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Dryout characteristics of natural and synthetic refrigerants in single vertical mini-channels

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ABSTRACT

Experimental results on dryout of seven refrigerants (R134a, R1234yf, R152a, R22, R245fa, R290 and R600a) in small, single vertical tubes under upward flow conditions are reported in this study. The experiments were conducted under a wide range of operating conditions in stainless steel tubes (0.64–1.70 mm and 213–245 mm heated length). The effects of operating parameters like mass flux, vapor quality, saturation pressure and channel size are discussed in detail. In general, dryout heat flux increased with increasing mass flux, and with increasing tube diameter. No effect of varying saturation temperature was observed. The experimental findings were compared with well-known macro and micro-scale correlations from the literature and it was found that Wu's correlation (in modified form) quite satisfactorily predicted the whole database. A new correlation for prediction of heat flux at dryout conditions is also proposed.

1. Introduction

The increased cooling demands from modern electronic devices coupled with restricted working temperature limit ($t < 85$ °C) makes phase change heat transfer a viable cooling solution. Two phase heat transfer in small channels has many practical applications like, miniature heat exchangers, high power electronics and miniature refrigeration systems [1]. Flow boiling in these compact channels offers many potential advantages like, ability to cope with high heating/cooling demands (enhanced surface area per unit volume of the fluid), less fluid inventory, uniform surface temperature, compactness in size, reduced material and overall weight, etc. Furthermore as heat transfer coefficient (HTC) increases with increase in applied heat flux local hot spots can also be managed/tolerated [2–4]. However, with small channels the channel layout has to be done with care to avoid pressure drop increase compared to larger scale channels.

The boiling heat transfer is strongly influenced by the imposed boundary conditions; Heat transfer coefficient (HTC) significantly drops when the liquid in the incoming fluid stream is unable to wet the heating surface either temporarily or permanently. Dryout refers a specific operating condition, when the heater surface (in a two phase system) is totally blanketed with vapor and consequently results in sharp decline for the heat transfer due to associated dry wall conditions [5]. The temperature of the heated surface shoots up and this may lead to physical burnout of test section/heating surface for heat flux controlled applications. The upper operational limit (from safety and efficiency point of view) for heat flux as well as temperature regulated devices is therefore defined by the dryout heat flux value. In the literature the terms "dryout" and "Critical Heat Flux" (CHF) have been used to address the above mentioned phenomenon. In this paper the term "dryout" has been used. Based on our experimental results we believe that the dryout condition is the consequence not of a high local heat flux but of the gradual thinning of a liquid film traveling on the tube wall. Furthermore it should also be mentioned here that physical burnout of the test section was not reached during our experimental campaign.

Dryout and CHF in minichannels has been studied by several investigators: Ong and Thome [6] reported results for CHF with R134a, R236fa and R245fa in small horizontal tubes (1.03, 2.2 and 3.04 mm inside diameter). They observed increased CHF

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Nomenclature

A_c	cross sectional area (m^2)
Co	confinement no (–)
C_p	specific heat capacity (J/kg K)
d_h	hydraulic diameter of the test section (m)
d_i	inside diameter of the test section (m)
d_{out}	outside diameter of test section (m)
$F1$–$F4$, B, C, n, $\dot{p}$	parameters in Bowring correlation
G	mass flux (kg/m^2 s)
h_{lg}	enthalpy of vaporization (kJ/kg)
I	current supplied (A)
k	thermal conductivity (W/mK)
l_h	effective/heated length (m)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	applied electric power (W)
q''	heat flux (W/m^2)
t	temperature (°C)
V	voltage (V)
$We_D = [G^2 d_h/\rho\sigma]$	weber no (–)
$We_L = [G^2 l_h/\rho\sigma]$	weber no (–)
x	vapor quality (–)
z	axial location (m)
z^*	non-dimensional length (z/l_h)
Abbreviations	
CHF	critical heat flux (W/m^2)
MAE	Mean Absolute Error (%)
Greek Letters	
α	heat transfer coefficient (kW/m^2 K)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension force (N/m)
Subscripts	
g	gas phase
i	dryout incipience conditions
in	at inlet conditions
l	liquid phase
lg	vaporization phase
sat	saturation

values with decreasing tube diameter until a threshold value (0.79 mm in this case) and afterward CHF decreased with further shrinking the tube size. Furthermore CHF increased with increasing mass velocity and decreased with increasing saturation temperature. No influence for inlet subcooling was observed. They proposed a new correlation for prediction of CHF. The proposition is a modified version of Katto–Ohno correlation [7] and includes channel confinement and viscous interfacial shear effects.

Mikielewicz et al. [8] reported experimental findings for dryout of four fluids (Solkatherm SES 36, R134a, R123 and ethanol) in small vertical silver tubes (1.15 and 2.3 mm in diameter) with 40–900 kg/m^2 s mass velocities. They observed that dryout heat flux increased with increasing mass flux, with the decrease of vapor quality and with the increase of tube diameter. They also suggested a correlation for prediction of dryout heat flux based on their experimental database.

Callizo et al. [9] conducted an experimental study for CHF with R134a, R22 and R245fa in a 640 μm vertical circular channel (185–335 kg/m^2 s at saturation temperature of 30 and 35 °C). They reported, that the critical heat flux increases with increasing mass flux while no effect of varying saturation temperature was observed. Based on their experimental data they proposed a correlation for prediction of CHF, which is also a modified version of Katto–Ohno correlation [7] and gave good predictions as confirmed by other authors [10,3].

Ali and Palm [10] reported on dryout tests with R134a in vertical, single stainless steel tubes (1.224 and 1.70 mm inside diameter and 220 mm heated length) at two operating pressures corresponding to 27 and 32 °C saturation temperatures at mass flux of 50–600 kg/m^2 s. They noticed that dryout heat flux increases with increasing mass flux, decreases with reducing tube diameter while remains almost unaffected with varying operating pressure.

Maqbool et al. [3] conducted dryout experiments with propane in resistively heated vertical tubes (1.7 and 1.224 mm inside diameter and 245 mm heated length) with 100–500 kg/m^2 s mass flux and for three saturation temperatures (23, 33 and 43 °C). They observed similar parametric effects like Ali and Palm [10] (both used the same experimental setup).

Mobile applications are responsible for a large share of the direct emission of refrigerant into the environment. R134a is a well established on the market refrigerant and has been used in many applications. The environmental concerns due to its high global warming potential (GWP) value (about 1300) require it's complete phase out in the near future. Among the HFC's R152a has similar thermophysical properties and quite low GWP value (about 140) compared to R134a and could be a suitable alternative. Being a natural refrigerant with zero ODP and negligible GWP makes Isobutane (R600a) another potential alternative. Both Isobutane and R152a are flammable in air and additional safety measures would be required for their utilization (control of charge amount, use of spark free electrical breakers, etc.) [4]. The recently developed HFO1234yf has similar thermophysical properties as those of R134a, and is also considered a good replacement candidate for R134a.

This study is based on a large database collected from recent and previous studies conducted at Royal Institute of Technology KTH, Sweden [9,3,4,11,12]. The combined database involves seven refrigerants, four test sections and had 72 data-points. The specific operating conditions for each case can be seen from Table 1. The objectives with this study are to clarify the effects of operating parameters like mass flux, vapor quality, saturation temperature, tube diameter, operating media, etc. and to assess the predictions of macro and micro-scale correlations from the literature.

2. Experimental setup

A closed refrigerant loop was used as experimental setup for the whole campaign and this is schematically shown in Fig. 1. The facility was designed in a way that the pressure, mass flow rate, heating and cooling conditions can be independently controlled. All the tests were conducted with stainless steel tubes (Table 1). The test section (in each case) was resistively heated by Joule's effect with a low voltage high ampere DC power supply. A gear pump (Ismatec MCP-Z) was used for fluid circulation through the loop. The setup was equipped with an absolute pressure sensor to record the system pressure while a differential pressure sensor was used to record pressure drop across the test section. The mass flow rate was recorded with a Coriolis mass flow meter, the wall temperatures were recorded with equally spaced thermocouples (T-type) attached on the outer periphery of the test section with the help of thermally conductive epoxy. Two insertion type