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THERMALLY INDUCED DEFORMATION OF A CAPILLARY BRIDGE AND POSSIBLE TECHNICAL APPLICATIONS

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ABSTRACT

The thermocapillarity-induced deformation and rupture of capillary bridges formed either by a pure or an emulsion liquid between hydrophilic /hydrophilic or hydrophilic /hydrophobic substrate configurations is presented herein. Good wettability of the lower substrate decreased the non-linearity of the deformation process in case of the emulsion bridge, whereas a hydrophobic lower substrate improved reproducibility and reduced process times. The experimental results for pure liquids are extrapolated by numerical simulations if the lower substrate is heated with a step-function. The thermally-activated rupture is also seen in the simulation. Feasible technical applications are briefly discussed.

Keywords *: Capillary bridge, Marangoni effect, emulsion, optical/electrical switch*

1. INTRODUCTION

The dynamics of capillary liquid bridges have recently experienced a revival of scientific interest due to new experimental methods and its versatility for novel technical application in the area of microfluidics. Most studies are concerned with capillary bridges between flat and curved surfaces , [1, 2], which are actuated by simple stretching, [3, 4], electrowetting and electric fields, [5], or temperature gradient induced Marangoni effects, [5, 6]. Other studies focus on the processes occurring during reversible separation or irreversible snap-off of the capillary bridge, [7, 8].

The thermocapillarity-induced deformation and separation of capillary bridge configurations is presented herein. The bridges are formed either by a pure or an emulsion liquid and the substrate combinations used are either both hydrophilic or hydrophilic/hydrophobic. A numerical simulation is conducted for a water bridge which is heated suddenly from below. Feasible technical applications such as optical/electrical switches or micro-pumps are discussed.

2. EXPERIMENT

2.1 Experimental Setup

The experimental setup is schematically shown in Figure 1 and consists of two horizontal parallel copper plates exhibiting good thermal conductivity. The copper plates are each mounted on top of a foil heater (Minca), which is fixed on a Peltier-element. In order to increase the cooling capability of the Peltier-element a small copper heat exchanger is attached to the cold side, which is connected to a thermostatic bath exhibiting a temperature of -10 °C. The different elements of the sandwich-structure are connected with thermally conductive glue. The walls of the capillary bridge opposing each other can be separately aligned in x-, y- , and z-direction. Additionally to the x-, y-, z-direction the upper sandwich structure can be rotated in the three space angles which allows for a parallel adjustment of the two copper plates. A PT100 thermoelement is placed in a convexity beneath each copper plate to measure the actual temperature which is compared to the target value. The copper plates are heated with the embedded foil heater or cooled by the Peltier-element, depending on the temperature difference. Different kind of substrates can be attached on top of the copper plates with a thermally conducting paste. Glass substrates (objective slides, Menzel) and PTFE (Teflon®) substrates are employed in this study.

Capillary bridges of pure liquids are built by placing a droplet of approximately 1 μl of the substance on the lower substrate and by approaching the lower plate slowly to the upper substrate. After the capillary bridge has formed the lower plate is lowered again in order to obtain an outstretched but stable capillary bridge. The capillary bridges of emulsions are built similarly by placing a droplet of approximately 1 μl of one liquid, usually the denser, on the lower substrate and a droplet of the same volume of the other substance on the upper substrate. The two droplets are aligned horizontally before the lower substrates is approached to the upper one and lowered again after contact of the two liquids.

After the capillary bridge is stabilized at a starting temperature in the range of 0 – 10 °C, the bottom plate is heated linearly up to an intermediate target value from which on it is kept constant to equilibrate the bridge. An image of the capillary bridge is taken after equilibration at the set-temperature and the next heating step is started. The temperature is increased until the capillary bridge brakes.

3. EXPERIMENTAL RESULTS

3.1 Capillary bridge of pure substances

In Figure 2 a capillary bridge of pure pentanediol between two glass substrates is shown. The bottom plate is heated from the starting point, where both substrates are at identical temperatures of 0 °C (a), to 60 °C (b) keeping the top plate at 0 °C. The shape of the capillary bridge did not change significantly. The liquid is transported upwards to the colder plate (c) after increasing the bottom plate to 95 °C. Increasing the temperature difference between the two plates further leads finally to the rupture of the capillary bridge (d). The bridge evolution is non-linear with respect to the lower wall temperature. This non-linearity, i.e. an only slow deformation in the beginning and a fast deformation and rupture for later stages, is also observed for a capillary bridge consisting of pure terpineol and enclosed between glass substrates as well, Figure 3.

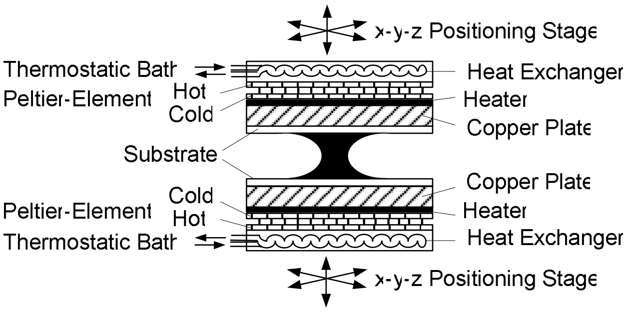

Figure 1 Heating/cooling sandwich structures. The different substrates are placed on the copper base plate. The copper plate is attached to a foil heater which is fixed on the cold plate of the Peltier-element. On the hot side of the Peltier-element a copper heat exchanger is removing the heat enhancing the capacity of the Peltier-element. Both identical sandwich structures are fixed on top of an x-y-z positioning stage to align the structures.

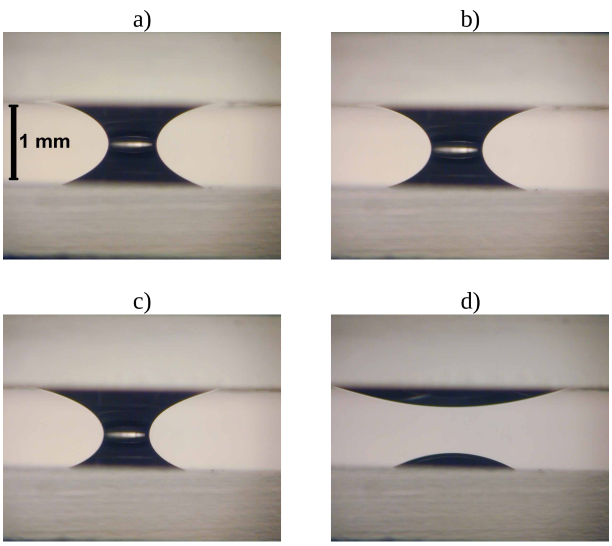

Figure 2 Capillary bridge between two glass substrates of pure pentanediol. The lower plate is heated stepwise: a) identical substrate temperature of $T_o = T_u = 0$ °C, b) $T_o = 0$ °C, $T_u = 60$ °C, c) $T_o = 0$ °C, $T_u = 95$ °C, the liquid is pulled towards the colder upper plate by Marangoni flow, d) $T_o = 0$ °C, $T_u = 100$ °C, the capillary bridge is broken

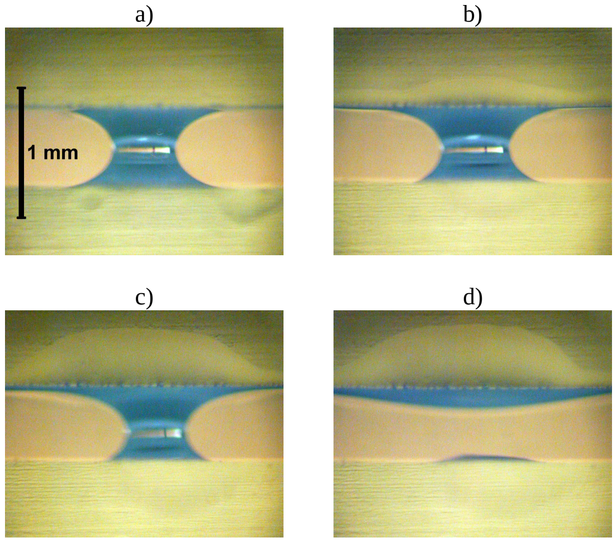

Figure 3 Capillary bridge between two glass substrates of pure terpineol. a) Identical substrate temperature of $T_o = T_u = 0$ °C, b) $T_o = 0$ °C, $T_u = 80$ °C, c) $T_o = 0$ °C, $T_u = 90$ °C, the liquid is pulled towards the colder upper plate by Marangoni flow, d) $T_o = 0$ °C, $T_u = 95$ °C, the capillary bridge is broken.

Note that the temperature difference of the upper substrate between a) and b) is 80 °C, whereas it is only 15 °C between b) and c). To explain this behavior, consider the power required to desorb the liquid from the lower substrate:

$$\dot{W}_{desorb} \approx \frac{\pi}{2} \cdot \left(\gamma_{sv} - \gamma_{sl} - \gamma_{lv} \cdot cos\,\theta_r\right) \cdot D \cdot d_t D \qquad (1)$$

γ_{sv}, γ_{sl} and γ_{lv} are the interfacial energies of the solid-vapor, solid-liquid and liquid-vapor interface. θ_r is the receding contact angle and D is the current foot print diameter of the capillary bridge on the lower substrate. The power available for the desorption process is roughly proportional to the temperature difference between the upper and lower substrate. Assuming a constant receding contact angle explains the non-linear foot–print behavior versus temperature difference.

3.2 Capillary bridge of emulsions

Figure 4 summarizes the thermally induced rupture of an emulsion capillary bridge. Silicon oil is initially located at the bottom PTFE substrate, whereas ink is used for the upper half. This can be also identified with the small contact angle of silicon and the larger one for ink at isothermal conditions (a). The separation line of the two liquids coincides with the neck of the meniscus. The pronounced feature upon heating of the lower substrate is the changing contact angle of the upper foot print (b and c). Since the temperature of the upper wall is kept constant at 10 °C, the change of contact angle must be due to the motion of the silicon oil along the ink free surface to the upper substrate. The previously mentioned non-linearity in the rupture process is weakened as the silicon remains well adsorbed to the lower substrate throughout the heating cycle. The neck of the meniscus is approaching the lower substrate while heating.

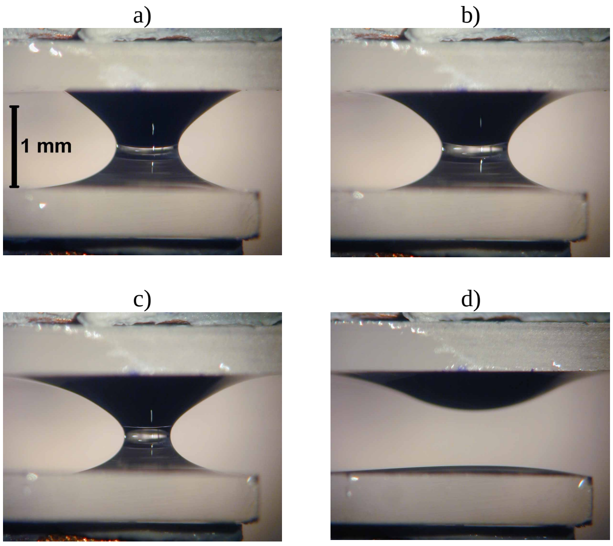

Figure 4 Capillary bridge between two PTFE substrates of an emulsion of ink (top) and silicon oil (bottom). The lower plate is heated stepwise: a) identical substrate temperature of $T_o = T_u = 10$ °C, b) $T_o = 10$ °C, $T_u = 40$ °C, c) $T_o = 10$ °C, $T_u = 60$ °C, the liquid is pulled towards the colder upper plate by Marangoni flow, d) the capillary bridge is broken.

Although this can be observed for single-component capillary bridges as well, the fact that the neck also marks the separation line between the two liquids in this emulsion bridge harbors the potential for using this feature e.g. as a thermally actuated optical deflection point.

3.3 Capillary bridges between different substrates

Instead of using two kinds of liquids and one kind of substrates, Figure 5 depicts an ink bridge between an upper glass substrate and a lower PTFE-substrate. The capillary bridge ink has an asymmetric shape with respect to the horizontal due to the hydrophobic lower substrate (b). This asymmetry is enhanced upon heating (c). A major part of the liquid mass is finally accumulated at the upper substrate after the rupture of the bridge (d). It is seen that reducing the wettability (hydrophobic material, increasing surface roughness, covering the lower substrate with fine powder [9]) of the lower substrate is a suitable measure to improve reproducibility and decrease the overall process time.

To ensure that the rupture of the capillary bridge investigated in Figure 5 is thermally induced, an experiment with ink and the same substrate arrangement is conducted, whereby the substrates remain isothermal, Figure 6. Instead, the separation distance of the opposing substrates is slightly enhanced after the bridge attained equilibrium condition (a). This leads to a mechanically induced rupture of the bridge (b). Contrary to Figure 5 d), where the prevailing part of the liquid is attached to the upper substrate, the mass of the liquid in Figure 6 b) is cleanly divided between an upper and a lower part, reassuring the thermal activity in Figure 5.

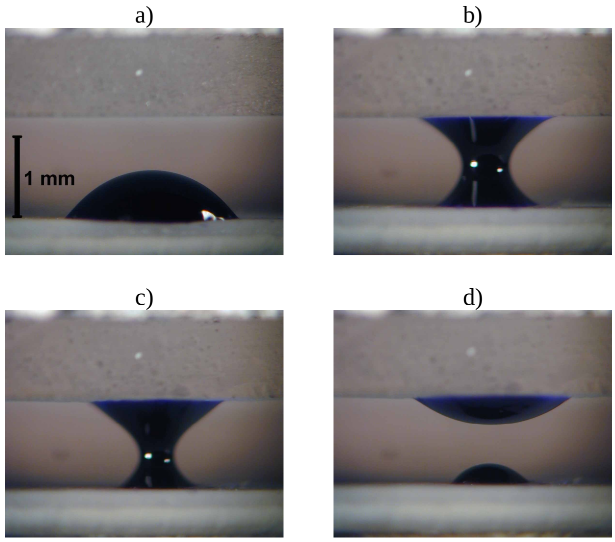

Figure 5 Capillary bridge of ink between a glass (top) and a PTFE substrate (bottom). The lower plate is heated stepwise: a) identical substrate temperature of $T_o = T_u = 2$ °C, b) $T_o = T_u = 2$ °C, c) $T_o = 2$ °C and $T_u = 30$ °C, d) $T_o = 2$ °C and $T_u = 35$ °C

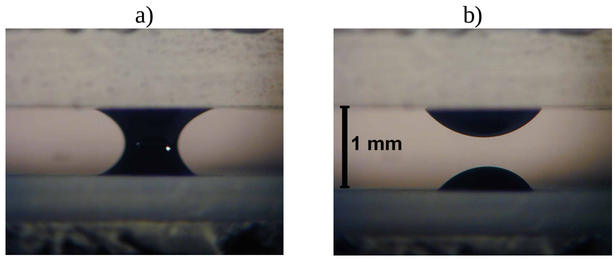

Figure 6 Capillary bridge of ink between a glass (top) and a PTFE substrate (bottom). a) capillary bridge built by approaching lower substrate, b) breakup of capillary bridge due to increase in gap width.

4. NUMERICAL SIMULATION

A numerical simulation tool, developed for free-surface microfluidic-problems incorporating a surface tension gradient and wetting effects [10], is used to model the rupture of a water bridge between two copper plates. It is based on the Galerkin discretization of the Navier-Stokes equations and energy equation in Lagrangian coordinates. After the capillary bridge has attained equilibrium shape (Figure 7 a), the bridge is suddenly heated from below, i.e. the wall temperature jumps from ambient conditions to 70 °C. The Marangoni effect generates a surface wave (b–c), which transports mass to the upper wall (d). A thin filament is generated in vicinity of the upper substrate, for which the continuum assumption breaks down. No additional model for this narrow neck, which is dominated by molecular effects, was implemented. A direct comparison with experiments could not be achieved so far. This is due to the strong evaporation of water at elevated temperatures, a feature not considered in the simulation.

Running the experiments under saturated conditions did not succeed as well due to condensation on the cooled upper wall. Additionally the simulations are computationally too expensive to re-run them with several liquids and heating functions of the lower substrate. However, the general trend of mass transport due to the surface tension gradient is captured by the model. The influence of viscosity appears to be underpredicted as the strength of the surface waves could not be observed in the experiments even for very rapid heating.

5. ADDITIONAL TECHNICAL APPLICATIONS

The thermocapillarity-induced mass transport directly suggests an application as a micro-pump. Figure 8 illustrates an electrically conductive liquid, forming a capillary bridge between two flat plates. If the lower substrate is heated, the thermal Marangoni-effect will initiate a mass flow to the upper plate, deforming (solid line) the bridge from its equilibrium shape (symmetric meniscus) and connecting the electrical contact *a* with *b*. Reversing the heat flow leads to a mirrored bridge shape (dashed line) and a connection of contact *a* with *c*. This arrangement can be used for a thermally actuated micro-switch or a self-controlled micro-engine.

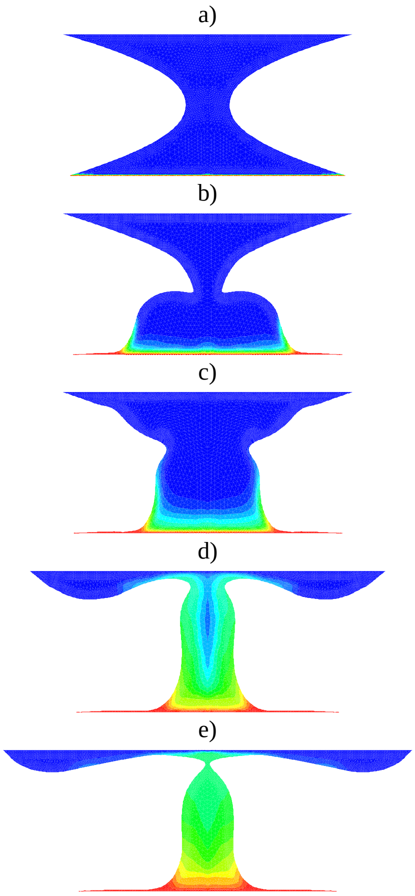

Figure 7 Simulation of a water capillary bridge between copper plates suddenly heated from below (wall temperature jumps from zero to unity). Upper wall temperature corresponds to 25 °C and the lower temperature corresponds to 70 °C. Overall process time shown is 86 micro seconds

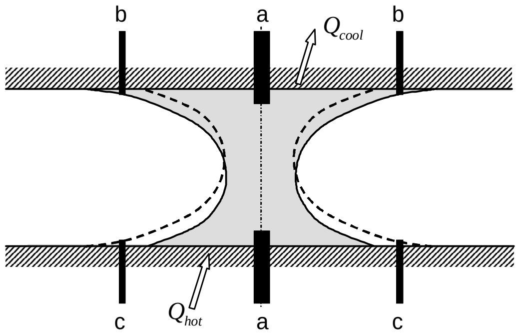

Figure 8 Concept of thermally actuated micro-switch

6. CONCLUSIONS

The dynamics of capillary bridges under the influence of a temperature gradient along the bridge symmetry axis was investigated experimentally and numerically. Pure liquids and two component emulsions were used as working fluid. The lower wall material was either identical to the one of the upper wall or more hydrophobic. Thermocapillarity led in all cases to a significant transport of liquid mass to the upper wall and finally to the rupture of the bridge. The deformation of the bridge was seen to be non-linear in time, which is partly due to the non-linear desorption process of the liquid from the lower substrate. This non-linearity is reduced if no desorption takes place, i.e. in well-wetting configurations. A hydrophobic lower substrate improved the reproducibility and reduced the actuation time. In case of the emulsion bridge, the separation line between the two liquids was located in the neck of the bridge, which was slightly shifted downwards during heating. This finding has potential for application in thermally actuated optical deflection devices. The simulation was limited to water bridges suddenly heated from beneath. No direct comparison with experiments could be obtained. The general trend of mass transportation to the colder side could however be observed as well.

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