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Effect of flow rate and subcooling on spray heat transfer on microporous copper surfaces

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ABSTRACT

In this work, we experimentally investigated spray boiling heat transfer performance with degassed HFE-7100 as the coolant on a conductive microporous copper surface, and observed enhanced heat transfer performance compared to that on a plain surface. Spray heat transfer data were measured using two full-cone spray nozzles spanning a range of volumetric flow rate from 1.1 cm^3/s to 15.8 cm^3/s. We also investigated the effect of different liquid subcooling levels ranging from 30 °C to 0 °C on the heat transfer data. Spray impingement on the microporous surface showed an enhancement of 300–600% in the heat transfer coefficient at a given wall superheat compared to spray impingement on a plain surface. The critical heat flux also increased by up to 80% for the case of spray impingement on a microporous coated surface as compared to impingement on a plain surface, depending on the flow rates and the subcooling levels. Contrary to the results in the literature, for a given nozzle we observed that the liquid spray at near-saturated temperature (0 °C subcooling) had higher heat transfer performance and critical heat flux than the subcooled spray on both plain and microporous surfaces except at the lowest flow rates. This likely results from the limited residence time of the liquid droplets in contact with the heater surface and the much higher efficiency of phase change heat transfer. The near-saturated spray undergoes phase change much faster than the subcooled liquid, removing heat more efficiently than the subcooled liquid. A modified correlation, based on the Estes–Mudawar correlation (1995) [22], utilizing the experimental data from the present study and literature is proposed for the critical heat flux for spray impingement on both plain and microporous surfaces.

1. Introduction

With the rapid miniaturization and integration of electronic components and the consequent increase in power density, conventional air cooling methods or single-phase liquid techniques for thermal management of electronic components are becoming inadequate [1]. In the cooling of electronic packages using dielectric coolants, aggressive flow configurations such as spray or jet impingement are required to obtain high heat transfer rates that would enable higher power densities and smaller device sizes. Spray cooling in conjunction with boiling of the coolant liquid is a promising candidate for enhancing heat removal from electronic devices because of its high heat flux capacity, small amount of liquid flow rate required, almost insignificant superheat of incipience of boiling, and relatively uniform temperature on the target surface [1]. In addition, even higher heat transfer coefficients can potentially be obtained by engineering structured surfaces to provide higher of density nucleation sites along with smaller superheat for the phase change heat transfer process [2].

Spray heat transfer in the boiling regime on the plain surface has been studied for several years. Most of the earlier research on spray cooling focused on the film boiling regime associated with the quenching of metals (see, for example [3], and references therein). Because of this focus, the results from these studies are of limited value in designing electronic cooling processes that are typically in the nucleate boiling regime [1]. In comparison with other phase change cooling techniques such as pool boiling, two-phase microchannel cooling, and jet impingement, spray cooling can remove significantly higher quantities of heat with much lower superheat [1,4]. Furthermore, spray cooling does not suffer from flow instability, which is a major concern with two-phase microchannel cooling. A uniform dispersal of the liquid droplets impinging on the target surface in a spray gives rise to a more uniform spatial surface temperature distribution over the entire spray impact area. Moreover, the boiling incipient superheat, which may cause a severe thermal shock to electronic components and make

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Nomenclature

A	area of heater surface
C_P	specific heat at constant pressure
C_{gas}	molar concentration of dissolved gas in liquid
C_H	Henry's law constant
d_0	diameter of nozzle orifice
d_{32}	Sauter mean diameter
h_{lv}	latent heat of vaporization
h	heat transfer coefficient
H	distance between the heater surface and nozzle exit
k	Thermal conductivity of copper
L	length of the square test surface
N	number of droplets generated per unit time
P_{gas}	partial pressure of non-condensable gas in the chamber
P_{sat}	pressure corresponding to the saturation temperature
P_{total}	total pressure in the chamber
ΔP	pressure drop across spray nozzle
Q	total volumetric flow rate of spray
$\bar{Q}''$	average volumetric flux across impact area of spray = $Q/\pi L^2/4$
Q''	local volumetric flux
q''	heat flux based on total area of test surface
q_{in}	power input to heater
R_a	mean surface roughness
T_{in}	liquid temperature at nozzle inlet
T_{sat}	saturation temperature in the chamber
$\Delta T_{sub} = T_{sat} - T_{in}$	degree of subcooling
T_w	surface temperature
$\Delta T_w = T_w - T_{sat}$	surface superheat temperature
U	mean speed of droplets

Greek symbols

η	experimentally obtained total evaporation efficiency
$\eta_{1\phi}$	single-phase portion of the total heat that could be transferred to the fluid
θ	spray cone angle
μ_l	liquid viscosity
ρ_l	liquid density
ρ_v	vapor density
σ	liquid surface tension

the heat transfer performance highly unpredictable, is much less pronounced in spray cooling systems than in pool or flow boiling systems.

Recent reviews of the spray cooling phenomenon from the perspective of cooling of electronics are provided in references [5–7]. Kim et al. [8] investigated evaporative spray cooling on a microporous coated surface using water at very low flow rates (1.25–2.4 cm^3/min) on a square heater surface with a side length of 5 cm. The low thermal conductivity microporous layer was fabricated using a mixture of aluminum powder, methyl–ethyl–ketone, and epoxy, and its maximum thickness was 500 µm. At all the flow rates tested, Kim and colleagues found that the critical heat flux (CHF) increased by 50% relative to that on the plain surface. Bostanci et al. [9] performed spray cooling experiments with ammonia on microstructured surfaces made of aluminum with indentations and protrusions at heat fluxes of up to 500 W/cm^2. They observed an enhancement of 49–112% in the heat transfer coefficient with respect to that on a smooth surface with a volumetric flux of 1.6 cm^3/cm^2/s. The increase likely results from the increased surface area, availability of a large range of nucleation cavity sizes, and increased three-phase contact line length density over the heater surface. Thiagarajan et al. [10] reported spray impingement boiling experiments on the copper surfaces coated with a thermally conductive copper microporous coating using HFE-7100 as the coolant. The microporous surface showed a 100–300% increase in the heat transfer coefficient over the plain surface at all subcooling levels ranging from 0 °C to 30 °C and flow rate levels ranging from 4.7 cm^3/s to 15.8 cm^3/s.

In the meantime, the effect of structured surfaces on pool boiling has received intensive attention. The different surface enhancements and their effects on pool boiling performance are summarized in reference [11], in which several forms of microstructure enhancement, including laser drilled cavities, reentrant cavities, microfins, porous coatings, and sputtered surfaces, are reviewed. In particular, porous surfaces made with microparticle coatings have been studied in the past as a means of enhancing heat transfer in pool boiling [12–15]. Such porous surfaces lead to enhanced boiling heat transfer through a combination of the following factors: an increase in the effective surface area, which leads to enhanced interaction of the liquid with the surface; an increase in the nucleation site density; the presence of capillaries that facilitate liquid return; and an increase in the solid–liquid–vapor contact line length throughout the pores. By proper design of the porous layer, the CHF could be enhanced by the capillary-assisted liquid flow toward the heater surface. This reduces liquid–vapor counter-flow resistance and impedes the development of localized dry-out conditions, which leads to a higher CHF [16].

The structured surfaces can also be used to enhance heat transfer with spray impingement. The use of enhanced surfaces in conjunction with dense spray cooling (i.e., when the flow rate is significantly higher than what evaporates from the surface) with dielectric liquids has received much less attention than their application to pool boiling. Because of the desirable properties of the fluid 3M Novec HFE-7100 (very low global warming potential, zero ozone depletion potential, nonflammable, and high dielectric strength, in addition to good thermophysical properties), it has been identified as a potential coolant for cooling power electronic components in automobiles [17]. No study exists in the literature, however, on the performance of HFE-7100 coolant spray impingement in conjunction with enhanced surfaces. The main objective of our study is to investigate the performance enhancement that can be obtained by the conductive copper microporous impinged on by sprays of the HFE-7100 coolant. The effect of the spray flow rate using two different spray nozzles and of liquid subcooling on the heat transfer phenomena are also studied. In the following sections, we describe the experimental setup, procedure, and the target surface enhancements, and then discuss the results.

2. Experimental apparatus and procedure

2.1. Setup

Fig. 1(a) and (b) shows the schematic diagram and a photograph of the experimental test loop, which is designed to deliver the test liquid at the desired pressure, temperature, and flow rate to the spray nozzle inside the test chamber [17]. The HFE-7100 liquid is circulated in a closed loop until it leaves the spray nozzle. The coolant is partially evaporated on impact with the target surface, which is electrically heated. The vapor rises to the top region of the vessel by buoyancy; the remaining liquid accumulates in the bottom of