# Viscosity, Refractive Index, Deviation of Viscosity and of Refractive Index of Biodiesel+Diesel Fuel (or Benzene) Binary Mixtures

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*Diesel fuel+biodiesel blends are currently commercialized as fuel for diesel engines. The liquid fuel behaviour in the internal combustion engine depends on the properties of the mixture components. Experimental viscosity and refractive index of binary biodiesel+diesel fuel and biodiesel+benzene mixtures are reported covering the whole composition range, at different temperatures from 293.15 to 323.15 K. The study was extended to biodiesel+benzene mixtures (benzene being an aromatic hydrocarbon totally miscible with biodiesel and diesel fuel respectively to better understand the behaviour of biodiesel+diesel fuel system. Viscosity data were correlated with Grunberg-Nissan one parameter equation. The values of interaction parameter ($G_{12}$) from Grunberg-Nissan equation were found to be negative for both studied systems at all investigated temperatures. Experimental viscosity and refractive index data have been used to calculate the property deviations of biodiesel + diesel fuel and biodiesel + benzene systems, these being then correlated by the Redlich – Kister polynomial equation. It was found that for both studied systems, the deviations in viscosity and refractive index, respectively, are negative.*

*Keywords: biodiesel, viscosity, refractive index, fuel mixture*

Besides the increasing of the efficiency of energy consuming, the current trend in the energy sector is to replace a part of fossil sources of energy with renewable sources. In the last years in the transport sector, a great consuming energy sector, two renewable fuels have penetrated the market: biodiesel and bioethanol. Biodiesel is commercialized blended with diesel fuel, while bioethanol is commercialized blended with gasoline. The mixing of biodiesel with diesel fuel results in the formation of a solution with nearly ideal behaviour [1]. In order to understand the behaviour of such mixtures used as fuel for internal combustion engine, their physico-chemical characteristics have been investigated. Research was focused on the most important properties directly affecting the behavior of the fuel in the internal combustion engine (viscosity, density) [2-7]. Other properties like flash point, oxidation stability, cetane number, refractive index were also investigated [8-16]. Viscosity of biodiesel+diesel fuel mixtures has been extensively studied, while only a few studies have been addressed to refractive index. Viscosity affects the flow and spray characteristics of the liquid mixtures. The refractive index of the pseudo-binary biodiesel+diesel fuel mixtures can be related to other liquid mixture properties [13,17] and also to the stage of transesterification process for biodiesel production from a vegetable oil and a monoalcohol [18].

Biodiesel can be obtained from a variety of animal and vegetable oils by transesterification with a monoalcohol. The differences in the chemical nature of biodiesel (soybean, sunflower, palm, and so on) may cause differences in the physico-chemical properties of the biodiesel + diesel oil blends, affecting engine performance and pollutant emissions [1, 19]. As a result, the knowledge of thermodynamics and transport properties of these blends and their dependence on composition and temperature is very important. In this regard, the present study reports experimental viscosity and refractive index data for rapeseed oil biodiesel+diesel fuel and rapeseed oil biodiesel+benzene mixtures covering the whole composition range at different temperatures from 293.15 to 323.15 K. The study was extended to biodiesel mixtures with benzene, an aromatic hydrocarbon totally miscible with this renewable fuel, to better understand the behavior of biodiesel+diesel fuel mixtures that are currently commercialized as fuel for diesel engines. Grunberg-Nissan one parameter equation has been used to correlate viscosity data of the pseudo-binary studied mixtures with biodiesel. From the experimental data, the deviation in viscosity ($\Delta\eta$) and the deviation in refractive index ($\Delta n_D$), have been calculated. These results have been fitted to Redlich-Kister polynomial equation.

## Experimental part

*Materials and methods*

The biodiesel sample was synthesized in the laboratory using rapeseed oil, according to a previously presented procedure [17]. Diesel fuel was purchased from a local company and benzene of 99.7 % purity was supplied by Merck.

The binary mixtures biodiesel+diesel fuel and biodiesel+benzene were prepared at room temperature for various volume fractions. The mixtures were prepared

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| Property | Biodiesel | Diesel fuel | Benzene |
|---|---|---|---|
| Density at 20°C (g/cm$^3$) | 0.8823 | 0.8414 | 0.8772 |
| Kinematic viscosity at 40°C (mm$^2$/s) | 4.6439 | 3.5439 | 0.5820 |
| Water content (mg/kg) | 231 | 130 | - |
| Sulfur content (mg/kg) | 0.00 | 0.14 | - |
| Flash point (°C) | 131 | 60 | −11.63 |
| Methylic esters of fatty acids (%, w/w) | 96.80 | 3.0 | - |

**Table 1**
PROPERTIES OF BIODIESEL, DIESEL FUEL, AND BENZENE

to cover the entire composition range, with an increasing step of 0.05 volume fraction. The experimental uncertainty in volume fractions was estimated to be less than ±0.002. All binary mixtures were completely miscible. Some properties of biodiesel, diesel fuel and benzene used in this study are presented in table 1. The properties of the biodiesel and diesel fuel are within the limits regulated by the EN 14214, and EN 590 standards, respectively.

The viscosity was measured using an Anton Paar SVM 3000 viscometer. This equipment is provided with a Peltier thermostat, whose accuracy of temperature is ±0.02 °C. The measurements for viscosity were performed at 293.15, 298.15, 303.15 K, 313.15 and 323.15 K with an accuracy of ±0.35%. The refractive indices were measured with a temperature-controlled Atago 3T refractometer with a reproducibility of refractive index data of $10^{-4}$. Water was circulated into the prism of the refractometer by a circulation pump connected to the external thermostated water bath. The temperature of thermostated bath had an accuracy of ± 0.05 °C. Refractive index was determined at 298.15 K, 303.15 K, 313.15 K and 323.15 K. All measurements were repeated three times, and the results were averaged.

Viscosity data were correlated with Grunberg-Nissan one parameter equation applied to biodiesel mixtures [5, 20]:

$$\ln \eta_m = v_1 \ln \eta_1 + v_2 \ln \eta_2 + v_1 v_2 G_{12} \qquad (1)$$

where $\eta_m$ is the kinematic viscosity of the binary mixture, $\eta_1$ and $\eta_2$ are the kinematic viscosities of the mixture components, v1 and v2 are the volume fractions of the mixture components and $G_{12}$ is the coefficient.

Deviation in viscosity and deviation in refractive index for the studied binary mixtures were obtained from experimental viscosity and refractive index data, respectively, for the mixture and pure components:

$$\Delta Y = Y_{exp} - (v_1 Y_1 + v_2 Y_2) \qquad (2)$$

where ΔY is the deviation in viscosity or deviation in refractive index, $Y_{exp}$ is the viscosity or refractive index, experimentally determined for the binary studied mixtures, $Y_1$ and $Y_2$ are the viscosity or refractive index of the mixture components.The deviations in property have been calculated using volume fraction to express mixture's composition, ussually used for biodiesel blends [21]. Deviation in viscosity and deviation in refractive index of the binary mixtures with biodiesel were fitted to the Redlich-Kister polynominal equation:

$$\Delta Y = v_1(1-v_1)\sum_{k=0}^{p} A_k (2v_1 - 1)^k \qquad (3)$$

where: Ak denotes adjustable parameters obtained by the method of least squares, k is the degree of the polynomial.

The accuracy of viscosity estimation using Grunberg and Nissan one parameter equation (1) was evaluated using the absolute average deviation (AAD, %):

$$AAD = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{\eta_{exp} - \eta_{calc}}{\eta_{exp}}\right| \qquad (4)$$

where AAD is the absolute average deviation, the subscripts *exp* and *calc* represent the experimental and calculated values, respectively, n is the number of experimental data points.

The standard deviation (σ) values were used to obtain the optimum number of adjustable parameters from equation (3):

$$\sigma = \left[\sum_{i=1}^{n}\frac{(\Delta Y_{calc,i} - \Delta Y_{exp,i})^2}{n-j}\right]^{1/2} \qquad (5)$$

where σ is the standard deviation, n is the number of experimental values and j is the number of coefficients.

## Results and discussion

*Experimental data*

Experimental results of viscosity for binary biodiesel+diesel fuel, and biodiesel+benzene mixtures, including those of pure components, over the entire composition range expressed by biodiesel volume fraction ($v_1$), and for temperature ranging from 293.15 K to 323.15 K are presented in table 2. In table 3 the refractive index data for binary biodiesel+benzene mixtures between 298.15 and 323.15 K are presented. Experimental results of refractive index data for biodiesel + diesel fuel system were previously presented [17].

In figure 1, the experimental data of viscosity variation with both composition and temperature for biodiesel + diesel fuel and biodiesel + benzene systems are suggestively presented. The refractive index variation with composition and temperature for biodiesel + diesel fuel and biodiesel + benzene mixture respectively, is presented in figure 2.

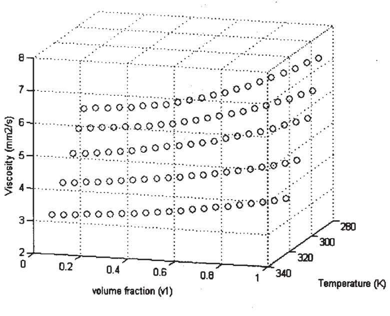
As seen from tables 2 and 3, the viscosity and refractive index, respectively, of studied mixtures with biodiesel decrease with temperature. For a given fixed temperature, viscosity of biodiesel + benzene mixtures is smaller than the viscosity of biodiesel + diesel fuel mixtures (fig.1). As viscosity of biodiesel is close to that of diesel fuel and much greater than the viscosity of benzene, it can be observed that the influence of composition on viscosity variation is more important for biodiesel + benzene system (fig.1b) than for biodiesel + diesel fuel system (fig.1a). The difference between the refractive index of mixtures components, biodiesel, diesel fuel and benzene, is not as important as in the case of viscosity. Therefore, it can be mentioned that the refractive index of biodiesel is slightly smaller than the refractive index of diesel fuel and benzene, respectively (fig. 2). As a result, refractive index variation of biodiesel + diesel fuel and biodiesel + benzene mixtures with composition is less important than in the case of viscosity.

*Calculation of viscosity and deviation in viscosity*

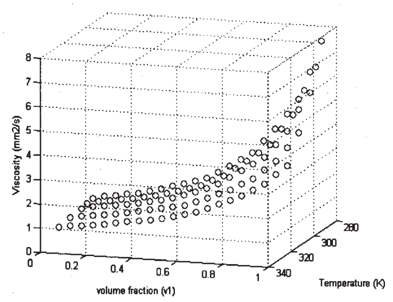
Biodiesel and diesel fuel are multicomponent system. Taking into account the similar structure of biodiesel (with straight chains chains of fatty acids monoalkylesters) and diesel fuel (with straight chains of alkanes), Benjumea et al. [1] considered the biodiesel+diesel fuel mixture as an ideal system. Also, the viscosity of biodiesel + diesel fuel mixtures was predicted with Grunberg and Nissan simplified equation, according to Tat and van Gerpen [22],

**Table 2**
EXPERIMENTAL KINEMATIC VISCOSITY VALUES ($mm^2/s$) OF BINARY BIODIESEL (1) + DIESEL FUEL (2) AND BIODIESEL (1) + BENZENE (2) MIXTURES FOR TEMPERATURE RANGING FROM 293.15 K TO 323.15 K

| Composition | Temperature (K) | | | | |
|---|---|---|---|---|---|
| $v_1$ | 293.15 | 298.15 | 303.15 | 313.15 | 323.15 |
| | Biodiesel+diesel fuel | | | | |
| 0.00 | 5.33121 | 4.83141 | 4.18670 | 3.54389 | 2.79180 |
| 0.05 | 5.36733 | 4.86551 | 4.21792 | 3.55900 | 2.81425 |
| 0.10 | 5.39566 | 4.89961 | 4.24914 | 3.59100 | 2.83670 |
| 0.15 | 5.42328 | 4.92724 | 4.29309 | 3.62700 | 2.86355 |
| 0.20 | 5.45810 | 4.96410 | 4.34087 | 3.66636 | 2.89041 |
| 0.25 | 5.50672 | 4.99774 | 4.38735 | 3.70303 | 2.91884 |
| 0.30 | 5.55475 | 5.04791 | 4.44558 | 3.74176 | 2.94727 |
| 0.35 | 5.61168 | 5.09636 | 4.50654 | 3.78600 | 2.98587 |
| 0.40 | 5.68050 | 5.15577 | 4.56751 | 3.82724 | 3.02794 |
| 0.45 | 5.76770 | 5.22796 | 4.62471 | 3.86920 | 3.06521 |
| 0.50 | 5.86755 | 5.30002 | 4.68958 | 3.91901 | 3.10803 |
| 0.55 | 5.96883 | 5.39266 | 4.75908 | 3.97530 | 3.15171 |
| 0.60 | 6.07407 | 5.48531 | 4.82684 | 4.03399 | 3.20443 |
| 0.65 | 6.19459 | 5.57114 | 4.92649 | 4.09439 | 3.25745 |
| 0.70 | 6.31908 | 5.65964 | 5.01123 | 4.15591 | 3.31017 |
| 0.75 | 6.47138 | 5.77275 | 5.10284 | 4.22021 | 3.36600 |
| 0.80 | 6.62493 | 5.88207 | 5.20360 | 4.28627 | 3.42876 |
| 0.85 | 6.78139 | 6.00677 | 5.31801 | 4.37083 | 3.49927 |
| 0.90 | 6.94369 | 6.13374 | 5.43343 | 4.45239 | 3.56423 |
| 0.95 | 7.13911 | 6.27665 | 5.55579 | 4.53076 | 3.63162 |
| 1.00 | 7.31270 | 6.42100 | 5.68225 | 4.64390 | 3.72665 |
| | Biodiesel+benzene | | | | |
| 0.00 | 0.73152 | 0.68990 | 0.64670 | 0.58203 | 0.51816 |
| 0.05 | 0.79073 | 0.74996 | 0.70369 | 0.62676 | 0.54878 |
| 0.10 | 0.85273 | 0.79746 | 0.76682 | 0.65881 | 0.58486 |
| 0.15 | 0.93795 | 0.87644 | 0.83855 | 0.71395 | 0.63441 |
| 0.20 | 1.01465 | 0.94710 | 0.90885 | 0.77169 | 0.68503 |
| 0.25 | 1.11661 | 1.03266 | 0.98365 | 0.83896 | 0.74442 |
| 0.30 | 1.21605 | 1.12300 | 1.06605 | 0.91106 | 0.80701 |
| 0.35 | 1.33445 | 1.22300 | 1.16115 | 0.99243 | 0.87826 |
| 0.40 | 1.46065 | 1.33705 | 1.26391 | 1.07795 | 0.95127 |
| 0.45 | 1.62452 | 1.48622 | 1.40035 | 1.19455 | 1.05225 |
| 0.50 | 1.79842 | 1.64120 | 1.54121 | 1.30840 | 1.14870 |
| 0.55 | 1.98415 | 1.80915 | 1.69215 | 1.44090 | 1.25970 |
| 0.60 | 2.23475 | 2.03155 | 1.89192 | 1.59900 | 1.39425 |
| 0.65 | 2.51281 | 2.28030 | 2.11432 | 1.77870 | 1.54270 |
| 0.70 | 2.88015 | 2.60325 | 2.40145 | 2.00970 | 1.73370 |
| 0.75 | 3.24221 | 2.92705 | 2.68745 | 2.24025 | 1.92005 |
| 0.80 | 3.72245 | 3.35075 | 3.03305 | 2.52805 | 2.14690 |
| 0.85 | 4.27511 | 3.83050 | 3.45050 | 2.85130 | 2.40615 |
| 0.90 | 5.07551 | 4.51715 | 4.04785 | 3.31025 | 2.76890 |
| 0.95 | 6.08945 | 5.38545 | 4.79620 | 3.87825 | 3.21295 |
| 1.00 | 7.31270 | 6.42100 | 5.68225 | 4.64390 | 3.72665 |




a) biodiesel + diesel fuel

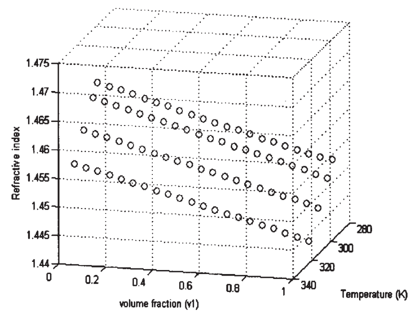



b) biodiesel + benzene

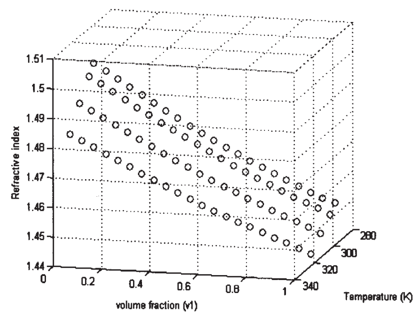
Fig.1. Viscosity variation with composition and temperature for biodiesel + diesel fuel (a) and biodiesel + benzene mixtures (b)

**Table 3**
EXPERIMENTAL REFRACTIVE INDEX VALUES OF BINARY BIODIESEL (1) + BENZENE (2) MIXTURES FOR TEMPERATURE RANGING FROM 298.15 K TO 323.15 K

| Composition | Temperature (K) | | | |
|---|---|---|---|---|
| $v_1$ | 298.15 | 303.15 | 313.15 | 323.15 |
| | Biodiesel+benzene | | | |
| 0.00 | 1.4968 | 1.4938 | 1.4876 | 1.4800 |
| 0.05 | 1.4944 | 1.4915 | 1.4855 | 1.4781 |
| 0.10 | 1.4920 | 1.4891 | 1.4832 | 1.4761 |
| 0.15 | 1.4894 | 1.4866 | 1.4809 | 1.4740 |
| 0.20 | 1.4870 | 1.4842 | 1.4787 | 1.4720 |
| 0.25 | 1.4846 | 1.4819 | 1.4765 | 1.4700 |
| 0.30 | 1.4822 | 1.4796 | 1.4743 | 1.4679 |
| 0.35 | 1.4799 | 1.4773 | 1.4722 | 1.4660 |
| 0.40 | 1.4776 | 1.4751 | 1.4701 | 1.4640 |
| 0.45 | 1.4754 | 1.4729 | 1.4680 | 1.4621 |
| 0.50 | 1.4732 | 1.4707 | 1.4660 | 1.4602 |
| 0.55 | 1.4710 | 1.4685 | 1.4640 | 1.4584 |
| 0.60 | 1.4689 | 1.4664 | 1.4621 | 1.4567 |
| 0.65 | 1.4668 | 1.4644 | 1.4603 | 1.4550 |
| 0.70 | 1.4648 | 1.4625 | 1.4585 | 1.4534 |
| 0.75 | 1.4629 | 1.4606 | 1.4567 | 1.4518 |
| 0.80 | 1.4610 | 1.4587 | 1.4550 | 1.4502 |
| 0.85 | 1.4591 | 1.4569 | 1.4532 | 1.4487 |
| 0.90 | 1.4572 | 1.4552 | 1.4516 | 1.4471 |
| 0.95 | 1.4554 | 1.4534 | 1.4499 | 1.4455 |
| 1.00 | 1.4540 | 1.4516 | 1.4480 | 1.4438 |




a) biodiesel + diesel fuel




b) biodiesel + benzene

Fig.2. Refractive index variation with composition and temperature for biodiesel + diesel fuel [17] (a) and biodiesel + benzene mixtures (b)

**Table 4**
VALUES OF INTERACTION COEFFICIENTS ($G_{12}$) AND AAD (%) FROM EQ. (1) AT DIFFERENT TEMPERATURES

| Parameter | Temperature (K) | | | | |
|---|---|---|---|---|---|
| | 293.15 | 298.15 | 303.15 | 313.15 | 323.15 |
| | Biodiesel + diesel fuel | | | | |
| $G_{12}$ | -0.2467 | -0.1930 | -0.1579 | -0.1375 | -0.1499 |
| AAD (%) | 0.1733 | 0.1191 | 0.0950 | 0.1586 | 0.0931 |
| | Biodiesel + benzene | | | | |
| $G_{12}$ | -1.0447 | -1.0240 | -0.8946 | -0.9586 | -0.7959 |
| AAD (%) | 2.5856 | 2.2951 | 2.7303 | 1.9789 | 1.2826 |

with errors less than 2.05% and 3.74%, depending upon the type of diesel fuel used in the mixture, or with errors less than 1.07%, according to Benjumea et al. [1].

In this study, in order to investigate the behavior of the studied mixtures, the viscosity of binary biodiesel+diesel fuel and biodiesel+benzene mixtures was calculated at different temperatures using Grunberg and Nissan one parameter equation (1). The values of $G_{12}$ interaction coefficients and AAD (%) values corresponding to viscosity estimation of binary biodiesel+diesel fuel and biodiesel+benzene mixtures using (1) are presented in table 4.

The accuracy of prediction of biodiesel + diesel fuel mixtures viscosity using eq. (1) is greater than the accuracy of viscosity prediction for biodiesel + benzene mixtures (table 4). The values of interaction parameter ($G_{12}$) from (1) are negative for both studied systems at all investigated temperatures and decrease with temperature. The absolute values of $G_{12}$ parameter are greater in the case of biodiesel + benzene mixtures, for all compositions.

It is known that if the Grunberg-Nissan interaction parameter values are positive, the interactions between unlike molecules are strong, whereas negative values mean weak interactions [23]. Hence, the negative values of Grunberg-Nissan interaction parameters in studied mixtures show weak interactions, more pronounced in the biodiesel + benzene system. This could be explained by the greater difference in mixture components structure in the case of biodiesel + benzene system compared to biodiesel + diesel fuel system.

The deviation in viscosity for the binary systems biodiesel+diesel fuel and biodiesel+benzene, was calculated over the entire composition range, from experimental viscosity data using (2) and was fitted to the Redlich-Kister polynomial equation (3). The values of adjustable parameters $A_k$ from (3), together with corresponding standard deviations ($\sigma$) calculated values are presented in table 5. As Vural et al. [8] observed in the case of biodiesel + benzene system, the optimum number of adjustable parameters from (3) is equal to 4 for both studied systems with biodiesel.

It was found that for both studied systems with biodiesel, the Redlich-Kister polynomial equation correlates well the experimental data. Thus the standard deviation is smaller than 0.006% for biodiesel + diesel fuel system, and approximately 0.02% for biodiesel + benzene system.

The plots of deviation in viscosity *vs.* volume fraction at 293.15, 298.15, 303.15, 313.15 and 323.15 K for biodiesel + diesel fuel and biodiesel + benzene mixtures are presented in figure 3. The points represent the experimental data and the solid line, the calculated curves with Redlich-Kister polynomials.

The values of deviation in viscosity are negative for both studied systems, over the entire composition range and at all investigated temperatures (fig. 3). Negative values for deviation in viscosity at 298.15 K and 303.15 K for biodiesel + benzene binary system were also reported by Vural et al. [8]. The absolute value of deviation in viscosity decreases with temperature for both binary studied systems.

The deviation in viscosity is a measure of deviation from ideality of the liquid mixtures, depending on molecular interactions, as well as on the size and the shape of the mixing molecules.

Biodiesel is a liquid fuel composed by numerous straight chain monoalkylesters of fatty acids, whereas diesel fuel is a liquid mixture of a large number of components, especially paraffinic and naphthenic hydrocarbons. Taking

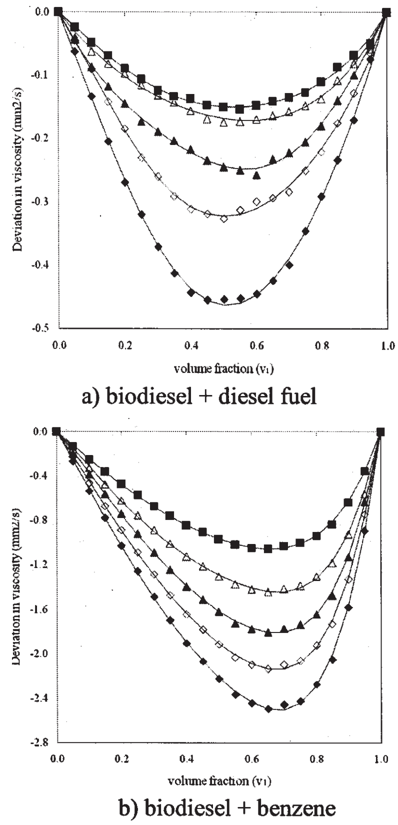



Fig.3. Deviation in viscosity of biodiesel + diesel fuel (a) and biodiesel + benzene mixtures (b) at different temperatures: ◆ 293.15K; ◇ 298.15 K; ▲ 303.15 K; Δ 313.15 K; ■ 323.15 K; – correlation with Redlich-Kister equation

into account the presence of hydrogen-carbon large chains in biodiesel and also in diesel fuel, Yuan et al. [24] highlighted the similar structure of the two fuels. Unlike benzene which is a non-polar aromatic liquid hydrocarbon, presenting an orientational type order due to high quadrupole moment [25], diesel fuel and biodiesel are made up of large molecules bound by weakly (Van der Waals) forces. As a result of the structure of the components, the system of biodiesel with diesel fuel differs from that with benzene. For the same temperature and biodiesel content in the mixture, the deviation in viscosity is greater for biodiesel + benzene system compared to biodiesel + diesel fuel system (fig. 3). The negative values of deviation in viscosity could be explained for biodiesel + diesel fuel mixtures and similar for biodiesel + benzene mixtures, by the existence of relatively weak inter-molecular interactions upon mixing. The negative deviations are consistent with the negative values of Grunberg-Nissan interaction coefficient (table 4), also showing weak interactions in both studied mixtures, weaker in the biodiesel + benzene system.

*Calculation of deviation in refractive index*

Deviation in refractive index was calculated over the entire composition range, from experimental values of refractive index of biodiesel + diesel fuel and biodiesel + benzene mixtures, using (2). The deviations in refractive index were fitted to the Redlich-Kister polynomial equation (3). The values of adjustable parameters $A_k$ from (3) together with corresponding standard deviations ($\sigma$) calculated values are presented in table 6. The plots of deviation in refractive index *vs.* volume fraction at 298.15, 303.15, 313.15 and 323.15 K for biodiesel + diesel fuel and biodiesel + benzene mixtures are presented in figure 4.

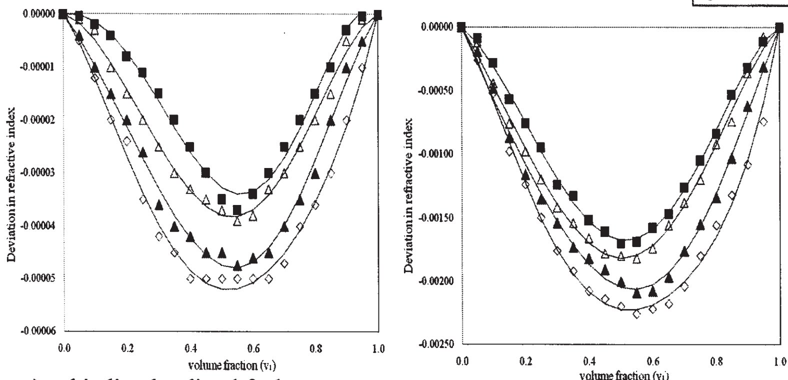
Redlich-Kister polynomial equation can very well represent the deviation in refractive index of biodiesel + diesel fuel and biodiesel + benzene systems. The deviation in refractive index was found to be negative for both studied systems with biodiesel over the entire composition range

**Table 5**
VALUES OF REDLICH-KISTER PARAMETER (EQ.3) AND STANDARD DEVIATION, σ (mm²/s), FOR DEVIATION IN VISCOSITY AT DIFFERENT TEMPERATURES

| Parameter | Temperature (K) | | | | |
|---|---|---|---|---|---|
| | 293.15 | 298.15 | 303.15 | 313.15 | 323.15 |
| | Biodiesel + diesel fuel | | | | |
| $A_0$ | -1.8521 | -1.2905 | -0.9753 | -0.6752 | -0.6016 |
| $A_1$ | -0.0814 | -0.0129 | -0.2657 | -0.1616 | -0.0583 |
| $A_2$ | 0.2765 | 0.0766 | -0.0842 | -0.1777 | -0.0731 |
| $A_3$ | -0.1822 | -0.3792 | 0.2740 | -0.0117 | -0.1537 |
| σ | 0.0056 | 0.0048 | 0.0041 | 0.0050 | 0.0032 |
| | Biodiesel + benzene | | | | |
| $A_0$ | -8.8551 | -7.6280 | -6.4635 | -5.1684 | -3.8708 |
| $A_1$ | -5.5339 | -4.6235 | -3.8674 | -2.8705 | -2.0627 |
| $A_2$ | -4.2510 | -3.3886 | -2.8460 | -2.5813 | -1.5641 |
| $A_3$ | -2.6949 | -2.2204 | -2.1038 | -2.0811 | -0.9557 |
| σ | 0.0204 | 0.0170 | 0.0172 | 0.0152 | 0.0099 |

**Table 6**
REDLICH-KISTER PARAMETERS (EQ.3) AND STANDARD DEVIATION FOR DEVIATION IN REFRACTIVE INDEX AT DIFFERENT TEMPERATURES

| Parameter· $10^3$ | Temperature (K) | | | |
|---|---|---|---|---|
| | 298.15 | 303.15 | 313.15 | 323.15 |
| | Biodiesel + diesel fuel | | | |
| $A_0$ | -0.2080 | -0.1899 | -0.1519 | -0.1308 |
| $A_1$ | -0.0206 | -0.0488 | -0.0383 | -0.0830 |
| $A_2$ | 0.0360 | 0.1036 | 0.1335 | 0.1693 |
| $A_3$ | -0.0663 | 0.0449 | 0.0360 | 0.1152 |
| σ | 0.0015 | 0.0015 | 0.0012 | 0.0014 |
| | Biodiesel + benzene | | | |
| $A_0$ | - 8.9006 | -8.1997 | -7.2749 | -6.7045 |
| $A_1$ | -0.8863 | -1.7186 | -0.2386 | -0.6924 |
| $A_2$ | -0. 2058 | 2.0679 | 3.9156 | 5.1156 |
| $A_3$ | -3.6752 | 1.4609 | 1.0998 | 1.0283 |
| σ | 0.0580 | 0.0526 | 0.0463 | 0.0291 |



a) biodiesel + diesel fuel
b) biodiesel + benzene

Fig.4. Deviation in refractive index of biodiesel + diesel fuel (a) and biodiesel + benzene (b) mixtures at different temperatures: ◇ 298.15 K; ▲ 303.15 K; Δ 313.15 K; ■ 323.15 K; – correlation with Redlich-Kister equation

and at all investigated temperatures, its values descrease with temperature. It could be observed, as in the case of deviation in viscosity, that the values of deviation in refractive index are greater for of biodiesel + benzene system compared to biodiesel + diesel fuel system. However, the values of deviation in refractive index are much smaller than the values of deviation in viscosity for the studied systems with biodiesel.

## Conclusions

Viscosity and refractive index data of biodiesel + diesel fuel and biodiesel + benzene mixtures were determined with good accuracy on the whole composition range and at different temperatures from 293.15 K to 323.15 K.

The viscosity of biodiesel + diesel fuel system is more accurately predicted by Grunberg-Nissan one parameter equation, than the viscosity of biodiesel + benzene system; the values of interaction parameter from Grunberg-Nissan equation are negative for both binary systems with biodiesel.

For studied mixtures, the experimental deviations in viscosity and refractive index are negative, more significant for biodiesel + benzene system, due to larger differences between system components structure in the case of biodiesel + benzene compared to biodiesel + diesel fuel mixture.

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