Hydrodynamics of Drop Impact and Spray Cooling through Nanofiber Mats

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Abstract

Spray cooling is one of the effective technologies has been promised for the thermal management of microelectronic systems and server rooms. The focus of this research is to increase the heat flux rate from a hot surface by applying a metal-coated electrospun polymer nanofiber mat. Samples were prepared from copper plate substrate coated with electrospun polymer nanofiber mat and electroplated with one of three different metals: nickel, copper and silver. Experiments were performed in which samples were subjected to impacting water droplets from a height of 17.95cm at various temperatures. The behaviors of droplet impact and subsequent evaporation were observed in order to evaluate and compare heat transfer characteristics of the different sample types. Silver-plated samples were found to provide the highest heat flux rate, followed by copper and then nickel. However, silver was not usable at higher temperatures due to its tendency to oxidize and degrade easily.

Introduction

Drop impact on dry surfaces is a key element of phenomena encountered in many technical applications, including spray printing, rapid spray cooling of hot surfaces, and ice accumulation on power lines and aircrafts. The drop diameter, surface tension, surface roughness, and drop impact velocity play important roles in hydrodynamics of droplet impact on a dry surface[1]. Spray cooling of hot surfaces using liquid sprays offers a very effective means of localized cooling of small areas. It is considered a key heat removal technology in many potential applications. Semiconductor chips, microelectronic devices, and server rooms demand high heat flux rates to operate. A formidable design challenge in microelectronic systems, particularly with the progression of miniaturization, is the ability to provide adequate cooling and maintain low operating temperatures. For example, silicon-based dies in modern integrated circuits typically have a maximum operating temperature of around 125 ℃. Spray cooling is attractive to cool electronic elements because the sprays can directly contact the elements and remove large amounts of heat continuously by water evaporation. However, a serious obstacle in spray cooling is the limited contact between the liquid and the hot surface due to the Leidenfrost effect. Application of a nanofiber mat coating to a surface has been shown to promote droplet spreading and adhesion[3]. It also has been proposed and shown that if a metal surface is coated with polymer nanofiber mat, the mass loss can be minimized to a great amount[4] and ameliorate our capability to remove heat through spray cooling economically and effectively. The thermal and structural properties of four different polymer nanofiber mats were measured[4]. Based on the demonstrated enhancement of heat transfer using polymer nanofiber mats, this new research investigated the use of metal-coated nanofiber mats to achieve even greater heat flux rates. The molten nanofiber mat allows drops evaporate completely inside the mat and avoid the receding, splashing, bouncing, and the Leidenfrost effect when water sprays on the heated surface.

Experiment

Procedure

The materials used to make these coatings were pure silver, pure copper, pure nickel, and PAN (poly-acrylonitrile). Metal-coated nanofiber mats were made by heating electrospun nanofibers that contained metal atoms in a reducing atmosphere[2]. The electrospinning process was performed at room temperature (~20 ^oC) and produced polymer nanofiber on a copper substrate plate (Figure 1). A high voltage power supply (Extech Instruments Regulated DC Power Supply 382-210) was used to charge a solution of 20 wt% PAN fed from a syringe fitted with a hypodermic needle. A potential difference of 15 kV was applied between the spinneret at the needle tip and the grounded copper collector plate. Polymer solution was fed at 1 mL/hr from a height of 15 cm above the collector. Upon application of the electric field, the polymer bead formed a Taylor cone geometry and developed a fluid jet. With each grounded copper plate sample, electrospinning was performed for 5 minutes to apply a PAN nanofiber mat coating. Samples were then heated and sensitized separately in preparation for electroplating. Samples were plated with copper, nickel, or silver. Two top view images of copper nanofiber mat were taken by scanning fluorescence phase microscope (Olympus Model BX51TRF) are shown in Figures 2a and 2b.

Experiment 1

For observations in this experiment, a high speed camera (Redlake Motiopro) was used to take images with the frame rate of 2000 frames per second at a shutter speed of 1/1000-1/2000 seconds. Experiment setup is shown in Figure 3. A small water drop of about 2 mm in diameter was produced by a drop generator that pumped at the speed of 1 mL/hr and then impacted onto a vertical target of plate at a room temperature. The needle was fixed and then a drop was accelerated by gravity and impact onto copper substrate or copper nanofiber mat. The distance between the needle and surface was varied from 15.88cm and 28.7cm. The drop impact velocity was ranging from 1.76 m/s to 2.72 m/s.

Experiment 2

This experiment setup is shown in Figure 4, one high speed camera (Redlake Motionpro) was used to take images with the frame rate of 2000 frames per second at a shutter speed of 1/1000-1/2000 seconds and one CCD camera (Pulnix TM-7EX) were used to record the video of evaporation. Copper substrate and different nanofiber mat plates were placed on a hot plate and heated to the temperature of 125 ^oC, 150 ^oC, and 200 ^oC. A small water drop of 2 mm in diameter was produced by a drop generator that pumped at the speed of 1 mL/hr and then impacted onto copper substrate or nanofiber mat coating plates from the height of 17.95cm at various temperatures.

Results and Discussion

Contact area analysis (Experiment 1)

According to the images that were taken by the high speed camera, drop impacted onto copper substrate and copper nanofiber mat deposited as a spherical sharp, and then it shrunk back. However, drop impacted on copper nanofiber mat deposited with a larger contact area between the water and surface than on copper substrate and stayed almost the same size afterward. For this experiment, radius of drop impact on copper substrate and copper nanofiber mat were measured by Adobe Photoshop. Figures 5 and 6 demonstrate that the radius of spherical spreading area of an impacting drop depending on its diameter and impact velocity. It was found that the spreading area radius of drop impacts on the copper nanofiber mat was larger than on copper substrate, as shown in Table 1. The overall droplet radius normalized by pre-impact droplet radius for copper nanofiber mat was from 2.5 to 2.8, and the average of overall radius ratio was 2.7. The normalized droplet radius on copper substrate ranged from 1.7 to 2.4 with an average of 2.0. The data showed that the spreading area on copper nanofiber mat was about 1/4 time more than on copper substrate and could therefore provide better heat transfer. The conduction of heat transfer is expressed as Fourier's Law:

$$\frac{\partial Q}{\partial t} = -k \cdot A \cdot \frac{\partial T}{\partial x} \qquad (1)$$

where $\frac{\partial Q}{\partial t}$ is the amount of heat transferred per unit time, A is the area normal to the direction of heat flow, k is the thermal conductivity, and is $\frac{\partial T}{\partial x}$ the temperature difference along the path of heat flow. Droplet impacted on copper substrate and copper nanofiber mat that spread to cover almost the same area and then droplet started to shrink. However, droplet on copper substrate had a smaller cover area than on copper nanofiber mat after it shrunk. This effect would lead to a rise of heat transferred per unit time due to the increasing area normal to the direction of heat flow.

	Copper Substrate Average radius/ initial radius ratio	**Copper Nanofiber Mat** Average radius/ initial radius ratio
Height 1 (15.877cm), Impact velocity (1.764m/s)	2.025	2.564
Height 2 (18.85cm), Impact velocity (1.922m/s)	1.843	2.500
Height 3 (21.55cm), Impact velocity (2.055m/s)	1.772	2.655
Height 4 (23.85cm), Impact velocity (2.162m/s)	2.360	2.706
Height 5 (26.25cm), Impact velocity (2.268m/s)	1.776	2.755
Height 6 (28.70cm)Impact velocity (2.272m/s)	2.263	2.808
Average radius/initial radius ratio	**2.007**	**2.665**

Table 1. Average radius ratio of copper substrate and copper nanofiber mat at room temperature

Thermal and mass loss analysis (Experiment 2)

Image data was analyzed by taking measurements in Adobe Photoshop. The base diameter of drop impact on the heated surface and mass loss during the evaporation were measured, and the heat flux rates were calculated by this equation:

$$\dot{q} = \frac{\rho \, \frac{4}{3} \, r_0^3 \, L \, \delta}{\pi \, d_0^2 \, \triangle t} \quad (2)$$

where L is water's latent heat of evaporation (2260 J/g), ρ is density of water (1 g/cm^3), δ is a correction factor accounting for volume loss due to spattering (1 – cumulative mass loss – 0.02), and d_0 is the average normalized base diameter. Because there was still small amount of water remained inside the mats, correction factor had to subtract by cumulative mass loss and 0.02.

It is clearly seen from Fig. 7 that the accumulation of volume loss due to spattering for copper substrate is much higher than others. The time needed for complete drop evaporation, the mass loss during the evaporation and the heat flux rate of all different nanofiber mats and copper substrate are shown in Table 2. Fig. 8 depicts the accumulation of volume loss due to spattering for copper, nickel and silver nanofiber mats at 150 ^{o}C. As shown in Table 2, silver nanofiber mat had the highest heat flux rate follow by copper nanofiber mat and copper substrate at 125 ^{o}C. Nickel and PAN nanofiber mats had lower heat flux rate than copper substrate because their thermal conductivities are both much lower than the thermal conductivity of copper. Also, mass loss during the vaporization on copper substrate was about 26 %, which was much higher than on other nanofiber mats below 10 %.

In some images from 200 ^{o}C experiments, poor visibility of the droplet base on the mat surface made accurate measurement problematic, and heat flux rates could not be calculated. Also, drop impacts onto copper substrate at 150 ^{o}C and 200 ^{o}C formed partial and complete rebounds, respectively, characteristic of the Leidenfrost effect. The Leidenfrost effect is a phenomenon occurring when a liquid drop contacts a surface having a temperature greater than the Leidenfrost point of the liquid. It causes a thin insulating layer of vapor between the hot surface and the liquid droplet that greatly reduces contact and heat transfer. Therefore, the Leidenfrost effect did not happen when drops impacted on nanofiber mat, but it occurred on copper substrate. As shown in Fig.8, silver nanofiber mat was the best choice for coating on heated surface to minimize the mass loss during spattering. However, silver oxidized quickly with air and water, when drop impacted on silver nanofiber mat at 200 ^{o}C, the mat was degraded easily and broke because the water vapor expelled during the experiment.

Table 2. Experiment 2 data

At 125 ^{o}C	Silver Nanofiber Mat	Copper Nanofiber Mat	Nickel Nanofiber Mat	PAN Nanofiber Mat	Copper Substrate
Time needed for complete evaporation	~0.3 second	~0.4 second	~0.4 second	~4 second	~ 3 second
Mass loss during evaporation	< 0.01%	~4%	~4%	< 10%	~26%
Heat flux rate (W/cm2)	257.94	203.8	168.575	9.497	180.21
At 150 ^{o}C	Silver Nanofiber Mat	Copper Nanofiber Mat	Nickel Nanofiber Mat	PAN Nanofiber Mat	Copper Substrate
Time needed for complete evaporation	~0.3 second	~0.4 second	~0.4 second	N/A	N/A
Mass loss during evaporation	< 0.06%	~8%	~19%	< 6%	~100%
Heat flux rate (W/cm2)	613.85	107.87	198.17	N/A	0
At 200 ^{o}C	Silver Nanofiber Mat	Copper Nanofiber Mat	Nickel Nanofiber Mat	PAN Nanofiber Mat	Copper Substrate
Time needed for complete evaporation	~0.2 second	~0.3 second	~0.4 second	N/A	N/A
Mass loss during evaporation	< 2%	~20%	~15%	< 6%	~100%

Conclusion

In this research, experiments were performed to observe hydrodynamics of drop impact onto copper substrate and different nanofiber mat coated copper substrates. The efficiency of spray cooling a heated surface is dependant on heat flux rate through the conducted area between water and hot surface. Experiment 1 showed that copper nanofiber mat coating increased the contact area between the hot surface and water. Our results demonstrated that use of copper nanofiber mat coating yielded a contact radius 25 % greater than bare copper substrate alone. It introduced a novel idea of improving spray cooling by use of metalized electrospun polymer nanofiber mat coating. Experiment 2 compared water evaporation and mass loss through different nanofiber mats and copper substrate. Image data revealed that use of the metalized nanofiber mat coating greatly reduced undesirable phenomena including rebounding (Leidenfrost effect), splashing, and receding. It was also found that silver and copper nanofiber mats had higher heat flux rates than others. Nickel and PAN nanofiber mats had lower heat flux rates than bare copper substrate. Experimental results demonstrated that use of metalized nanofiber mat coatings on copper substrates improved heat flux rates. Although the heat flux rates for sliver-plated mats were high, silver's tendency to quickly oxidize and degrade made copper-plated mats the more practical option. This investigation of Copper-plated nanofiber mat may lead to a breakthrough in the development of a new generation for spray cooling of microelectronic systems, radiological elements and server rooms.

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Fig. 1. Diagram of experimental electrospinning setup

Figs. 2a and 2b. Two top view scanning fluorescence phase microscope images of copper nanofiber mat

Fig. 3. Experimental setup 1

Fig. 4. Experimental setup 2

Fig. 5. Measurements of radius ratio for drop impacted on copper substrate at room temperature with different impact velocities.

Fig. 6. Measurements of radius ratio for drop impacted copper nanofiber mat at room temperature with different impact velocities.

Fig. 7. Measurements of mass loss for drop impact on nanofiber mats and copper substrate at 125 ^{o}C

Fig. 8. Measurements of mass loss for drop impact on nanofiber mats at 150 ^{o}C.