Hot-spot cooling using microliter liquid drops

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HIGHLIGHTS
- The electrowetting phenomenon can change the apex and contact radius of a drop.
- Attaching a mercury drop to the surface of a hot-spot can decrease its temperature.
- Increasing the drop contact angle by 31° leads to 82% heat transfer enhancement.
- A TCRI can suppress hot-spots on a surface with non-uniform heat flux.

ABSTRACT
In this paper, a new concept is developed for cooling integrated circuits (IC) in the electronic and computer industries. Microliter liquid drops are employed in combination with the electrowetting phenomenon to form a thermal conductance regulating interface (TCRI) between the heat-sink and the cooling target. An experimental setup was arranged in which a mercury drop could be attached to/detached from the surface of a hot-spot and, hence, influence its temperature. In addition, an in-house numerical code was developed to further investigate various parameters of the cooling system. The Navier–Stokes and energy equations were solved in a 2D/axisymmetric domain and the volume-of-fluid (VOF) technique was used to track the deformation of the free surface of the drops under the effect of the electrowetting phenomenon. Finally, as a sample case, a 4 × 4 array of mercury drops was considered to form a TCRI between a cooling target with non-uniform heat flux and a heat-sink. It was shown that the TCRI can be used to effectively suppress hot-spots on the surface of the cooling target. Various parameters of the cooling system were also examined.

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1. Introduction
In recent years, thermal management has become an important issue in designing and manufacturing high-performance electronic devices including microprocessors. The Moore’s law generally predicts that the number of transistors on integrated circuits (IC) nearly doubles every two years [1]. Moreover, based on the International Technology Roadmap for Semiconductors (ITRS), it is expected that the number of transistors in high-performance computers increases from 1 to 150 billion until 2026 with the transistor size decreasing constantly from 40 nm to 6 nm [2]. Since the chip size in these computers remains constant at about 260 mm², these changes will lead to a higher concentration of transistor in microprocessors. As a result of this concentration, the heat generated by a set of transistors will be dissipated from a much smaller surface area. This fact poses new cooling challenges with more emphasis on the design of new cooling systems to cope with the ever-increasing requirements of the computer and electronic industries in the future.

Up until now, several cooling technologies have been proposed and examined. Heat pipes, thermosyphons, MEMS-based systems [3,4], thermoelectric and vapor-compression refrigeration systems are among these technologies. However, the most widespread cooling system used in the computers is the fan-cooled heat-sink. Despite its simplicity and acceptable performance for existing computers, this system is not suitable for cooling purposes in the small dimensions, considering the decrease in the size of the transistors. Another drawback of this system stems from the fact that the heat-sink has a constant thermal conductance. As a result, if a heat-sink is used for dissipating the heat from a surface with highly non-uniform heat flux, a non-uniform temperature distribution will appear. Non-uniform temperature distributions, mostly
known as hot-spots, may result in high thermal stresses which eventually lead to the failure of the electronic device.

Considering the multicore CPUs with each core working independently and the above-mentioned developments in the semiconductor technology, the formation of highly non-uniform heat fluxes on the surface of the ICs is inevitable. Therefore, developing new methods of IC cooling to suppress the undesirable hot-spots has been the focus of many studies in the literature. For instance, Farnam [5] used a numerical method to study the application of microchannels in microprocessor cooling. By passing a fluid through a microchannel, he showed that the fluid flow can spread the dissipated heat on the surface of the microprocessor to bring about a more uniform temperature distribution. In a different method, Wang and Bar-Cohen [6] employed the thermoelectric features of the silicone used in the microprocessor itself to dissipate the generated heat.

An alternative to the new cooling technologies mentioned above is the drop-based/digital microfluidic devices where discrete liquid drops are actuated over an array of electrodes using the electrowetting phenomenon. The electrowetting phenomenon was first introduced by Gabriel Lippmann [7]. After that, Berge [8] suggested using a dielectric to prevent from drop electrolysis and derived the Lippmann relation for the first time using an energy minimization approach. Since then, electrowetting-on-dielectric (EWOD) and digital microfluidics have been widely investigated and applied in various fields by other researchers [9–13].

Possessing exceptional benefits, the electrowetting phenomenon has made its way in several novel applications such as lab-on-a-chip devices [14], variable focus lenses [15,16], electronic displays [17], medical diagnostics and biosensors [18]. In addition, the electrowetting phenomenon can be used for IC cooling purposes. This idea was first put into action by Paik [19] using printed circuit boards (PCB). Using an experimental setup, a 6 μL water liquid drop was moved through an array of 9 electrodes to dissipate the heat from a hot-spot with 30 W/cm² heat flux. To cool a hot-spot with a heat flux of 7.6 W/cm² on a 2D array of electrodes, Cheng and Chen [20] manipulated a 39 μL water drop in a similar manner. It was found that the drop is capable of dissipating 86% of the generated heat by the hot-spot. Oprins et al. [21] used the FLUENT software to simulate the movement of a drop between two parallel plates and its effects on cooling the top plate. Using a simple 2D model, they found that the generated circulation inside the drop improve the heat transfer from the top plate. In other studies performed in this area, the potential capability of using liquid drops in cooling ICs has been examined [22].

In this paper, a new concept of hot-spot cooling is proposed in the form of a thermal conductance regulating interface (TCRI). The structure of the TCRI is such that it can be used to transform a fan-cooled heat-sink into a system with the capability of hot-spot cooling. The proposed TCRI includes a 2D array of liquid drops which can be actuated using the electrowetting phenomenon to change the thermal conductance between the cooling target and the heat-sink. Therefore, a PCB-based experimental setup is designed to study the effects of the electrowetting phenomenon on various geometrical parameters of the drops in combination with Image-processing techniques. In the next step, an experimental setup is arranged in the form of a hot-spot cooling system to investigate the influence of mercury drops on the temperature of a hot-spot. Numerical simulations are also employed to support the proposed hot-spot cooling concept. The Navier–Stokes and energy equations are solved in a 2D/axisymmetric domain and the volume-of-fluid (VOF) technique is used to track the deformations of the drop free surface under the effect of electrowetting phenomenon. In addition, the FLUENT software is used to test the capabilities of a sample TCRI in suppressing hot-spots on the surface of a cooling target with non-uniform heat flux. Detailed descriptions of the experimental and numerical studies are discussed in the paper.

2. Hot-spot cooling technique

The electrowetting is a phenomenon in which the apparent contact angle of a polarizable/conductive liquid drop and, hence, the wetting behavior of the drop on the surface can be changed by employing an electric field. The change of the apparent contact angle in this phenomenon is generally governed by the Young–Lippmann relation:

$$\cos(\theta_f) = \cos(\theta_0) + \frac{\varepsilon_d \varepsilon_0 V^2}{2d \gamma_L}$$

where $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_d$ the dielectric constant, $d$ the dielectric thickness, and $\gamma_L$ is the liquid/gas surface tension. Since electrowetting is an electromechanical phenomenon [23], it has no effect on the local contact angle of the drop $\theta_0$ (i.e. the actual contact angle very close to the surface) [24]. Equation (1), however, shows that the apparent contact angle will change to a lower value $\theta_f$. Therefore, the new shape of the drop is the result of the equilibrium between the surface tension forces and the electrical forces generated upon applying the voltage $V$ [25]. This fact can be seen in Fig. 1.

As seen in Fig. 1, when the voltage is applied, the drop further spreads on the surface resulting in a reduction of the height of the drop apex. Possessing this feature, the electrowetting phenomenon is a great candidate for manipulating liquid drops to design a cooling system with variable thermal conductance. Based on this feature in this paper, a new system is designed which manipulates

![Fig. 1. The schematic of the electrowetting phenomenon. (a) Before applying a voltage, the apparent contact angle of the drop is higher. (b) After applying the voltage, the apparent contact angle decreases and the drop spreads on the surface.](image-url)
single liquid drops using the EWOD technology to adapt thermal conductance in the presence of hot-spots. The fundamentals of this system, which is based on the idea of thermal switch method proposed by Paik [19], is shown in Fig. 2.

As displayed in Fig. 2, a liquid drop is sandwiched between two parallel surfaces. The top surface is the heat source (e.g., the surface of a microprocessor) and the bottom surface is a heat-sink which dissipates the heat to the environment. In the default mode, a voltage is applied to the drop to detach it from the top surface. In this condition, the heat conduction between the heat source and the heat-sink is mainly accomplished through the surrounding fluid which can be air or an immiscible liquid such as silicone oil. Since the thermal conductivity of the surrounding fluid is generally lower than that of the drop, the heat transfer is lower in this condition and the heat transfer coefficient is basically under the influence of the surrounding fluid. Now, if more heat transfer is needed, the voltage can be removed to let the drop attach to the top surface. This action provides a higher heat transfer coefficient between the heat source and heat-sink.

The cells containing single liquid drops, illustrated in Fig. 2, can be juxtaposed in a 2D array to form a thermal conductance regulating interface (TCRI). The TCRI, shown schematically in Fig. 3, can be placed between a fan-cooled heat-sink and a microprocessor. Consequently, if a hot-spot appears on the surface of the microprocessor, the thermal conductance can be increased in that region to suppress the hot-spot and provide a uniform thermal distribution. To increase the accuracy of the TCRI in cooling hot-spots, the number of the cells should be increased while the size of the cells should be decreased.

Taking advantage of this interface, an old-fashioned cooling system can perform more efficiently in the presence of hot-spots without a complete change in the system design. In addition, the cooling system could be adapted with the ever-increasing requirements of the microprocessor and computer industries. To design such an interface, fundamental studies have to be performed in order to find and optimize the various design parameters. In this paper, therefore, a numerical study along with experiments is performed to investigate the effects of the electrowetting phenomenon on various geometrical parameters of the drop, such as apex, contact angle, and contact radius. Moreover, the influence of a single drop on the temperature of a hot-spot is investigated based on which, the capabilities of the TCRI are tested.

3. Experimental method

Fig. 4 illustrates the experimental setup used for testing the various parameters of a hot-spot cooling system including a single liquid drop. In this figure, various components of the setup are schematically shown. Detailed descriptions of each component are discussed in this section.

The experimental setup contains a PCB-based system for studying the effects of a drop on the temperature of a hot-spot. The design of this system is schematically shown in Fig. 5. A fan-cooled heat-sink was placed under the drop to dissipate the generated heat by the hot-spot.

The bottom surface of the drop is a PCB involving the base and ground electrodes to manipulate the drop. These electrodes are shown in Fig. 6. Because of its excellent thermal characteristics, mercury was selected as the material for the drops. Also, mercury is a super hydrophobic material which removes the need for a hydrophobic coating on top of the dielectric.

Since the drop must be in permanent electrical contact with a ground electrode, traditionally, a thin wire is inserted in the drop for this purpose (as shown schematically in Fig. 1). However, in the hot-spot cooling method presented here, the wire interferes with the movement of the drop. In addition, the mercury drop repels the wire due to its super hydrophobic features. Consequently, as seen in Fig. 6, the ground electrode was placed under the drop in the same plane as of the base electrode. Also, a solder-mask layer with a thickness of $33 \pm 2 \mu m$ and a dielectric constant of 6 was coated and baked on top of the base electrode to serve as a dielectric material. A 50 Hz AC power supply was used to apply the voltage to the drop. The advantages of the AC voltage over DC are the lower probabilities of dielectric breakdown, dielectric charging, and contact angle saturation at higher voltages.

To obtain the required data from various conditions of the drop during the experiments, a CCD Camera (Grasshopper, Point Grey Inc.), mounted with a low-distortion telecentric microscope lens (TEC-55, Computar Company), was used to capture images from the drop. A diffuse light source was placed on the opposite side with regard to the camera such that the interface of the drop could be

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Fig. 2. Schematic view of the cooling method using the electrowetting phenomenon. (a) When the drop is detached from the top surface, the heat transfer rate is lower, while (b) when it is attached, the heat transfer rate increases.

Fig. 3. Schematics of the TCRI with variable thermal conductance along its thickness. The top surface of the TCRI is cut to reveal the interior details of the interface.
clearly detected. An image-processing program was developed in the MATLAB software to facilitate data collection from the images. In this program, the free surface of the drop is detected and tracked such that the drop volume, apex, contact angle and contact radius with the bottom surface could be measured. To calibrate the measurements, a needle with a specified diameter was placed near the drop in the first image of each set of experiments as a reference. The error of the measurements using this technique was found to be less than ±0.02 mm.

To simulate a hot-spot on the top surface of the drop, a small heater was embedded in the top PCB in the form of a thin copper film. To prevent a short circuit between the drop and the heater, a 15 μm layer of solder-mask was coated on top of the heater. Also, the top surface of the heater was insulated to prevent dissipation of the generated heat from the top surface. A close-up view of the heater on the top PCB is shown in Fig. 7.

Since the drop is in contact with the heater, measuring the temperature at the point of contact becomes a challenge. Although thermocouples with small probes are available, a bump will be formed on the surface of the heater if a thermocouple is used to measure the temperature. This bump may interfere with the drop movement. Furthermore, thermocouples have low sensitivity in general and are not suitable for this purpose. Alternatively, some researchers have employed multilayered PCB fabrication techniques to embed thin films of copper, platinum or gold as resistive temperature detectors (RTD) in their cooling setups [19,20]. In this study, however, based on a novel technique, the heater also works as an RTD to measure the temperature of the hot-spot (as seen in Fig. 7). This method simplifies the process of the PCB fabrication. For this purpose, a constant DC electrical current was fed into the heater to generate heat based on the joule effect. At the same time, the variation of voltage across the heater was recorded using a digital multimeter (UT71D-Uni-Trend). To increase the accuracy of the measurements and eliminate the error caused by the lead wire resistance, a four-wire configuration was used to assemble the RTD. The RTD was calibrated using a precise datalogger (177-T4, Testo) in the range of 20 °C–120 °C and a trend line was obtained to measure the temperature based on the variations in electrical resistance of the RTD. It was found that the average error for the temperature measurements is less than 0.1%.

4. Numerical method

To develop the studies on the hot-spot cooling idea presented in this paper, an in-house numerical code was developed. Fig. 8 shows the computational domain for simulating the electrowetting phenomenon along with the hot-spot cooling process. To simulate a hot-spot, a constant heat flux was applied to the top surface. Also, the temperature of the bottom surface was taken constant to simulate the heat-sink.

In the numerical code, the N–S equations were solved in a 2D/axisymmetric domain to simulate the fluid flow in the electrowetting phenomenon. Considering the flow to be incompressible,
of the electrowetting phenomenon, the volume-of-fluid method proposed by Mirzaii and Passandideh-Fard [26] was used.

Continuity equations simultaneously, a three step projection method has been shown to take long computational times. On the other hand, Mugele and Buehrle [24] showed that for a small thickness of the dielectric in comparison with the size of the drop, the electrostatic forces will be concentrated very close to the drop contact line on the solid surface. As a result, the Young–Lippmann relation is sufficient to simulate the electrowetting phenomenon. Therefore, Equation (1) is first used to calculate the change in the contact angle under the effect of the voltage. Next, the new contact angle is applied in the numerical method as a boundary condition at the drop contact line on the surface. To model the hot-spot cooling process, the energy equation was solved using the enthalpy method. The energy equation may be written in terms of enthalpy, as follows [30,31]:

$$\frac{\partial h}{\partial t} + (\mathbf{u} \cdot \nabla) h = \frac{1}{\rho} \nabla \cdot (k \nabla T)$$

where $h$, $T$, and $k$ are the enthalpy, temperature and thermal conductivity, respectively. Detailed description of this method is given elsewhere [32] and is not repeated here.

5. Experimental results

5.1. Effects of the electrowetting phenomenon on the geometrical parameters of the drop

The hot-spot cooling technique proposed in this paper requires an understanding of the effects of voltage on geometrical parameters of the drop. For this purpose, a mercury drop with an approximate volume of 8.6 μL was placed on the base electrode without a top PCB. Next, different values of AC voltage were applied (0–260 V) and the changes in the drop shape were recorded using the CCD camera. Some of the captured images can be seen in Fig. 9.

After processing the images, the changes in the drop apex, contact radius and contact angle were obtained as shown in Fig. 10. As the voltage increases, it can be seen that the contact angle of the drop is decreased. Also, the results from Young–Lippmann relation are seen to agree well with the experiments at lower voltages. However, as the voltage is increased, a discrepancy can be seen which is probably due to the alternating nature of the AC voltage.

Fig. 10 also shows that the contact radius of the drop increases constantly against the voltage. In contrast, due to the 0.25 mm increase in the contact radius, the apex of the drop is forced to experience a 0.23 mm decrease. The same experiment was repeated for other drops with different volumes and a similar trend was observed in the change of drop apex and contact radius. Based on these results, it can be concluded that the drop will experience a decrease in the apex as a result of the applied voltage and this
behavior seems to be taking place independent from the drop volume. This feature can be used in the presented hot-spot cooling system in which the drop must be forced to detach from the top surface.

Next, the behavior of a drop between two parallel surfaces is investigated. For this purpose, an 8.6 μL drop is placed between two parallel PCBs with a gap distance of 1.7 mm. To actuate the drop, the PCB involving the base and ground electrodes was located at the bottom. In this case, the voltage was first increased to detach the drop from the top surface after which the voltage was gradually decreased to zero to test the reversibility of the process. Fig. 11 shows the first stage of the experiment where the voltage was increased.

In addition, the changes in the profile of the drop are depicted in Fig. 12a. It can be seen that until 210 V, despite a 0.1 mm increase in the contact radius, the drop is still attached to the top surface. However, at 260 V, the drop is detached from the top surface and the contact radius reaches 1.4 mm. Increasing the voltage to 310 V seems to have a small effect on the contact radius and drop profile. Accordingly, it may be concluded that the drop has reached a contact angle saturated condition where the contact angle is not further increased. This phenomenon is reported to occur at higher voltages in the electrowetting phenomenon due to various reasons [33–35]; however, a consensus about the nature of this phenomenon has not been reached.

The variation of the drop contact angle for the same case is illustrated in Fig. 12b. It can be seen that the contact angle is constantly decreasing as the voltage is increased. Compared to Fig. 10a, a better agreement is observed in this case between the measurements and those of the Young–Lippmann relation. This improvement may be due to the fact that the drop is restrained by the top surface which decreases the effects of the oscillations related to the AC voltage. The effects of contact angle hysteresis are also depicted in Fig. 12b. As a result of this phenomenon which is believed to be due the surface roughness, the values of contact angle are lower when the voltage is gradually decreased. More information regarding this phenomenon can be found elsewhere in the literature [36,37].
The variation of the contact radius and apex of the 8.6 μL drop with voltage can be seen in Fig. 13. As it was seen before, the apex of the drop remains unchanged until 210 V which means that the drop is still attached to the top surface. However, the contact radius is constantly increasing up to 260 V after which, due to the saturation phenomenon, the contact radius shows no further change. To study the effects of the hysteresis on drop apex and contact radius, the voltage was then gradually decreased to zero. However, the difference between the values of these parameters at a specific voltage is less pronounced compared to that of the contact angle.

Considering the observations regarding the drop apex and contact radius of a drop between two parallel surfaces, it can be concluded that the behavior of the drop is suitable for hot-spot cooling purposes. However, it should be mentioned that for a certain gap distance (the distance between the two parallel surfaces), the volume of the drop has an optimum value. If the drop is not large enough, it will not attach to the top surface and if the drop is too large, it could not be detached from the top surface even at higher voltages. In the next section, the results regarding the hot-spot cooling system will be discussed.

5.2. Hot-spot cooling using the liquid drops

To test the capabilities of a single drop in cooling a hot-spot using the experimental setup shown in Fig. 5, first different values of electrical current were supplied to the heater. In this case, the experiment was performed without a drop and the gap distance was set to 1.7 mm. Using the RTD, the variation in the temperature of the heater was recorded. For each applied current value, the measurements continued until a steady-state was reached. Next, to investigate the influence of a drop on the temperature of the heater, a 14.5 μL mercury drop was placed between the heater and heat-sink (the top and bottom PCBs, respectively). The measured values of the steady-state temperature against the applied current for both cases are shown in Fig. 14.

Based on this figure, it can be realized that a 30 °C decrease of temperature is achieved for a 2 A current, only by placing a 14.5 μL drop between the heater and heat-sink. However, this heat transfer improvement is only about 6.6 °C for the 1 A current. The figure shows that the temperature of the heater changes linearly against the square of the applied current. This trend can be explained using the Joule’s first law which indicates that the rate of heat generation in an electrical resistance is linearly proportional to the square of the current. This linear behavior could be used to predict the temperature of the heater at higher input powers as well as the temperature reduction caused by the drop presence.

Finally, to test the capabilities of the presented cooling system, a drop of volume 7.0 μL was placed between the top and bottom PCBs. While the drop was attached to the top surface (Fig. 15a), a 2 A current was applied to the heater which led to a heat generation
rate of 720 W/mm³. As a result, after about 700 s, the temperature of the heater reached a steady-state value of 78°C, as shown in Fig. 16. At this time, a 310 V voltage was applied to detach it from the top surface (Fig. 15b). As a result of this change, the temperature of the heater started to increase. In the steady-state condition, a 16°C increase in the heater temperature was observed due to the detachment of the drop. These changes can be seen in Fig. 16.

It should be indicated that in the above experiment, the drop only covers a portion of the heater surface area and the rest is in contact with the surrounding. As a result, the existence of the drop in cooling the heater is less effective compared to the case with a 14.5 mL drop (previous case, Fig. 14 with the drop). Based on this fact, it can be concluded that a decrease in the contact area of the drop with the heater causes the steady-state temperature to be increased.

To observe the repeatability of the hot-spot cooling process using the technique proposed above, several other experiments were carried out with the same conditions as of the previous case (Figs. 15 and 16). A good agreement was observed between the measured temperature values of the hot-spot for each experiment. In the best condition, a 17°C temperature difference was achieved due to the presence of the mercury drop.

6. Numerical results

In the previous section, the potential abilities of a single mercury drop were experimentally tested in cooling a hot-spot. However, further studies are required to develop the proposed cooling system. Due to the contact angle saturation and dielectric breakdown at higher voltages, further decrease in the drop apex was not possible during the experiments. Since image-processing techniques were employed in the experiments to monitor the behavior of the drop under the effect of the electrowetting phenomenon, the drop could not be placed inside a cell. However, in the TCRI every single drop must be enclosed in a cell to prevent the neighboring drops from merging or any unwanted lateral movement. As a result, to study the same scenario as in the TCRI, numerical simulations are presented in this section to examine more aspects of the cooling system.

To validate the numerical results presented in this paper, an 8.6 mL spherical drop was initially considered inside the computational domain. By applying the same contact angle value obtained from Fig. 9 for 0 V to the bottom wall and the boundary conditions seen in Fig. 8, the equilibrium profile of the drop was obtained. Fig. 17a compares the simulated profile of the drop with those of the experiments. In this figure, a mesh refinement study has also been performed. The mesh size, characterized by the number of cells per radius (CPR) of the drop, was gradually decreased until no significant changes could be seen in the results. A good agreement can be observed between the profiles obtained from the simulations (for 40 CPR) and experiments at 0 V. A mesh corresponding to CPR = 40 is seen to be fine enough after which the numerical results will experience no significant changes.

Fig. 17b shows the results of simulations performed for the electrowetting phenomenon in comparison with the experimental results presented in Fig. 10b. In these simulations, the contact angle of the 8.6 mL mercury drop was calculated for each value of the voltage and applied in the numerical scheme. Although at lower voltages a good agreement can be seen between the numerical and experimental results, some discrepancies at higher voltages are observed due to the alternating nature of the AC voltage. Nevertheless, it can be seen that the drop apex and contact radius experience a similar behavior as the voltage increases.

6.1. Hot-spot cooling scenarios and related parameters

To study the effects of heat flux on the cooling performance of the system, a 7 μL mercury drop was considered between two parallel walls with a gap distance of 1.8 mm. In the absence of a voltage, the contact angle of the drop with a wall was considered to

**Fig. 14.** Steady-state temperature of the heater against the square of current for the cases with and without the 14.5 μL mercury drop. The lines between the data points are plotted based on linearly-fitted values.

**Fig. 15.** Hot-spot cooling experiment using the electrowetting phenomenon. (a) The 7.0 μL drop is attached to the surface of the heater. After a steady-state was reached, (b) the drop is detached by applying 310 V to the drop. Horizontal dashed lines demonstrate the contact level of the drop with the top and bottom surfaces.
be 141°. This value was experimentally obtained by measuring the contact angle of mercury drops with different volumes on the surface of the solder-mask dielectric and in the absence of an applied voltage. Based on Equation (1), for a certain voltage, the change of contact angle depends on the thickness and constant of the dielectric. In the experiments presented in this paper, the change of contact angle due to the applied voltage for the mercury drops on solder-mask was limited to 20° in the best case, while, contact angle changes as high as 74° has been also reported in the literature for mercury drops [38]. For this reason, to have a more comprehensive study on various aspects of the cooling system, the simulations were performed regardless of the dielectric properties, and different values of contact angle were applied to the drops to simulate the effects of the electrowetting phenomenon.

For the first case, it was assumed that a voltage is applied to the drop to decrease the contact angle from 141° to 110° and detach the drop from the top surface. Fig. 18a illustrates the equilibrium shape of the drop which was obtained by solving the N–S equations.

Next, a 1400 W/m² heat flux was applied to the top wall. Assuming the bottom wall of the cell to be a heat-sink, the temperature of this wall was set to 298 K. Fig. 18a shows the steady-state temperature distribution inside the cell for this case. The temperature variation on the top wall against the radial distance from the axis of symmetry is also shown in Fig. 18b. It can be seen that the temperature of the top wall is higher at the corner of the cell, while due to the existence of the drop, the temperature is lower in the central regions. If the average temperature of the top wall $T_{av,\text{top}}$ is taken into account, an equivalent thermal conductivity
$k_{eq}$ can be defined between the top and bottom walls, based on the Fourier’s law:

$$k_{eq} = \frac{q' d_{gap}}{T_{av,top} - T_{bottom}}$$  \hspace{1cm} (8)

In this relation, $d_{gap}$ is the gap distance between the top and bottom walls and $q'$ is the heat flux applied to the top wall. Using this relation, the equivalent thermal conductivity $k_{eq}$ is calculated to be 0.056 W/mK for this case. Now, if a higher rate of heat transfer is desired between the top and bottom walls, the contact angle on the bottom wall can be changed to 141° to let the drop attach to the top wall. After changing the contact angle, the N–S equations along with the energy equation were solved to obtain the new steady-state as shown in Fig. 19.

In the steady-state, the temperature of the top wall is decreased nearly 27 K in the regions which are in contact with the drop. However, the decrease of temperature is not more than 14 K at the corners of the domain. The value of $k_{eq}$ in this case is equal to 0.102 W/mK which shows an 82% improvement compared to the previous case.

The above observation may be further elaborated by considering the transient temperature variation of the top wall as depicted in Fig. 20. It can be seen that after the contact angle is changed to 141° (to let the drop attach to the top wall), the temperature on the axis of symmetry has sharply decreased. A close inspection of the results revealed that the temperature decrease occurred in approximately 20 ms. As a consequence, it may be inferred that the cooling process has nearly taken place instantly. In addition, two jumps can be seen in the temperature curves as a result of the movements of the drop when it is attaching to the top wall. In the experiments, these jumps could not be captured because of limitations in the data reading interval which was 1 s.

To have a more comprehensive study, different values of heat flux were applied to the top wall. Fig. 21 shows the steady-state temperature values of the top wall on the axis of symmetry. It is clear that upon increasing the heat flux, the temperature of the top wall is increased linearly. This observation applies to both cases in which the drop is attached to or detached from the top surface. However, the rate of the temperature increase is faster when the drop is detached. Moreover, it can be seen that the temperature reduction caused by the attachment of the drop to the top wall is increasing linearly against heat flux. These observations can be used to predict the effects of the drop on top wall temperature at higher heat fluxes.
Fig. 22a shows various profiles of the drop which are simulated by applying different values of contact angle to the bottom wall. It is clear that upon decreasing the contact angle (i.e., increasing voltage), as a result of further spreading of the drop on the bottom surface, the distance between the drop apex and the top wall increases. For contact angle values between 130° and 141°, the drop is still attached to the top wall while for 125°, the drop is detached for the first time. These observations are displayed quantitatively in Fig. 22b in which decreasing the contact angle is seen to decrease the drop apex and increase the contact radius on the bottom wall.

Fig. 23a shows the changes in the temperature of the top wall on the axis of symmetry against the distance between the drop apex and the top wall. As seen in the figure, reducing this distance leads to a decrease of the top wall temperature. As a result of this behavior, for a decrease as small as 0.2 mm in the distance of the drop apex from the top wall, a 10 K decrease in temperature occurs. In addition, after the drop attaches to the top surface for a contact angle value of 130° at the bottom surface, a further decrease in the temperature is achieved by increasing the contact angle up to 141° (see Fig. 23a at a zero abscissa). This observation is due to the increase in the drop contact area with the top wall and is in agreement with the measurements explained in detail in Section 5.2.
vestigations revealed that the height of the cell has no effect on the drop nears the top wall, different distances between the drop apex and top wall. Before the section and various related parameters were taken into account. As (including liquid drops) one of which was tested in the previous 2. For this purpose, it is necessary to form a 2D array of cells variable thermal conductance (i.e. the TCRI) as discussed in Section on these studies, it is now possible to propose an interface with drops in combination with the electrowetting phenomenon. Based

Fig. 23b shows the calculated values of $k_{eq}$ inside the cell for different distances between the drop apex and top wall. Before the drop nears the top wall, $k_{eq}$ is seen to increase linearly. However, upon attaching the drop to the top wall at the contact angle of 130° (see Fig. 23b at a zero abscissa), the value of $k_{eq}$ increases more rapidly and reaches 0.093 W/mK. Also, this parameter further increases up to the value of 0.102 W/mK by increasing the contact angle to 141°. This improvement is due to the increase in the contact area of the drop with the top wall.

More studies on the simulations presented in this section revealed that in addition to the parameters such as the surrounding fluid, the drop material, and its distance from the top wall, other parameters influence the effects of the drop in hot-spot cooling process. These parameters include the contact radius of the drop with the top wall and the portion of the cell occupied by the drop. Increasing both of these parameters showed to increase the equivalent thermal conductivity $k_{eq}$ of the cell. Further investigations revealed that the height of the cell has no effect on the value of $k_{eq}$.

6.2. Developing the concept of the TCRI

In previous sections, fundamental studies were carried out to examine the possibility of hot-spot cooling using microliter liquid drops in combination with the electrowetting phenomenon. Based on these studies, it is now possible to propose an interface with variable thermal conductance (i.e. the TCRI) as discussed in Section 2. For this purpose, it is necessary to form a 2D array of cells (including liquid drops) one of which was tested in the previous section and various related parameters were taken into account. As a sample case, a $4 \times 4$ array of cells was considered which is combined of sixteen 3 mm $\times$ 3 mm cells with 1.8 mm height. The schematic view of this array is shown in Fig. 24 where the cells are consecutively numbered to be addressed more easily.

To test the capabilities of the above array, a 3D model was arranged in the FLUENT software. To simulate the effect of a drop on the heat transfer process inside each cell, instead of solving flow and energy equations, the value of thermal conductivity of each cell was simply modified according to the calculated values of $k_{eq}$ in Section 6.1. The heat diffusion equation was then solved to obtain the temperature distribution on the top surface of the array. While the temperature of the bottom surface of the TCRI was kept constant at 298 K, a background heat flux of 1000 W/m² was applied to the top surface. Initially, it was assumed that all of the drops inside the cells are detached from their top surfaces by applying a contact angle value of 110° to their bottom surfaces. Based on the results obtained in the previous section, an equivalent thermal conductivity $k_{eq}$ of 0.056 W/mK was considered for each cell. In this condition, the temperature of the top surface of the TCRI was calculated to be equal to 330 K, as shown in Fig. 25a. Next, a heat flux of 1400 W/m² was applied at the location of the cell (3,2). As a result of the non-uniform heat flux, a hot-spot was formed with a maximum temperature of 338 K (Fig. 25b). To suppress the hot-spot, the value of $k_{eq}$ can be simply modified to 0.079 W/mK by decreasing the distance between the drop apex and top surface inside the cell (3,2). As a result, the hot-spot was completely suppressed and a uniform temperature distribution of 330 K was recovered. As another test for the cooling system, this time a heat flux of 1800 W/m² was applied to the cell (3,3) in addition to the 1400 W/m² heat-flux of the cell (3,2). The highly non-uniform temperature distribution formed in this case can be seen in Fig. 25c. Similarly, to suppress both of the hot-spots, values of $k_{eq}$ were changed to 0.079 W/mK in cell (3,2) and 0.102 W/mK in the cell (3,3).

The results of simulations presented in this section, show the capabilities of the TCRI to suppress hot-spots in any point of the cooling target. However, to fabricate a true TCRI for cooling microprocessors, there is a long way to go. For this purpose, the number of the cells should be greatly increased while the size of the cells should be decreased. Also, various studies have to be performed to improve the equivalent thermal conductivity $k_{eq}$ by testing other materials for drops or the surrounding fluid inside the cell. Silicone oil is a good choice for the surrounding fluid, as it can also improve the reversibility of the electrowetting phenomenon. Alternatively, the geometry of the cell should be optimized to
a numerical method was presented in which the N–S and energy equations were solved in a 2D/axisymmetric domain. The VOF technique was used to simulate the electrowetting phenomenon by tracking the free surface of the drops. Simulation results showed that the value of equivalent thermal conductivity $k_{eq}$ between the hot-spot and the heat-sink increases with the drop attachment to the hot-spot surface. Decreasing the distance of the drop apex from the hot-spot surface was also shown to increase the value of $k_{eq}$. As a result, increasing the contact angle from 110° to 141° led to an 82% increase in the value of $k_{eq}$. Finally, a 3D model was arranged in the FLUENT software to test the performance of a thermal conductance regulating interface (TCRI). The TCRI was composed of a 4 × 4 array of mercury drops which could be actuated to modify the value of thermal conductance on the surface of the cooling target. The simulations showed that the TCRI can be effectively used to suppress hot-spots on the surface of a cooling target with a non-uniform heat flux.

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References


![Fig. 25. (a) 3D view of the temperature distribution on the top surface of the TCRI with an applied heat flux of 1000 W/m². (b) Non-uniform temperature distribution caused by a hot-spot with a heat flux value of 1400 W/m². (c) Non-uniform temperature distribution caused by two adjacent hot-spots with heat flux values of 1400 W/m² and 1800 W/m².](image-url)


