International Journal of Heat and Mass Transfer 112 (2017) 236–247

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Pool boiling heat transfer on deformable structures made of shape-memory-alloys

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A R T I C L E I N F O

Article history:
Received 9 November 2016
Received in revised form 20 April 2017
Accepted 24 April 2017
Available online 4 May 2017

Keywords:
Pool boiling
Shape memory alloys
Heat transfer enhancement
Adaptive control

A B S T R A C T

More and more fixed geometry structures are being manufactured to enhance the boiling heat transfer (BHT). However, they usually perform well at a special heat load and don't always have good BHT properties. Applying shape memory alloy (SMA) material to change the geometry is a new solution to achieve optimal effect at different boiling condition. Pool boiling heat transfer on deformable structures made of SMA in three fluids (ethanol, FC-72, water) with different thermal properties was explored. Comparing heat flux versus wall superheat and heat transfer coefficient (HTC) at different fluxes with fixed geometry, it was found that deformable structure combines the merits of closed-tunnel and open-tunnel. At low heat fluxes, it can increase the number of nucleation sites inside the closed tunnels with bent fins and after reverting to the original shape, the nucleation sites are activated and the bubble growth and departure is accelerated to enhance the HTC significantly. So by choosing the appropriate time and opportunity for different fluids to open the tunnels, the deformable structures can be used to achieve adaptive-control of boiling heat transfer. In terms of theoretical analysis, the existing correlations for fixed structures have not been fit for deformable structures, because large-scale deformation make the heat transfer mechanism different from the fixed geometry structure. Thus experimental results are compared with fitting curves and a new correlation was deduced.

1. Introduction

Boiling is a very efficient heat transfer mode which has long been a hot research topic due to its wide-span applications in diverse engineering disciplines including chemistry, refrigeration, solar power, and thermal management of optoelectronic-devices [1]. As a typical phenomenon of phase change, the physics of boiling is quite complex where multi-scale processes are involved making the geometry and thermo-physical properties of fluid-solid interfaces be a major impact on heat transfer performances [2].

Over the past century, many techniques have been proposed to predict and enhance BHT by micro structures and nano structures (such as machined cavities, fins, pins or grooves, channels, or porous surfaces, porous layers and coatings) were proved to be very efficient ones. Starting from the pioneering paper of Nukiyama [3], extensive data have accumulated from experimental studies dealing with a diverse array of conditions. In 1931, Jakob and Fritz investigated the effect of surface finish on nucleate boiling performance, as reported by Jakob [4]. Since then, many researchers began to study the effects of surface roughness and artificial nucleation sites. Corty and Foust [5] and Bankoff [6] proposed that bubbles will emerge from cavities in which a gas or vapor phase preexists. According their work, Griffith and Wallis [7] made a further study to understand how an artificial nucleation site may function. They found that the cavity geometry is important in two ways: the mouth diameter which determines the superheat needed to initiate boiling, and its shape which determines its stability once boiling has begun.

In the mid-1960s, industrial research was underway to achieve the goal of a practical enhanced boiling surface for commercial application. Two different concepts were being investigated: a porous coating and cold reworking of the surface to form nucleation sites. Fig. 1 shows some well-known commercial products which are widely used in various industries, including GEWA-T, High-flux, Turbo-B and Thermoexcel-E [8]. Stephan and Mitrovic [9] studied the performance of a GEWA-T tube within a bundle of such tubes in R-11. At constant heat flux, they observed a 3 times enhancement than smooth tubes. Pool boiling results of Marto and Lepere [10] indicated that the GEWA-T surface did not exhibit much of an enhancement at low heat fluxes, whereas at high heat

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.04.113

Nomenclature

BHT	boiling heat transfer
SMA	shape memory alloy
CHF	critical heat flux (W/m^2)
HTC	heat transfer coefficient (W/(m^2·K))
b	empirical constant
$c_{p,l}$	specific heat capacity (J/(kg·K))
C_{wl}	empirical constant
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (W/(m^2·K))
h_{lv}	vaporization latent heat (kJ/kg)
Ja	Jakob number
k	thermal conductivity (W/(m·K))
Pr	Prandtl number
Re	Reynolds number
q	heat flux (W/m^2)
s	empirical constant
T	temperature (K)
ΔT	superheat temperature (K)

Greek symbols

μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ν	kinematic viscosity (m^2/s)

Subscripts

Cu	copper
l	liquid
NiTi	nickel-titanium
s	saturation
v	vapor
w	wall

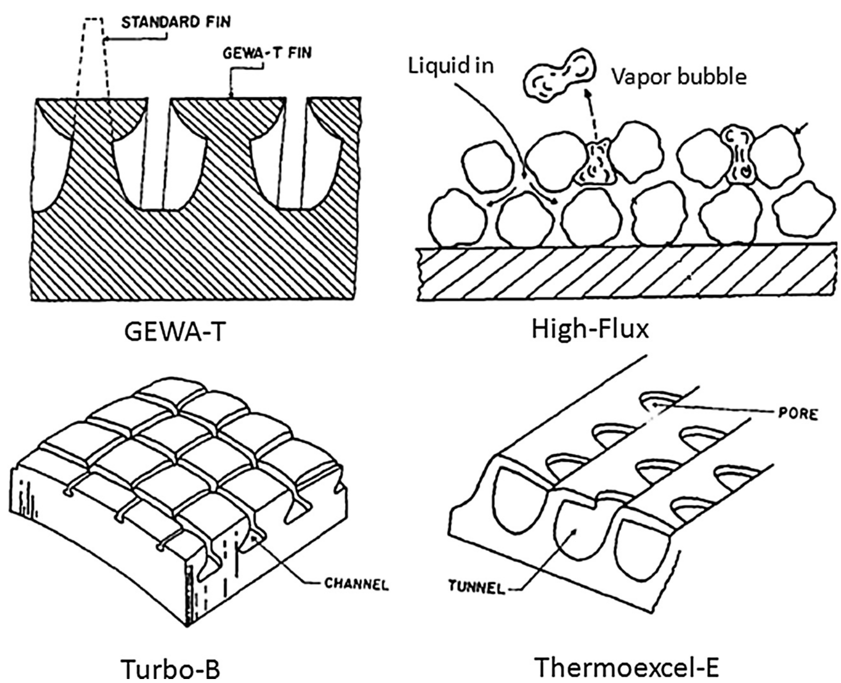

Fig. 1. Structured surface of heat transfer enhancement.

fluxes its performance improved [11]. Chien and Webb [12,13] conducted systematic series of experiments to investigate the effects of the geometric parameters and proposed that the Thermoexcel-E and Turbo-B having surface pores operated by the enhanced boiling heat transfer mechanism. They found the boiling heat transfer curves can be optimized by selecting proper combination of pore diameter and pore pitch [14]. Milton [15–17] applied a 0.25 mm thick sintered copper coating to the surface of a plain tube known as the HIGH-FLUX™ tube to achieve the enhancement.

Enhanced surfaces have been developed specifically for pool nucleate boiling and hundreds of experiments have been reported [18]. However, after the molding process, numerous micro/nano enhancement structures are only in optimal heat transfer state at a special heat load or at a special boiling condition. They may not always have good BHT properties at every heat transfer conditions. For example, it is well known that a porous layer with small cavities and a small porosity is good at boiling onset but cannot withstand high heat flux and the critical heat flux (CHF) appears earlier, and vice versa [19]. Furthermore, a structure with high heat transfer coefficient for a kind of fluid can probably be not good for others because of different latent heat of vaporization and surface tension of the fluids [19,20].

Hence, it's very important and meaningful to invent a kind of mini structures that can adaptively change their shapes according to the heat transfer condition. However, achieving this object is difficult by using common materials because the deformation produced by thermal expansion is too small to satisfy the requirement. Instead, the large-scale deformation can be obtained by shape-memory-alloys. SMA, first discovered by Arne Ölander in