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Flow boiling heat transfer in minichannels at high saturation temperatures: Part I – Experimental investigation and analysis of the heat transfer mechanisms

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ABSTRACT

This paper presents new experimental data concerning flow boiling heat transfer in minichannel at high saturation temperatures. The experimental data were obtained in a horizontal 3.00 mm inner diameter stainless steel tube with R-245fa as working fluid. The mass velocity ranges from 100 to 1500 kg/m^2 s, the heat flux varies from 10 to 50 kW/m^2 and the inlet vapor quality from 0 to 1. This experimental work is characterized by a saturation temperature ranging from 100 °C to 120 °C. Flow boiling heat transfer coefficients in these conditions have not been reported in the open literature so far. Four flow patterns are likely to appear in these conditions: intermittent flow, annular flow, dryout flow and mist flow regimes. The kind of flow pattern has a major influence on the heat transfer mechanisms. The influence of the mass velocity and the heat flux was investigated to identify the dominant heat transfer mechanisms. At high saturation temperatures, the experimental results clearly show the dominance of nucleate boiling over a wide range of vapor quality.

1. Introduction

Despite technological improvements, transport CO$_2$ total emissions have constantly increased since 1990 and all transport modes have increased their greenhouse gas emissions due to the fuel combustion. Some technologies are being developed to reduce the fuel consumption and to reduce the emissions of CO$_2$. Energy recovery by means of Organic Rankine Cycles or Hirn Cycles is one investigated track to answer these issues. Indeed, these cycles could represent an effective way to recover the waste heat energy of internal-combustion engines (ICE). At present, some systems based on Organic Rankine Cycles (ORC) are available in industry but advanced studies are needed to allow their application in the road transport industry. A better understanding of the two-phase fluid behaviour is necessary to optimize the design models of the components containing a two-phase refrigerant (evaporator and condenser). As reported by [41], the evaporator is the key heat exchanger in Organic Rankine Cycle system. Indeed, the key characteristic of the ORC is the evaporation saturation temperature. Exhaust gases temperature ranges from 400 °C to 900 °C and the refrigerant evaporation occurs at temperatures higher than 120 °C. Almost all the flow boiling heat transfer models or correlations have been obtained for saturation temperatures ranging from −20 °C to 40 °C which correspond to standards relevant to refrigeration or air conditioning systems or electronic component cooling. The empirical models for boiling in such conditions are limited by the experimental data on which they are based, whereas analytical and theoretical approaches are needed to gain improved knowledge on the thermohydraulic behaviour two-phase refrigerant. Thus, it is very risky to extrapolate two-phase flow boiling heat transfer models to high saturation temperatures. Providing accurate and reliable heat transfer models is hence the first step to optimize the design of the Organic Rankine Cycles. An accurate prediction of heat transfer coefficients can reduce costs by avoiding both undersizing and oversizing of evaporators. Moreover, the optimal design of the evaporator permits to reduce the weight of these embedded systems on cars or trucks.

1.1. Experimental studies on flow boiling heat transfer

Prior to presenting experimental studies on flow boiling heat transfer, a few words should be given regarding the classification of the tube geometry in which boiling takes place into “macro-”, “mini-”, and “microchannels”. As a matter of fact, the mechanisms governing flow boiling are obviously very different whether

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capillary forces are negligible or not, which is related to the channel diameter. In the literature no universal agreement exists and thus different definitions are available. Nonetheless, [26] proposed a general definition with an engineering practice and application areas which is based on the following ranges of hydraulic diameters:

- Macrochannels: $d_h > 3$ mm
- Minichannels: $d_h = 200$ μm–3 mm
- Microchannels: d_h = 10 μm–200 μm

Experimentally, two mechanisms were assumed to govern flow boiling heat transfer in macrochannels: (i) the nucleate boiling and (ii) the convective boiling. Nucleate boiling is related to the formation of bubbles at the tube wall, whereas, convective boiling is related to conduction and convection through a thin liquid film with evaporation at the liquid–vapor interface. These boiling mechanisms are often assumed when trying to describe flow boiling, for simplicity, to be independent the one from the other. In fact, it is indeed well known (see [11]) that these mechanisms can coexist when the vapor quality increases.

These mechanisms were experimentally related to the heat transfer coefficient:

- when nucleate boiling is dominant, the heat transfer coefficient is independent of the mass velocity and vapor quality, dependent on the heat flux and sensitive to the saturation pressure level.
- when convective boiling is dominant, the heat transfer coefficient is independent of the heat flux and dependent on the mass flux and vapor quality.
- when both nucleate and convective boiling are of the same order importance, the heat transfer coefficient is dependent on the heat flux, mass velocity and vapor quality.

Another heat transfer mechanism can exist in particular conditions which is called dryout. A concise summary of experimental research on two-phase heat transfer coefficient is presented below for different geometries: macrochannels, minichannels and microchannels. The objective is not to describe all the works that were published on this topic but rather to describe those sufficient to illustrate typical trends observed in the literature. This review draws attention to three main points:

- the different mechanisms that govern flow boiling heat transfer.
- the difference between flow boiling heat transfer in macrochannels and microchannels.
- the effect of the temperature on the heat transfer coefficient.

The main features of the analysed experimental studies are summarised in Tables 1–3.

1.2. Flow boiling heat transfer studies in macrochannels

During the five last decades, flow boiling of refrigerants in tubes has been intensely investigated especially in sight of refrigeration applications. This concise review focuses on experimental studies of flow boiling heat transfer in circular macroscale tubes to illustrate the typical trends observed in such geometry. [22] reported a heat transfer investigation during flow boiling of R-134a inside a 12.00 inner diameter horizontal tube. The heat transfer coefficients were dependent of mass velocity and heat flux indicating that nucleate boiling and convective boiling were both present.

[47] studied phase-change heat transfer coefficient characteristics for R-22 and R-410A flowing inside a smooth tube with a 6.54 mm inner diameter. They noticed two different trends according to the mass velocity:

- For a mass velocity of 100 kg/m^2 s, the effect of heat flux was very pronounced for both R-22 and R-410A and the heat transfer coefficients did not increase with the vapor quality. These trends were the clue for a predominance of nucleate boiling in the heat transfer mechanisms.
- For a mass velocity of 400 kg/m^2 s, the heat transfer coefficients increased with the vapor quality. The flow regime visualized was annular flow pattern. In this region, the heat transfer was dominated by convective boiling.

[28] presented an experimental study on flow boiling heat transfer for five refrigerants (R-134a, R-123, R-402A, R-404A and R-502) evaporating inside horizontal tubes with two diameters: 12.00 mm and 10.92 mm. They observed a significant increase in the heat transfer coefficient with heat flux. They defined three different trends:

- At low vapor quality (from 8 to 15%), they observed a maximum in heat transfer coefficients which could correspond to a change in flow pattern or a change in the respective contribution of nucleate boiling and convective boiling to the overall heat transfer.
- For intermediate vapor quality, the heat transfer coefficient decreased monotonically with increasing vapor quality at the lowest mass flow rate, in their case 100 kg/m^2 s.
- At high vapor quality, they observed a decrease of the heat transfer coefficient which was caused by the transition from annular flow to annular flow with partial dry-out.

[23] performed experiments on flow boiling in horizontal tube with an inner diameter of 12.7 mm for three refrigerants: R-22, R-134a and R-404A. They discovered new trends in connection to the effects of heat flux and mass velocity. They found that nucleate boiling effects could persist at high vapor quality, especially for higher heat fluxes. [35] investigated flow boiling heat transfer with R-410A and carbon dioxide in a 6.1 mm inner diameter horizontal smooth tube. The heat transfer trends of carbon dioxide revealed the predominance of nucleate boiling, i.e. dependence upon the heat flux and independence upon the mass velocity and the vapor quality. Nucleate and convective boiling heat transfer mechanisms are active for R-410A flow boiling heat transfer (influence of heat flux, mass flux and quality).

The experimental conditions of these studies are reported in Table 1. In conclusion, for macrochannels, nucleate and convective

Table 1
Summary of experimental flow boiling heat transfer studies in macrochannels.

Author	Fluid	Geometry	d_h [mm]	$\dot{q}$ [kW/m^2]	G [kg/m^2 s]	T_{sat} [°C]	x [–]	Type
Hambraeus [22]	R-134A	Circular	12.0	2–10	60–300	−6.0	0–1.0	A
Wang et al. [47]	R-22/R-410A	Circular	6.54	2.5–20	100–400	2.0	0–0.95	A
Ebisu and Torikoshi [17]	R-410A/R-22/R-407C	Circular	7.0	7.5	150–300	5.0	0–0.9	A
Kattan et al. [28]	R-134a/R-123/R-402A/R-404A/R-502	Circular	10.9–12.0	0.4–37.0	100–500	−1.3 to 30.7	0.02–1.0	A
Jabardo and Filho [23]	R-22/R-134a/R-404A	Circular	5–20		50–500	8.0–15.0	0.05–0.95	A
Park and Hrnjak [35]	CO_2/R-410A/R-22	Circular	6.1	5–15	100–400	−30.0 to −15.0	0.1–0.8	A