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Article

Formation and sticking of air bubbles in water in d-block containers

Gaurav Gupta[1], Md. Laraib Salam[2], Dr. Arunabha Adhikari[3]
[1] Kendriya Vidyalaya No.1 AFS Kalaikunda, West Bengal, India.
[2] Air Force Golden Jubilee Institute, New Delhi, India.
[3] West Bengal State University, West Bengal, India.

SUMMARY
Bubble formation is a common observation encountered on a daily basis. Although bubble formation takes place in all kinds of containers, containers made of d-block elements such as copper and steel present a specific phenomenon. The water bubbles stick to the walls of the container after formation and show a high mechanical and structural stability. In this study, we aimed to improve our understanding of the formation of bubbles that result from pouring water. We hypothesized that interstitial hydrogen present in the d-block metals form hydrogen bonds with the water bubbles accounting for the structural and mechanical stability. To test this, we poured water in containers of different cross-sectional areas and different materials from different heights. We also varied the temperature of water. Through these experiments, we found mathematical relations to predict the number of bubbles forming at different initial conditions and the force of H-bonding between the interstitial hydrogen and the water bubbles.

INTRODUCTION
When water is poured in a container from a certain height, the water falls as a turbulent stream on the container's surface, initially colliding with the empty bottom of the container. Then, the water settles as a thin layer and the later stream collides with the stable thin layer of water. The inelastic collision of the stream and the surface results in the displacement of the surface water. The collision creates a vacant space and a low-pressure region at the site of collision, which is filled by air. As the displaced water moves again towards the region to attain equilibrium, it also traps the air already present in the region. This leads to the formation of air bubbles.

As the collision is inelastic in nature, most of the energy of the falling water is lost. Water drops falling normally on the surface lose about 90%–95% of their energy (1). So, it can be estimated that the net usable energy is about 5%–10% of the original kinetic energy. This net usable energy is converted to surface energy and kinetic energy of the bubbles. The bubbles formed are of different sizes and their diameter usually varies from 0.1 mm to 10 mm.

After formation, the bubbles rise up towards the surface, ultimately bursting. The density of the water bubble is lower than that of the surrounding water particles. If a material has low density compared to that of its surrounding, it will experience an upward thrust which will result in the surfacing of the material spontaneously. This explains the rising of bubbles to the surface of the water.

In this study, we were interested in determining why bubbles stick to walls of containers made of copper and steel (d-block metals) and show high stability there compared to bubbles in containers made of other materials. Copper and iron in the form of steel are transition metals commonly used to make cookware and tableware (2). Transition metal atoms are bound to themselves through the metallic bonding which gives rise to the interstitial spaces in their crystalline structures (3). These interstitial spaces can be occupied by small atoms. In this case, hydrogen atoms are usually present in these interstitial spaces in both copper and steel crystalline structures (4,5).

With this knowledge, we devised our hypothesis that the H-atoms present in the interstitial spaces form H-bonds (an intermolecular force that is formed between a H-atom and any other highly electronegative atom such as oxygen, nitrogen and fluorine) with water bubbles that collide with the wall during their journey towards the surface. The H-bond, being one of the strongest chemical bonds, would account for the structural and mechanical stability of the water bubbles sticking to the wall (6).

The bubble maintains its stability by self-adjusting the force of hydrogen bonding by varying its radius of contact. This maintains equilibrium by balancing the force vectors of hydrogen bonding and the force generated by the pressure inside of the bubble *(Force = Pressure * Area)*. Therefore, to understand this phenomenon better, we can imagine the water bubble as a party balloon. Pressing the balloon against a rigid wall simulates the described phenomena at a macro level. The force applied by the hand is changing the shape of the balloon (here the force applied by hand is equivalent to the force of pressure applied by the water and the force of hydrogen bonding). One noteworthy point is that from the point of view of the air bubble, the force due to the inside pressure is constant and the bubble has only one option left to maintain its stability by varying its radius of contact to adjust the force of hydrogen bonding.

Another question that arises is why this phenomenon of interaction of bubbles with the sidewall is not seen throughout the whole container's wall? This question can be answered using collision theory (7). This theory states that not all the collisions between reactant molecules are effective. There are many factors contributing to a perfect collision like orientation barrier, energy barrier, etc. Thus, only a few bubbles find that precise collision circumstance and attach to the sidewalls while others rush to the top or burst in the process.

Based on the collision theory, we can deduce the following factors which contribute towards a perfect collision resulting in the sticking of bubble to the wall (7). As the kinetic energy of the water bubble increases, the chances of the bubble hitting the walls increases. This means that more bubbles will be sticking to the walls according to the collision theory. The kinetic energy can be altered by changing the height of falling water and temperature of the water. The geometry of the container also affects the chances of collision of bubbles with the wall. Thus, the hypothesis and the derived mathematical relations can be tested by calculating the number of bubbles forming in different initial conditions (i.e. different height of falling water, water at different temperatures and different geometry of container). A change in the number of bubbles sticking to the wall with alterations in the described conditions shows that the number of bubbles forming changes depending on the described initial conditions. It will also show that a chemical bond is being formed between the water bubble and the interstitial H-atoms of the wall, thus supporting our hypothesis and mathematical relations. Later, we conducted the described experiments and derived the mathematical relations. The experiment results satisfied our hypothesis and the derived mathematical relations.

RESULTS

In order to understand the formation of the bubbles, we generated mathematical formulas to explain the phenomenon for the number of bubbles formed and the force of hydrogen bonding. We then tested our hypothesis and the derived mathematical relations through four experiments. We calculated the number of bubbles sticking to the walls of the test container in different initial conditions (i.e. different height of falling water, water at different temperatures and different geometry of container) under the experiment.

Calculation of Number of Bubbles

The number of bubbles formed can be predicted and roughly calculated with basic mathematics and mechanics. The following three assumptions were made for the sake of simplicity in derivation of the mathematical relations: 1) the size of all the bubbles formed is equal, 2) the water is assumed to be an ideal fluid, and 3) viscous force is neglected. Let *h* be the height of the falling water, '*m*' be the mass of the falling water, '**σ**' be the surface tension of the water, '*A*' be the change in area, '*r*' be the radius of the bubble, '*n*' be the number of bubbles formed, **'ρ'** be the density, '*e*' be the fraction of usable energy in the total energy, 'm_b' be the mass of the bubble, and 'v_b' be the velocity of bubble moving up.

The free body diagram of the bubble is shown in **Figure 1A** where the two forces acting on the bubble are its weight and the upward thrust. The upward thrust is responsible for accelerating the bubble to the surface against gravity.

Since we are ignoring the viscous force and water is assumed to be ideal, we can rule out any kind of loss of energy due to the viscous force. As a result, using the law of conservation of energy we have the following relation:

Kinetic energy (K.E.) of falling water = Gravitational potential energy of the water (mgh)

The kinetic energy of falling water height decreases by a factor 'e' due to the inelastic collision of water stream with the surface as described earlier. The energy of bubbles is comprised of the energy used for the formation of the bubble and its kinetic energy inside the water.

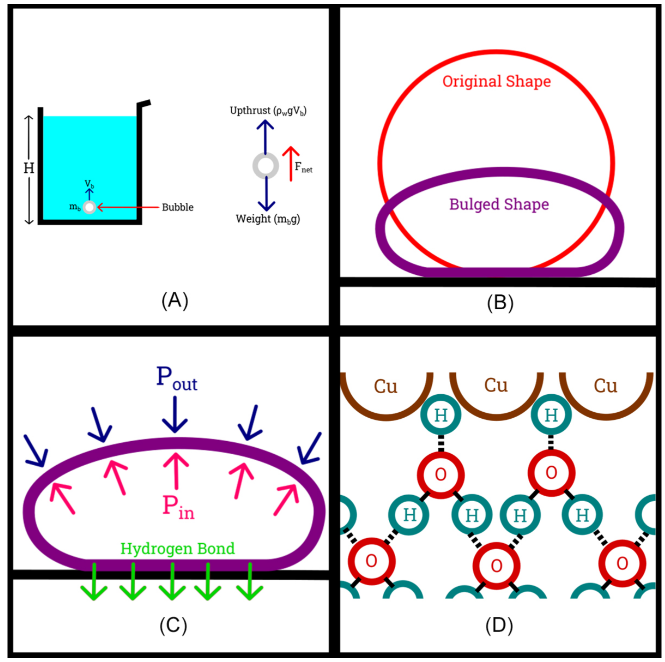

Figure 1: Physical properties of water bubbles. (A) Free Body Diagram of a bubble inside a container after its formation. An upward force is acting on the bubble and its own weight is acting downwards. The net force on the bubble is upwards while moving up to the top. (B) Original shape versus bulged shape of the bubble. The change in shape of the bubble as it interacts with the wall where the H-Bond pulls the bubble towards the wall so as to reduce the surface energy of the bubble. We can imagine the bubble as a party balloon and if we push the balloon against a wall, a distortion in the shape of bubble takes place. This demonstrates the change in shape of the bubble as it interacts with the wall. (C) The various forces inside and outside the bubble in which the H-Bond force is pulling the bubble towards the wall. The H-Bond force and pressure outside the bubble balance the pressure inside the bubble. (D) A representation of the chemical bonding between the water molecule and the Interstitial-H stuck in between the copper atoms of the wall. It explains how the oxygen atom of the water molecule forms a H-Bond with the interstitial H present in between the spaces of Cu atoms.

K.E. of falling water = Energy of bubbles

$$emgh = n\left(\sigma(\Delta A) + \frac{1}{2}m_b {v_b}^2\right)$$

$$\Rightarrow emgh = n\left(\sigma\left(A_f - A_i\right) + \frac{1}{2}m_b {v_b}^2\right)$$

$$\Rightarrow emgh = n\left(\sigma(\pi r^2 - 0) + \frac{1}{2}m_b {v_b}^2\right) \quad [\because\ A_i = 0\,]$$

$$\textbf{Equation i} \Rightarrow emgh = n\left(\sigma\pi r^2 + \tfrac{1}{2}m_b {v_b}^2\right)$$

After the formation of the bubble, the bubble moves downwards due its kinetic energy. An upward thrust force also acts on the bubble which slows down the bubble and ultimately stopping it. The upward thrust can be calculated to provide us the work done by upward thrust, because the kinetic energy of the bubble is converted to the work done by upward thrust. We can calculate the kinetic energy of the bubbles formed with the following equations:

Net force on the bubble while rising up to the top →

$$F_{net} = \rho_w V_b g - \rho_b V_b g$$

$$\Rightarrow F_{net} = V_b g(\rho_w - \rho_b)$$

Using Work - Energy theorem →

$$F_{net} H = \frac{1}{2} m_b {v_b}^2$$

$$\Rightarrow V_b g H(\rho_w - \rho_b) = \frac{1}{2} m_b {v_b}^2$$

Equation ii $\Rightarrow \frac{4}{3}\pi r^3 g H(\rho_w - \rho_b) = \frac{1}{2} m_b {v_b}^2$

From the above formulated equations (i) and (ii), we can formulate,

$$n\left(\sigma\pi r^2 + \frac{4}{3}\pi r^3 g H(\rho_w - \rho_b)\right) = emgh$$

$$\Rightarrow n\left(\frac{3\sigma\pi r^2 + 4\pi r^3 g H(\rho_w - \rho_b)}{3}\right) = emgh$$

Equation iii $\Rightarrow n = \frac{3emgh}{3\sigma\pi r^2 + 4\pi r^3 g H(\rho_w - \rho_b)}$

Therefore, the number of bubbles formed in a container depends upon several factors. The core factor is the height from which we suspend the water into the container. The factors affecting the number of bubbles are the mass of the falling water (*m*), height of falling water (*h*), surface tension of the water (σ), radius of the bubbles formed (*r*), height of the water in the container (*H*), density of water (ρ_w), and density of bubble (ρ_b).

Calculation of Force of Hydrogen Bond

With the use of simple mechanics, we can calculate the force of the hydrogen bonding of the air bubble. Here, '*h*' refers to the depth of the air bubble from the top of the container and 'P_o' refers to atmospheric pressure. In the following example, we assumed '***h***' to be 0.1 m, '$\boldsymbol{\sigma}$' to be 0.075 N/m and '$\boldsymbol{\rho}$' to be 1000 kg/m^3. The physical and chemical interactions in work during the sticking of bubbles to the wall is represented in **Figure 1B-D**.

$$F_{HB} = P_{in} A$$

$$\Rightarrow F_{HB} = (P_{out} + \frac{2\sigma}{R})A$$

$$\Rightarrow F_{HB} = (\frac{2\sigma + P_{out}R}{R})A$$

$$\Rightarrow F_{HB} = (\frac{2\sigma + P_{out}R}{R})\pi R^2$$

(Here A = πR^2, since the area of bubble in contact with wall is a circle of radius R)

$$\Rightarrow F_{HB} = (2\sigma + (P_0 + \rho g h)R)\pi R$$

$$\Rightarrow F_{HB} = 2\sigma\pi R + (P_0 + \rho g h)\pi R^2$$

We calculated the P_{out} for a particular case, where "***h***" = 0.1 m and P_0 is the atmospheric pressure. The calculated value was used to obtain the parabolic graph in **Figure 2** which explains the quadratic relation of F_{HB} and *R*. We varied the radius of the bubble from the 0.1 mm to 10 mm.

$$P_{out} = P_0 + \rho g h$$

$$\Rightarrow P_{out} = P_0 + (1000\ kg\ m^{-3}) * (9.8\ ms^{-2}) * (0.1\ m)$$

$$\Rightarrow P_{out} = (101325 + 980)\ N\ m^{-2}$$

$$\Rightarrow P_{out} = 102305\ N\ m^{-2}$$

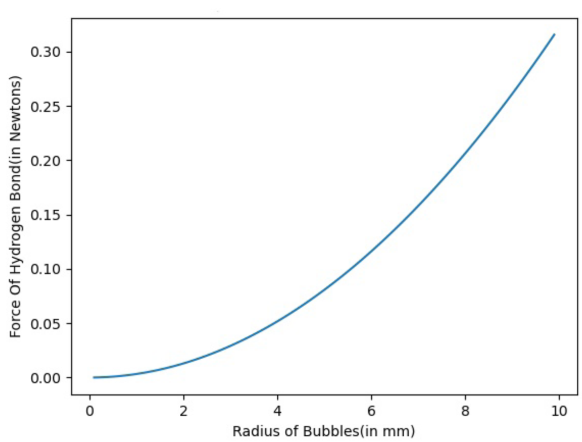

Figure 2: Force of H-Bond between the bubble and the radius of the bubble. A parabolic graph between the force of H-Bond between the bubble and radius of bubble computed using the derived mathematical formulation. The x-axis represents the radius of bubble (mm) while the y-axis represents the force of H-Bond (N).

Graph of Number of Bubbles versus Height of Suspension of Water

We predicted the number of bubbles increases with the height from which the water is suspended into the container under different conditions using the formulated equation of number of bubbles in the previous section. We altered the mass of the falling water from 1 g to 100 g and the radius of the bubble from 0.1 mm to 10 mm (**Figure 3**).

Assessment of Experimental Observations

We conducted four different experiments to test our hypothesis and derived mathematical relations. In each of the experiments the number of bubbles sticking to the wall of the container was counted. The quantitative determination of the exact number of bubbles formed during the pouring of experiment is indefinite. The number of bubbles sticking to the walls depends on the total number of bubbles formed and counting them was considerably easy, so a comparison can be drawn between different experiments and initial conditions. In the first experiment, we calculated the number of bubbles sticking to the wall when water is suspended from different heights. We not only observed an increase in the number of bubbles sticking to the walls when increasing the height of the falling water, but we also saw the radius of bubbles sticking to the wall increase (**Table 1**, **Figure 4**). In **Equation iii**, the height of the falling water is directly proportional to the number of the bubbles formed and the results from experiment 1 validate it as well as the hypothesis.

In the second experiment, we calculated the number of bubbles sticking to the wall when the temperature of the falling water was altered. We observed an increase in the number of bubbles with the increase in the temperature of the falling water (**Table 2**). In our hypothesis, we mentioned that the kinetic energy of the water is directly proportional to the number of bubbles forming and sticking to the walls based on the collision theory. Also, the alteration in temperature of the water is directly proportional to the kinetic energy of the

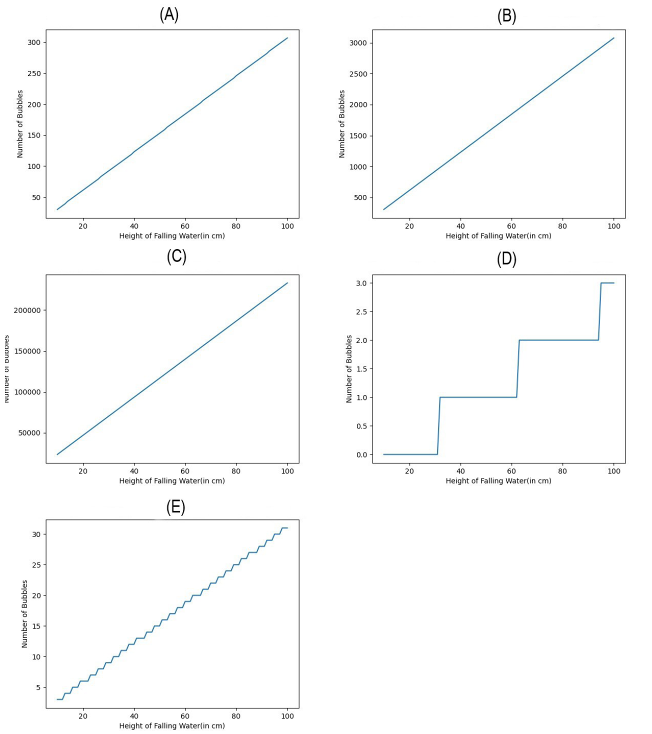

Figure 3: Effect of mass and height of falling water on bubble formation. The graph was computed using the derived mathematical formulation for the number of bubbles (Equation iii). The mass of the falling water and the radius of the bubble was altered in each case to obtain the graphs A (Mass of Falling Water = 1 g & Radius of bubble = 1 mm); B (Mass of Falling Water = 10 g & Radius of Bubble = 1 mm); C (Mass of Falling Water = 1 g & Radius of Bubble = 0.1 mm); D (Mass of Falling Water = 10 g & Radius of Bubble = 10 mm); E (Mass of Falling Water = 100 g & Radius of Bubble = 10 mm). For all these values were used for the following variables: 'σ' = 0.072 N/m, 'ρ_w' = 1000 kg/m^3, 'ρ_b' = 1.225 kg/m^3, 'e' = 0.1, 'H' = 0.15 m and 'g' = 9.8 m/s^2.

water. So, the observation of the experiment validates the hypothesis.

In the third experiment, we calculated the number of bubbles sticking to the wall when the water was suspended into different containers having a circular cross-section. We observed a decrease in the number of bubbles with an increase in the surface area of the container. Three containers of different cross-sections and heights were used in this experiment (**Table 3**). In our hypothesis, we also mentioned that geometry also affects the number of the bubbles sticking to the wall and the observations of the experiment 3 further validates the hypothesis.

In the fourth experiment, we poured water in different containers and observed that bubbles were sticking to the wall of the containers made of copper and steel. In glass, ceramic, plastic and aluminum containers, we did not observe bubbles sticking to the walls.

During these experiments, we also observed that the mass of falling water played an important role in determining the number of bubbles formed during the process. However, due to the lack of an adequate apparatus to measure and control the volume of water falling in a unit time during the experiments, we were unable to determine the exact change in the number of bubbles with changes in the mass of the falling water.

Table 1: Height of Falling Water v/s Number of Bubbles Sticking to wall.

Height of Falling Water (cm)	Number of Bubbles sticking to the wall
10	25
20	75
30	96
40	155

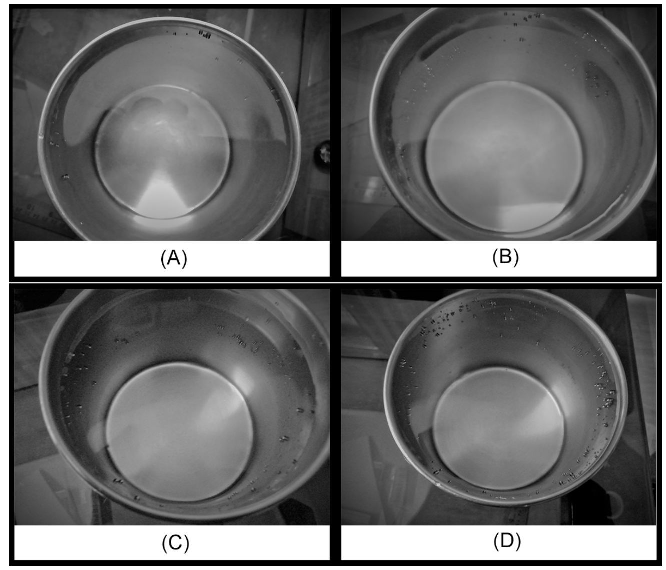

Figure 4: Bubble Formation during Experiment 1. Bubble formation in the container when the water was suspended from (A) 10 cm, (B) 20 cm, (C) 30 cm, and (D) 40 cm above the base of the container during experiment 1 respectively.

DISCUSSION

Although our experiments were not performed under highly controlled lab conditions, our observations from the experiments support the predictions made by our hypothesis and mathematical formulations. The change in the initial conditions resulted in a change in the energy of the bubbles overall. As the energy of bubbles increased, more and more bubbles were able to find the "sweet spot" for combining with the interstitial H of the wall, as predicted and explained by the collision theory.

In the first experiment, the increase in the radius of bubbles as we increased the height of the falling water points to the fact that the surface energy of a bubble is also increasing

Table 2: Temperature of Falling Water v/s Number of Bubbles Sticking to the wall

Temperature of Falling Water (K)	Number of Bubbles sticking to the wall
275 (Freezing Water)	10
304 (Room Temperature)	29
373 (Boiling Water)	48

Table 3: Decrease in number of bubbles with the change in geometry of the container.

Diameter of the Container (cm)	Height of the Container (cm)	Geometry of the container	Number of Bubbles Sticking to the Wall
7.2	11.5	Cylindrical	33
11.5	4.8	Hemispherical (Bowl)	6
16	6	Hemispherical (Bowl)	0

Figure 5: Experimental Setup. The experimental setup used during the experiments 1, 2, 3 and 4. The apparatus consists of a container and a meter scale to measure the height of the falling water.

with the increase in kinetic energy of the falling water. This result matches the prediction in the theory that kinetic energy is being converted to surface energy and kinetic energy of the bubbles.

In the later experiments, we also observed that the increased temperature of the water caused increased energy of the water and resulted in an increase in the number of bubbles. This increased energy of the bubbles allowed them to stick to the walls in more and more quantity. The geometry of the container also played an important role in determining the number of the bubbles sticking to the wall. As the cross-section of the container increased, fewer bubbles were colliding with the wall and hence fewer bubbles were sticking to the wall. In some cases, we observed that more bubbles were sticking in wide containers using hot water than with normal water.

The effect of changing the mass of falling water on the number of bubbles sticking to the wall still needs to be studied experimentally. We plan to use a pump with variable flow control to test this effect. The experiments conducted in this study could also be improved in the future with adequate materials such as pump with variable flow control, a chamber with better temperature control and other equipment. This will result in more precise observations and data.

After investigating the cause of the phenomenon of bubbles sticking to container walls, we can use this particular property of steel and copper to distinguish them from other metals. It can also be used to determine if hydrogen is present in the interstitial spaces of the metal. In the future, we can test the occurrence of bubbles sticking to the walls for other metals, like platinum, palladium, or nickel, which are known to have prominent amount of interstitial hydrogen. This will help us solidify our hypothesis and will provide more data about the phenomenon. We can also use the occurrence to differentiate between steel and aluminum, or other metals such as platinum or palladium in industries.

MATERIALS AND METHODS

In each of the experiment, we calculated the number of the bubbles sticking to the walls in each experimental run. The water was poured in the container to the brim and then the number of bubbles were counted. In our hypothesis, we assumed the bubbles to be of the same size for the sake of simplicity. But here bubbles of different size were obtained and we counted all of them.

In the first experiment, alteration in the number of bubbles sticking to the walls was studied as the height of the falling water was altered. The water was poured from a height in the range of 10 cm to 40 cm in a container made of stainless steel. The height was measured from the bottom of the container. The water used was at room temperature and the geometry of the container was cylindrical. The container used had a radius of 4.4 cm and a height of 9 cm. Only the height of the falling water was altered, keeping all other conditions constant. The setup of the experiment is shown in **Figure 5.**

In the second experiment, the alteration in number of bubbles sticking to the walls was studied with alterations in the temperature of the water. The water was poured from a constant height into the same container from the first experiment. Three readings were taken where the temperature of water poured was 275 K (ice water), 304 K (room temperature), and 373 K (boiling water). All other conditions i.e. height of falling water, geometry of container and the material of the container were kept constant.

In the third experiment, the geometry of the container was altered. We used three steel containers of different cross-section, height, and geometry. We used containers of cylindrical and hemispherical geometry (**Table 3**). All other conditions were kept constant during the experiment. The number of the bubbles sticking to the walls was again noted in each case.

In the last experiment, we tested the occurrence of the phenomenon in containers of different materials. Materials commonly used in the household, including glass, copper, steel, ceramic, plastic, and aluminum, were tested while keeping rest of the initial conditions constant.

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