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Nozzleless spray cooling using surface acoustic waves

Kar M. Ang[a], Leslie Y. Yeo[b], James R. Friend[b], Yew M. Hung[a], Ming K. Tan[a,*]

[a] School of Engineering, Monash University Malaysia, 47500 Bandar Sunway, Selangor, Malaysia
[b] Micro/Nanophysics Research Laboratory, RMIT University, Melbourne, VIC 3001, Australia

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ABSTRACT

Surface acoustic wave (SAW) atomization is an attractive approach for generating monodispersed microdroplets for a diversity of applications, from drug delivery to mass spectrometry, due to its reliability, miniaturizability, and portability. Here, we demonstrate a nozzleless spray cooling technique based on SAW atomization, with the key advantage of downward scalability: increasing the operating frequency facilitates the fabrication of a chip-sized atomizer to use in compact cooling of electronic devices. Using deionised water, cooling is improved by 15% when the atomization rate is increased by 40%; when the gap separating the SAW device and heat source is halved, the cooling is improved by 20%. By constructing the device such that the atomized droplets are easily deposited upstream of the flow circulation, the performance is improved further. The atomization of CuO nanoparticle suspensions (at 3%) increased the cooling performance by 30%. Merely increasing the nanoparticle mass concentration in the suspension from 1% to 3% leads to an improvement in the cooling by 10% due to the deposition and formation of nanoparticle clusters on the heated surface, thereby increasing the total surface area. Further increases in the nanoparticle concentration to 10% however results in a diminution in the cooling due to the increase in the suspension viscosity μ, that leads to a reduction in the atomization rate $\dot{m} \sim \mu^{-1/2}$ for a given input power. Finally, we demonstrate the concept of using tapered finger transducers to selectively enhance local cooling in a desired area by simply changing the excitation frequency, without requiring repositioning of the SAW device.

1. Introduction

With the ever-increasing demand for high density electronic devices packed with millions to billions of transistors, and the associated heat generated during their operation, proper thermal management has long been important and is now a key driver of device design. This is because the performance and lifetime of these compact electronic devices, including microprocessors, laser diode arrays, X-ray anodes, light-emitting diodes (LED) and many others, are intrinsically limited by the cooling efficiency. For instance, Narendran & Gu (2005) reported that the life span of LEDs decreases exponentially with increasing temperature. Many different types of cooling techniques have been proposed to address these problems, handling extreme heat fluxes in confined spaces. Such techniques include (Agostini et al., 2007; Ebadian & Lin, 2011; Kim, 2007): single- and two-phase flow microchannel and porous media heat exchangers, thermosyphons, heat pipes, jet impingement cooling, and spray cooling.

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[*] Corresponding author.
E-mail address: tan.ming.kwang@monash.edu (M.K. Tan).

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Among these techniques, spray cooling is one of the most promising due to its high heat-flux removal capability. Spray cooling involves the generation of fine droplets, which subsequently impinge on a heated surface (i.e., the heat source). The impinged droplets then either form a thin liquid film atop the heated surface which subsequently evaporates, or, evaporates immediately without formation of the thin film. Considering a small droplet at room temperature that deposits on a heated surface, the amount of heat required to vaporize the droplet consists of the sensible and latent heats, i.e.,

$$Q = m(c_p \Delta T + h_{fg}), \tag{1}$$

where m is the mass of the droplet, c_p is the specific heat at constant pressure, ΔT is the change in temperature from the droplet's initial condition to its saturation temperature, and h_{fg} is the latent heat of vaporization. Smaller droplets require less energy for vaporization and therefore vaporize at a faster rate than their larger counterparts, altogether leading to a faster rate of cooling as the droplet size is reduced.

Generally, nozzles are employed to deliver the spray in spray cooling techniques, and the diameter of the nozzles used define the droplet size. A piezoelectric transducer is frequently used as the actuator to pressurize the liquid in a chamber such that it is repeatedly forced through an orifice, forming individual droplets at high speed, resulting in the generation of many fine droplets that impinge on the heated surface (Hsieh et al., 2014; Lim et al., 2008). Another technique known as electrohydrodynamic atomization or electrospraying (Cloupeau & Prunet-Foch, 1994; Nguyen et al., 2014; Wang & Mamishev, 2012a,b; Wilhelm et al., 2003) employs an electric field as the droplet generation mechanism wherein counterions in the fluid are attracted to the tip of the meniscus protruding from a nozzle when it is raised to an applied potential. Due to Coulombic repulsion, the tip, which deforms into a conical shape known as the Taylor cone (Taylor, 1964), subsequently disintegrates to produce a thin jet that breaks up due to Coulombic fission or hydrodynamic instabilities to form the droplets (Sen et al., 2007), which are then attracted to the surface of the collection electrode, which acts as the thermal exchange surface. While electrospray cooling is able to achieve high heat removal rates, a disadvantage of the technique is the requirement of a very high DC voltage supply ($\sim 10^3$ V). Moreover, one of the limitations of nozzle-based devices is their propensity to clog, either by condensates or by vapor lock with gas entrapment in the orifice (Lohse et al., 2008). Clogging can also be caused by the hydrodynamic bridging (Lee et al., 2012; Ramachandran & Fogler, 1999), which occurs upon the arrival of several foreign particles or impurities at the nozzle simultaneously, forming particle bridges. The size of these foreign particles can be an order of magnitude smaller than the diameter of the nozzle. In a different study reported by Georgieva et al. (2010) on the microchannel flow of a solution suspended with nanoparticles, they found that hetero-coagulation of these suspended nanoparticles with the micron-sized impurities in the solutions can lead to flow induced aggregation and clogging; the diameter of impurities can be significantly smaller than the size of the channels. Due to the higher possibilities of clogging on nozzle-based devices, regular shutdown for cleaning and maintenance is required. In contrast, nozzleless devices employ a spatiotemporally varying, externally applied force to destabilize the free surface of the liquid, leading to its breakup into a mist of fine droplets whose size is a function mainly of the fluid's physical properties. In the remaining portion of this paper, nozzleless spray cooling using surface acoustic waves is shown to be an effective technique to generate a plume of microdroplets for cooling.

In this study, we demonstrate a spray cooling technique that employs surface acoustic wave (SAW) atomization as the spray droplet generation mechanism. The SAW device consists of an interdigital transducer (IDT) patterned on a piezoelectric substrate, which, upon application of a sinusoidal electrical wave, generates a mechanical wave that is mostly confined adjacent to the surface of the substrate, i.e., within one acoustic wavelength from the surface. Upon contact with a fluid placed atop the substrate, the leakage of acoustic radiation into the fluid generates sound that propagates into the fluid responsible for both an acoustic radiation pressure at the free surface of the liquid and a bulk momentum transport in the liquid known as acoustic streaming (Ding et al., 2013; Friend & Yeo, 2011). Consequently, different phenomena—vibration (Miyamoto et al., 2002), transport (Tan et al., 2007), mixing (Shilton et al., 2008, 2014), and jetting (Guo et al., 2014; Tan et al., 2009)—can be induced within the liquid body depending on the magnitude of the surface acceleration on the substrate, itself controlled by the amount of input power delivered to the device. Beyond a critical power or substrate acceleration, however, these phenomena are subsumed by the breakup of the free surface of the liquid as it atomizes to produce a mist of aerosol droplets, approximately 1–10 μm in diameter, typically ejected at velocities up to 1 m/s (Chono et al., 2004; Collins et al., 2012; Qi et al., 2008, 2009). The focus of this work is to harness this ability to produce a high-velocity stream of atomized droplets to reduce the surface temperature of a heated plate placed at a certain separation distance, h_{gap}, from the substrate as a means for efficient nozzleless spray cooling. A major advantage of the technique is the ease with which the SAW devices can be miniaturized for portable applications, an important consideration in future electronic chip cooling applications. A brief comparison of the important characteristics between the nozzle-less spray using SAW device and the nozzle-based spray using piezoelectric transducer and electrospray is shown in Table 1.

2. Experiments

Figure 1(a) illustrates the focusing single-phase unidirectional transducers (Fig. 3(a)) used in the experiments, fabricated on a 128° rotated Y-cut X-propagating, single-crystal lithium niobate ($\mathrm{LiNbO_3}$) piezoelectric substrate. A sinusoidal electric signal generated from a function generator (WF1966, NF Corporation, Japan) was amplified using a high frequency amplifier (25A250A, Amplifier Research, USA), and subsequently applied to the IDT to generate a SAW that propagates on the substrate. The frequency of the signal was set to match the resonant frequency f_{SAW} of the device, set by the gap and spacing