Study of Variations of Concentration, Temperature, and Intermolecular Interactions on the Viscosity of Liquids*

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A simple extension to the undergraduate laboratory experiment for the determination of viscosity using Ostwald's viscometer is proposed in this work. This fits in well for any undergraduate laboratory demonstration. Ostwald's viscometer is used to investigate the effect of concentration, temperature, and intermolecular interactions on the viscosity of liquids using distilled water as the reference liquid. The viscosity values obtained for acetic acid (v/v%) and sugar solutions (w/v%) have been found to increase with an increase in the concentration of solutions and are synchronous with the literature trends. A drastic decrease in viscosity is observed with an increase in temperature due to a decrease in intermolecular forces of attraction. The temperature variation is found to be a more dominating and contributing factor towards changing viscosity values as compared to the concentration variation. Liquids with stronger intermolecular interactions are found to have greater viscosity values. However, this result was found to be dominated by the factor of greater molecular mass. Nonetheless, the trends obtained in this work are synchronous with literature data.

Keywords
Viscosity, concentration, temperature, intermolecular interactions, chemistry laboratory, Ostwald viscometer, chemistry education.

Introduction

Viscosity is an important property of liquids. It denotes opposition/resistance/friction to the flow of a liquid. Viscosity is a crucial parameter as it controls the liquid flow in processes such

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as spraying, injection, molding, surface coating, etc., and is a major factor in determining the forces that must be overcome when liquids are used in lubrication and transported. Many physical factors alter viscosity values, such as temperature, structure, particle size, concentration, intermolecular forces of interaction, etc. Precise measurements of viscosity are extremely important in many industries to maximize production efficiency and cost-effectiveness [1–3]. Many approaches have been developed to measure the viscosity of liquids. These include capillary viscometers, rotational rheometry, vibrating viscometers, microfluidic rheometers, non-contact rheology, falling sphere viscometers, etc., among others [3–6]. The determination of the viscosity of liquids is an important laboratory experiment for undergraduate students. The most common method employed for measuring viscosity in university laboratories is Ostwald's viscometry method which employs a capillary viscometer [2]. In this study, we have used Ostwald's viscometer to investigate the effect of concentration, temperature, and intermolecular interactions on the viscosity of liquids [7]. With an objective to understand the role of inter-molecular interactions on the liquid flow and, in turn, on viscosity, three types of intermolecular interactions viz., ion-dipole, dipole-dipole, and H-bonding have been considered in this study. Such a procedure is suitable for any undergraduate laboratory demonstration for understanding and demonstrating the impact of various factors on the viscosity of liquids along with their determination.

Materials and Methods

In this study, Ostwald's viscometer has been used to study the variation of viscosity with concentration, temperature, and intermolecular forces of attraction. The variation in the viscosity values has been investigated in three parts. The effect of concentration on viscosity has been examined using acetic acid and sugar solutions of different concentrations, respectively. The effect of temperature on viscosity has been studied by determining the viscosities of different concentrations of acetic acid and sugar solutions under different temperature conditions, and the effect of intermolecular forces of interaction, mainly H-Bonding, ion-dipole, and dipole-dipole interactions on viscosity has also been investigated using different solutions.

Viscosity Measurement Using Ostwald's Viscometer

The determination of viscosity using Ostwald's viscometer [2, 7] is based on the Hagen–Poiseuille law, which states that rate of flow of a liquid through a capillary depends upon the constant vertical pressure head for maintaining the uniform volume flow (P), the radius of the capillary (r), the length of the capillary (l), and the viscosity of the liquid flowing through the capillary (η) (1).

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$$\frac{V}{t} = \frac{\pi . P . r^4}{8 . \eta . l}, \tag{1}$$

where, V/t is the rate of flow of discharged volume (m^3/sec), P is the vertical pressure head (Pa), l is the length of capillary (m), r is the radius of capillary (m), and η is the viscosity of liquid flowing through the capillary ($Pa.s$). Substituting the pressure as (2):

$$P = h.\rho.g, \tag{2}$$

where ρ is the density $\rho = m/V$ of liquid, h is the height of liquid, and g is the gravitational constant; substituting (2) in (1) gives the final expression of viscosity,

$$\eta = \frac{\pi . h . \rho . g . r^4 . t}{8 . l . V}. \tag{3}$$

(3) is used to determine viscosity, provided all the parameters defined in the equation are known. For a given capillary, besides *pi* and 8, r and l are also constants. And for a fixed volume V of the liquid, height (h) also becomes constant in a given capillary, modifying (3) to,

$$\eta = k.\rho.t, \tag{4}$$

where k includes all the constant terms. If the same viscometer is used to determine the viscosity of the two different liquids (one as a reference liquid with a known viscosity value), the constant k remains the same allowing easy calculation of viscosity [7–10].

$$\frac{\eta_1}{P}\eta_2 = \frac{\rho_1 t_1}{\rho_2 t_2} = \frac{m_1 t_1}{m_2 t_2}. \tag{5}$$

In this study, we made use of this relative method using distilled water as the reference liquid to determine the viscosities of acetic acid and sugar solutions.

Experimental Set-up

The apparatus used includes Ostwald's viscometer, conical flasks (250 *mL*), beakers (250 *mL*), clamp stand, weighing bottle, specific gravity bottle, stop-watch, pipette, burner, spatula, tripod stand, and wire gauze. This article deals with distilled water, acetic acid solution (1%, 2%, 3%, 5%, 7% and 10% v/v), sugar solution (1%, 2%, 3%, 5%, 7% and 10% w/v), sodium chloride solution (10% w/v), ammonium chloride solution (10% w/v), and hydrochloric acid solution (10% v/v) because they are inexpensive, easy to handle at various concentrations and temperatures, and are commercially available. It is also easy to find literature data on their physicochemical variables at different temperatures.

Analysis of Variation of Viscosity with Concentration

Distilled water was used as the reference liquid. First, the room temperature was measured. The required liquid solution was pipetted and poured into Ostwald's viscometer till its upper mark. Time taken by the liquid to flow between the two marks (A and B) was measured (*Figure* 1). The density of the same liquid at the same temperature was determined using a specific gravity bottle. This process was performed with distilled water, acetic acid

Figure 1. Ostwald viscometer (time taken by the liquid to flow between the two marks (A and B) was measured).

solutions (1%, 2%, 3%, 5%, 7%, and 10% v/v), and sugar solutions (1%, 2%, 3%, 5%, 7%, and 10% w/v) and finally, the viscosities of acetic acid and sugar solutions were determined at above-mentioned concentrations using time of flow, the density of liquid and (5).

Analysis of Variation of Viscosity with Temperature

The viscosities of acetic acid solutions (1%, 2%, 3%, 5%, 7%, and 10% v/v) and sugar solutions (1%, 2%, 3%, 5%, 7%, and 10% w/v) were determined with distilled water as reference liquid at different temperatures. The temperature of the solution was determined using a thermometer (least count 0.1°C). At that temperature, the time of flow between the two marks and density was measured using which viscosity was calculated. The temperature of the solution was then increased approximately 2°C above the recorded temperature by warming it in a beaker over a Bunsen burner. This solution was then taken in the viscometer, and its time of flow between the two marks was measured, and the density was also determined. After taking out the solution from the viscometer, the temperature of the solution was recorded again to calculate the viscosity value. Since the experiment was performed under usual laboratory conditions, the average of the above two temperatures (one before heating and the other after heating) were recorded to scale the impact of the increase in temperature on viscosity value, and the same liquid was heated at this average temperature to approximately 2°C above the recorded temperature. This process was performed with distilled water, acetic acid solutions, and sugar solutions at five different temperature values ranging between 20–42°C. (Temperatures higher than this were not considered keeping in mind the nature of liquids and generality of the proposed procedure for undergraduate laboratory experience). The viscosity of acetic acid and sugar solutions was determined using the time of flow, the density of the liquid, and (5).

Analysis of Effect of Different Intermolecular Forces of Interaction on Viscosity

Viscosity was determined using (5) for acetic acid (10% v/v), sugar solution (10% w/v), NaCl solution (10% w/v), NH_4Cl solution (10% w/v), and HCl solution (10% v/v) at 20–21°C using distilled water as the reference liquid.

Results and Discussion

This section describes the experimental results obtained from the experiment performed to determine the effect of change in concentration, temperature, and intermolecular forces of interaction on viscosity of different liquids.

Study of Effect of Change in Concentration on Viscosities of Sample Liquids

In the present study, Ostwald's viscometer was employed to determine the viscosities of acetic acid solutions (1, 2, 3, 5, 7, 10 (v/v %)) and sugar solutions (1, 2, 3, 5, 7, 10 (w/v %)) at temperature 21 °C. Here, distilled water was used as the reference liquid to calculate the absolute viscosity value of the sample liq-

Concentration of acetic acid (v/v %)	**Coefficient of viscosity** ($mPa.s$)
1	0.94
2	0.96
3	1.07
5	1.09
7	0.99
10	1.06

Table 1. Viscosity values obtained using Ostwald's viscometer for different concentrations of acetic acid solutions.

Concentration of sugar solution (w/v %)	**Coefficient of viscosity** ($mPa.s$)
1	0.96
2	1.07
3	1.00
5	1.09
7	1.25
10	1.29

Table 2. Viscosity values obtained using Ostwald's viscometer for different concentrations of sugar solutions.

uids using (5). The results are reported in *Table* 1 for acetic acid solutions and *Table* 2 for sugar solutions.

The viscosity values obtained for acetic acid and sugar solution are found to increase on increasing the concentration. This trend is in good correlation with the literature data. It is due to the presence of a larger amount of solute per volume that increases the resistance to the flow of solvent, hence, increasing the viscosity. It could also be due to an increase in the number of interactions with the increase in concentration. This result establishes that the viscosity of a liquid can be altered by varying its concentration. Also, the increase in viscosity with concentration is more prominent in the sugar solution attributing to the fact that the nature of solute plays an important role.

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Temperature range (°C) / Concentration ($v/v\%$)	20–22	26–28	30–32	36–38	40–42	
Average temperature (°C)	21	27	31	37	41	Standard Deviation
1	0.94	0.76	0.65	0.56	0.50	0.174
2	0.96	0.77	0.69	0.61	0.54	0.162
3	1.07	0.86	0.74	0.64	0.58	0.195
5	1.09	0.89	0.78	0.67	0.59	0.200
7	0.99	0.81	0.70	0.59	0.52	0.186
10	1.06	0.90	0.90	0.67	0.62	0.182
Standard deviation	0.063	0.060	0.089	0.045	0.046	

Table 3. Temperature variation and coefficient of viscosity ($mPa.s$) reported for acetic acid solutions of different concentrations.

Study of Effect of Change in Temperature on Viscosities of Sample Liquids

In this part of the experiment, the absolute viscosity value has been determined for the same solutions as considered in the first part of this study but at different temperatures. The temperatures of these different sample liquids were varied, and their viscosities were calculated using Ostwald's viscometer and (5). The different temperature ranges and the values of viscosity calculated (in $mPa.s$) are reported in *Table* 3 and *Table* 4 for acetic acid and sugar solutions, respectively.

A significant decrease in viscosity value is observed with an increase in temperature.

A significant decrease in viscosity value is observed with an increase in temperature. The decrease is observed for all concentrations of acetic acid and sugar solutions, respectively. This is due to the decrease in the intermolecular forces of attraction with increasing temperature. Furthermore, the rate of decrease in viscosity with an increase in temperature for all concentrations is found to be nearly the same as depicted by the slope for plots of viscosity vs. temperature (both acetic acid solutions and sugar solutions of different concentrations) (*Figures* 2(a) and (b)). (The chosen temperature value is taken as the average temperature range). The trend observed is nearly the same for different concentrations of acetic acid and sugar solutions.

Temperature range (°C) / Concentration (m/v%)	20–22	26–28	30–32	36–38	40–42	
Average temperature (°C)	21	27	31	37	41	Standard Deviation
1	0.96	0.79	0.69	0.58	0.52	0.175
2	1.07	0.88	0.74	0.65	0.59	0.193
3	1.00	0.83	0.72	0.61	0.55	0.180
5	1.09	0.90	0.78	0.67	0.60	0.194
7	1.25	1.00	0.86	0.73	0.65	0.237
10	1.29	1.01	0.98	0.80	0.70	0.226
Standard deviation	0.133	0.089	0.108	0.081	0.066	

Table 4. Temperature variation and coefficient of viscosity (*mPa.s*) reported for sugar solutions of different concentrations.

The graphical display of temperature and concentration variations indicates that temperature variation is a more dominating and contributing factor towards changing viscosity values compared to concentration variation. This is also depicted by standard deviation plots for temperature and concentration in *Figures* 3 and 4 for acetic acid and sugar solutions. It is also observed that the decrease in absolute viscosities is higher with an initial increase in temperature (17–20%), and as temperature rises, the decrease in viscosity value slows down (10–12%). This indicates that viscosity cannot be decreased beyond a certain point, thus providing a lower viscosity limit.

Study of Variation of Viscosity with Intermolecular Forces of Interaction

In this part of the experiment, the variation in viscosity values was investigated with respect to different intermolecular forces of interaction: hydrogen bonding, ion-dipole interactions, and dipole-dipole interactions. The viscosity of different solutions was determined using Ostwald's viscometer by the relative method using distilled water as the reference liquid in the temperature range 20–21°C. Two viscometers were used for viscosity determination in order to verify the precision of the observed data. The solutions

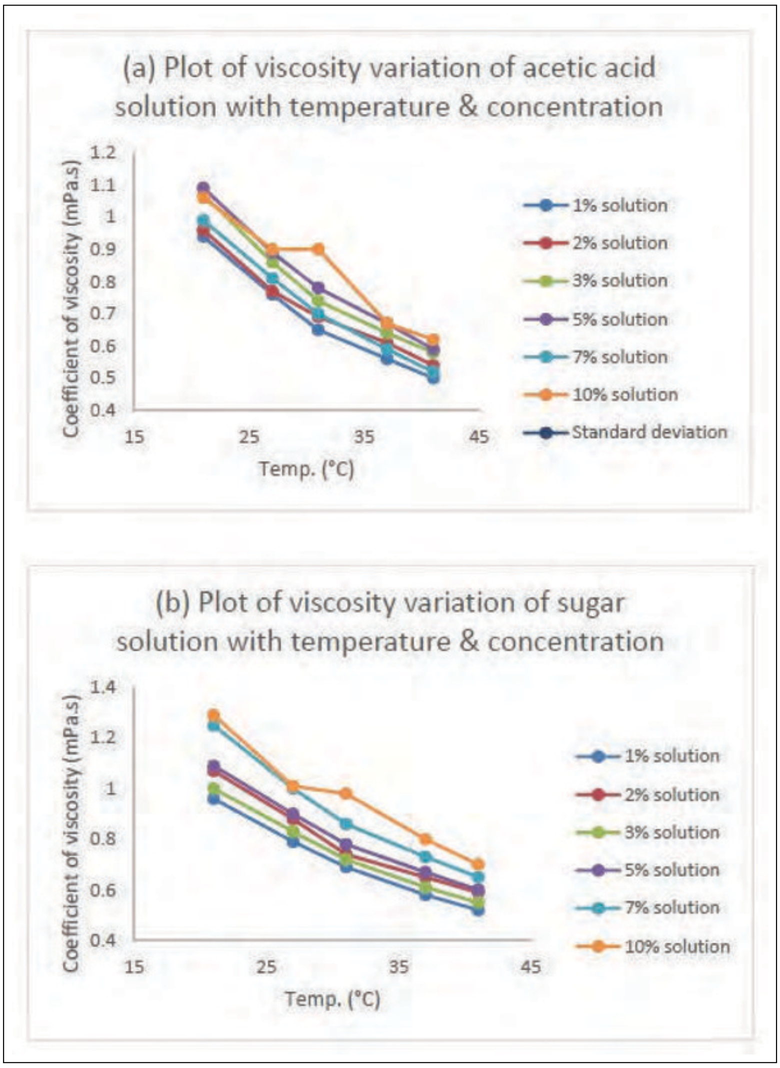


Figure 2. Variation of coefficient of viscosity with temperature for **(a)** different concentrations of acetic acid solution and **(b)** different concentrations of sugar solution.

used for the experimentation include acetic acid and sugar solutions (representative of H-bonding), NaCl and NH_4Cl solutions (representative of ion-dipole interactions), and HCl solution (representative of dipole-dipole interactions). The densities of various liquids were determined using a specific gravity bottle. The results obtained using different viscometers are reported in *Table* 5 for all the solutions.

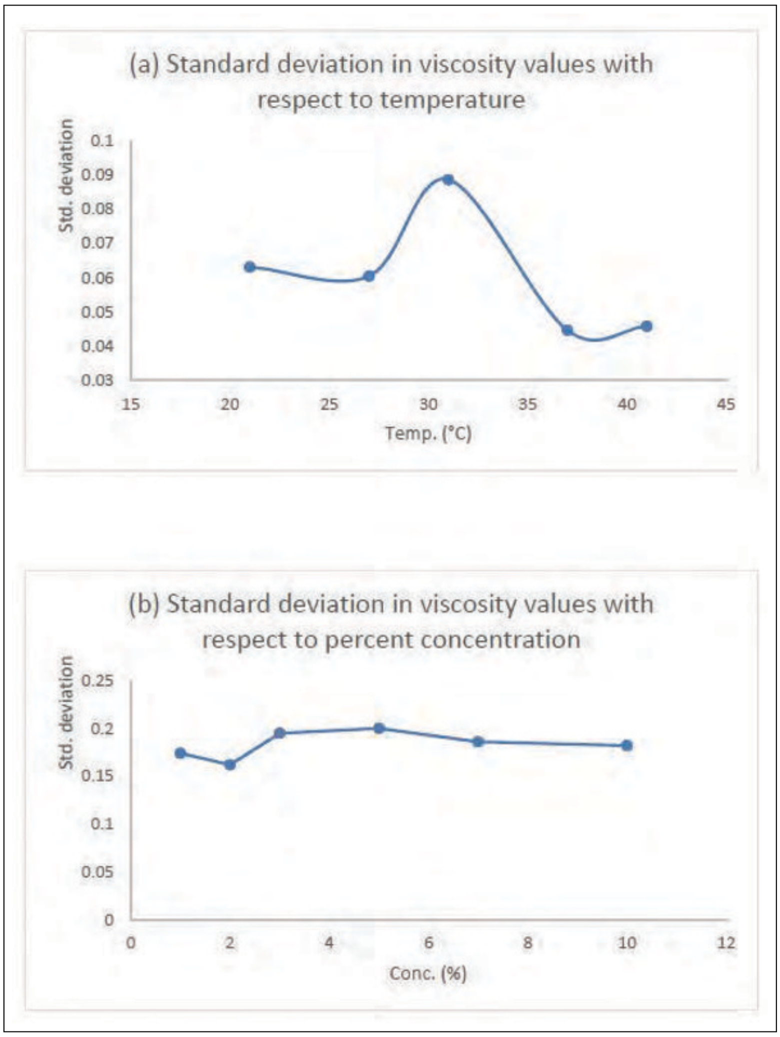


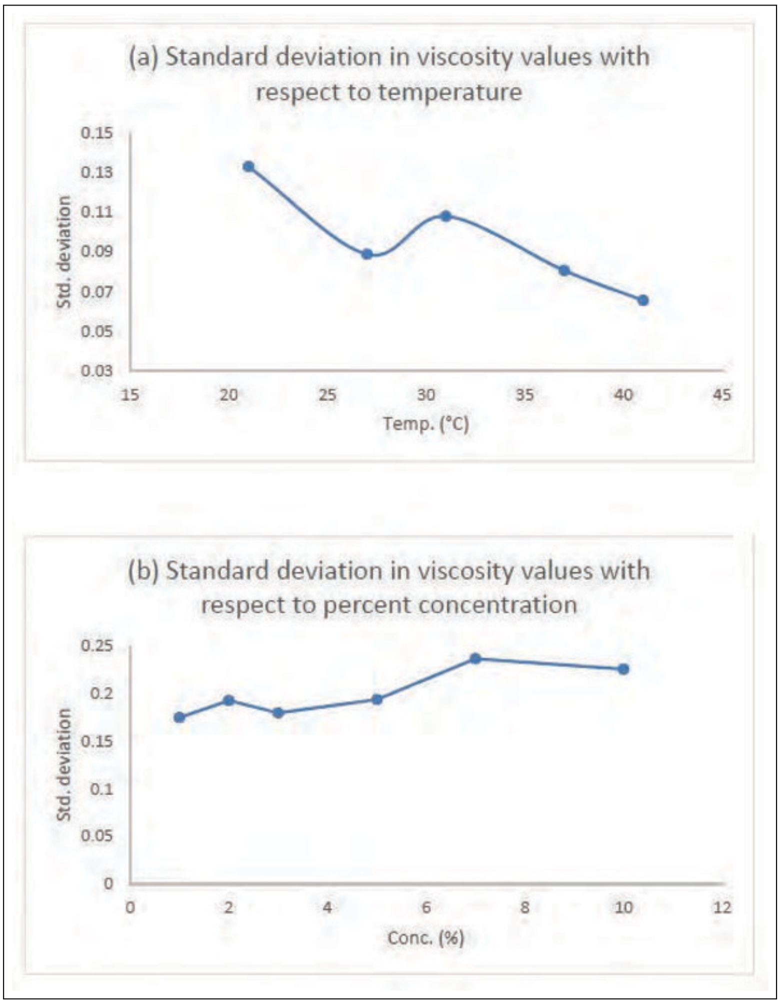
Figure 3. Plot of standard deviation in viscosity values with respect to **(a)** temperature and **(b)** concentration for acetic acid solutions.

From the data obtained in *Table* 5, it is observed that viscosity is minimum for HCl solution and maximum for sugar solution, while the viscosities of other liquids lie in between them.

From the viscosity comparison of NaCl and NH_4Cl solution with HCl solution, it is found that liquids with ion-dipole interactions have greater viscosities than liquids with dipole-dipole interaction, which is synchronous with the theoretical knowledge. This is because, in the case of ions and dipoles, a stronger Coulom-

From the viscosity comparison of NaCl and NH_4Cl solution with HCl solution, it is found that liquids with ion-dipole interactions have greater viscosities than liquids with dipole-dipole interaction.

Figure 4. Plot of standard deviation in viscosity values with respect to **(a)** temperature and **(b)** concentration for sugar solutions.



bic force of attraction exists between the particles compared to the attraction between the polar molecules, as ions have fully developed charges. Between solutions showing dipole-dipole interactions (HCl solution) and H-bonding (sugar and acetic acid solutions), it is observed that sugar solution and acetic acid solution have higher viscosities as H-bonding is stronger that dipole-dipole interactions. The comparison of viscosities of NaCl and NH_4Cl solutions with acetic acid and sugar solutions indicate viscosities higher for the latter, which is not in sync with the liter-

Interactions	**Solution** (v/v % **or** (w/v)% 10%	**Absolute viscosities** ($mPa.s$)	
		Viscometer I	Viscometer 2
Hydrogen bonding	Acetic acid	1.17	1.17
	Sugar solution	1.32	1.23
Ion-dipole interactions	NaCl solution	1.14	1.15
	NH_4Cl solution	0.95	1.05
Dipole-dipole interactions	HCl solution	0.82	0.83

Table 5. Coefficient of viscosity obtained for different solutions (at same concentration) exhibiting different intermolecular forces of interactions.

ature trend suggesting ion-dipole interactions to be stronger than hydrogen bonds. This signifies the dominance of another critical factor which is the molecular mass. Here, the high molecular mass factor outweighs the effect of intermolecular forces of attraction where H-bonding is weaker than ion-dipole interactions. It is mainly attributed to the high molecular mass of sugar (180 g/mol).

Out of NaCl and NH_4Cl, i.e., two liquids with similar interaction forces, NaCl has greater viscosity. This is attributed to its higher molecular mass (molecular mass of NaCl is 58.5 g/mol and of NH_4Cl is 53.5 g/mol). The same is true for acetic acid and sugar solutions in the category of hydrogen bonding. The viscosity is higher for sugar solution owing to its higher molecular mass compared to the acetic acid solution. Overall, the results very well indicate the dependence of viscosity of a liquid on the type of force of interactions that exist and the molar mass.

Out of NaCl and NH_4Cl, i.e., two liquids with similar interaction forces, NaCl has greater viscosity. This is attributed to its higher molecular mass.

Conclusions

In this article, we have drawn a comparative study of viscosity results with respect to concentration, temperature, and intermolecular forces of interaction using Ostwald's viscometer.

In the first part of the study, the viscosity values obtained for acetic acid ($v/v\%$) and sugar solutions ($w/v\%$) are found to increase with the increase in the concentration of solutions (from 1% to 10%). This is due to the presence of a larger amount of solute per volume and an increase in the number of interactions, thus increasing the resistance to the flow of the solvent.

In the second part of the study, a drastic decrease in viscosity is observed with an increase in temperature due to a decrease in intermolecular forces of attraction with the rise in temperature. The rate of decrease in viscosity with an increase in temperature for all concentrations was found to be nearly the same, indicating that temperature change is dominating over concentration change. This observation is of industrial use, as the viscosity of different liquids can be controlled by a change in temperature. Hence machinery can be protected as no high concentration liquid would be passed through it. The viscosity of a solution can be changed based on temperature without changing its concentration, thus consuming and disposing fewer chemicals. It was also observed that the decrease was higher with an initial increase in temperature. As further temperature increases, the rate of decline slowed down indicating that viscosity cannot be decreased beyond a certain point, thus providing a lower limit of viscosity for the development of machinery.

In the last part of this work, an increase in the strength of intermolecular forces of interactions is shown to result in increased viscosity. However, this effect was found to be dominated by another factor—greater molecular mass—because additional stronger van der Waal's forces come into play along with the existing Coulombic forces of attraction. Our group is exploring the impact of the above discussed factors on viscosity of other liquid solutions as well to give this effect a complete picture. Nonetheless, the trends reported in this article are synchronous with the literature trends.

The procedure presented in this study fits well as an extension to the existing laboratory exercise on the determination of viscosity. This method will help students appreciate the ability to investigate the variation of viscosity with concentration, temperature, and intermolecular forces of interaction with commonly available chemicals in university laboratories.

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Suggested Reading

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