Journal of Molecular Liquids 291 (2019) 111349

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

Impact of viscosity of nanofluid and ionic liquid on heat transfer

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ARTICLE INFO

Article history:
Received 20 January 2019
Received in revised form 5 July 2019
Accepted 9 July 2019
Available online 10 July 2019

Keywords:
Ionic liquids
Nanofluid
Viscosity
Central composite design
Artificial neural network

ABSTRACT

The effect of viscosity on heat transfer behaviour is analyzed for binary mixtures (ionic liquid + water and nanofluid + water) over the base fluid (water). Viscosities of 1-butyl-3-methylimidazolium bromide with water under ambient pressure are studied at different concentrations (0.1–0.6% w/w) and temperatures (296–336 K). Viscosities of nanofluid (γ-Al_2O_3/water) are estimated at the same concentration and temperature range and then compared with the ionic liquid solution. Viscosity of aqueous 1-butyl-3-methylimidazolium bromide solution increases with concentration and decreases with temperature. A similar trend is observed for γ-Al_2O_3/water. In addition, a model is developed with response surface methodology and artificial neural network to predict the viscosity of 1-butyl-3-methylimidazolium bromide with water.

1. Introduction

Viscosity is a property which describes the internal friction of a moving fluid. It is an important thermophysical property in fluid flow and heat transfer. In many fluid flow problems, viscosity is assumed to be a constant parameter. However, viscosity varies with temperature when the flow is associated with transfer of heat. To accurately model the flow behaviour and estimate heat transfer rates, it is essential to consider the variation of viscosity with temperature [1,2]. When compared with other thermophysical properties viscosity demonstrates a considerable variation. Hence it becomes necessary to incorporate the correction in the fluid flow model based on the behaviour of fluid with respect to temperature-dependent viscosity [3]. The variation in temperature-dependent viscosity plays a major role in laminar heat transfer and friction factor for non-circular conduits or ducts of different geometries [3–5]. It has been shown that the variation in temperature-dependent viscosity in a curved circular tube with water as a working fluid, plays a relatively major role on velocity and thermal profiles, compared to other thermophysical properties like specific heat, thermal conductivity and density [6].

In regards to viscosity variation, it results in a larger local Nusselt number when compared with that obtained from using constant viscosity [3,7]. The use of constant viscosity ignores the effect of decreased flow resistance leading to the generation of the secondary flow of fluid and its impact on convective heat transfer enhancement. Frictional losses in the fluid – the result of the microscopic interaction of molecules between layers – are governed by the viscosity of the fluid. Hence, when the viscosity variation is taken into account, there is a decreased friction factor due to the reduced viscosity at higher temperatures instead of a constant value [3].

In industrial applications, convective heat transfer plays a major role in the heat transfer mechanism and is dependent on the transport properties of the flowing fluid. In boilers and heat exchangers, the pertinent variables in convective heat transfer mechanism are characteristic length, fluid velocity, fluid density, fluid viscosity, fluid specific heat, fluid thermal conductivity, fluid temperature and surface characteristics [8]. Generally, the heat transfer fluid used in these applications, possess properties like low viscosity, high thermal stability and high heat capacity. Fluids with high heat capacity and low viscosity are preferred for heat transfer applications of medium temperature ranges. Whereas, in the specific applications like metallurgy and nuclear power industry, there is a need of heat transfer fluids with special properties like high thermal stability, radiation stability, low volatility and viscosity. Of the various alternatives explored, two types of fluids have attracted the attention of researchers in recent years, namely nanofluid and ionic liquids [9–13].

Conventional heat transfer fluids such as water, oil and ethylene glycol mixture show poor heat transfer characteristics due to their low thermal conductivity [14]. Choi et al. [15] have shown that the addition of small amounts of nano-sized particles enhance the thermal conductivity of base fluid by two times approximately. Initially the studies concentrated on assessing the performance of the nanofluid under constant physical properties. Later studies focused on the variation of properties of nanofluids with temperature, more specifically viscosity and its effects on heat transfer characteristics of nanofluids [14]. For example, the effect of temperature-dependent viscosity and the nanoparticle volume concentration on heat transfer characteristics of Ag–water, Cu–water nanofluid has been reported.

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https://doi.org/10.1016/j.molliq.2019.111349
0167-7322/

Various nanoparticles have been tried and reported in the literature [16–18]. Metal oxides of nanoparticles have also been broadly utilized as part of numerous applications, for example in medical science as sensors, semiconductors, catalysis, batteries and capacitors. As seen from the literature, extensive research has been carried out with Alumina (Al_2O_3)/water systems [19]. The very interesting properties of Al_2O_3 such as high hardness, high stability, high insulation and transparency, facilitate use of Al_2O_3)/water system. It is a white oxide which exists in several phases like alpha, gamma, delta and theta. Alpha phase is the most thermodynamically stable phase [20]. However, the gamma phase possessing a higher specific surface area equal to 200 $m^2\ g^{-1}$, is advantageous especially in heat transfer applications. In the present study, temperature and concentration-dependent viscosities of this system are explored.

Ionic liquids have attracted attention in recent years as a potential heat transfer fluid; the operating temperature range of ionic liquids can be altered by adding additives [9]. The accurate knowledge of the physiochemical properties is helpful in design and scale-up of heat transfer equipment [21]. Viscosity gains special attention since its range varies from 50 to 5500 cP, which arises from hydrogen bonding, Van der waals forces and the columbic interaction between anions and cations. As viscosity of ionic liquids depends on the selection of anion, it can be tuned according to the application. Literature shows that the physiochemical properties of ionic liquids, especially viscosity, have not been characterized for many of its members. The viscosity of ionic liquids is a strong function of temperature. Hence, it is necessary to develop temperature-dependent viscosity data for ionic liquids to gain knowledge on the possible use of ionic liquids as a heat transfer medium. The heat transfer enhancement with ionanofluid in the presence of 1-butyl-3-methylimidazolium bromide (BMImBr) has been studied in a shell and tube heat exchanger. In the present study, BMImBr with water as a working fluid has been considered for viscosity data development, which will be useful to calculate heat transfer rate enhancement.

Temperature and concentration are known to be the major factors affecting viscosity [22,23]. The temperature-dependent viscosity has been studied for many pure ionic liquids, but the study on temperature-dependent viscosity for binary mixtures of ionic liquids is scarce [24–27]. In the present work, the variation of viscosity with temperature and concentration for a binary mixture of BMImBr with water has been studied. The studies are conducted with a concentration change from 0.1 to 0.6% w/w and temperatures are varied from 296 K to 336 K. Earlier, the viscosity of pure BMImBr has been measured from 293.15 to 373.15 K and its value is found to vary significantly with temperature. The value of viscosity decreases from 380 mPa·s at 293.15 K to about 10 mPa.s at 373.15 K. Similarly, the temperature-dependent viscosities of a binary mixture of γ-Al_2O_3 with water have also been studied in the present work. The results of the viscosities of nanofluid and BMImBr are compared with those of the basefluid. Further, modelling is performed with response surface methodology and feed forward neural network with back propagation for determining viscosities of the aqueous BMImBr solution. The relevance of the viscosity measurements to heat transfer application and the possible effects on heat transfer rate are then discussed.

2. Experimental

2.1. Materials and preparation

BMImBr ionic liquid (99% purity) is purchased from a commercial source M/s. Alfa Aesar. The ionic liquid is stored in a cool, dry place. The spherical shaped γ-Al_2O_3 nanoparticle of size 20-30 nm is purchased from M/s. Otto is used. The electronic weighing balance (Schimadzu AY220) with a precision of $\pm$0.001 g is used for weighing samples. Magnetic stirrer supplied by M/s. Remi is employed for the preparation of the sample.

0.02 L BMImBr sample solution of each concentration is prepared by mixing the ionic liquid with water on weight-by-weight basis. The concentration ranges from 0.1 to 0.6% w/w. The range of concentration is selected in accordance with the conventional values worked in industry. The samples are mixed well in a magnetic stirrer until the ionic liquid dissolves completely in water. The samples are tightly sealed before and after stirring. Viscosity measurements are performed with a Brookfield Viscometer DV2TLVT JO equipped with a water bath system (TC 150) for the temperature control of the sample.

2.2. Viscosity measurement

The viscosity of the aqueous BMImBr solution is measured with the Brookfield Viscometer (Model: DV2TLVT JO) fitted with UL Adaptor. The viscosity is measured with spindle number zero (ULA 0). About 16 mL of the sample is transferred to the UL adaptor for the measurement. The viscosity is measured by varying the spindle angular rotational rates from 60 to 80 rpm. The viscosities of samples with different concentrations 0.1–0.6% w/w for varying temperatures from 296 to 336 K are determined. The required temperature is set in water bath and the water is circulated around the UL adaptor for about 20 min prior to the experiment so that the sample, sample holder and the spindle are all in the same temperature. The accuracy of the equipment is verified with viscosity standard solution (silicone). The dynamic viscosity values of the γ-Al_2O_3 with water nanofluid are calculated directly from Einstein relation [28]. The non-experimental data of the nanofluid is determined for the same concentrations and temperature ranges considered in this study for aqueous BMImBr solution.

3. Model development

3.1. Response surface methodology (RSM)

The RSM is a collection of statistical methods that are established on the fit of empirical models to the experimental data. Central composite design (CCD) is the most popular RSM design that has three groups of design points namely center points, two-level factorial or fractional factorial design points and axial points [29]. Central composite face centred design (CCFCD) with two independent variables coded at three levels between -1 and $+1$ is applied to model the dynamic viscosity of aqueous solutions of BMImBr. Temperature and concentration of aqueous BMImBr solution are the two independent factors. A total of 13 runs are generated in this work. The experimental data from the CCD model for the dynamic viscosity of the BMImBr ionic liquid solutions are fitted to a second-order polynomial equation and the regression coefficients are obtained. Design Expert 10.0.3.3 software is used to model the equation for the dynamic viscosity of the fluids.

3.2. Artificial neural networks

The functioning of Artificial neural networks (ANNs) is established from the behaviour of biological neurons [30]. ANN is very productive for anticipating the information by learning through training. The 'nntool' in Matlab is applied for modelling. In the present study, experimental data are arbitrarily divided into three separate groups of training, testing and validation, respectively. Concentration and temperature are the input variables; and dynamic viscosities of BMImBr solutions serve as the output variable.

The dynamic viscosity of the BMImBr solutions within the training set is used as target value. All target and input variables are normalised independently in the range from 0 to 1. A feed forward back-propagation neural network with the single hidden layer is proposed since a network with only one hidden layer is able to correlate any complexities [18]. Mean square error (MSE) is used as the performance function. The log-sigmoid transfer function (Eq. (1)) is utilized as the activation function for input-hidden layers is an appropriate choice for

nonlinear functions [31]. The hidden to output layer employed Purelin transfer function (Eq. (2)). The Levenberg–Marquardt training algorithm is used for training the network.

Log-sigmoid transfer function

$$s_p = f(y_p) = \frac{1}{1+e^{-y_p}} \quad \text{for } p = 1 \text{ to m} \quad (1)$$

where s_p is the output of the p^{th} hidden neuron, y_p is the input to the p^{th} hidden neuron from the input layer and m is the total number of hidden neurons in a first hidden layer.

Purelin transfer function

$$H = f(S) = S \quad (2)$$

where H represents the output from the output neuron and *S* represents inputs to output neuron.

The network is trained for 1000 epochs and all the other parameters are set to default as in ANN tool. The optimum network is obtained by amending the number of hidden neurons in the hidden layer on a trial and error basis. In this study, the training terminates as the number of validation checks reaches six. Later, the network is tested with the testing set. The optimum ANN model is chosen by comparing MSE (Eq. (3)), percentage average relative error (PARE) (Eq. (4)) and percentage average absolute error (PAAE) (Eq. (5)) of the testing data for different ANN models [32].

$$MSE = \left(\frac{1}{N}\right)\sum_{n=1}^{N}\left(\mu_n^{exp} - \mu_n^{pre}\right)^2 \quad (3)$$

$$PARE = \left(\frac{1}{N}\right)\sum_{n=1}^{N}\frac{\left(\mu_n^{pre} - \mu_n^{exp}\right)}{\mu_n^{exp}} \times 100 \quad (4)$$

$$PAAE = \left(\frac{1}{N}\right)\sum_{n=1}^{N}\left|\frac{\left(\mu_n^{pre} - \mu_n^{exp}\right)}{\mu_n^{exp}}\right| \times 100 \quad (5)$$

In Eqs. (3), (4), (5), N represents the total number of testing data, μ_n^{exp} and μ_n^{pre} are experimental and predicted dynamic viscosity of the n^{th} data in mPa·s.

3.3. Estimation of the viscosity of γ-Al_2O_3 nanofluid

The dynamic viscosity of the nanofluid of 0.1–0.6% w/w concentration with γ-Al_2O_3 nanoparticle dispersed in the water (base fluid) is calculated using Einstein relation [28] given by Eq.6 for the temperature ranges similar to those of the experiments conducted for BMImBr/water solution. The density of the γ-Al_2O_3 nanoparticle is 3700 kgm^{-3} [33].

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi) \quad (6)$$

where μ_{nf} represents the dynamic viscosity of the nanofluid (Pa·s), μ_{bf} is the dynamic viscosity of the basefluid (Pa·s) and φ is the volume fraction of the nanoparticle.

4. Results and discussion

The experimental data collected for dynamic viscosity for concentrations ranging from 0.1 to 0.6% w/w aqueous BMImBr solutions at different temperatures (296–336 K) under ambient pressure are analyzed and presented below.

4.1. Effects of temperature and concentration on dynamic viscosity of aqueous BMImBr solution and nanofluid

The effects of temperature and concentration on the dynamic viscosity of aqueous BMImBr solutions are illustrated in Fig. 1a. The dynamic viscosity varies from 0.948 to 1.31 mPa·s for 0.1–0.6% w/w solutions of BMImBr in the temperatures 296–336 K under ambient pressure. From Fig. 1, it is evident that the dynamic viscosity of the BMImBr solution increases with increase in concentration. The incremental addition of the BMImBr to the water leads to an increase in the density of the resultant solution, which in turn restricts the flow of molecules or ions, thereby increasing the viscosity. As the temperature of the sample solution increases, the dynamic viscosity decreases for a particular concentration. This may be due to the gain in the kinetic energy of the ions of the solution and the decrease in the density of the aqueous BMImBr, with an increase in temperature for a particular concentration. The binary mixtures of 1-ethyl-3-methylpyridiniumethylsulfate with water also follows a similar trend of increase in dynamic viscosity with an increase in concentration (mole fraction = 0 to1) and decrease in dynamic viscosity with an increase in temperature (298.15–328.15 K) [27]. The dynamic viscosities of the binary mixtures of 1-butyl-3-methylimidazolium dimethylphosphate + water and 1-ethyl-3-methylimidazolium dimethylphosphate + water are measured in the temperature range of 293.15–333.15 K by Gong et al. [34] showing a similar behaviour. Pure BMImBr also shows a similar trend with temperature and concentration [35]. The dynamic viscosities of the binary mixture of 1-butyl-3-methylimidazolium trifluoromethane sulphonate with water over the entire mole fraction, in the temperature range 303.15–343.15 K in atmospheric pressure by Ge et al. [26] also follow the same trend.

The effect of temperature and concentration on the dynamic viscosity of aqueous γ-Al_2O_3 solutions is illustrated in Fig.1b. The result shows that the viscosity decreases with the increase in temperature as expected. As temperature increases from 296 K to 336 K, the viscosity decreases by 48%. Unlike the ionic liquid shown in Fig. 1a, the interaction between nanoparticles of γ-Al_2O_3 and the base fluid is disturbed with the increase in temperature resulting in decreased viscosity.

Nevertheless, the dynamic viscosity does not show appreciable change when the concentration of γ-Al_2O_3 in the solution is increased. When the concentration increased from 0.1 to 0.6% w/w at the temperature ranges considered, the maximum change in the viscosity is only 0.41%. Almost all the nanofluids show an increase in the viscosity with the nanoparticle concentration. Some systems have shown an exceptional rise in viscosity with concentration as reported [36]. On the contrary, the relative apparent viscosity of CuO nanofluid is independent of concentration when the base fluid is non-Newtonian (CMC- carboxy methyl cellulose) [37]. Concentration is the major factor influencing the viscosity of ionic liquid system, whereas temperature is the main factor influencing viscosity for the nanofluid system.

4.2. RSM analysis

The experimental data from the CCD model for the dynamic viscosity of the BMImBr ionic liquid solutions are fitted to a second-order polynomial equation (Eq.6) and the regression coefficients are obtained as:

$$\mu^{pre} = -3.4807 + 0.0304\,T + 0.4674\,C + 0.0005\,TC - 0.1233\,C^2 - 0.000052\,T^2 \quad (7)$$

where μ^{pre} is the predicted dynamic viscosity of the BMImBr solution (mPa.s), C is the concentration of BMImBr solution (% w/w) and T is temperature (K).

The validity of the quadratic model is confirmed by comparison with the experimental data and Fig. 2 depicts that the values are close to the diagonal line. The quadratic regression model of dynamic viscosity of BMImBr solution implies the coefficient of determination R^2 and adjusted R^2 as 0.99 and 0.99 respectively, thus illustrating the quality of fit of the developed second-order quadratic model.

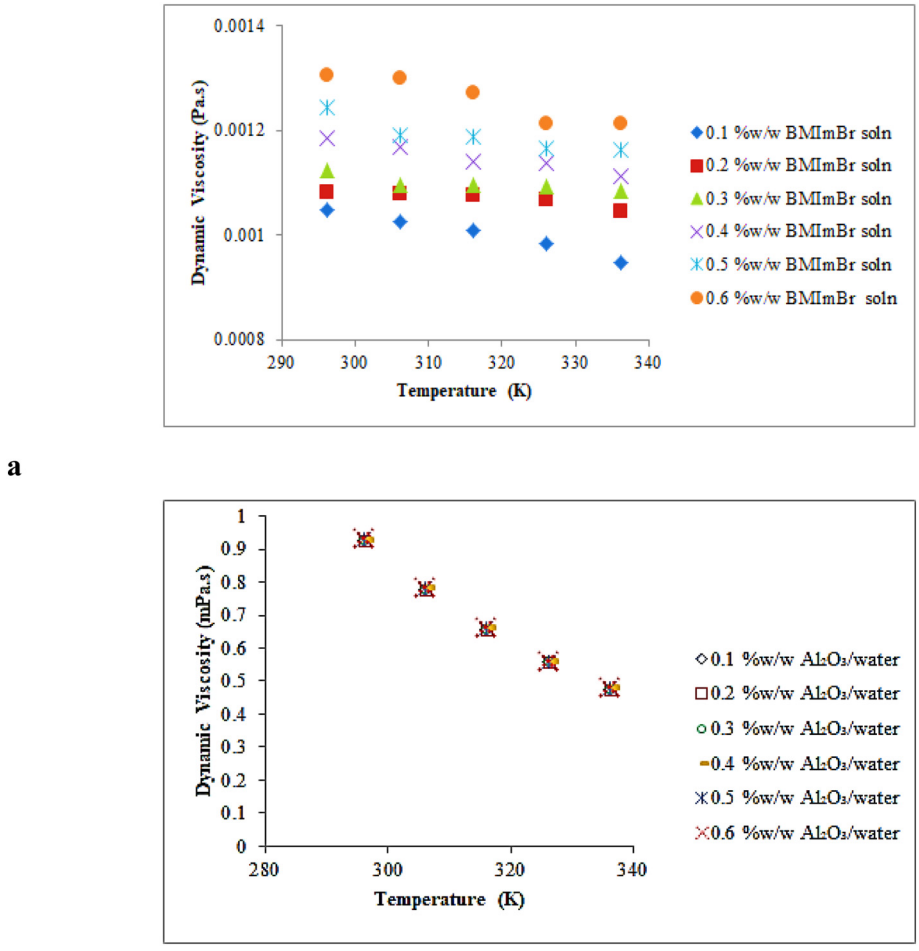

Fig. 1. a. Effect of temperature and concentration on dynamic viscosity of BMImBr b. Effect of temperature and concentration on dynamic viscosity of γ-Al_2O_3.

4.3. ANN analysis

The performance of the different ANN models is investigated. The predicted responses of the different networks are affected by changing the number of neurons in the hidden layer as shown in Fig. 3. In the present study, only one hidden layer is considered for modelling as a two-layered input-output and one hidden layer network is believed to be efficient for predicting data with greater accuracy [18]. Compared to other networks, ANN 2–3-1 (two input neurons, one hidden layer with three hidden neurons and one neuron in output layer) with the least MSE = 0.0002, PARE = 0.461 and PAAE = 1.15 is the optimum network.

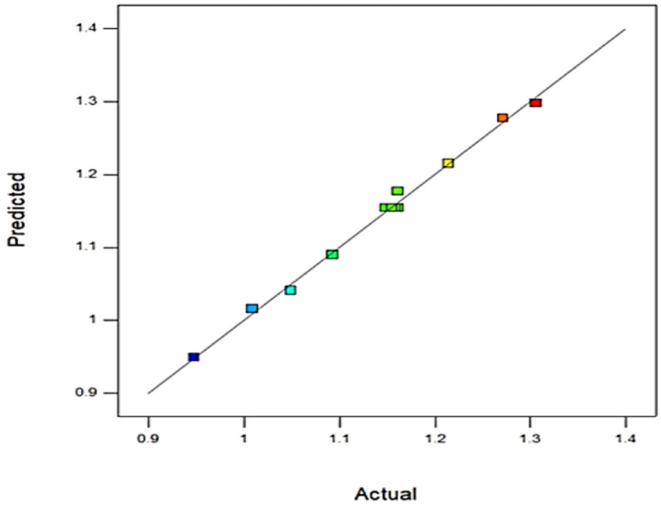

Fig. 2. Comparison plot between predicted and experimental dynamic viscosity in mPa·s.

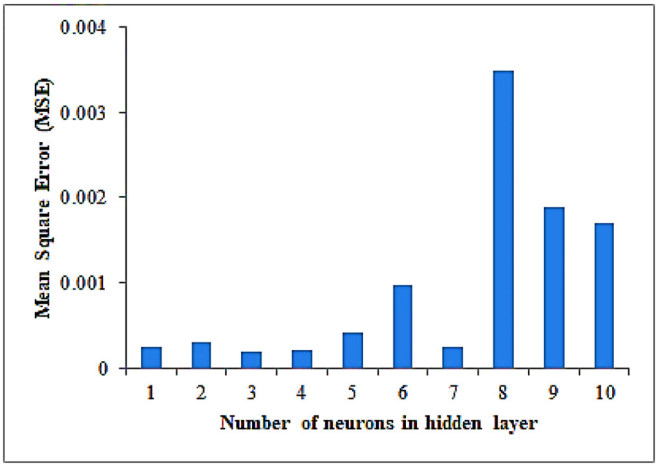

Fig. 3. Comparison of MSE of test data for two-layered architecture of ANN.

Training is terminated when fairly good regression coefficients are obtained for training, testing and validation sets. From the regression plot (Fig. 4), it is clear that the cluster line and the data line almost fit with each other with R values of 0.998, 0.995 and 0.994 for training, testing and validation sets respectively. This shows that the model predictions and the experimental data are in fairly good agreement.

4.4. Comparison of RSM and ANN dynamic viscosity models of BMImBr solution

The dynamic viscosity predicted by two different models developed by RSM and ANN approach is compared with that of BMImBr solutions (data included for its modelling is not considered) based on the statistical quality parameters MSE, Root Mean Square Error (RMSE) (as given in Eq.8) and PAAE (Table 1).

$$\mathrm{RMSE} = \left[\left(\frac{1}{N}\right)\sum_{n=1}^{N}\left(\mu_n^{exp} - \mu_n^{pre}\right)^2\right]^{1/2} \quad (8)$$

where N represents the total number of testing data, μ_n^{exp} and μ_n^{pre} are the actual value of experimental and predicted dynamic viscosity of n^{th} data in mPa·s.

Based on the lower values of MSE = 0.0002, RMSE = 0.014 and PAAE = 1.148, it is clear that the predictions of the ANN model are more robust and accurate than the RSM model. The dynamic viscosity of aqueous BMImBr solutions is estimated at different concentrations ranging from 0.1 to 0.6% w/w and 296–336 K temperature under ambient pressure. The experimental dynamic viscosity values of the aqueous BMImBr solution vary in the range 0.948–1.31 mPa·s for the range of temperatures and concentrations investigated. From ANOVA, it is inferred that concentration is the most significant operating parameter affecting the dynamic viscosity, even more than temperature. The proposed models are beneficial in predicting the dynamic viscosity of aqueous BMImBr solutions at the required temperature and concentration without conducting any further experiments. However, the applicability of the developed models can further be raised by encompassing an extensive range of temperatures and concentrations.

4.5. Comparison of dynamic viscosities of nanofluid, aqueous BMImBr solution with base fluid

The effects of temperature and concentration on the dynamic viscosities of the BMImBr + water and γ-Al_2O_3 + water nanofluid are plotted and compared with base fluid–water [38] as shown Fig. 5. For both binary mixtures, the dynamic viscosity increases with an increase in concentration from 0.1 to 0.6% w/w and decreases with an increase in temperature for a particular concentration. It is observed that the dynamic viscosity of the BMImBr aqueous solutions is higher when compared with water and nanofluid. Even the increase in the viscosity is more in BMImBr when compared with that in nanofluid. This is due to the increase in the density of the BMImBr solution when compared to water. For water, the change in dynamic viscosity is 48.6% as the temperature increases from 296 to 336 K, whereas for BMImBr solution, the change in dynamic viscosity for 0.1% w/w and 0.6% w/w, is 9.5% and 6.8% respectively. The change in viscosity with temperature is higher for water when compared with the aqueous BMImBr owing to the difference in the interactions involved in the solutions. In water, the decrease in viscosity is due to the break of the strong hydrogen bonds, whereas in the BMImBr the decrease in the dynamic viscosity is due to the Van der Waals forces and hydrogen bonding and columbic interaction of ions, which are difficult to break. Hence, the decrease in viscosity for ionic liquid is not appreciable when compared with water.

From the literature, it is observed that binary mixtures of water with other ionic liquids also followed a similar trend. The binary mixtures of 1-ethyl-3-methylpyridiniumethylsulphate with water also followed a similar trend of increase in dynamic viscosity with an increase in concentration and decrease in dynamic viscosity with an increase in temperature (298.15–328.15 K) [27]. The dynamic viscosities of the binary mixtures of 1-butyl-3-methylimidazolium dimethylphosphate + water and 1-ethyl-3-methylimidazolium dimethylphosphate + water are measured in the temperature range of 293.15–333.15 K in Gong et al. [34] studies. Similar behaviour is observed for pure

Table 1
Comparison of RSM and ANN models.

S·No	Temperature (K)	Concentration (% w/w)	Dynamic viscosity (mPa·s)		
			Experimental	RSM	ANN (2-3-1)
1	296.2	0.1	1.05	1.02	1.05
2	306.2	0.2	1.08	1.07	1.09
3	306.2	0.3	1.10	1.13	1.11
4	316.2	0.3	1.09	1.11	1.11
5	306.2	0.4	1.17	1.18	1.15
6	306.2	0.5	1.19	1.23	1.28
7	326.2	0.6	1.21	1.24	1.23
8	336.2	0.6	1.21	1.20	1.20
MSE				0.0006	0.0002
RMSE				0.024	0.014
PAAE				1.882	1.148

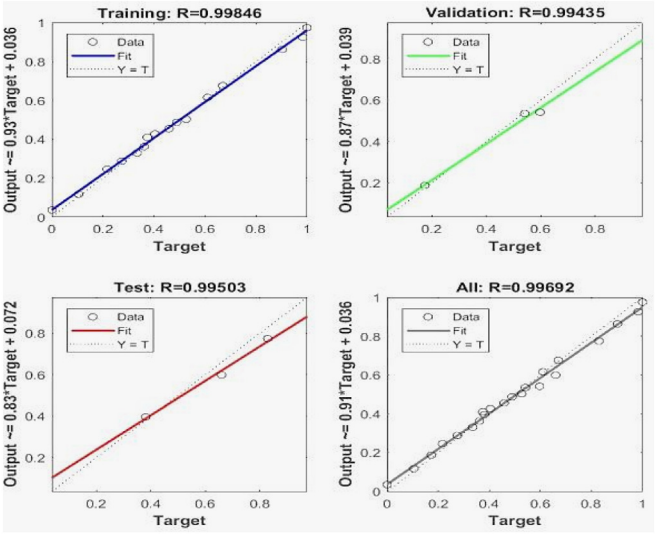

Fig. 4. Regression plots of optimized model 2-3-1.

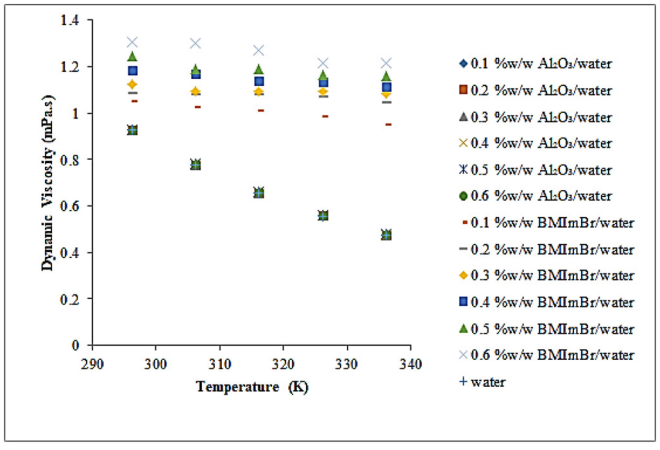

Fig. 5. Comparison of viscosities of nanofluid (Al_2O_3), an ionic liquid (BMImBr) with base fluid (water).

BMImBr also [35]. The dynamic viscosities of a binary mixture of 1-butyl-3-methylimidazolium trifluoromethane sulphonate with water over the entire mole fraction range in the temperature range 303.15–343.15 K in atmospheric pressure by Ge et al. [26] also follows the same trend.

The viscosity of nanofluid shows appreciable variation with temperature than with respect to concentration. In the concentration range studied, the viscosity is almost similar to that of water. Hence, it can be concluded that the addition of nanoparticles of γ-Al_2O_3 would increase the thermal conductivity of the system without much increase in viscosity. This has a positive effect on the secondary flow pattern that would generate during flow. When compared with other properties like density, thermal conductivity and heat capacity, studies on the viscosity of ionic liquids are less. The viscosity of ionic liquids at room temperature is high and ranges from 10 to 726 cP which is actually a disadvantage in terms of power required for pumping, mixing etc. Thus, the temperature variation of viscosity is more important. The viscosity of ionic liquids is a strong function of the anion. Out of the anions investigated, PF_6 contributes much to viscosity, whereas the NTf_2^- has lower viscosity [39]. So, the ionic liquids with NTf_2^- anions are given preference in various studies. It has been shown that the viscosities of imidazolium-based pure ionic liquids (with PF_6, NTf_2^-, BF4, $EtSO_4^-$ anions) decrease sharply [40]. In the present investigation, BMImBr with water does not show a significant reduction in viscosity when compared with nanofluid. Further investigation of other thermophysical properties could provide the needed insight into the effect on the heat exchange systems.

4.6. Implications of viscosity measurement

The convective heat transfer coefficient depends on the Nusselt number and the physical properties of the fluid which in turn depend on the values of Reynolds and Prandtl number. These physical properties and other variables are responsible for the transition from laminar to turbulent flow, which is due to unsteady state structures that develop naturally within the fluid or small disturbances that exist within many typical boundary layers. These kinds of disturbances may develop due to fluctuations in the free stream or due to surface characteristics. The onset of turbulence depends on the rate at which the triggering mechanisms are magnified in the direction of fluid flow, which in turn depends on the Reynolds number (dvρ/μ). Another dimensionless number which takes care of the heat transfer rate in the heat exchanger is Prandtl number. Prandtl number does not contain length scale like Reynolds number; it is dependent only on the fluid and the fluid state and is given by C_p μ/K. Increase in temperature reduces the viscosity of fluid flow, which tends to increase the Reynolds number resulting in a more secondary flow. The addition of nanoparticles/ionic liquids in the fluid causes an increase in viscosity and it tends to increase the Prandtl number, thereby reducing heat transfer rates. Fluids with low Prandtl numbers are good as heat transfer fluids. But, the addition of nanoparticles/ionic liquids which causes an increase in thermal conductivity would offset the effect of an increase in Prandtl number due to increased viscosity of nanofluids. Hence, variation in each of the fluid properties especially the change in viscosity and thermal conductivity during heat transfer is to be explored to incorporate corrections in the heat transfer models for calculating heat transfer enhancement. In the case of ionic liquids also, even though viscosity increased with increase in ionic liquid concentration, the thermal conductivity increase results in higher heat transfer rates when compared with pure base fluid like water. Recently, ionanofluids have attracted much attention for advanced heat transfer applications [21]. With the addition of nanoparticles to the base ionic fluid, the heat transfer rates have increased significantly when compared to that without nanoparticles [11]. Though the nanofluids and ionic liquids show almost similar trends in the properties for most systems, the impact of viscosity on heat transfer can be understood only with further experimentation and computing of other thermophysical properties of the system. Since the pressure drop and pumping power depends on viscosity, the results of the experiments can be used in the design stage to judicially select heat transfer fluids.

5. Conclusion

It is observed from the results that the presence of the ionic liquid, BMImBr in the fluid increases the viscosity of the fluid at all concentrations, when compared with the base fluid. As reported in the literature, the viscosity of γ-Al_2O_3 decreases with increase in temperature, but the effect of concentration on viscosity is negligible. The concentration of nanoparticles in the base fluid is kept low such that the Newtonian flow behaviour is maintained. Since overall heat transfer coefficient is a function of physiochemical properties of fluids, the velocity of the fluid and the type of flow, it is expected that heat transfer would increase in the presence of nanoparticles/ionic liquids along with the base fluid. The presence of ionic liquids would also likely produce a similar trend. The presence of nanoparticles or ionic liquid members considered in the present study in the cold side would enhance energy absorption from hot fluid. Since, the viscosity decreases with an increase in temperature, it would have a direct effect in the turbulence of the fluid flow resulting in increased heat transfer rates. However, the increased concentrations of nanofluid/ionic liquid also need to be explored.

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