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Carbon dioxide flow boiling in a single microchannel – Part II: Heat transfer

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ABSTRACT

Flow boiling heat transfer coefficients of CO_2 have been measured in a single microchannel. Experiments were carried out in a horizontal stainless steel tube of 0.529 mm inner diameter, for three temperatures (−10, −5 and 0 °C), with the mass flux ranging from 200 to 1200 kg/m^2 s and the heat flux varying from 10 to 30 kW/m^2. The investigation covered qualities from zero to the dryout inception, i.e. pre-dryout conditions. Compared to larger microchannels and positive temperatures, a higher contribution of convective boiling was found, with a larger heat transfer coefficient than for pure nucleate boiling. Mainly two heat transfer regimes were found, depending on the boiling number (*Bo*). For $Bo > 1.1 \times 10^{-4}$, the heat transfer coefficient was highly dependent on the heat flux and moderately influenced by the quality and the mass flux. For $Bo < 1.1 \times 10^{-4}$, the heat transfer coefficient was hardly affected by the heat flux but strongly influenced by the quality and the mass flux. In addition, dryout results were reported. The effect of the mass flux on the dryout inception quality was found to be highly dependent on the heat flux and the saturation temperature.

1. Introduction

Among the re-emerging environment friendly natural working fluids, carbon dioxide probably offers the wider range of possible applications. Indeed, in spite of its toxicity, ammonia is mostly used in large industrial refrigeration plants, and hydrocarbons, considering there flammability, must be used in systems of limited capacity. Instead, CO_2 is neither flammable nor toxic. It can be used in the low temperature refrigeration cycle of a cascade system (commercial or industrial plants), in automobile air-conditioning devices, and in transcritical water heater heat pumps. It is also seen as a two-phase secondary refrigerant for commercial refrigeration and building air-conditioning applications. Some efficient transcritical systems for medium temperature refrigeration can also be developed provided that modified thermodynamic cycles are used (parallel or two-stage compression, expansion through an ejector).

In a CO_2 compression cycle, the evaporator is one of the components to be optimized due to the peculiar thermophysical properties of this fluid. Indeed, the CO_2 critical temperature is particularly low, i.e. close to 31 °C. Hence, the vaporization occurs relatively close to the critical point compared to conventional refrigerants. This means a higher reduced pressure for a given saturation temperature. As an example, for 0 °C, the R-134a reduced pressure is only 0.07 while the CO_2 reduced pressure is 0.47. This leads to unexpected properties compared to classical refrigerants: a higher vapour to liquid density ratio (10 times higher than R-134a), a lower surface tension (2.5 times lower), and a lower liquid viscosity (3 times lower). As a consequence, with carbon dioxide, flow boiling heat transfer is generally mainly driven by a promoted nucleate boiling contribution due to the low surface tension whereas the convective boiling is weaker due to a low vapour velocity. Hence, the carbon dioxide heat transfer coefficient during vaporization is higher than that of conventional fluids which is commonly interpreted as a consequence of an excellent nucleate boiling heat transfer. Such observations were made in macrochannels for positive temperatures [1,2] and negative temperatures [3], and also for single and multi-channel microtubes at positive temperatures [4–6]. Thus, it is of prime importance to take advantage of the CO_2 heat transfer peculiar characteristics in the design of an effective evaporator.

In more details, the CO_2 heat transfer characteristics mainly depend on the channel hydraulic diameter (D_h) and the saturation temperature (T_{sat}). From the open literature, three main regions of investigation can be distinguished; each of them corresponding to a particular thermal behaviour [7,8]. In macrochannels (arbitrarily, $D_h > 3$ mm) at high saturation temperatures ($T_{sat} > -10$ °C), the heat transfer coefficient is high at low qualities due to the important nucleate boiling contribution. However, beyond a qual-

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