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Flow boiling heat transfer in minichannels at high saturation temperatures: Part II – Assessment of predictive methods and impact of flow regimes

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ABSTRACT

In order to evaluate the reliability of the current flow boiling heat transfer prediction methods for conditions of high saturation temperatures, this paper focuses on the comparison between experimental results (presented in the first part of this two-part article) and results predicted with the commonly used correlations or models from the literature. The dataset was obtained with R-245fa as working fluid in a 3.00 mm inner diameter stainless steel tube. It is characterized by a saturation temperature ranging from 60 °C to 120 °C. The database is composed of 5964 data points covering four flow patterns: (i) intermittent flow, (ii) annular flow, (iii) dryout flow, and (iv) mist flow regimes. An extensive literature review was performed to select the flow boiling heat transfer prediction methods that were classified according to their theoretical background. Finally, thirty flow boiling prediction methods were assessed against our database. The results are presented graphically but also statistically. The effect of the saturation temperature and the kind of flow pattern on the ability of the methods to predict the flow boiling heat transfer coefficient were investigated. At 60 °C, most of the prediction methods produce homogeneous results and are able to predict with accuracy the flow boiling heat transfer coefficient. On the contrary at 120 °C, the existing methods fail to predict the heat transfer coefficient with accuracy. The only methods able to capture the experimental trends are those developed from carbon dioxide data with or without other fluids.

1. Introduction

The simultaneous appearance of new refrigerants and new technologies requires robust and reliable prediction correlations or models to maintain the energy efficiency of these systems. As explained in the first part of this two-parts article, the present study deals with the development of Organic Rankine Cycle (ORC) systems to recover waste heat energy from exhaust gas of internal combustion engines (ICE). The evaporator is considered as the key-component for development of ORC systems because of the high saturation temperature for refrigerant evaporation. Evaporation occurs at around 120 °C which is much higher than the standards relevant to refrigeration, air conditioning, or electronic component cooling. Flow boiling experiments at such a high saturation temperature have, so to say, almost never been reported in the open literature so far.

As a result, the existing prediction methods have been compared to data taken in a limited range of evaporation temperature and reduced pressure. Thereby, they cannot be extrapolated with accuracy for different fluids, different geometries or different thermodynamic conditions (pressure, temperature) from those for which they were initially developed. As a consequence, the two-phase heat exchangers design in the conditions of the ORC systems does not provide guarantee.

To achieve a reliable design of an ORC evaporator, two steps are required:

(i) provide experimental two-phase flow boiling heat transfer data at high saturation temperature (Part I)
(ii) assess the existing prediction methods with the new experimental heat transfer data (Part II)

In Part II, the attention is focused on the comparison between the experimental heat transfer coefficients provided in Part I and theoretical results obtained with predictive methods from literature. In order to provide a comparison with previous results, a summary of an extensive literature survey on flow boiling heat transfer prediction models or correlations is presented. In the first section, the prediction methods were classified according to their theoretical

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Symbols

A	area m^2
C	constant of Lockhart and Martinelli m
d	tube diameter m
E	multiplier factor of Gungor and Winterton
F	multiplier factor
f	frequency Hz
G	mass velocity kg/m^2 s
h	specific enthalpy J/kg
M	molar mass kg/mol
$\dot{m}$	mass flow rate kg/s
P	pressure Pa
$\dot{q}$	heat flux W/m^2
S	suppression factor
T	temperature K
t	time s
x	vapor quality
Y	factor of Groeneveld
z	longitudinal abscisa m

Greek letters

α	heat transfer coefficient W/m^2 K
β	contact angle °
δ	film thickness m
λ	thermal conductivity W/m K
Φ	two-phase multiplier
Ψ	enhancement ratio
ρ	density kg/m^3
σ	surface tension N/m
τ	period s

Dimensionless numbers

Bo	Boiling number
Fa	Fang number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
X	Martinelli's parameter
We	Weber number

Sub and superscripts

cb	convective boiling
crit	critical
d	dryout
dry	dried
di	dryout inception
de	dryout completion
dryout	dryout
exp	experimental
film	film
H	homogeneous
h	hydraulic
L	liquid
LV	boiling
min	minimum
mist	mist flow
nb	nucleate boiling
O	only
pred	predicted
red	reduced
sat	saturation
TP	two-phase
V	vapor
wet	wetted

Abbreviations

A	annular
A	annuli
C	circular
D	dryout
H	horizontal
I	intermittent
ICE	internal combustion engine
M	mist
MAE	mean absolute error
MRE	mean relative error
ORC	organic Rankine cycle
R	rectangular
V	vertical

background. Moreover, assessing the same prediction methods over the whole range of vapor quality is not consistent, hence the prediction methods have to be firstly classified into two groups: (i) pre-dryout and (ii) post-dryout heat transfer prediction methods. For pre-dryout, prediction methods were developed following several approaches: (i) asymptotic approach, (ii) Nusselt-type correlations, (iii) enhancement-factor approach and (iv) phenomenological approach. According to the conclusions of Part I and especially the dominance of nucleate boiling heat transfer mechanism, pool boiling correlations are included in the pre-dryout methods. For post-dryout heat transfer, fewer prediction models or correlations are available; they will hence all be grouped together. Moreover, some prediction methods developed exclusively or not for carbon dioxide will be evaluated for both pre-dryout and post-dryout regions.

2. State-of-the-art on two-phase flow boiling heat transfer prediction methods

In spite of the enormous number of research works undertaken to date, the prediction of flow boiling heat transfer coefficients remains essentially empirical due to the complex hydrodynamic and heat transfer processes. A number of methods have been developed to predict the heat transfer coefficient in horizontal and vertical smooth tubes for natural and synthetic refrigerants.

2.1. Pre-dryout heat transfer prediction methods

The pre-dryout region gathers intermittent flow and annular flow regimes and ends by the inception of the dryout at the top of the tube at the location where the heat transfer coefficient begins to decrease sharply.

2.1.1. Pool boiling correlations

[1] proposed an assessment of several predictive methods by comparing them against 10 independent data sets from the published literature covering a range of hydraulic diameter from 0.16 to 2.01 mm. They found that the correlation of [15] provided the lowest deviation between predictions and measurements for their database and that the correlation of [24] resulted in smaller deviations from the experimental database than most of the flow boiling methods. This is remarkable in view of the fact that these correlations were developed specifically for pool boiling and do not contain any effects of mass velocity or vapor quality. They concluded by noting that these good agreements could indicate a