



## Analysis of accuracy of burette in determination of surface tension of liquids and study of its variation with detachment time and inclination angle

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A simple laboratory experiment to measure the surface tension of liquids has been proposed in this work, which is well suited for any undergraduate laboratory demonstration. Burette with modified Tate's law has been found to return surface tension values as good as those obtained using Traube's stalagmometer. Experimental data and error analysis show similar result accuracy. Also, a comparative study brings to notice the exactitude of drop weight method over drop number method, both from stalagmometer and burette. The rate of flow of 11–23 drops per minute has been found to be highly suitable for minimization of errors due to evaporation and satellite drop formation. Angular dependence of surface tension has been proposed numerically and validated for the respective case with the angle of  $0^\circ$  to deviate the least from literature value. The results obtained in this study are synchronous with the established theoretical understanding of the concept.

**Keywords:** Burette, Chemistry laboratory, Drop, Liquids, Surface science, Surface tension, Tate's law, Traube's stalagmometer, Drop weight method

Liquids exhibit many properties which can only be explained in terms of the action at surface. Surface tension is one such important surface property that has been recognized for more than a century. At the liquid – air interfaces, the surface tension results from the greater attraction of liquid molecules to each other making them move towards the bulk than to the molecules in the air at the surface (Fig. 1a). Many everyday phenomena are a consequence of surface tension: shape of liquid droplets, formation of bubbles, sticking of rain droplets on windows, water striders sliding on water surface and many more. Surface tension of liquids is a crucial physical parameter in many industrial applications such as in printing; pharmaceuticals; cake & agglomeration; paper industry; oil recovery; formulation of creams, emulsions, inks, sprays and lubricants among others<sup>1-5</sup>. The surface tension of liquids is studied extensively in laboratories and industries for the reason that it influences the size of the liquid droplets<sup>6</sup>. It is, therefore, essential to accurately measure surface tension of liquids. Many approaches have been developed to measure the surface tension of liquids. These include drop weight method, capillary rise method, pendant drop method, Du Noüy ring method, Wilhelmy plate technique, maximum bubble pressure method, growing drop method, micro-pipette method and spinning drop method among others<sup>7-13</sup>. The

determination of surface tension of liquids is an important laboratory experiment for undergraduate students. The most common method employed for measuring surface tension in university laboratories is the drop weight method using Traube's stalagmometer<sup>12</sup>. Traube's stalagmometer is a specialized apparatus used for measuring the surface tension of liquids. In this study, we have used an inexpensive and conventional equipment, i.e. burette, which is available in most university laboratories for measuring surface tension. We have drawn a comparative study of the surface tension results as obtained from burette with those of Traube's stalagmometer.

The usage of a stalagmometer requires adjustment of rate of flow as the rate of flow influences the size of liquid droplet. Since, the rate of flow can easily be controlled using a burette, the same was used to analyze the variation of surface tension with detachment time in this work and the results were also compared with the conventional method outcomes. Also, the effect of inclination angle on surface tension of the liquid was studied using burette.

The proposed method in this study provides a simple and accurate experiment to measure the surface tension of liquids. This approach also helps in easy investigation of rate of flow and inclination angle of apparatus on surface tension. Such a method is suitable for any undergraduate laboratory demonstration.

## Materials and Methods

In this study, a burette has been used to determine the surface tension of 10% v/v acetic acid solution using drop weight method. This work is divided into three parts:— analysis of accuracy of burette in determination of surface tension of liquid using drop weight method and its comparison with stalagmometer method, study of variation of surface tension of liquid with detachment time using burette and study of variation of surface tension of liquid with inclination angle of burette.

### Surface tension measurement using Traube's stalagmometer

The drop weight method is based on the measurement of weight of the falling drop from the bottom of a vertical capillary tube<sup>12,14</sup>. This method is derived from the idea that the liquid drop falls from the end of the capillary tube when the force due to gravity equals the vertical force created by the surface tension of the liquid. According to Tate's law<sup>12</sup>, just before detachment of drop and under equilibrium conditions, the weight of the drop about to fall under the force of gravity equals the vertical component of force exerted by surface tension which is proportional to the wetted perimeter of the boundary between the liquid and the capillary tube (Fig. 1b). This is expressed as

$$mg = 2\pi r\gamma \quad \dots (1)$$

Where,  $m$  is the mass of the falling drop,  $g$  is the acceleration due to gravity,  $\gamma$  is the surface tension of liquid – air interface,  $r$  is the outer/inner radius (depending on the wetting behavior of the liquid) of the end of the capillary tube and  $2\pi r$  is the wetted perimeter of the interface. The drop falls from the tip of the capillary when its weight force ( $mg$ ) exceeds surface tension force ( $2\pi r\gamma$ ).

From Eqn (1), the surface tension of a liquid may be determined experimentally if exact mass of a

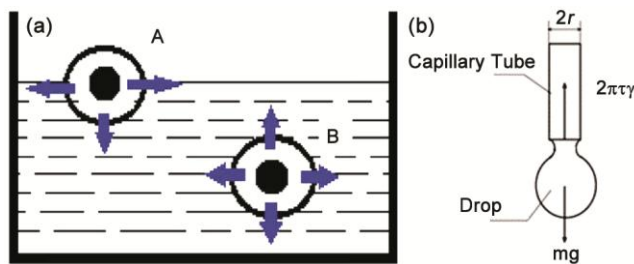


Fig. 1 — (a) Surface tension at the liquid-air surface: (A) liquid molecule at the surface experience a force normal to the surface downwards and (B) Molecule in the bulk experience no average resulting force due to equal pull in all directions; and (b) drop forming at the tip of the capillary. (Forces acting vertically upward and downward on the drop according to Tate's law)

single drop and wetted perimeter are known. When the liquid completely wets the bottom surface of the capillary, drop circumference can be taken to be the same as that of the tip of capillary. This assumption is valid only when the tip of the capillary is sharp edged or it has a clean ground flat surface. With this in place, a referral approach is followed to determine the surface tension of the given liquid without needing the measurement of wetted perimeter. If we have two liquids such that

$$m_1g = 2\pi r\gamma_1; m_2g = 2\pi r\gamma_2; \frac{m_1}{m_2} = \frac{\gamma_1}{\gamma_2} \quad \dots (2)$$

In this work, we used the reference liquid as distilled water with known surface tension to determine the surface tension of acetic acid solution using the drop weight method. The drop number method has also been employed to draw a comparative study. Drop number method is a comparative approach that works on the principle of counting the number of drops from equal volumes of the two liquids, respectively. With two different liquids, masses of equal volumes are proportional to their densities. With  $n_1$  and  $n_2$  as the number of drops produced from the same volume  $v$  of either of the two liquids, volume of single drop can be calculated.

$$\text{Volume of a single drop of liquid}_1 (v_1) = v/n_1 \quad \dots (2a)$$

$$\text{Volume of a single drop of liquid}_2 (v_2) = v/n_2 \quad \dots (2b)$$

Correspondingly, the mass of single drop can be obtained using density data.

$$m_1 = v_1 \cdot \rho_1 = \frac{v}{n_1} \cdot \rho_1 \quad \dots (2c)$$

$$m_2 = v_2 \cdot \rho_2 = \frac{v}{n_2} \cdot \rho_2 \quad \dots (2d)$$

Where  $m_1$  and  $m_2$  refer to the masses of a single drop of respective liquids.  $\rho_1$  and  $\rho_2$  refer to the densities of the respective liquids.

Using the mass of single drop of the respective liquids in Eqn (2), we get the expression for surface tension in terms of drop number method:

$$\frac{\gamma_1}{\gamma_2} = \frac{n_2 \rho_1}{n_1 \rho_2} \quad \dots (3)$$

Using the knowledge of density and surface tension for water, we calculated the surface tension of acetic acid solution using Eqn (3).

In the first part of the study, we have used Traube's stalagmometer (Fig. 2) and determined the surface tension using Eqns (2) and (3), respectively. Traube's stalagmometer works on the principle of Tate's law. It

consists of a capillary tube with a thick wall and a ground glass flattened end with sharp edges. The capillary tube functions to slow down the rate of flow of the liquid while the flattened tip helps in large well-formed drops. For drop weight method, mass of twenty drops of the respective liquid has been considered while for drop number method, the number of drops have been determined using same volume of the two liquids (same volume has been taken by etching marks above and below the bulb & counting the number of drops falling from upper etched mark to lower etched mark). The results are comparable to the literature values.

#### Drop weight method using burette and correction factor

The basic use of stalagmometer in drop weight method and drop number method is of a drop measurer. Using this idea, we propose in this work usage of a burette for performing the same task<sup>15</sup>. However, there are certain complexities associated with usage of burette with Tate's law.

Tate's law considers the ideal condition, i.e. the whole drop formed at the end of the capillary falls. This means that the falling drop has the same mass as that of the original drop that formed at the tip of the capillary obeying Tate's law. However, the experimental results diverge from this ideal assumption. The reason for divergence could be the nature of the liquid or the geometry of the capillary among others. It has been reported that up to 40% of

the drop volume may be left on the capillary tip and therefore, the weight of the detached drop is lower than that predicted by Tate's Eqn (3). To overcome this issue, a correction factor  $F^{16-18}$  is usually inserted in Tate's law which modifies Eqn (1) as,

$$mg = F \cdot 2\pi r \gamma \quad \dots (4)$$

Use of a burette for surface tension measurement brings in three points of concern: (i) stable drop formation; (ii) uniform pressure gradient and (iii) rate of flow. So, the correction factor must resolve these three issues. One accepted form of correction factor  $F$  published by Earnshaw et al.<sup>16</sup> relates the ratio of actual to ideal drop volume against the dimensionless capillary radius  $r/v^{1/3}$  as

$$F\left(r/v^{1/3}\right) = v_{actual}/v_{ideal} \quad \dots (5)$$

This factor  $F$  is adjusted to good range of accuracy by applying the mathematical fit proposed by Lee-Chan-Pogaku<sup>3</sup>, which is used in this paper,

$$F\left(\frac{r}{v^{1/3}}\right) = 1.000 - 0.9121\left(\frac{r}{v^{1/3}}\right) - 2.109\left(\frac{r}{v^{1/3}}\right)^2 - 13.38\left(\frac{r}{v^{1/3}}\right)^3 - 27.29\left(\frac{r}{v^{1/3}}\right)^4 + 27.53\left(\frac{r}{v^{1/3}}\right)^5 - 13.58\left(\frac{r}{v^{1/3}}\right)^6 + 2.593\left(\frac{r}{v^{1/3}}\right)^7 \quad \dots (6)$$

In the limit  $r/v^{1/3} \ll 1$ , Tate's law is recovered with  $F \rightarrow 1$  from Eqn (6).

In this part of the study using burette (Fig. 2), the surface tension of acetic acid solution is determined using original Tate's law and the corrected Tate's law and the results are compared to literature pertaining to stalagmometer method.

#### Experimental set-up

The apparatus used in this experiment are analytical balance, beaker (250 mL), burette (50 mL), clamp stand, tile, weighing bottle, specific gravity bottle, stop watch, stalagmometer and screw gauge. This paper deals with distilled water and 10% v/v acetic acid solution because they are inexpensive and commercially available liquids, and it is easy to find data in the literature of their physicochemical variables at different temperatures.

#### Analysis of accuracy of burette in determination of surface tension of liquid using drop weight method & its comparison with stalagmometer method

The surface tension of a given liquid was determined using the following methods with a stalagmometer.

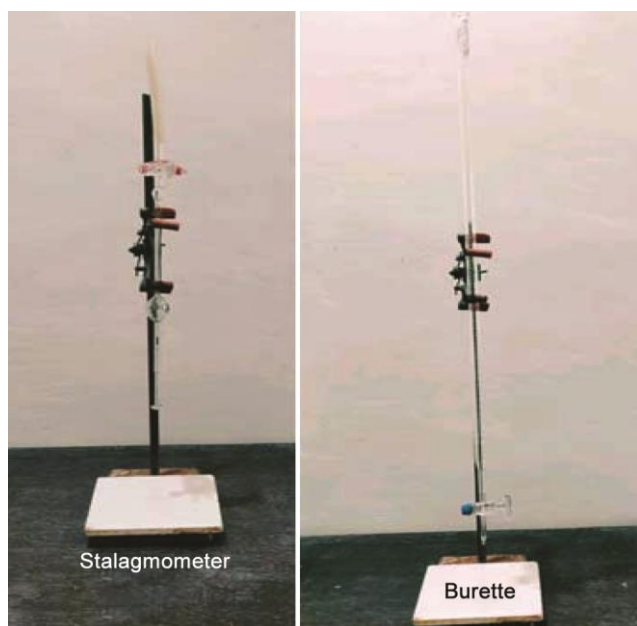


Fig. 2 — Stalagmometer and Burette set-up for determination of surface tension

**Drop Weight Method:** First the room temperature was measured. A clean and dry stalagmometer was clamped and filled with the liquid. The drop formation time was regulated slowly and the rate of flow was adjusted to 12 drops per minute for the set of liquids chosen in this study. 20 drops of the respective liquid was collected from the stalagmometer and weighed with an analytical balance. Then, average drop weight was calculated. This process was performed with distilled water and acetic acid solution, respectively and finally, surface tension of acetic acid is determined using Eqn (2).

**Drop Number Method:** The room temperature was measured. A clean and dry stalagmometer was clamped and filled with the liquid. Two marks were etched above and below the bulb of the stalagmometer. The number of drops falling between the etched marks were determined for the respective liquids. The density of the liquid was determined using specific gravity bottle. This process is performed with distilled water and acetic acid solution respectively and surface tension of acetic acid is determined using Eqn (3).

The same set of procedures was followed using a clean burette and the surface tension was determined using original Tate's equation (Eqns 2 & 3) and using corrected Tate's equation (Eqns 4, 5 & 6). For corrected Tate's equation, an additional step was performed, i.e. the outer radius<sup>19</sup> of burette's tip was measured using a screw gauge (The reason for using screw gauge was its easy availability in undergraduate laboratories).

***Study of variation of surface tension of distilled water with detachment time using burette***

For the study of variation of surface tension, a clean and dry burette was clamped vertically and filled with distilled water. The room temperature was

measured. The rate of flow was varied from 5 drops per minute to 26 drops per minute and its impact on surface tension was studied. Drop weight method was followed to determine surface tension using corrected Tate's law (Eqns 4, 5 and 6) in each case.

***Study of variation of surface tension of liquid with inclination angle of burette***

For studying this variation, a clean and dry burette was clamped vertically and filled with distilled water. The room temperature was measured. The angle which burette made with the vertical axis was changed from 0° to 75° (Fig. 3). Rate of flow has been set to 12 drops per minute in each orientation. Drop weight method is followed to determine surface tension using corrected Tate's law (Eqns 4, 5 and 6) for each orientation.

**Results and Discussion**

This section describes the experimental results obtained for the experiments performed to determine the surface tension using stalagmometer and burette under different set of conditions.

**Comparative study of the surface tension using stalagmometer and burette**

In the present study, we have employed drop weight method to determine the surface tension of 10% v/v acetic acid solution using both Traube's stalagmometer and burette. The rate of flow has been set to 12 drops per minute and the measurements have been performed at 17 °C temperature (This was the room temperature observed using laboratory thermometer). Eqn (2) has been used to determine the surface tension of acetic acid solution.

$$\gamma_{AA} = \frac{m_{AA}}{m_{water}} \gamma_{water} \quad \dots (7)$$

Since the drops formed are not always identical, average drop mass has been calculated using

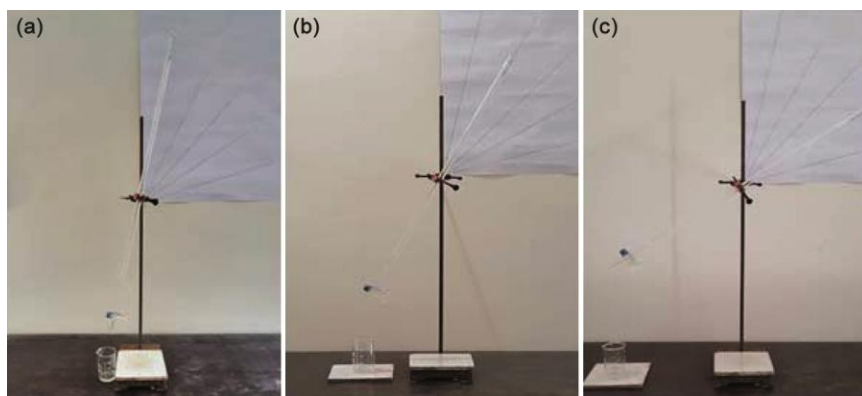


Fig. 3 — Photographs of different angle orientations using a burette

20 falling drops of the respective liquid. The drop masses obtained using stalagmometer and burette for distilled water and acetic acid solution, respectively are reported in Table 1.

Using the drop mass data as reported in Table 1, the surface tension of acetic acid has been calculated using Eqn (7) and is reported in Table 2. The surface tension of distilled water reported in literature at 17 °C is 0.0731 N/m. Clearly, the results in Table 2 indicate the supremacy of stalagmometer over burette. Stalagmometric results are found to be 1.01% more accurate than that obtained using burette. In order to verify, the measurements were performed based on drop number method (using Eqn 3) as well.

$$\gamma_{AA} = \frac{\rho_{AA} \cdot n_{water}}{\rho_{water} \cdot n_{AA}} \gamma_{water} \quad \dots (8)$$

The number of drops obtained using stalagmometer and burette for distilled water and acetic acid solution per fixed volume are reported in Table 3 along with the density obtained using specific gravity bottle. Using the data in Table 3, the surface tension of acetic acid has been calculated using Eqn (8) and has been reported in Table 4.

It is again inferred from Table 4 that a Traube's stalagmometer is more accurate in determination of surface tension of liquids than burette. The results bring to notice that the stalagmometric results are 0.92% more accurate than that obtained using burette.

Table 1 — Drop Mass data in grams obtained using stalagmometer and burette for distilled water and acetic acid solution, respectively

Parameter	Water ( $m_{water}$ )		Acetic acid (10% v/v) ( $m_{AA}$ )	
	Stalagmometer	Burette	Stalagmometer	Burette
Drop mass (g)	0.1372	0.0607	0.0987	0.0472

Table 2 — Surface tension for acetic acid solution  $\gamma_{AA}$  (N/m) obtained using drop weight method (Eqn 7) from stalagmometer and burette along with percentage error and percentage accuracy with respect to literature value of surface tension of 10% acetic acid solution at 17 °C (0.0543 N/m)

Apparatus	Stalagmometer	Burette
$\gamma_{AA}$ (N/m)	0.0526	0.0568
Error %	3.13	4.60
Accuracy% (100- error %)	96.87	95.40

Table 3 — Number of drops per fixed volume and density data obtained using stalagmometer and burette for distilled water and acetic acid solution, respectively

Parameters	Water		Acetic acid (10% v/v)	
	Stalagmometer	Burette	Stalagmometer	Burette
Number of drops per fixed volume ( $n$ )	83	17	118	22
Density (g/mL) ( $\rho$ )	1.2226	1.2225	1.2408	1.2409

Also, a comparative study drawn between drop weight method (Table 2) and drop number method (Table 4) brought to notice the exactitude of drop weight method over drop number method, both from stalagmometer and burette respectively.

The surface tension value obtained for acetic acid solution experimentally is very much similar to the literature value. So, using this literature value of surface tension of acetic acid solution, we attempt to account for the inaccuracy in the burette result by using it for determining the surface tension of water, minimizing the usage of chemicals. A correction factor as given by Eqn (6) is introduced in Tate's Law and the surface tension of liquid using burette is calculated following drop weight method and compared with that obtained using stalagmometer. To calculate the correction factor, outer radius of tip of burette is measured using a screw gauge and its value is found to be 2.02 mm. The literature value of surface tension of 10% v/v acetic acid solution at 17 °C is 0.0543 N/m. The mass of water drop is taken from Table 1 and the value of  $F$  so calculated using Eqn 6 is obtained as 0.62. The surface tension obtained using this correction factor  $F$  is reported in Table 5.

From Table 5, it has been found that the burette results with correction factor are as good as obtained using stalagmometer. In fact, burette gains more accuracy in determination of surface tension on introduction of the correction factor. This result establishes the use of burette appropriate in place of more sophisticated apparatus for determination of surface tension of liquids in university laboratories.

#### Analysis of variation of surface tension of distilled water with detachment time using burette

Since the results obtained from burette using correction factor are as good as those obtained using stalagmometer, it is employed to study the variation of rate of flow on surface tension of water using drop weight method. The advantage of using a burette is easy control over rate of flow using knob which is not so convenient while using a stalagmometer. The rate of flow is varied from 5 to 26 drops per minute at 17 °C temperature in this study. In each respective

setting, 20 drops of the liquid are collected and weighed. The measurements so obtained in each case are shown in Table 6 along with surface tension values using correction factor and absolute deviation.

Fig. 4 displays the variation of absolute deviation in surface tension values with respect to variation in rate of flow. The absolute deviation is significantly high initially but it decays rapidly with increase in rate of flow. Moreover, it is observed that the value of absolute deviation attains a nearly constant value in the flow range 11–23 drops per minute. The shape of the curve also indicates that for appropriate surface tension measurements using burette, the rate of flow must be kept in a range of 11–23 drops per minute where the graph is nearly smooth. The molecular interpretation for choosing such a flow range can be done on the basis of the following two effects:

- Evaporation effect – When the rate of flow is very small, the drop takes much time for its complete formation. In the case of volatile liquids and aqueous solutions, evaporation of the liquid from

its surface could well be a reason for the error that has occurred. This is evident from the increasing absolute deviation on moving from a high rate of flow to a low rate of flow.

- Satellite drop formation – When the drop falls, there is formation of a small satellite drop as well which adds up to the weight of the drop in the weighing bottle (Fig. 5). So, the average mass of the drop increases with increase in rate of flow and this accumulation of satellite drop in the primary drop may lead to experimental error.

The impact of rate of flow on surface tension values can be discussed as follows:

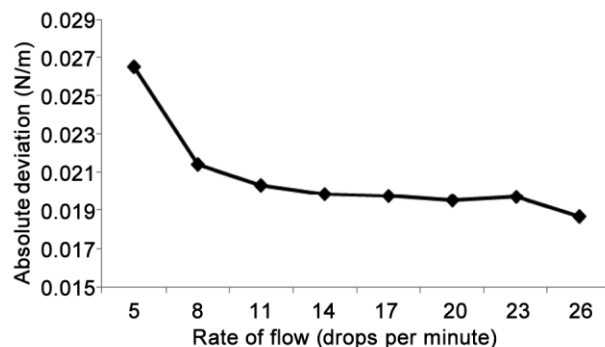


Fig. 4 — Plot of absolute deviation in surface tension value with variation in rate of flow

Table 4 — Surface tension for acetic acid solution  $\gamma_{AA}(N/m)$  obtained using drop number method (Eqn 8) from stalagmometer and burette along with percentage error and percentage accuracy

Parameters	Stalagmometer	Burette
$\gamma_{AA}(N/m)$	0.0522	0.0573
Error %	4.22	5.14
Accuracy% (100- error %)	95.78	94.86

Table 5 — Surface tension for water  $\gamma_{water}(N/m)$  obtained using drop weight method from stalagmometer and burette (using correction factor) along with percentage accuracy (Literature value of  $\gamma_{water}$  at 17 °C is 0.0731 N/m)

Apparatus	Stalagmometer $\gamma_{water} = \frac{m_{water}}{m_{AA}} \gamma_{AA}$	Burette $\gamma_{water} = \frac{m_{water}g}{2\pi r F}$
$\gamma_{water}(N/m)$	0.0758	0.0756
Accuracy %	96.31	96.59

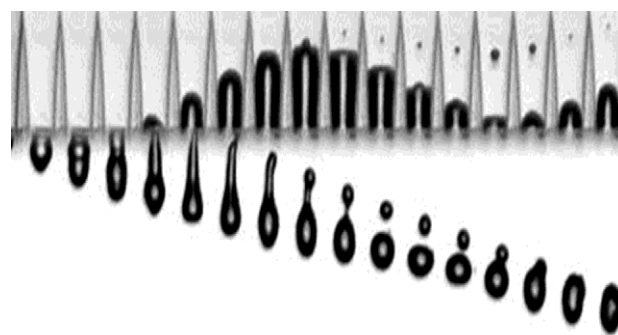


Fig. 5 — View of satellite drop formation

Table 6 — Variation in mass of drops and surface tension of water with different rates of flow using a burette. Absolute deviation also reported from literature value

Rate of flow (drops/min)	Mass of 20 drops of distilled water (g)	Mass of one drop of distilled water (g)	$\gamma_{water} = \frac{m_{water}g}{2\pi r F}$	Absolute Deviation (N/m) $ \gamma_{water} - 0.0731 $
5	0.7478	0.0374	0.0466	0.0265
8	0.8298	0.0415	0.0517	0.0214
11	0.8467	0.0423	0.0527	0.0204
14	0.8543	0.0427	0.0532	0.0199
17	0.8560	0.0428	0.0533	0.0198
20	0.8600	0.0430	0.0536	0.0195
23	0.8566	0.0428	0.0533	0.0197
26	0.8740	0.0437	0.0545	0.0186

Table 7 — Variation in mass of drops and surface tension of water with different inclination angles of a burette. Absolute deviation also reported from literature value

Angle of inclination (°)	Mass of 20 drops (g)	Mass of one drop (g)	$\gamma_{water}$ (N/m)	Absolute deviation (N/m) $ \gamma_{water} - 0.0724 $
0	0.9146	0.0457	0.0569	0.0155
15	1.0047	0.0502	0.0625	0.0099
30	1.1195	0.0560	0.0698	0.0026
45	1.1956	0.0598	0.0745	0.0021
60	1.2272	0.0614	0.0765	0.0041
75	1.3145	0.0657	0.0819	0.0095

Case I: Low rate of flow (less than 10 drops per minute) – The drop in this case takes considerable time to form at the tip of the capillary. As a result, the evaporation effect dominates the liquid-air interface and at such low rates almost no jetting occurs (that means satellite drop formation is negligible). For this reason, extremely low rates are avoided under room temperature and higher temperature conditions.

Case II: Comparatively higher rate of flow (11–23 drops per minute) – At low rate of flow, volume of the primary drop formed is high (complete formation) in comparison to that formed at high rate of flow. This erroneous decrease in drop volume gets compensated by increasing satellite drop formation on increasing the rate of flow. This balancing of effects result in range of 11–23 drops per minute as the most appropriate rate of flow for performing the experiment with minimum external intrusions.

Case III: High rate of flow (more than 23 drops per minute) – Due to excessive jetting, mass of falling drop increases because of satellite drop formation which may result in experimental errors. Because of this predominance of satellite drop formation, high rate of flow is avoided.

Hence, a range of 11–23 drops per minute is well suited for experimental determination of surface tension of liquids with minimization of errors due to evaporation and satellite drop formation.

#### Analysis of variation of surface tension of water with inclination angle of burette

In this part of the experiment, the impact of vertical inclination of burette on surface tension of water has been analyzed using drop weight method. The surface tension of water is determined by varying the vertical inclination of burette from 0° to 75°. The results obtained are reported in Table 7. The experiment was performed at 22° with literature value of surface tension of water as 0.0724 N/m.

Considering the vertical position as 0°, the burette has been inclined at various angles with respect to the

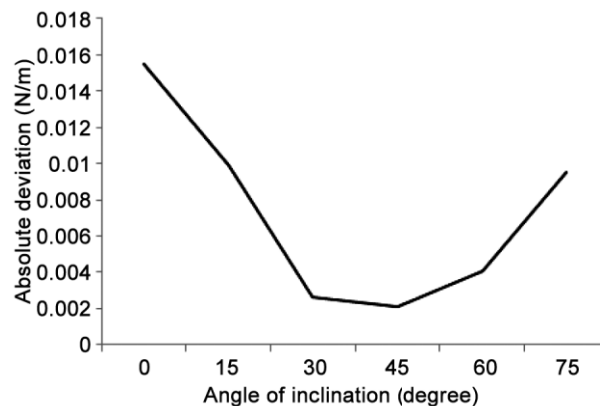


Fig. 6 — Plot of absolute deviation in surface tension value with variation in angle of inclination

vertical position, namely 0°, 15°, 30°, 45°, 60° and 75°, respectively. It has been observed that the mass of drop increases with an increase in the angle of inclination of the burette. This is because with an increase in the angle of inclination, the drop formed shifts from the end of the capillary tube to the outer wall of the burette due to the force of adhesion between the glass walls and the water droplet. More and more drops get accumulated in a single drop. As a result, this effect becomes prominent at higher angle which leads to erroneous values. This behavior is also expected because as the angle is increased, the rate of flow becomes more and more disturbed which results in incorrect measurements. However, calculation of absolute deviation gives a different picture altogether as it gives minimum deviation corresponding to inclination angle of 45°. This is even evident from Fig. 6 where the deviation in surface tension is found to be maximum at 0°. This is contrary to the theoretical understanding. This variation in the experimental observation and the expected behavior is because angular dependence has not been incorporated into the correction factor  $F$ .

To account for this angular dependence, the correction factor  $F$  has been modified by our group incorporating angle variation as

Table 8 — Calculation of surface tension of water at different inclination angles of a burette using Eqn 10. Absolute deviation also reported from literature value

Angle of inclination (°)	$\left[\left(\cos\left(\frac{2\pi}{360}\theta\right)\right) - 0.2\right]$	$\gamma'$ (N/m)	Absolute deviation' (N/m) $ \gamma_{water} - 0.0724 $
0	0.8000	0.0711	0.0013
15	0.7659	0.0816	0.0092
30	0.6660	0.1048	0.0324
45	0.5071	0.1469	0.0745
60	0.3000	0.2550	0.1826
75	0.0588	1.3929	1.3205

$$F' = \frac{F}{\left[\left(\cos\left(\frac{2\pi}{360}\theta\right)\right) - 0.2\right]} \quad \dots (9)$$

The angle  $\theta$  is in degrees and  $F'$  represents the modified correction factor incorporating the angle variation in Eqn (9). This equation has been derived from the trends obtained in deviation with angular variation as shown in Table 7. The deviation reaches a minimum on moving from 0° to 45° and so does  $\cos \theta$  as  $\theta$  varies from 0° to 45°. This indicates an inverse angular dependence in correction factor. The factor 0.2 in Eqn (9) has been chosen to best fit to the literature data of surface tension of distilled water and therefore, is referred to as best fit value. This angular dependence modifies Eqn (4) as

$$mg = F' \cdot 2\pi r \gamma' \quad \dots (10)$$

The calculations of surface tension and deviation obtained using Eqn (10) are shown in Table 8. The trend obtained for absolute deviation in surface tension using Eqn (10) with variation in angle of inclination is shown in Fig. 7. It clearly depicts that the angle of 0° deviates the least from literature value. The percentage error in surface tension for 0° position is ~3.4% which is well in the limits. While, the value of surface tension deviates the maximum from literature value at higher angles i.e. 60° and 75°. This indicates the Eqn (9) so devised to account for angular dependence very well demonstrates the reason for keeping the burette in almost vertical position to get the most accurate results. The result so obtained at 22 °C holds true under other normal temperature conditions as well. Hence, the Eqn (9) validates the theoretical basis for keeping the apparatus in the vertical position following drop weight method for determination of surface tension and stands accepted for the respective case.

**Conclusions**

In this paper, we have drawn a comparative study of the surface tension results obtained using burette

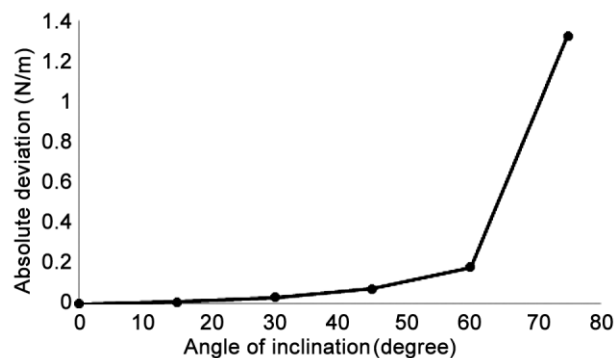


Fig. 7 — Plot of Absolute deviation' in surface tension value with variation in angle of inclination obtained using Eqn (10).

with that obtained from Traube’s stalagmometer using drop weight method. Additionally, the variation in surface tension has been analyzed with respect to detachment time of drop and inclination angle of apparatus respectively. The surface tension values obtained using modified Tate’s law for burette are as good as those obtained using Traube’s stalagmometer. In fact, burette gains more accuracy on introduction of the correction factor. Hence, we conclude that the use of burette is appropriate for determination of surface tension of liquids in university laboratories. Also, a comparative study of drop weight method and drop number method brings to notice the exactitude of drop weight method over drop number method, both from stalagmometer and burette respectively. The variation in detachment time has been found to influence the surface tension values. The least deviations have been observed for the rate of flow of 11–23 drops per minute. The results obtained indicate this rate of flow highly suitable for minimization of errors due to evaporation and satellite drop formation. Another variation of inclination angle brought to notice that the angle of 0° deviates the least from literature value while maximum deviation has been obtained at higher angles. The Eqn (9) proposed validates the angular dependence of surface tension following drop weight method and stands accepted for the case studied.



Our group intends to generalize the angular dependence equation for surface tension by studying and tabulating the surface tension of various liquids. The results obtained in this study are synchronous with the established theoretical understanding of the concept. The proposed method using burette with modified Tate's law provides a simple and accurate laboratory experiment to measure the surface tension of liquids. This approach also helps to easily investigate the variation of rate of flow and inclination angle of apparatus on surface tension. The procedure presented fits well not only for any undergraduate laboratory demonstration but can even be useful for research work.

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