Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Energy 30 (2005) 807–819
ENERGY
www.elsevier.com/locate/energy

The law of stable equilibrium and the entropy-based boiling curve for flow boiling

Francisco J. Collado *

Dpto. Ingeniería Mecánica-Motores Térmicos, CPS-B, Universidad de Zaragoza, María de Luna 3, 50018 Zaragoza, Spain

Abstract

Convective flow boiling in sub-cooled fluids is recognized as one of the few means of accommodating very high heat fluxes. There are many available correlations for predicting the inner wall temperature of the heated duct in the several regimes of the empirical Nukiyama boiling curve, although unfortunately there is no physical fundamentals of such curve. Recently, the author has shown that the classical entropy balance could contain key information about boiling heat transfer. So, it was found that the average thermal gap in the heated channel (the inner wall temperature minus the average temperature of the coolant fluid) was strongly correlated with the efficiency of a theoretical reversible engine placed in this thermal gap. From this new correlation, a new boiling curve plotting the wall temperature versus the average fluid temperature was derived and successfully checked against low- and high-pressure water data. This curve suggested a new and simple definition of the critical heat flux (CHF) namely, the value of the coolant average temperature at the maximum. In this work, after briefly reviewing the entropy balance of a non-equilibrium boiling flow and its relationship with the thermodynamic average temperature and the law of stable equilibrium (LSE), the possibilities of the new approach for the design of flow boiling cooling systems are highlighted. Finally, the strong correlation found between the reversible engine efficiency and the thermal driving force is verified again, now with high-pressure refrigerant 22 (R-22) data.

1. Introduction

Boiling heat transfer cannot be predicted [1] by the formulations derived for convection. Then, it has been usual to represent the heat transfer by the boiling curve: the heat flux is plotted versus the wall-minus-saturation temperature difference. However, the problem is quite

* Tel.: +34-9-7676-2551; fax: +34-9-7676-2616.
E-mail address: fjk@unizar.es (F.J. Collado).

0360-5442/$ - see front matter
doi:10.1016/j.energy.2004.04.007

complex and the experts [1,2] themselves have noticed the limitations of the classic boiling curve formulations.

The critical heat flux (CHF) is the most important piece of thermal–hydraulic information [3–5] required for design of cooling configurations (based on sub-cooled flow boiling) of systems under high heat flux as fusion reactor first walls and plasma limiters, fission research reactors, ion beam targets, high power electronic tubes, etc. For example, in a nuclear reactor system the CHF is defined [2,6] as the state of the system characterized by a sharp reduction of the local heat transfer coefficient causing a sudden rise on the fuel rod surface temperature and, subsequently, a failure of the cladding material when the heat flux is the independent variable. The importance of CHF in nuclear engineering has led to intensive investigations worldwide over several decades. In spite of a great quantity of experimental and theoretical studies, knowledge of the precise nature of CHF is still incomplete and the mechanisms of a boiling crisis are still not well understood [6]. So a recent and comprehensive review [7] of more than 100 CHF correlations found large deviations.

A physical characteristic [2] of flow boiling is that in the sub-cooled region, the wall temperature remains essentially constant a few degrees above saturation, whilst the mean bulk fluid temperature is increasing to saturation. This suggested using the entropy balance for predicting the wall temperature [8–10].

Following Bejan [11] in the thermodynamic optimization of a heat-exchange passage at the steady state, the heat transfer crosses the temperature gap between the wall temperature and the bulk temperature of the stream. So, in sub-cooled flow boiling, the heat transfer would be crossing from a constant wall temperature (a reservoir) to the fluid temperature.

Thus, choosing as boundary of our open system the inner wall of the channel, the entropy transfer rate (via heat transfer) would be simply the heat transferred divided by a constant wall temperature, whereas the entropy-generation rate would be mainly due to the heat transfer across a finite thermal gap. Using an average temperature of the bulk fluid in the channel, which would embody in the applied heat flux and the inlet conditions, this entropy balance could help predict the wall temperature.

From this new approach, it was found [8–10] that the average thermal gap in the heated channel (the wall temperature minus the average bulk fluid temperature) was strongly correlated with the efficiency of a theoretical reversible engine placed in this thermal gap.

In fact, the reversible engine efficiency is equal to the generation-increment entropy ratio, a non-dimensional expression of the irreversibility due to the finite thermal gap. Logically, this entropy generation should be related to the finite driving force of the transport process [12]; in this case the finite thermal gap between the inner wall and the bulk fluid.

These correlations were worked out with careful measurements taken by General Electric [13] under the so-called Task I (low-pressure water at 0.11–0.31 MPa, including transversal profiles of the liquid temperature in the channel) [8,9], and Task III (high-pressure water at 0.8–7 MPa) [10].

From the new correlation, a quadric function of the wall temperature was found, where the coefficients included the average fluid temperature [9,10]. Hence, the wall temperatures were the two roots of the quadric function. The new proposed boiling curves for each inlet pressure were obtained plotting the predicted wall temperature versus the average fluid temperature. These curves resembled to the first part of the Nukiyama empirical curve in which the CHF is located