Rheological Characterization of Shear-Thinning Fluids with a Novel Viscosity Equation of a Tank-Tube Viscometer

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Abstract:
A tank-tube viscometer and its novel viscosity equation were developed to determine flow characteristics of non-Newtonian fluids. The objective of this research is to test capabilities of the tank-tube viscometer and its novel non-Newtonian viscosity equation by characterizing rheological behaviors of well-known polyethylene oxide (MW 8000000) aqueous solutions as non-Newtonian fluids with 60-w% sucrose aqueous solution as a reference calibration fluid. Non-Newtonian characteristics of 0.3 - 0.7 wt% polyethylene oxide aqueous solutions were extensively investigated with the tank-tube viscometer and its non-Newtonian viscosity equation over the 294 - 306 K temperature range, and 55 - 784 s^{-1} shear rate range. The 60-w% sucrose aqueous solution was used as a reference/calibration fluid for the tank-tube viscometer. Dynamic viscosity values of 60 w% sucrose aqueous solution were determined with the calibrated tank-tube viscometer and its Newtonian viscosity equation at 299.15 K, and compared with the literature values.

Zusammenfassung:
Ein Wasserbad-Röhren-Viskosimeter und seine neuartige Viskositätsgleichung wurden entwickelt, um die Fließeigenschaften von nicht-Newtonschen Fluiden zu bestimmen. Die Zielsetzung dieser Forschung ist, die Einsatzfähigkeit des Wasserbad-Röhren-Viskosimeters und seiner neuartigen nicht-Newtonschen Viskositätsgleichung zu testen, indem das rheologische Verhalten von bekannten wässrigen Polyethylenoxidlösungen (Mw 8000000) (als ein nicht-Newtonsches Fluid) mit Hilfe einer wässrigen 60 Gew.%-Saccharoselösung (als Kalibrationsfluid) charakterisiert wird. Die nicht-Newtonschen Eigenschaften einer wässrigen 0.3 - 0.7 Gew.%-Polyethylenoxidlösung wurden mittels des Wasserbad-Röhren-Viskosimeters und seiner nicht-Newtonschen Viskositätsgleichung im Temperaturbereich von 294 bis 306 K und im Schergeschwindigkeitsbereich von 55 bis 784 1/s ausgiebig untersucht. Die wässrige 60 Gew.%-Saccharoselösung wurde als Referenz-/Kalibrationsfluid für das Wasserbad-Röhren-Viskosimeter verwendet. Die Werte der dynamischen Viskosität der wässrigen 60 Gew.%-Saccharoselösung wurden mit dem kalibrierten Wasserbad-Röhren-Viskosimeter und seiner Newtonschen Viskositätsgleichung bei 299.15 K bestimmt und mit Literaturwerten verglichen.

Résumé:
Un viscosimètre réservoir-tube ainsi que sa nouvelle équation de viscosité ont été mis au point afin de déterminer les caractéristiques d'écoulement de fluides non Newtoniens. L'objectif de cette recherche est de tester les aptitudes du viscosimètre réservoir-tube et de sa nouvelle équation de viscosité non Newtonienne, en caractérisant les comportements rhéologiques de solutions aqueuses bien connues d'oxyde de polyéthylène (MW 8000000) qui servent de fluides non Newtoniens, et d'une solution aqueuse contenant 60% en masse de sucrose qui sert de fluide de référence pour la calibration. Les caractéristiques non Newtoniennes des solutions aqueuses d'oxyde de polyéthylène avec des concentrations de l'ordre de 0.3-0.7% en masse ont été beaucoup étudiées avec le viscosimètre réservoir-tube et son équation de viscosité non Newtonienne dans une gamme de températures allant de 294 à 306 K et une gamme de vitesses de cisaillement allant de 55 à 784 s-1. La solution aqueuse de 60% en masse de sucrose a été utilisée comme un fluide de référence/calibration pour le viscosimètre réservoir-tube. Les valeurs de la viscosité dynamique de cette solution ont été déterminées avec le viscosimètre réservoir-tube et son équation de viscosité Newtonienne à 299.15 K, et ont été comparées avec les valeurs de la littérature.

Key words: tank-tube viscometer, Newtonian viscosity equation for a tank-tube viscometer, non-Newtonian viscosity equation for a tank-tube viscometer, polyethylene oxide aqueous solutions, sucrose aqueous solution, shear-thinning fluids

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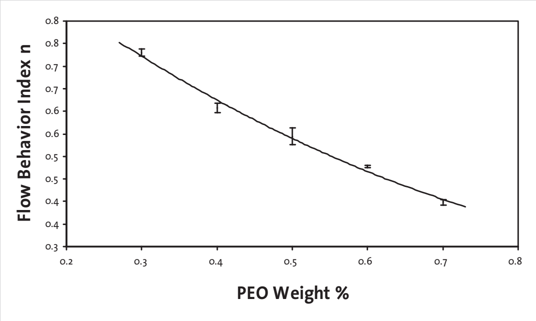

Figure 10 (left): Flow behavior index versus PEO weight % in aqueous solutions at 298.99 K, using quadruple experimental data.

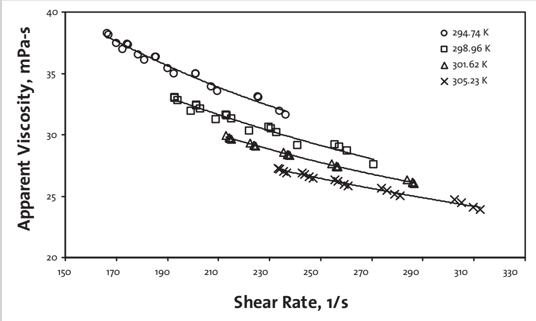

Figure 11 (right): Apparent viscosity versus shear rate for the 0.5 wt% PEO aqueous solution at 294 - 306 K.

Table 2: Average dynamic viscosity (DV) values of quintuple experimental DV values, their standard deviations (SDs) and percentages of SDs, and error % of average experimental DV values in comparison of the literature DV value 41.7 mPa·s of 60-w% sucrose aqueous solution at 299.15 K.

Drain Tube Length, m	Average Experimental DV, mPa-s	SD of Average Experimental DV, mPa-s	SD % of Average Experimental DV	Error % of Average Experimental DV from Literature DV
0.20	41.8309	0.3146	0.7522	0.1272
0.25	41.6083	0.2018	0.4849	-0.4057
0.30	41.5270	0.1643	0.3956	-0.6004
0.35	41.7564	0.1347	0.3227	-0.0513
0.40	41.8396	0.3002	0.7176	0.1478

Table 3: Average quadruple left-hand side (LHS) values of non-Newtonian viscosity equation (NNVE), and their standard deviations (SDs) and percentages of standard deviations for average LHS values with 0.5 wt% PEO aqueous solution.

Average Temperature (AT), K	Standard Deviation of AT, K	Standard Deviation % of AT	Drain Tube Length, m	Average LHS Value, ln(1/s)	SD of LHS Value, ln(1/s)	SD % of LHS Value
294.74	0.11	0.49	0.20	3.8321	0.0115	0.2998
			0.25	3.7358	0.0201	0.5374
			0.30	3.6385	0.0088	0.2428
			0.35	3.5771	0.0118	0.3294
			0.40	3.5262	0.0105	0.2968
298.96	0.05	0.19	0.20	3.9852	0.0170	0.4260
			0.25	3.8781	0.0063	0.1622
			0.30	3.8043	0.0079	0.2065
			0.35	3.7336	0.0083	0.2233
			0.40	3.6961	0.0126	0.3415
301.62	0.08	0.26	0.20	4.0798	0.0052	0.1285
			0.25	3.9772	0.0031	0.0780
			0.30	3.9021	0.0047	0.1200
			0.35	3.8350	0.0017	0.0456
			0.40	3.7942	0.0068	0.1785
305.23	0.04	0.13	0.20	4.1734	0.0044	0.1063
			0.25	4.0930	0.0064	0.1558
			0.30	4.0091	0.0011	0.0274
			0.35	3.9554	0.0097	0.2447
			0.40	3.9068	0.0046	0.1171

Table 4: Average flow behavior indexes of 0.5 wt% PEO aqueous solution at 294 - 306 K, using quadruple experimental data.

Average Temperature, K	Average Flow Behavior Index, n	Standard Deviation of n	Standard Deviation % of n
294.74	0.5133	0.0144	2.8
298.96	0.5445	0.0192	3.5
301.62	0.5521	0.0011	0.2
305.23	0.5919	0.0191	3.2

Table 5: Average apparent viscosity values, and their standard deviations (SDs) and percentages of standard deviations for quadruple experimental data of 0.5 wt% PEO aqueous solution at various average temperatures, and apparent viscosity values predicted from the Ahrrenius equation.

Average Temperature, K	Average Apparent Viscosity (AV), mPa-s	Standard Deviation (SD) of AV, mPa--s	SD % of AV	Predicted AV from Ahrrenius Relationship, m-Pa-s
294.74	35.4094	2.0153	5.69	35.2924
298.96	30.9332	1.5792	5.11	30.9813
301.62	28.1886	1.3120	4.65	28.5914
305.23	25.8996	1.0504	4.06	25.7059

Table 6: Average flow behavior indexes of PEO aqueous solutions at the average temperature 298.99 K, using quadruple experimental data.

w% of PEO	Average Temperature, K	Average Flow Behavior Index, n	Standard Deviation of n	Standard Deviation % of n
0.3	299.02	0.7299	0.0083	1.1
0.4	299.02	0.6071	0.0114	1.9
0.5	298.96	0.5445	0.0192	3.5
0.6	299.00	0.4780	0.0029	0.6
0.7	298.95	0.3983	0.0065	1.6

against temperatures, using quadruple experimental data, as shown in Fig. 8. The average flow behavior indexes and their standard deviations at the temperatures 294.74, 298.96, 301.62, and 305.23 K are shown in Tab. 4. Flow behavior index values n increase with increased temperatures.

Apparent viscosity values of 0.5 wt% PEO aqueous solution are calculated with Eqs. 2, 5, 8, 9 and known n and k values obtained from the NNVE over the temperature range of 294 - 306 K. Apparent viscosity values of 0.5 wt% PEO aqueous solution are plotted against temperatures, as shown in Fig. 9. The average apparent viscosity values and their standard deviations of 0.5 wt% PEO at the average temperatures of 294.74, 298.96, 301.62, and 305.23 K are shown in Tab. 5. Apparent viscosity values of 0.5 wt% PEO aqueous solution decreases with increased temperatures over the temperature range of 294 - 306 K. The temperature dependence of apparent viscosity values of 0.5 wt% PEO aqueous solution is correlated very well by the Arrhenius equation, as shown in Fig. 9.

Flow behavior index values n of various PEO aqueous solutions at the average temperature 298.99 K are plotted against PEO concentrations, using quadruple experimental data, as shown in Fig. 10. The flow behavior indexes and their standard deviations for the 0.3, 0.4, 0.5, 0.6, and 0.7 wt% PEO aqueous solution are shown in Tab. 6. Flow behavior index values *n* decrease with increased PEO concentrations. Apparent viscosity values of 0.5 wt% PEO aqueous solution over the temperature range of 294 - 306 K are plotted against shear rates, as shown in Fig. 11. Apparent viscosity values of the PEO aqueous solution decrease with increased shear rates and temperatures. This observation indicates that the 0.5 wt% PEO aqueous solution be a shear-thinning fluid. Shear stress values of the 0.5 wt% PEO aqueous solution over the temperature range of 294 - 306 K are plotted against shear rates, as shown in Fig. 12. Figure 12 also suggests that the 0.5 wt% PEO aqueous solution is a shear-thinning fluid, since the curves in Fig. 12 are concave downward.

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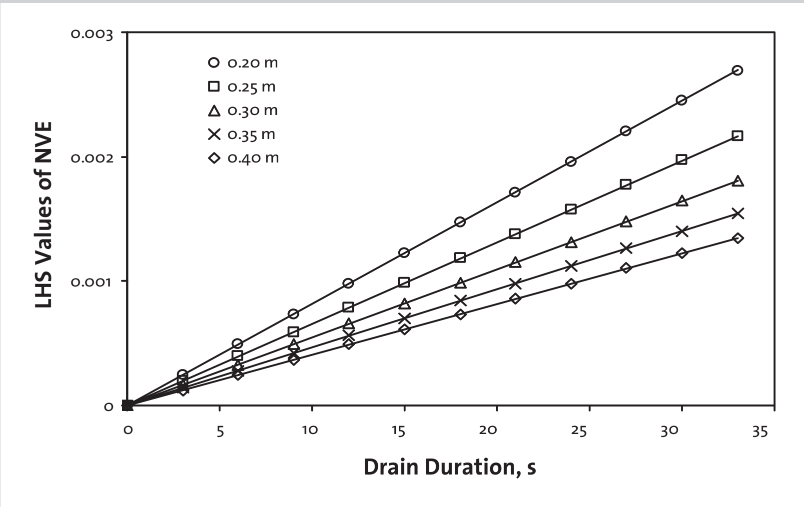

Figure 12: Shear stress versus shear rate for the 0.5 wt% PEO aqueous solution at 294 - 306 K.

5 CONCLUSIONS

A tank-tube viscometer and its viscosity equation were developed to determine flow characteristics of non-Newtonian fluids. A sucrose aqueous solution was chosen as the reference/calibration fluid for the fabricated tank-tube viscometer and its viscosity equation. The dynamic viscosity values of 60 wt% sucrose aqueous solution, obtained from both this calibrated tank-tube viscometer and its Newtonian viscosity equation, are agreeable with the literature dynamic viscosity value. The viscosity values obtained from this study are very agreeable with that from the literature at 299.15 K with an average error of -0.16 %, which is way below the literature accuracy ± 1 %.

Non-Newtonian behaviors of 0.3 - 0.7 wt% aqueous polyethylene oxide solutions at 294 - 306 K were characterized with the various lengths of the drain tube of the tank-tube viscometer calibrated with 60-w% sucrose aqueous solution and its non-Newtonian equation to test capabilities of the tank-tube viscometer in determining flow characteristics of non-Newtonian fluids. The range of flow index n values for 0.3 - 0.7 wt% aqueous polyethylene oxide solutions at 294 - 306 K is 0.3 - 0.7. Flow behavior indexes n decrease with increased PEO concentrations, and decreased temperatures.

Apparent viscosity values of various PEO aqueous solutions decrease with increased shear rates and temperatures over the shear rate range of 160 - 310 s^{-1}. PEO aqueous solutions containing 0.3 - 0.7 w% PEO behave as shear-thinning fluids. The temperature dependence of apparent viscosity values of PEO aqueous solutions is correlated very well over the temperature range of 294 - 306 K and the shear rate range of 225 - 241 s^{-1} by the Arrhenius equation. Temperature of the viscometer assembly is controlled with a circulator, where the standard deviations of the temperatures are 0.04 - 0.11 K in comparison with the literature standard deviation 0.3 K.

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