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Flow boiling heat transfer on a Carbon/Carbon surface

Luca Doretti [a], Giovanni A. Longo [b], Simone Mancin [b,*], Giulia Righetti [b], Claudio Zilio [b]

[a] Dept. of Civil, Architectural and Environmental Engineering, University of Padova, Via Venezia, 1, Padova 35131, Italy
[b] Dept. of Management and Engineering, University of Padova, Str.lla S. Nicola, 3, Vicenza 36100, Italy

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ABSTRACT

Carbon/Carbon (C/C) is one of the most high-tech materials developed by the aerospace industry and then applied to critical components in several different applications. This composite material appears to be a viable option for future thermal management devices because it exploits interesting properties having a low density and a relatively high thermal conductivity as compared to copper; moreover, it has already been used in many industrial applications where it is shaped in various forms even complex. This study explores C/C heat transfer capabilities during the boiling process of a synthetic refrigerant. In particular, this paper presents the experimental measurements carried out during flow boiling heat transfer of R134a on a C/C surface. The sample was tested in a new experimental facility especially designed for studying the flow boiling heat transfer process on innovative materials and enhanced micro- and nano-structured surfaces. The tests were run at constant mean saturation temperature of 30 °C, by varying the heat flux from 50 kW m^{-2} to 100 kW m^{-2}, and the refrigerant mass velocity from 50 to 200 kg m^{-2} s^{-1}. The heat transfer measurements were compared with flow visualizations of boiling heat transfer at different operating conditions. Finally, a new model was developed and validated to estimate the refrigerant flow boiling heat transfer coefficients on C/C surface.

1. Introduction

Since early 1960s, Carbon/Carbon (C/C) composite materials have been studied for several industrial applications related to noteworthy thermal and mechanical characteristics. They combine light weight, exceptional strength, and stiffness with excellent refractory properties, making them the material of choice for severe-environment applications, such as atmospheric reentry, solid rocket motor exhaust, and disk brakes in high performance military and commercial aircrafts, high speed trains, and racing cars. Emerging areas of applications include biomedical devices, aero-engine components, heating elements with 2000 °C temperature, and hardware for metal forming and glass making [1]. Their development is limited by economical and technical constraints, both of them being critical [2].

As the number of electrical and electronic systems increases, their physical sizes decrease, and the spacing between electrical components decreases, both the total amount of heat generated (hence to be dissipated) and the power density (the heat generated per unit volume) increase significantly. There is a general agreement in the scientific community that current air-cooling technologies are asymptotically approaching their limits imposed by available cooling area, available air flow rate, fan power, and noise. Boiling can be a very efficient heat transfer mechanism, thus it can be used to maintain the junction temperature of electronics devices at values compatible with the technology using compact heat sinks.

It is well-know that surface treatments may provide a remarkable boiling enhancement; for this reason, in the last decades, surface modifications, such as integral fins, microfins, microporous coatings, and, more recently, Carbon Nano Tubes coatings, or micro- and nano-structured surfaces have been proposed. [3–16]. Unfortunately, most of these surface treatments involve somewhat cumbersome and very expensive technique, which still remain at laboratory level.

A possible alternative to the use of treated surfaces, may be represented by the adoption of textured composite materials. Carbon/Carbon composite materials are candidates for use in advanced thermal protection systems, as thermal shields; furthermore, there are not any constrains in applying them as interface materials for advanced efficient heat spreaders. In fact, having a low density and a tailored thermal conductivity, C/C composites could be used in replacement of heavy copper spreaders to dissipate high heat

* Corresponding author.
E-mail addresses: luca.doretti@unipd.it (L. Doretti), tony@gest.unipd.it (G.A. Longo), simone.mancin@unipd.it (S. Mancin), righetti@gest.unipd.it (G. Righetti), claudio.zilio@unipd.it (C. Zilio).

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Nomenclature

A	area (m^2)
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
$d_{h,t}$	thermal hydraulic diameter (m)
g	gravitational acceleration ($m\ s^{-2}$)
G	mass velocity ($kg\ m^{-2}\ s^{-1}$)
HTC	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
HF	heat flux ($W\ m^{-2}$)
J	specific enthalpy ($J\ kg^{-1}$)
k	coverage factor (–)
La	Laplace number (–)
I	electrical current (A)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
M	molar mass ($kmol\ kg^{-1}$)
p	pressure (Pa)
P_{EL}	electrical power (W)
Pr	Prandtl number (–)
q	heat flow rate (W)
R	correlation index (–)
Ra	roughness parameter (μm)
Re	Reynolds number (–)
Rku	roughness parameter (–)
Rsk	roughness parameter (–)
RSm	roughness parameter (mm)
Rp	roughness parameter (–)
Rq	roughness parameter (μm)
Rz	roughness parameter (μm)
s	thickness (m)
Sa	roughness parameter (μm)
Sku	roughness parameter (–)
Sp	roughness parameter (μm)
Sq	roughness parameter (μm)
Ssk	roughness parameter (–)
Sv	roughness parameter (μm)
Sz	roughness parameter (μm)
t	temperature (°C)
T	temperature (K)
x	vapor quality (–)
Greek symbol	
Δt	temperature difference (°C)
ΔV	electric potential (V)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($N\ m^{-1}$)
Subscript	
1-D	1-dimension
base	reference area
C/C	Carbon/Carbon
cv	convective boiling
evap	evaporator
eq	equivalent
i	i-th
in	inlet
L	liquid
loss	loss
mean	mean
nb	nucleate boiling
out	outlet
pb	pool boiling
r	refrigerant
red	reduced
sat	saturation
sub	subcooled liquid
TS	test section
V	vapor
w	water
wall	wall

fluxes while lowering the weight and volume of the heat sinks. For this reasons, this work investigates a novel and previously unexplored application of C/C materials as boiling surface for high heat flux dissipation. Thus, this paper presents the heat transfer measurements collected during flow boiling of R134a on an electrically heated C/C surface by varying the refrigerant mass velocity from 50 $kg\ m^{-2}\ s^{-1}$ to 200 $kg\ m^{-2}\ s^{-1}$ and the imposed heat flux from 50 $kW\ m^{-2}$ to 100 $kW\ m^{-2}$, keeping constant the mean saturation temperature at 30 °C. Furthermore, the heat transfer measurements were complemented with two-phase flow visualization. Finally, a new model was developed and validated to estimate the refrigerant flow boiling heat transfer coefficient on C/C surface.

2. Carbon/Carbon sample

Carbon fiber reinforced carbon matrix (C/C) composites have been widely used in aeronautic and aerospace industries for several decades [17]. As described by Delhaes [18], the C/C composites are frequently fabricated by Chemical Vapor Infiltration (CVI) of porous carbon fiber preforms. This method was also applied to the present sample, which was obtained by CVI of a 3D preform, previously heated up to more than 1800 °C. The obtained C/C block was then re-heated to improve the thermal conductivity of the deposited carbon matrix. The bulk density of the C/C sample is around 1600 $kg\ m^{-3}$ while the thermal conductivity through the thickness was estimated by the manufacturer to be 65 $W\ m^{-1}\ K^{-1}$.

The tested sample was obtained by machining the C/C block to realize a 180 mm long, 10 mm wide, and 20 mm thick plate. On lateral side walls, 18 holes (9 on each side), 5 mm deep, were drilled below the surface (distance between the probe and the top surface 0.5 mm) to monitor the wall temperature distribution by locating as many calibrated T-type thermocouples. On the bottom face, a guide was milled to install a calibrated Ni-Cr electrical wire resistance. The surface was scanned by means of a Scanning Electron Microscope (SEM) imaging (FEG-ESEM, Quanta 250) to analyze its morphology; a few samples of the acquired images are reported in Fig. 1. As clearly shown by the SEM images, the surface is characterized by the presence of deep valleys, randomly distributed all over the surface, (a) and (b). When increasing the magnification (600× and 2400×), the 3D tailored texture appears and carbon fibers can be easily observed, (c) and (d); the (e) image permits to highlight a thin deposited layer of carbon micro-structures on the fibers bundle; by further zooming the surface (20,000×), this layer appears to be quite uniformly distributed on the primary carbon fibers preform (f).

Fig. 2 collects some images and results of the carbon topography obtained by means of a 3D optical profilometer (Form Talysurf i-Series). In particular, the image named 2a reports the 3D profiles recorded by the optical sensor, while the related 2D map permits to identify the deep valleys, which were also noticed in the SEM images (green[1] and blue pixels). Fig. 2c shows an example of the

[1] For interpretation of color in Figs. 2 and 5, the reader is referred to the web version of this article.