Investigation of the Teapot Effect

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It is an annoying event when the tea or any liquid spilling from the teapot flows outside the spout surface onto the table instead of into a cup. In this study, this event, which is called the teapot effect, is investigated experimentally and numerically using a porcelain teapot. The liquid was poured from the teapot at different flow rates, while the teapot was positioned at an angle of 5–25° to the ground. Therefore, the liquid flow was provided from the teapot's spout at different flow rates (in the range of 0.2–0.54 l/min). Experiments and simulations were performed using two types of teapot spouts: one with a hydrophilic surface and the other with a superhydrophobic spout surface. While the liquid's momentum ensures that the liquid tends to maintain its flow direction, the liquid adjacent to the spout surface is slowed down by the capillary adhesion force. The balance between the liquid's forward momentum and the capillary adhesion force determines the flow direction. The liquid flowing from the superhydrophobic spout flows without creating the teapot effect. In the case of a hydrophilic spout, the velocity of the liquid is the dominant factor in the teapot effect. The capillary adhesive force of the spout surface is the dominant parameter for the teapot effect. Pressure has a second-order effect due to the velocity gradient created by the change in the direction of the liquid flow due to the capillary adhesion force.

topics: teapot effect, superhydrophobic surface, adhesion force, numerical study

1. Introduction

The phenomenon of any liquid poured from the teapot adhering to the surface and spilling onto the table is an annoying event that is often encountered daily. This phenomenon, which is called the "teapot effect," is experienced in all areas where the liquid should be poured, especially in the food and paint industries. Furthermore, the teapot effect is present in aircraft design, the behavior of raindrops on flying insects, and in the diagnosis of heart disease [1–3]. This effect depends on various parameters, such as the liquid velocity, the sharpness of the spout lip, the surface tension of the liquid, and the wettability of the spout [4]. The sharp edge of the underside of the spouts [5], the non-wettable surfaces [4], and the high velocity of the liquid [6] play the most crucial roles in preventing this effect. The terms teapot effect and Coanda effect are often used interchangeably. A following distinction may be introduced between the two cases — no interface is formed since the Coanda effect occurs between the gas and the solid surface, whereas the teapot effect has an interface between the liquid and gas phases.

Reiner [7] was a pioneer in demonstrating the teapot effect. He conducted several experiments to examine this effect. He stated that the teapot effect was not caused by the surface tension or adhesion between the liquid and solid surfaces. Instead, it was assigned to the vortices in a plane perpendicular to a solid surface throughout the flow. Shortly afterward, Keller [8] studied the teapot effect, ignoring gravity and surface tension, assuming that the flow was two-dimensional, stationary, non-rotational, and incompressible. He was the first to argue that the teapot effect is caused by atmospheric pressure pressing the liquid against the teapot. Vanden-Broeck & Keller [9, 10] then improved this theory with regard to gravity. Kistler & Scriven [5] conducted extensive theoretical modeling and experimental studies on the teapot effect. They investigated the influence of viscosity, flow rate, wettability, contact angle hysteresis, the inclination angle of the solid surface, and curvature on the teapot effect. The effect of wettability on the teapot effect was first discussed in their study. Dong et al. [11] performed a liquid flow separation on curved surfaces with varying wettability. They indicated that surface wettability is essential for separating the liquid from the surface. Scheich et al. [12] performed a comprehensive theoretical study of this complex phenomenon. They reported that the most significant finding was that the liquid layer was separated from the trailing edge of the lower wedge of the spout, the nose of which was rounded.

Numerical analysis is a powerful tool for the examination of many flow phenomena that cannot be detected through experiments. This tool has also been used extensively in studies of the teapot effect. Nishio et al. [13] recently investigated experimentally and numerically liquid spilled from a beverage can. They indicated that condensation reduced the effective contact angle and affected the flow trajectory of the flowing liquid. The flow field in the rinsing process of a beverage was examined numerically and experimentally by Kawachi et al. [14]. In a recent review study, Zhou et al. [6] and then Liu et al. [15] examined the manipulation of liquid over a solid surface, considering the surface wettability. They summarized the studies on manipulating liquid overflow around solid edges. E. Jambon-Puillet et al. [16] examined a liquid jet flowing by wrapping it on a solid surface in the form of a helix. They proposed an inertial-capillary adhesion model in their study. They also stated that parameters such as impingement rate and jet velocity were critical parameters for helix formation. Shi et al. [1] studied the influence of viscosity, surface tension, and additive molecules of the liquid on the teapot effect. They stated that the teapot effect was significantly affected by these parameters.

In particular, the wettability of the solid surface can have a significant effect on overflow phenomena such as the teapot effect [4, 17]. The liquid does not bend over the spout because of the low capillary adhesion force between the superhydrophobic surface and the liquid [18, 19]. Duez et al. [4] demonstrated that using a superhydrophobic surface could prevent the teapot effect under all conditions, such as the geometry of the solid and the velocity of the liquid (round edge and low velocity, etc.). They indicated that the wettability of the solid was the most important factor in separating the liquid from solid surfaces. Kibar et al. [20] studied the flow and spreading of a liquid jet impinging over superhydrophobic and hydrophobic surfaces. They classified the liquid flow behavior on the surface into braiding, spreading, reflection, and splashing. Kibar [18] examined the impingement of a liquid jet on the edge of the non-wetting surfaces. Although the liquid jet impinging on the superhydrophobic surface was reflected from the superhydrophobic surfaces under all conditions, it was reflected from or wrapped around the surface depending on the curvature of the surface, the inertia of the jet, and the impingement rate on the hydrophobic surfaces [21, 22].

The teapot effect is affected by certain factors, including the sharpness and wettability of the spout and the velocity, surface tension, and viscosity of the liquid. When the inertia of the liquid dominates all other high-velocity effects, the possibility of a teapot effect decreases. While the velocity of the liquid decreases, the dominance of other factors increases. Since the capillary adhesion forces are greatly reduced by reducing the wettability of the surface, which is the other factor, the inertia forces of the liquid are dominant, no matter how low. Therefore, the teapot effect does not occur on high-wettable surfaces, even at very low speeds. At low liquid velocities and low-wettable surfaces, the direction of the fluid is primarily determined by capillary adhesion force [20].

On the hydrophilic surface, the liquid flows by being held onto the surface by capillary adhesive forces [18, 22]. This capillary adhesive force creates the centripetal force, which is composed of the pressure, capillary, and shear stress forces [18]. While the capillary force is effective along the three-phase contact line of the liquid, the shear and pressure forces are effective in all spreading areas of the liquid. When the forward momentum of the liquid from the spout is not of sufficient magnitude (i.e., low flow velocity), the liquid attached to the surface pulls the forward-flowing liquid to the surface by cohesion force. The phenomenon is called the teapot effect.

This study examines in detail the phenomenon of the teapot effect using numerical results validated by experimental data. For this purpose, the flow occurring on the teapot's spout has been investigated, varying the flow rate and surface wettability. Additionally, the outflow of the spout at different flow rates is analyzed using simulation results.

2. Experimental setup and methods

Figure 1 shows the experimental setup to send a liquid jet into the teapot. The teapot's spout was coated with a NeverWet® superhydrophobic coating, with a contact angle of 162°. Experiments were performed both without coating (hydrophilic surface) and with a coating (superhydrophobic surface). The teapot was positioned at the 5° and 25° inclined angles, as shown in Fig. 1b. The liquid was drawn from the reservoir tank through a centrifugal pump and pumped into a teapot using a straight glass tube. The tube used as a nozzle was positioned vertically. Distilled water, whose physical properties are given in Table I, was used to produce the liquid jet. The liquid flow rate in the system was measured using the McMillan S-114-7 flow meter (in the range of 0.1–2 l/min, with an accuracy of ±1%). A precision needle valve was used to adjust the flow rate. Images recorded via a CCD camera were transferred to a computer and analyzed.

TABLE I

Physical properties of fluids.

Parameter	Domain	Value
density [kg/m^3]	water	997.4
	air	1.19
viscosity [Pa s]	water	9.8×10^{-4}
	air	1.82×10^{-5}

3. Numerical method

In this study, the simulations were examined as multiphase and unsteady in a 3D domain. Incompressible Navier–Stokes equations were used to simulate pouring liquid from a teapot. The flow was solved under laminar consideration. An interpolation scheme was used to avoid non-physical oscillations in a collocated grid arrangement in the pressure field [23]. The first-order implicit and second-order upwind schemes were applied to the temporal discretization and convective terms of the flow, respectively. The solver under-relaxation factors were applied, respectively, as 0.8 and 0.2 for the velocity and pressure. The SIMPLE algorithm was used to achieve the coupling of pressure and velocity [24].

The governing equations of incompressible flow are the conservation of the equations of continuity and momentum, as given, respectively, by

$$\nabla \cdot \boldsymbol{v} = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla(\rho \boldsymbol{v} \cdot \boldsymbol{v}) = -\nabla p + \nabla \cdot \left[\mu\left(\nabla \boldsymbol{v} + \nabla \boldsymbol{v}^T\right)\right] + \rho \boldsymbol{g} + \gamma \kappa \boldsymbol{n}, \tag{2}$$

where γ and ρ are the surface tension and density of the liquid, respectively; p and $\boldsymbol{v}$ are the pressure, and velocity vectors, respectively. The tangential component of the force vanished due to the determination of the constant surface tension. The surface tension of the liquid and gravity were both considered in the simulations. The continuum surface force (CSF) model was adapted to the interface to define the surface tension force [25].

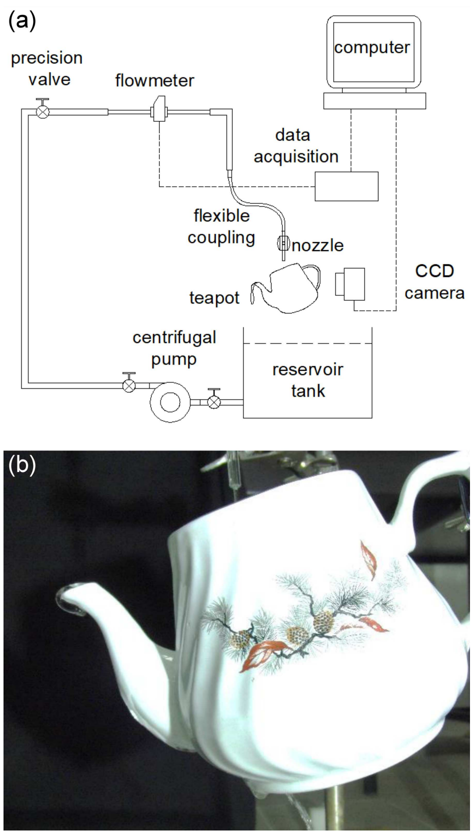

Fig. 1. (a) Experimental setup, (b) the teapot used in the experiments.

The normal unit vector ($\boldsymbol{n}$) directed perpendicularly from the primary fluid (liquid) to the secondary fluid (gas) at the interface was obtained by the smooth field of the phase volume fraction (δ_i) given as

$$\boldsymbol{n} = \frac{\nabla \delta_i}{\nabla(1 - \delta_i)}. \tag{3}$$

The interface curvature for the secondary phase (κ) is described by

$$\kappa = -\nabla \cdot \frac{\nabla \delta_i}{|\nabla \delta_i|}. \tag{4}$$

An interface of the immiscible fluids is described by the phase fraction

$$\frac{\partial \delta}{\partial t} + \boldsymbol{v} \nabla \delta = 0 \tag{5}$$

in the volume of fluid (VOF) method [26].

The rate of the phase in a cell is defined as the phase fraction. Three possible cases can be defined for the phase fraction, i.e., $\delta_i = 0$ (completely gas), $\delta_i = 1$ (completely liquid), and $0 < \delta_i < 1$ (partially filled with liquid and gas). In the last case, the interface is formed.

The sum of these two-phase fractions should be one, i.e.,

$$\delta_L + \delta_G = 1. \tag{6}$$

The density and viscosity are calculated locally, as defined, respectively, by

$$\rho = \delta \rho_L + (1 - \delta)\rho_G \tag{7}$$

and

$$\mu = \delta \mu_L + (1 - \delta)\mu_G, \tag{8}$$

where ρ_G and ρ_L are the gas and liquid densities, respectively; and μ_G and μ_L are the dynamic viscosities of the gas and liquid, respectively.

The VOF multiphase model has been used to solve problems involving multiple immiscible fluid interfaces and free surfaces [26]. This model shares the pressure, velocity, and temperature fields for all immiscible fluid phases [26]. Therefore, the governing equations were solved for a single equivalent fluid. The physical properties of this fluid were computed based on the physical properties of the volume fractions [26]. The volume fraction average density and viscosity equations can be defined, respectively, by

$$\rho = \sum_i \rho_i \delta_i, \tag{9}$$

$$\mu = \sum_i \mu_i \delta_i, \tag{10}$$

where ρ_i, μ_i, and δ_i are the density, dynamic viscosity, and volume fraction for the i-th phase, respectively.

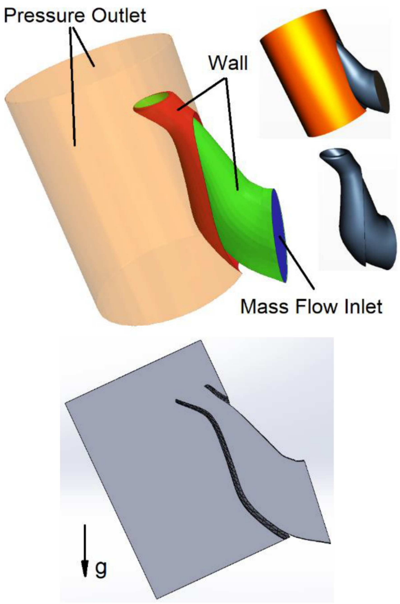

Fig. 2. 3D computational domain of simulation and boundary conditions.

The convective Courant number was observed on both a monitor and a graph for the liquid jet boundary. The time step value was determined so that the Courant number of the liquid jet boundary was below 0.5, as suggested by the Star-CCM+ user guide for free-surface flow. The Courant number given by

$$C = \Delta t \frac{v_x}{\Delta x} \tag{11}$$

is a dimensionless number that represents the physical time step for a particle to stay in a cell of the mesh. In (11), Δt, v_x, and Δx are the physical time step, local velocity, and characteristic cell length scale, respectively.

3.1. Boundary conditions and mesh domain

Only the teapot's spout was considered in the analysis instead of the whole teapot (see Fig. 2). The spout was subtracted from a cylinder with 70 mm in diameter and 100 mm in height. Initially, the phase (δi) value was taken as 0 for the whole volume, so the entire domain was given as air. The mass flow inlet was defined by the elliptical-shaped part, where the liquid enters the spout, as shown in blue in Fig. 2. Therefore, the entry of the liquid into the domain was enabled by defining the value for phase (δ_i) as 1. All surfaces of the cylinder, shown in orange in Fig. 2, were defined as the pressure outlet. The interior and exterior surfaces of the spout were defined as the wall with no-slip boundary conditions, as shown in green and blue in Fig. 2, respectively. The contact angles of the interior and exterior surfaces were defined as 20° for hydrophilic and 160° for superhydrophobic surfaces. The teapot was located at an angle of 25° with gravity, as shown in Fig. 2. During the experiments, the

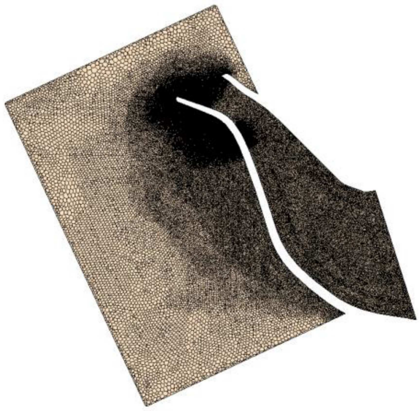

Fig. 3. Mesh domain as mid-plane section 3D domain.

flow rate of the liquid filling the teapot was in the range of 0.10–0.54 l/min. The time-step was taken as 5×10^{-5} s so that the Courant number was less than 0.5. The Courant number indicates how much information is traversed in a given time step. The convergence criterion for the residuals of all governing parameters was specified as 10^{-5}. The mesh validity was checked using a mesh diagnostics report, which included face validity (> 1.0), minimum volume change (> 0.01), and maximum skewness angle ($< 85°$). The validity of the mesh was verified to ensure that the quality of the cells was good.

The polyhedral mesh was used in this study to simulate the flow, as shown in Fig. 3. The most significant benefit of this mesh structure is that each cell has many neighboring cells, so the gradient may be predicted well [27]. The mesh structure consisted of approximately 10 500 000 cells. A fine mesh was used inside and outside the spout to obtain a smooth flow. These regions were finely meshed because the flow occurred at the spout outlet. The waste of time caused by the too long duration of the analysis had not been considered so that the mesh size did not affect the result. It took several days for the liquid to enter the inlet, reach the spout, and stabilize. Once the flow stabilized, the analysis was conducted at the lowest flow rate, and then the analysis was performed at other flow rates.

4. Results and discussions

The numerical simulations, validated experimentally, are conducted to clarify the phenomenon of the liquid pouring from the teapot. Figure 4 shows two examples of the teapot effect and compares the experimental and numerical results. The numerical results are in mostly good agreement with the experimental results. Both experimental and numerical results of the flow phenomena obtained under the same conditions are obtained close to each

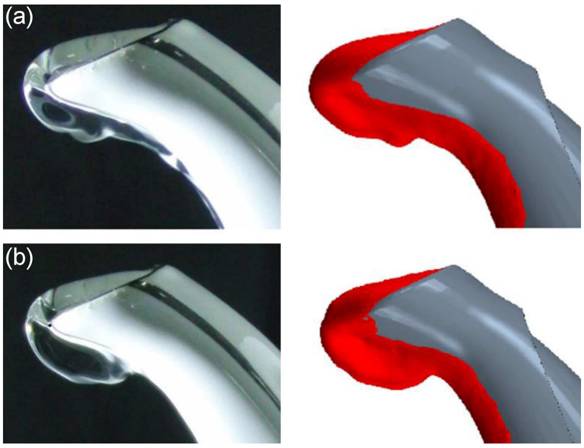

Fig. 4. Comparison between experimental and numerical results for a flow rate of (a) 0.2 l/min, (b) 0.28 l/min of the liquid poured from the teapot.

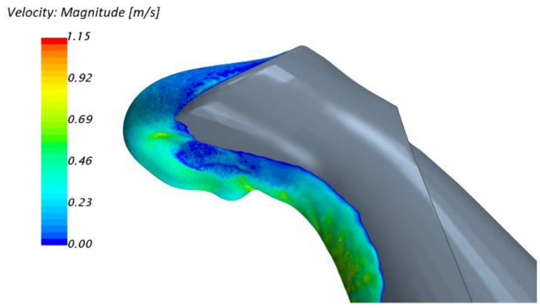

Fig. 5. Magnitude of the velocity of pouring liquid from the spout with a flow rate of 0.2 l/min.

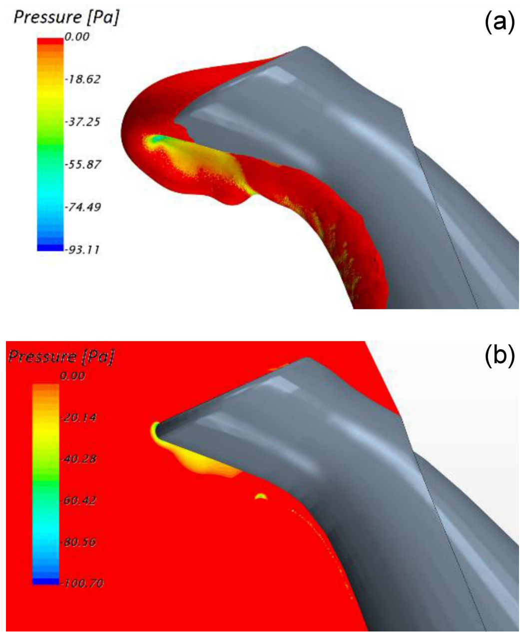

Fig. 6. The negative pressure of pouring liquid from the teapot (flow rate of 0.2 l/min) at (a) the free surface of the liquid as an iso-surface and (b) mid-plane. Only negative pressures are considered. Positive pressure is shown in red.

other. Therefore, the numerical results are used to investigate the liquid flow of the teapot in order to explain and understand the phenomenon in detail. Liquids flowing from the teapot at a low velocity and a slightly higher velocity than this low velocity are compared in Fig. 4a and b, respectively. The low-velocity liquid flows by adhering to the spout, as shown in Fig. 4a. With a slight increase in the liquid velocity, the liquid starts to move away from the spout due to the increase in the inertia force of the liquid in the flow direction. Nevertheless, the pouring liquid cannot be separated from the spout and flows, creating a teapot effect. In such cases, the capillary adhesive force, rather than the inertia force, dominates the flow in determining the flow directions.

Figure 5 shows the velocity magnitude of pouring liquid from the teapot as an iso-surface. The iso-surface was obtained by defining 0.5 for the phase fraction. The velocity of the liquid adjacent to the solid surface at the outlet of the spout lip is low. The liquid molecules in contact with the spout adhere to the solid surface because of the capillary adhesive force. As a result, the liquid coming in contact with the spout flows from the bottom of the spout, following the surface under the influence of gravitational force. The momentum of the liquid (i.e., the inertia force) ensures that the liquid tends to maintain its flow direction [12, 18]. Alternatively, the liquid adjacent to the solid surface is slowed down by the capillary adhesive force and the viscous force. The reduction of the velocity of the liquid makes the viscous and capillary adhesion forces more dominant. The force balance between the liquid gaining momentum forward on the free surface and the liquid adhering to the solid surface by the capillary adhesion force determines the flow direction [12]. The balance between these two opposite forces is dependent on the viscosity of the liquid. Because the inertia of the liquid is low in this case (Fig. 5), the forward momentum of the liquid at the spout's exit cannot overcome the momentum of the liquid flowing along the surface. As a result, the teapot effect occurs, in which the liquid is held outside the spout surface. The liquid velocity in the regions close to the surface is very low, as shown in Fig. 5. In such low inertial flows, capillary adhesion and viscous forces become the dominant factors.

Figure 6a and b indicate the negative pressure on the free surface of the pouring liquid and in the mid-plane, respectively. Although atmospheric pressure acts on the free surface of the liquid, a negative pressure occurs because of the curvature effect due to surface tension. The bending of the liquid creates negative pressure on the free surface of the pouring liquid. The capillary force also dominates this flow owing to the low-momentum jet.

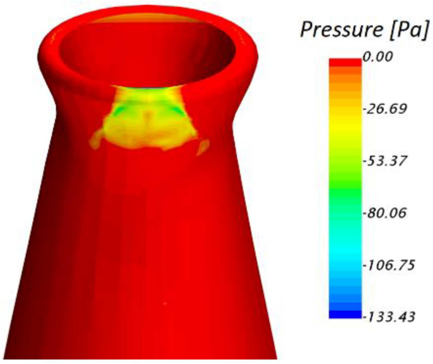

Fig. 7. The negative pressure over the spout produced by pouring liquid (flow rate of 0.2 l/min). Only negative pressures are considered. Positive pressure is shown in red.

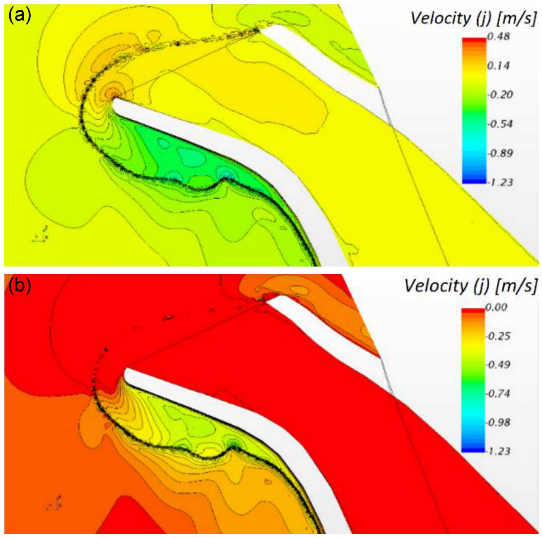

Fig. 8. The velocity gradient of the fluid in the mid-plane on the horizontal axis. (a) The whole scale and (b) the velocity gradient in the $-y$ direction (flow rate of 0.2 l/min). Velocities in the $+y$ direction are shown in red.

The centrifugal force produced by bending the liquid is compensated by the attractive centripetal force of the surface [18], resulting in negative pressure on the spreading area of the liquid on the spout surface, as shown in Fig. 7. The momentum of the deflecting liquid over the spout lip is associated with the capillary adhesion force between the spout surface and the liquid. As a result, the force balance between the capillary adhesion force and the centrifugal force determines the liquid flow by adhering to the surface [1].

The capillary adhesive force between the liquid and the spout surface is linked by the momentum of curved surfaces in bending. The centrifugal force of the bending liquid must be pulled by the centripetal force of the spout in order for momentum to be maintained [4, 18]. Therefore, the centrifugal force of the bending liquid is compensated by the centripetal force, resulting in negative pressure on the surface, as shown in Fig. 7. The capillary adhesive force balances the liquid's momentum in the flow direction on the spout surface of the liquid. In other words, the centrifugal force of the liquid and the capillary adhesive force are formed in opposite directions. The viscous force of the liquid counters these two opposing forces. Therefore, two opposing forces create a negative pressure on the spout surface, as shown in Fig. 7.

The forward velocity of the liquid ($+y$) is high just at the end of the spout, as shown in Fig. 8a. The horizontal velocity of the liquid (y) adhering to the spout is high. This velocity decreases towards the free surface of the liquid, forming a velocity gradient, as shown in Fig. 8a and b. When the capillary adhesive force, which allows the liquid to flow along the surface, is greater than the inertia of the liquid moving forward from the spout, the liquid flows along the surface and creates the teapot effect. When Fig. 7 and Fig. 8b are compared, it can be seen that the liquid flows rapidly along the spout in the middle part adhering to the spout, while the velocity of the liquid on the free surface is slow.

The velocity of a liquid is an essential parameter for the teapot effect. The teapot effect may be completely or partially prevented by increasing the velocity of the liquid (i.e., the inertial force of the liquid), as shown in Fig. 9. In this case, the liquid's forward momentum is dominant compared with the capillary adhesion force between the adhering liquid and the spout. The liquid velocity is very low just at the exit of the spout, as seen in Fig. 10. The liquid, which has a significant flow momentum due to its high forward velocity, creates a large centrifugal force as it bends through the spout. This flow occurs on the liquid, which has remained stable by adhering to the surface just at the outlet of the spout due to the capillary adhesive force. In this case, the capillary adhesive force is insufficient to provide the centripetal force [1]. Therefore, the liquid is separated from the spout by centrifugal force.

When the flow rate is low, the pressure difference can be neglected. Nevertheless, the capillary adhesive force is the most critical factor in the formation of a centripetal force [6, 20]. This centripetal force pulls the liquid adhering to the solid in the direction of the flow. With the increase in the liquid velocity, the forward inertia of the liquid competes with the capillary adhesion force, causing the liquid to change from the overflow state to the separation state [6].

Figure 11 shows the liquid flowing from the hydrophilic and superhydrophobic surfaces in the same conditions. In this case, the velocity of the liquid is quite slow, and the inclination of the teapot is very low. When the teapot's spout is covered with superhydrophobic material, the teapot effect does not occur under almost any condition, such as low

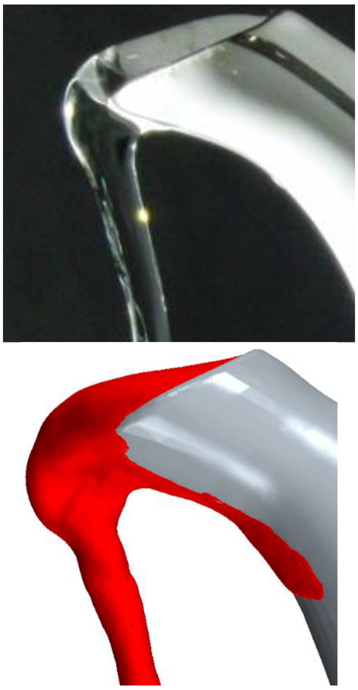

Fig. 9. Pouring liquid from the teapot at high velocity.

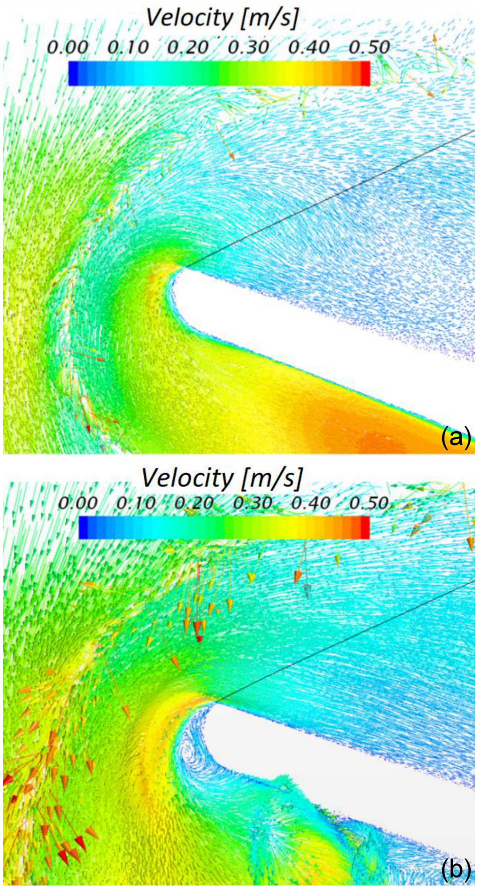

Fig. 10. Velocity vectors in the mid-plane for (a) 0.2 l/min (b) 0.36 l/min. Velocities below 0.5 m/s are shown for a better understanding of the velocity differences.

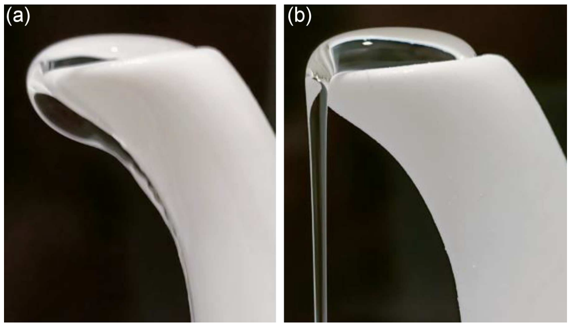

Fig. 11. Pouring liquid from a teapot's (a) hydrophilic and (b) superhydrophobic spout (flow rate of 0.1 l/min).

Fig. 12. The standing of the water before its discharge from the superhydrophobic spout.

liquid velocity and a low inclination angle, as shown in Fig. 11b. While the liquid flows by sticking to the hydrophilic surface, it flows downwards under the influence of gravity without sticking to the superhydrophobic surface (Fig. 11). Superhydrophobic surfaces have extremely low surface energy, which results in a very low adhesive force between the liquid and the superhydrophobic surface [28]. Hence, surface tension dominates over other forces, such as adhesion. Since the surface tension tries to make the free surface of the liquid as small as possible, the liquid tends to approach the shape of a sphere with the smallest surface area, as shown in Fig. 12.

Additionally, the wetting velocity is primarily influenced by the surface wettability. The wetting velocity and thus liquid spreading speed on the solid surface is low on the Cassie–Baxter state superhydrophobic surfaces. As a result, since the flow velocity of the liquid is higher than this low wetting velocity at the three-phase contact line, the liquid flows out of the superhydrophobic teapot spout without adhering. In this case, the inertial force of the liquid becomes dominant over the capillary adhesive force, and the liquid separates without spreading through the spout, as shown in Fig. 13.

Experimental and numerical analyses have also been conducted to investigate the wettability impact on the teapot effect. The numerical results are

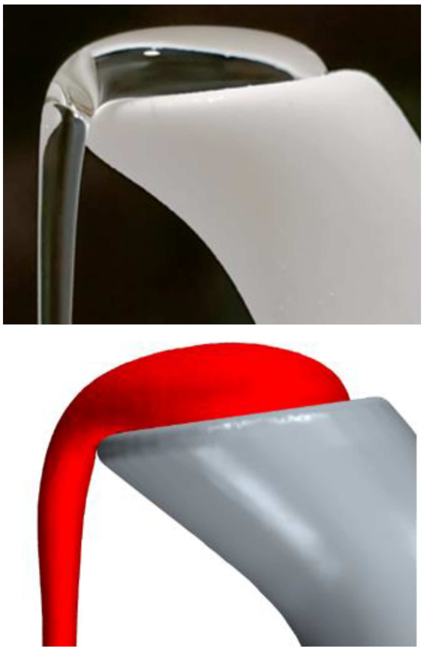

Fig. 13. Liquid flowing from superhydrophobic teapot spout (flow rate of 0.15 l/min).

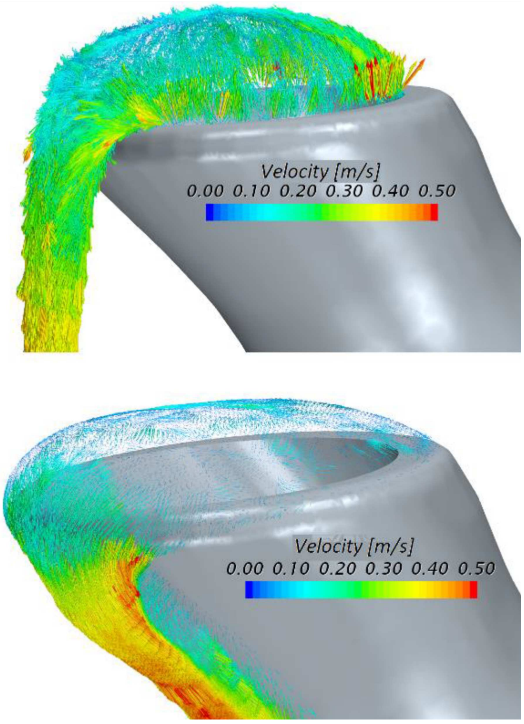

Fig. 14. Liquid flowing from superhydrophobic and hydrophilic teapot's spout (flow rate of 0.15 l/min).

also almost in agreement with the superhydrophobic experimental results. On the superhydrophobic surface, the liquid flows out from the spout at high speed, with the surface tension being dominant due to low adhesive force on the edges at the exit of the spout, as shown in Fig. 14. On the hydrophilic surface, the liquid layer close to the surface is slowed down by a strong adhesion force. A velocity gradient is formed in the flow, with the effect of that slow-down as well as the viscosity of the liquid. The liquid flows, bending through the spout due to the velocity gradient, resulting in centrifugal force. Since the centrifugal force cannot overcome the centripetal force created by the capillary adhesion force due to the low speed, the liquid continues its way without separating from the surface. The velocity of the liquid on a superhydrophobic surface is higher close to the solid surface, while in the case of a hydrophilic surface, it is higher on a liquid-free surface, as shown in Fig. 14.

5. Conclusions

The teapot effect, which occurs when tea falls onto the table rather than into a cup, is quite annoying. In this study, this disturbing event is studied experimentally and numerically by analyzing the pouring of liquid from a teapot spout.

The velocity of the liquid poured out of the spout is one of the critical parameters of the teapot effect. Wettability is another important parameter for the prevention of the teapot effect. With the decrease in wetting, the adhesion force between the liquid and the surface decreases, so the momentum of the liquid is more dominant than the capillary adhesion, resulting in the teapot effect. The conclusions are summarized as follows:

- The present study provides detailed information on the teapot effect that may be difficult to obtain using experimental studies.
- The centrifugal force of the deflection liquid is balanced by the centripetal force, resulting in a negative pressure on the spout surface.
- The velocity of the water pouring from the teapot and the wettability of the teapot spout are two crucial factors in the teapot effect.
- The main reason for the teapot effect is the capillary adhesive force on the solid surface. The pressure has a secondary effect due to the velocity gradient that occurs with a change in the direction of the fluid due to the capillary adhesive force.

References

[1] L. Shi, Y. Li, Y. Meng, G. Hu, Y. Tian, *J. Phys. Chem. C* **122**, 21411 (2018).

[2] A.K. Dickerson, P.G. Shankles, D.L. Hu, *Phys. Fluids* **26**, 027104 (2014).

[3] G. Pitton, A. Quaini, G. Rozza, *J. Comput. Phys.* **344**, 534 (2017).

[4] C. Duez, C. Ybert, C. Clanet, L. Bocquet, *Phys. Rev. Lett.* **104**, 084503 (2010).

[5] S.F. Kistler, L.E. Scriven, *J. Fluid Mech.* **263**, 19 (1994).

[6] S. Zhou, L. Jiang, Z. Dong, *Chem. Rev.* **132**, 2276 (2022).

[7] M. Reiner, *Phys. Today* **9**, 16 (1956).

[8] J.B. Keller, *J. Appl. Phys.* **28**, 859 (1957).

[9] J.M. Vanden-Broeck, J.B. Keller, *Phys. Fluids* **29**, 3958 (1986).

[10] J.M. Vanden-Broeck, J.B. Keller, *Phys. Fluids A Fluid Dyn.* **1**, 156 (1989).

[11] Z. Dong, L. Wu, N. Li, J. Ma, L. Jiang, *ACS Nano* **9**, 6595 (2015).

[12] B. Scheichl, R.I. Bowles, G. Pasias, *J. Fluid Mech.* **926**, A25 (2021).

[13] Y. Nishio, T. Ogawa, K. Niwa, H. Chiba, *J. Food Eng.* **291**, 110237 (2021).

[14] T. Kawachi, T. Sasaki, A. Kaneko, Y. Nishio, T. Ogawa *Am. Soc. Mech. Eng. Fluids Eng. Div.* **85291**, V002T03A023 (2021).

[15] Z. Liu, J. Peng, C. Yu, Z. Dong, *Chem. Commun.* **58**, 9051 (2022).

[16] E. Jambon-Puillet, W. Bouwhuis, J.H. Snoeijer, D. Bonn, *Phys. Rev. Lett.* **122**, 184501 (2019).

[17] H. Isshiki, B.S. Yoon, D.J. Yum, *Phys. Fluids* **21**, 082104 (2009).

[18] A. Kibar, *Fluid Dyn. Res.* **49**, 015502 (2017).

[19] A. Kibar *Fluid Dyn. Res.* **48**, 015501 (2016).

[20] A. Kibar, H. Karabay, K.S. Yigit, I.O. Ucar, H.Y. Erbil, *Exp. Fluids* **49**, 1135 (2010).

[21] A. Kibar, *J. Appl. Fluid Mech.* **15**, 1881 (2022).

[22] A. Kibar, *Prog. Comput. Fluid Dyn. An Int. J.* **18**, 150 (2018).

[23] C.M. Rhie, W.L. Chow, *AIAA J.* **21**, 1525 (1983).

[24] S.V. Patankar, D.B. Spalding, *Int. J. Heat Mass Transf.* **15**, 1787 (1972).

[25] J.U. Brackbill, D.B. Kothe, C. Zemach, *J. Comput. Phys.* **100**, 335 (1992).

[26] C.W. Hirt, B.D. Nichols, *J. Comput. Phys.* **39**, 201 (1981).

[27] M. Sosnowski, J. Krzywanski, K. Grabowska, R. Gnatowska *EPJ Web Conf.* **180**, 02096 (2018).

[28] B. Zhang, W. Xu, Q. Zhu, F. Guan, Y. Zhang, *J. Ind. Eng. Chem.* **107**, 259 (2022).