot plant, the feed stock was found to have a water content of around 20 wt. %.

The basic information conveyed by Oasmaa's model is that all kinds of bio-oil showed a decrease in viscosity when water content is increased. This is physically explainable by a change in surface tension and density due to the micro-emulsion of water. In order to investigate the same analysis here, the range of dynamic viscosity with water content is studied and plotted as shown in figure 10a&b

The model developed by Oasmaa (considered kinematic viscosity) and current developed model (used dynamic viscosity) shows the similar analogous trend. This leads to the conclusion that the density variation has less or no effect and surface tension has to play the major factor of dependency for the comparison of viscosity.

It was observed during experiments that the phase separation is visible at higher temperatures; lower temperatures had to be used in order to reach good phase stability.

Heat transfer drop in Tar and Glycol:

The Nusselt number for the flow inside a circular pipe for laminar flow is calculated by the following formula [12]:

$$Nu = \left(3.66^3 + \left(1.62 + 0.293 \left(Re * \frac{d}{l} \right) \right) \left(Re * Pr * \frac{d}{l} \right) \right)^{\frac{1}{3}} \quad (7)$$

The Nusselt number is calculated for glycol and organic condensate sample 2014-1313 by substituting the physical parameters of the above formula. To quantitatively investigate the viscosity dependence on heat transfer is done as follows: the Nusselt number is calculated by varying the viscosity from 2 to 30 centi-poise and plotted for both glycol and organic condensate. The selected range of viscosity for investigation is chosen by the operational temperature of heat exchangers. The operational temperature was 96°C on which viscosity for glycol and organic condensate was determined and the range was selected. From the Figure 11 as the viscosity of the fluid varies the heat transfer characteristics explained by the Nusselt number reduces. This might be able to explain that if the liquid used in the heat exchanger has higher viscosity then the heat transfer is predominantly affected.

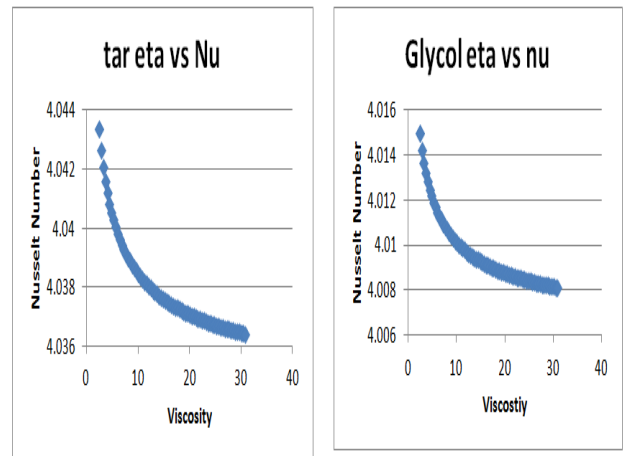


Figure 11: Nusselt number variation with viscosity for glycol and organic condensate.

The investigation of heat exchanger is co-related with model 1 because the operating temperature (i.e. 96°C) viscosity was determined by the developed model 1.

Conclusion:

The Experimental determination of viscosity for organic condensate is carried out and the model is developed for the temperature dependent viscosity. To test the technical feasibility of the organic condensate cycle, the variation of the temperature, solid content in tar and the water content in tar is studied. From the above discussed results it can be concluded that the model 1 gives accurate results and it proves the Arrhenius model is well adapted for the tar. Other model developed (model 2&3) have a high confidence interval due to negligence of important factors such as the volume fraction and evaporation. The density variation and boundary layer thickness are also negligible in heat exchanger calculations. The variation of the mixture properties such as the solid and water mass fraction is studied. It was concluded that viscosity has exponential increase with increase of solid contents. In case of water content viscosity decrease was observed and at higher temperatures evaporation effect was also

determined that is proved by analytical lab in KIT, Germany

The investigation of the previous used heat exchangers network is studied by model 1 (i.e. the model of viscosity and temperature). The laminar flow inside a pipe condition is used to calculate the heat transfer characteristics. The heat transfer characteristics dependence on viscosity is formulated and major factor influencing the reduction in performance of heat exchanger can be interpreted from the Nusselt number dependence on viscosity. The major factor which influences the heat exchanger performance is studied from the rheology point of view in this whole report but in practical case, the heat exchanger performance is more dependent on the physical dimensions of heat exchanger and the fouling resistance determined by the manufacturer's data sheet. By studying the organic condensate physical properties, the heat exchanger used has to be adapted to the rheological properties and the pressure drop of the condensate.

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