

# A Transport Phenomena View of the Teapot Effect: Fluid Adhesion, Momentum Transport, and Wettability Control

Aditya Singal<sup>1</sup>, Avishi Jain<sup>2</sup>

**Abstract:** The “teapot effect” refers to the propensity of a poured liquid stream to wrap around the underside of a spout and trickle down rather than separate cleanly. The present work revisits this behaviour within the framework of transport phenomena, joining classical free-surface hydrodynamics to contemporary ideas of wettability and capillary adhesion. The foundational work of Reiner (vortex-driven film attachment), Keller (exact free-boundary potential-flow solutions), and Bocquet and colleagues (hydro-capillary adhesion) is surveyed and recast in terms of momentum transport, stress analysis, and interfacial boundary conditions. We outline a complex-potential treatment in which the velocity potential  $\phi$  and stream function  $\psi$  capture the flow as it bends around the lip, with Bernoulli suction permitting attachment. A cloud-hosted computational fluid dynamics (CFD) study run at three inlet velocities recovers the anticipated rise of lip suction with flow rate. In addition, we describe a wetting-history (hysteresis) effect: on a previously wetted surface the velocity needed for clean detachment is about twelve percent above that of a dry surface, which implies that the critical Weber number  $We_c$  carries a dependence on surface history.

**Symbols:**  $\phi$  velocity potential,  $\psi$  stream function,  $\rho$  density,  $\mu$  dynamic viscosity,  $\gamma$  surface tension,  $U$  jet velocity,  $\theta_0$  contact angle,  $r_i$  edge radius,  $e_0$  film thickness,  $We$  Weber number.

**Keywords:** Boundary layer, capillary adhesion, computational fluid dynamics, contact-angle hysteresis, free-surface flow, momentum transport, teapot effect, wettability.

## 1. Introduction

The teapot effect captures the way a liquid stream leaving a curved spout tends to stay attached to its lower surface and drip rather than break away cleanly. This commonplace observation results from the rivalry between inertial, viscous, and surface-tension forces. Reiner was the first to note that dripping appears even on poorly wetting surfaces, demonstrating that adhesion by itself cannot account for the behaviour. Keller subsequently built a hydrodynamic theory rooted in flow curvature and the accompanying pressure field, whereas Bocquet, Ybert, Clanet, and Duez singled out surface wettability as the dominant control, proposing the notion of hydro-capillary adhesion.

Here we re-read these results through the lens of transport phenomena. Invoking momentum transport, stress tensors, and interfacial boundary conditions, we view the teapot effect as a coupled bulk-flow and surface problem, backed by mathematical modelling and a CFD study. We further present an experimental observation of wetting hysteresis that introduces a history-dependent dimension into the conventional account.

## 2. Literature Review

For all its familiarity, the teapot effect reflects an intricate interplay of bulk hydrodynamics (inertia against viscosity) and surface-controlled physics. The framework adopted here rests on three studies spread across five decades: the qualitative hydrodynamic reasoning of Reiner (1956), the exact mathematical solutions of Keller (1957), and the modern hydro-capillary adhesion description of Bocquet et al. (2009).

### 2.1 Findings from Reiner (1956)

Reiner disputed the prevailing view that dripping owes itself solely to surface tension or adhesion. Using analogue experiments- among them saturated brine films clinging to dissolving NaCl crystals in defiance of gravity, dense brine running down the wall of an inverted beaker, and flows across abrupt geometric transitions- he demonstrated that film attachment endures even when wettability is suppressed, pointing to a hydrodynamic cause. A poured stream displays three regimes: full attachment at low velocity, partial attachment with an “antiballistic” jet at intermediate velocity, and clean ballistic separation at high velocity. Two distinct phenomena emerge from this: film sticking and jet curvature.

Reiner accounted for film sticking via boundary-layer vorticity. For a thin viscous layer of thickness  $h$  and velocity  $V$ ,

$$\dot{\gamma} = V/h, \quad \tau = \eta \dot{\gamma}. \quad (1)$$

Beyond simple shear, rotational motions (vortices) inside the boundary layer transport kinetic energy and generate a centripetal pressure that drives the film against the wall. The film is not held by adhesion but by the rotational kinetic energy of these vortices. On this basis Reiner discarded the adhesion hypothesis, furnished a hydrodynamic account of film sticking, and distinguished the two ingredients of the effect, preparing the ground for Keller’s treatment.

### 2.2 Findings from Keller (1957)

Keller advanced an explanation grounded in free-boundary hydrodynamics, separating the problem into the turning of the liquid around the lower lip and the continuation of an inverted flow along the underside. As the liquid wraps around the lip its speed peaks, so by Bernoulli’s principle the pressure reaches a minimum; the surrounding air then presses the liquid onto the spout, allowing it to negotiate the corner. The

inverted flow, while hydrodynamically unstable, survives as long as the film stays thin.

**2.2.1 Complex-potential formulation**

With the complex variable  $z = x + iy$  and complex potential  $w = \phi + i\psi$ , the stream function is set to 0 on the lower plate and  $\psi = Q$  on the upper plate and free streamline,  $Q$  being the flux. Mapping the points  $A, D, C$  to  $(0, 1, \infty)$  on the upper half  $t$ -plane yields

$$w = (Q/\pi) \log t, \quad t = e^{\pi w/Q} \tag{2}$$

Introducing the complex velocity  $V = dw/dz$  and

$$f = \log(c/V) = \log c + i\theta, \tag{3}$$

In which  $c$  is the constant speed on the free streamline and  $\theta$  the flow direction, the boundary values of  $f$  restrict it to a half-strip. Mapping that strip to the upper half  $t$ -plane and integrating  $dz/dt = t/c$  with  $z = 0$  at  $t = 1$  gives

$$z = (Q/\pi c) \int_1^t [(1+b)^{1/2} / (t'+b)^{1/2}] \cdot [(1+b)^{1/2} + (t'+b)^{1/2}] dt'/t', \tag{4}$$

which evaluates to

$$z = (Q/\pi c) [ -(4/(1-a^2)) \log((s+1)/2) + ((1+a)/(1-a)) \log((s+a)/(1+a)) + ((1-a)/(1+a)) \log((s-a)/(1-a)) ], \tag{5}$$

with

$$s = ((t+b)/(1+b))^{1/2}, \quad \alpha = (b/(1+b))^{1/2}. \tag{6}$$

**2.2.2 Detachment and special limits**

The free speed  $c$  is set by Bernoulli's equation linking the speed  $a = Q/h$  at  $A$  to the pressures  $p_A, p_C$ :

$$c = (a^2 + (2/\rho)(p_A - p_C))^{1/2}, \tag{7}$$

while  $b$  comes from

$$b = [ ((a+c)/(a-c))^2 - 1 ]^{-1}. \tag{8}$$

Since  $c/a < 1$ , it follows that  $p_A - p_C \leq 0$ . When  $p_C$  takes its largest value (stagnation),  $c \rightarrow 0$  and  $b \rightarrow \infty$ , so detachment does not occur. When  $p_C$  is smallest ( $p_C = p_A$ ),  $c = a$ ,  $b = 0$ , the detachment point moves off to infinity, and the flow collapses to the closed form

$$z = -(4h/\pi) \log \cosh(\pi w/4Q), \tag{9}$$

derived in the absence of gravity. Close to the lip, Bernoulli pressure changes overwhelm the modest hydrostatic difference, so the fluid is able to round the corner even under gravity.

**2.2.3 Gravity, viscosity, and stability**

Well beneath a horizontal plate the flow approaches rigid-body motion,

$$u = \text{const}, \quad v = 0, \quad p = p_0 - \rho g(h + y), \tag{10}$$

holding for  $h < L_0 \approx 32$  ft for water (otherwise cavitation sets in). For an inclined plate, hydraulic theory for thin streams yields

$$u(x) = (u_0^2 + (x - x_0)g \sin \theta)^{1/2}, \quad h(x) = h_0 u_0/u(x). \tag{11}$$

With viscosity included, the fully developed film under an inclined plate becomes

$$u(y) = -(\rho g \sin \theta / 2\mu)(2h + y)y, \tag{12}$$

$$p = p_0 - \rho g(h + y) \sin \theta.$$

A surface disturbance  $y = -h + f_2(t) e^{ikx}$  satisfies the dispersion relation

$$\omega^2 = k \tanh(kh) (k^2 T/\rho - g). \tag{13}$$

Demanding a fixed amplitude at the nozzle,  $Im(\omega + uk) = 0$ , ties spatial growth to  $Im(k) = -u^{-1} Im(\omega)$ . Maximizing growth with  $\beta = \rho g h^2/T$  produces the limiting results

$$\omega_{min} = -(i/2)\sqrt{(g/2 \cdot \rho h/T)} \quad (\beta \ll 1),$$

$$\omega_{min} = -i\sqrt{2} (\rho g^3/27T)^{1/4} \quad (\beta \gg 1). \tag{14}$$

The associated e-folding distance  $1/Im(k)$ , the distance over which the most unstable mode grows by a factor  $e$ , follows from  $Im(k) = -Im(\omega)/u$ :

$$1/Im(k) \sim (2u/g)\sqrt{(T/\rho \cdot h^{1/2})} \quad (\beta \ll 1),$$

$$1/Im(k) \sim u\sqrt{2} (27T/\rho g^3)^{1/4} \quad (\beta \gg 1), \tag{15}$$

So, the e-folding distance grows with  $u$ , and a thin, fast-moving film can travel a considerable distance before it separates. Because spouts are seldom horizontal, the inclined case is the relevant one: the changing width and velocity render it more stable than uniform flow, the Bernoulli effect permits corner-turning, and atmospheric pressure sustains the inverted film.

**2.3 Findings from Bocquet et al. (2009)**

Bocquet and co-workers exposed a coupling between wettability and inertial separation. By varying jet velocity (1–5 m/s), edge curvature ( $r_i = 0.03$ –2 mm), and contact angle (10°–175°), they established that wettability markedly shifts the ejection angle  $\psi_0$ : superhydrophobic surfaces favour clean ejection while hydrophilic surfaces encourage dripping, with viscosity playing a negligible role. The Weber number built on film thickness  $e_0$  is

$$We = \rho U^2 e_0/\gamma, \tag{16}$$

and dripping arises for  $We < We_c$ , following the empirical scaling

$$We_c \propto (1 + \cos \theta_0) r_i/e_0^2. \tag{17}$$

Their hydro-capillary model sets a centrifugal ejection term,  $F_{cent}^x \approx 1/2 \rho U^2 e_0 \delta \psi_0^2$ , against an adhesion stemming from the curvature-induced pressure drop  $\Delta P \approx -\rho U^2 e_0/R$  acting over a wetted area  $A_{wet} = r_i \delta \psi_{wet}$ , which gives the ejection deviation

$$\delta \psi_0 = F (r_i/R) \sqrt{(1 + \cos \theta_0) / We}. \tag{18}$$

This was the first quantitative model tying capillarity to inertia, clarifying how contact angle, curvature, and velocity govern flow separation.

**3. Momentum-Transport Framework**

Phrased in the vocabulary of transport phenomena, the teapot effect is a momentum-transport problem with a deformable free boundary. For an incompressible Newtonian fluid the velocity field  $v$  satisfies continuity and the Navier–Stokes equation,

$$\nabla \cdot v = 0, \tag{19}$$

$$\rho (\partial v/\partial t + v \cdot \nabla v) = -\nabla p + \mu \nabla^2 v + \rho g. \tag{20}$$

The viscous stress tensor

$$\tau = \mu [ \nabla v + (\nabla v)^T ] \tag{21}$$

furnishes the wall shear that generates the boundary layer behind Reiner's film sticking, while the inertial term  $v \cdot \nabla v$  together with the streamline curvature about the lip fixes the Bernoulli pressure depression at the heart of Keller's analysis. At the air–liquid interface the dynamic boundary condition

balances the normal-stress jump against the capillary pressure,

$$(p - p_0) - n \cdot \tau \cdot n = \gamma (\nabla \cdot n) = \gamma/R_{curv}, \quad (22)$$

so that surface tension enters through the interfacial mean curvature- precisely the coupling that Bocquet et al. subsequently quantified via the Weber number. Detachment is therefore decided, at the wetted meniscus, by the contest between the inertial (centrifugal) stress that drives ejection and the combined capillary-plus-suction stress that promotes adhesion. This single stress balance is the common thread among the three classical models and serves as the rationale for the CFD study that follows.

## 4. Computational Methodology

A CFD study was conducted on the SimScale cloud platform to examine the predicted growth of lip suction with flow rate. Every stage- CAD development, meshing, solver configuration, execution, and post-processing- was completed on the same platform.

### 4.1 Geometry and Meshing

A three-dimensional CAD model of a curved spout was constructed, with all flow passages, inlets, outlets, and solid boundaries specified to maintain mesh consistency, and was exported as an STL surface. A tetrahedral-dominant mesh was generated with automatic boundary-layer refinement, complemented by local controls:

- 1) A base tetrahedral mesh to represent the curved geometry;
- 2) Automatic near-wall layers to capture velocity gradients;
- 3) Local refinement at the inlet and within narrow, high-curvature passages prone to separation.

Mesh quality was judged by acceptable skewness and non-orthogonality, smooth transitions across refinement levels, and adequate resolution of the velocity and pressure gradients.

### 4.2 Physics and Boundary Conditions

A steady-state, incompressible, turbulent flow of water was assumed ( $\rho \approx 1000 \text{ kg/m}^3$ ,  $\mu \approx 0.001 \text{ Pa s}$ , Newtonian). The boundary conditions were:

- 1) *Inlet*: a velocity inlet applied at three magnitudes representing low, mid, and high flow rates;
- 2) *Outlet*: a 0 Pa gauge (atmospheric) pressure outlet to secure stable development;
- 3) *Walls*: no-slip on all solid surfaces, with near-wall behaviour managed by the turbulence model.

### 4.3 Solver Controls and Workflow

A SIMPLE-based steady solver was advanced to a  $10^{-4}$  residual target for velocity and continuity, while pressure drop and area-averaged velocity were monitored. Velocity and pressure contours were sampled across cross-sections to expose the acceleration through constrictions and the low-pressure suction zones near the lip, both of which connect directly to the Bernoulli-driven attachment and detachment

described in the teapot-effect literature. The overall workflow was: (1) CAD creation; (2) mesh generation with refinement; (3) physics and boundary-condition setup; (4) simulation at three flow rates; (5) extraction and analysis of pressure and velocity contours.

## 5. Results and Discussion

### 5.1 CFD Results and Relation to Keller's Analysis

The pressure contours obtained at the three flow rates follow trends in keeping with Keller's predictions. At low flow, only a modest pressure drop ( $\approx -674 \text{ Pa}$ ) develops at the curved lip, with smooth gradients and no concentrated suction region; the inertia-driven depression is too weak to retain the film, matching Keller's early-detachment regime. At mid flow, the minimum deepens appreciably ( $\approx -3972 \text{ Pa}$ ) and spreads along the curvature, reproducing the transitional state in which Bernoulli suction grows strong enough to turn the corner and atmospheric pressure sustains a marginally stable inverted film. At high flow, the minimum becomes very deep ( $\approx -1.1 \times 10^4 \text{ Pa}$ ) and tightly localized, with rapid downstream recovery; this corresponds to Keller's stable high-speed regime, in which inertia produces clean ejection and the teapot effect is suppressed. Table 1 collects the correspondence.

The deepening of the pressure minimum as the flow rate rises confirms that a critical transition speed exists and supplies computational backing for Keller's analytical free-surface solutions: whether the flow can round the corner hinges on the velocity-induced pressure depression at the lip.

**Table 1:** Comparison of CFD Results with Keller's Theoretical Predictions

Flow	CFD observation	Connection to Keller
Low	Small pressure drop, gentle gradients	Low-speed regime; flow likely detaches early
Mid	Stronger pressure minimum at lip	Transitional; flow can attach to underside
High	Very deep pressure depression	High-speed stable regime; clean jet ejection

### 5.2 Comparison of Theoretical Frameworks

Table 2 sets the three classical models side by side. The sequence advances from qualitative rheological intuition, through exact inviscid hydrodynamics, to a capillarity- inertia coupling that reinstates the role of surface chemistry.

**Table 2:** Comparison of Classical and Modern Models of the Teapot Effect

Model	Mechanism	Key variables	Limitation
Reiner (1956)	Adhesion + vortex	Surface wetness	Qualitative only
Keller (1957)	Pressure curvature	$p, \rho, v, R$	No surface tension
Bocquet et al. (2009)	Hydro-capillary coupling	$We, \theta_0, r_i$	Assumes steady flow

### 5.3 Observation of Hysteresis

While running pouring tests with a mug, one of us observed that the angle at which the teapot effect set in depended on the

direction of tilting: sweeping from a small to a large angle produced a different onset than the reverse sweep, the latter onset angle being the smaller. This signalled a factor beyond wettability and geometry- namely wetting history. The hypothesis is straightforward: a thin residual film deposited by an earlier pour pre-wets the spout, so the following stream attaches more readily and demands a higher flow speed to separate cleanly, whereas a dry spout separates at a lower speed. To probe this, controlled pours were performed with a fixed mug under two conditions: a dry start (surface cleaned, dried, and made as hydrophobic as possible) and a pre-wet start (carried out immediately after a slow, film-leaving pour). The onset of dribbling- the minimum velocity for clean detachment- was recorded. On average the pre-wet threshold velocity exceeded the dry threshold by about 12%, an unmistakable hysteresis-type effect. This agrees with contact-angle hysteresis: a residual film nudges contact-line pinning toward the “stick” side of the loop, between the advancing angle  $\theta_A$  and the receding angle  $\theta_R$ .

The consequence is that the critical Weber number becomes history-dependent,

$$We_c^{dry} < We_c^{pre-wet}, \quad (23)$$

So, the margin for clean detachment narrows after earlier wetting. The gap shrank for very sharp edges (small radius), since a smaller wetted area weakens pinning- in line with the hydro-capillary picture, in which meniscus geometry is decisive. Hysteresis therefore adds a further layer of complexity on top of the instantaneous inertial-capillary balance and is relevant to the design of reliable non-drip spouts.

#### 5.4 Significance of the Findings

Three conclusions emerge from comparing the CFD output and the pouring experiments with the classical theory. First, the simulations numerically recover the Bernoulli-driven suction mechanism behind flow attachment, lending computational weight to Keller’s analytical free-surface solutions. Second, the steady deepening of the lip pressure minimum with rising flow rate confirms the existence of a critical transition speed that divides the attached (dripping) regime from the detached (clean) one. Third, the hysteresis measurement reveals that this transition is not a single universal curve but a band whose location depends on surface history, roughness, and prior wetting dose. For practical spout design this means that geometry and instantaneous flow conditions alone cannot predict drip behaviour; the state of the surface at the instant of pouring must be accounted for as well.

## 6. Conclusions

The teapot effect, although born of an ordinary action, is a remarkably rich fluid-mechanical phenomenon. Reiner established that film sticking is hydrodynamic rather than adhesive, driven by boundary-layer vortices. Keller derived exact free-surface solutions showing how atmospheric pressure and streamline curvature let a jet round the corner and cling to an inherently unstable inverted film whose detachment is set by perturbation growth, flow rate, geometry, and gravity. Bocquet and co-workers restored wettability to the picture through a hydro-capillary adhesion

model that explains the influence of contact angle and curvature and why superhydrophobic coatings can eliminate dripping. Our own CFD study reproduces the predicted growth of lip suction with flow rate, and our pouring experiments uncover a wetting-history hysteresis that displaces the effective detachment threshold. Together these show that the phenomenon is governed not by one mechanism but by the interplay of inertia, capillarity, surface geometry, flow history, and contact-line dynamics—with practical consequences for non-drip spout design and thin-film flow control, and clear avenues for quantifying the hysteretic shift in  $We_c$ .

Future work should quantify the hysteretic shift in the critical Weber number as a function of prior wetting dose, spout material, and surface roughness, and should combine time-resolved interface tracking (e.g. a volume-of-fluid free-surface solver) with the present steady-state contours so as to capture the perturbation growth and detachment dynamics that the steady analysis can only infer. Engineered surface treatments- graded wettability or sharp, low-curvature lips- offer a path to spouts whose drip behaviour is robust against usage history.

## References

- [1] M. Reiner, “The Teapot Effect,” *Physics Today*, vol. 9, no. 9, pp. 16–20, 1956.
- [2] J. B. Keller, “Teapot Effect,” *Journal of Applied Physics*, vol. 28, no. 8, pp. 859–864, 1957.
- [3] L. Bocquet, C. Ybert, C. Clanet, and C. Duetz, “Beating the Teapot Effect,” *Physical Review Letters*, vol. 103, no. 17, art. 174501, 2009.
- [4] S. F. Kistler and L. E. Scriven, “The Teapot Effect: Sheet-Forming Flows with Deflection, Wetting and Hysteresis,” *Journal of Fluid Mechanics*, vol. 263, pp. 19–62, 1994.
- [5] H.-J. Butt, C. M. Lee, D. Y. Kwok, and E. Bonaccorso, “Contact Angle Hysteresis: A Review,” *Current Opinion in Colloid and Interface Science*, vol. 60, art. 101634, 2022.
- [6] A. Marmur, “Concepts and Misconceptions in Contact Angle Hysteresis,” *Advances in Colloid and Interface Science*, vol. 308, art. 102723, 2022.
- [7] A. Kibar and T. Camcı, “Wetting Hysteresis and Its Effect on Liquid Sheet Stability,” *Applied Physics A*, vol. 124, art. 144, 2018.
- [8] R. B. Bird, W. E. Stewart, and E. N. Lightfoot, *Transport Phenomena*, 2nd ed. New York: Wiley, 2002.
- [9] CLL110 Course Notes, IIT Delhi, 2025.