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Review

Prediction methods for pool boiling heat transfer: A state-of-the-art review[☆]

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Dedicated to David Kenning paying tribute to his great achievements in nucleate boiling science.

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ABSTRACT

Prediction of heat transfer in the evaporator of a refrigeration unit should be as accurate as possible for the successful operation of the whole appliance. The predictive methods used at present are empirical or semi-empirical, particularly for the heat transfer conditions relevant in practice, because theoretically consistent calculation of the heat transfer coefficient in nucleate boiling is not yet possible. One of these which is included in the VDI Heat Atlas and has been updated recently, is presented in the first main part below and is compared with experimental data for 55 fluids. In the second part, eight more prediction methods from the literature are tested using the same experimental database, and the deviations between measurement and calculation are discussed in detail together with the different results calculated with the various methods.

Méthodes de prévision pour le transfert de chaleur en ébullition libre nucléée : état de l'art

Mots clés : Transfert de chaleur ; Ebullition libre nucléée ; Méthode de prévision ; Influence des propriétés thermophysiques ; Banque de données expérimentales

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Nomenclature

A	factor ($kW\ m^{-2}\ K^{-1}$) in Eq (6)
c	heat capacity ($J\ kg^{-1}\ K^{-1}$)
D	diameter of heated tube (m)
d_b	bubble departure diameter (m)
F	functions of q, p^*,f,w in Eq (1)
f	factor for intensity of convection
g	gravitational acceleration ($m\ s^{-2}$)
h	height of fins (mm)
$\Delta h_{\ell g}$	enthalpy of vaporization ($J\ kg^{-1}$)
M	molar mass ($kg\ kmol^{-1}$)
m,n	exponent in Eq (6) or Eq (2)
Nu	Nusselt number
P_f	$=(dp/dT)_{VPC}/\sigma$, characteristic boiling parameter of the fluid ($K\ \mu m)^{-1}$
p	pressure (bar or $N\ m^{-2}$)
p^*	$=p/p_c$, reduced pressure
q	heat flux ($W\ m^{-2}$ or $kW\ m^{-2}$)
q_{crit}	heat flux at burnout ($W\ m^{-2}$)
q_{min}	heat flux at Leidenfrost Point ($W\ m^{-2}$)
R	individual gas constant ($J\ kg^{-1}\ K^{-1}$)
Ra	Rayleigh number
R_a	arithmetic mean roughness height (μm) (ISO4287)
$R_{p,old}$	$=R_a/0.4$, “Glättungstiefe” (DIN4762) (μm)
r	radius of bubble or of bubble nucleus (μm)
T	temperature (K or °C)
T_{sN}	temperature at normal boiling point (K or °C)
ΔT	superheat, surface of heated wall (K)
t_ℓ	gap width between fins (mm)

Greek:

α	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$ or $kW\ m^{-2}\ K^{-1}$)
α_0	$=\alpha$ for a copper tube at $q_0 = 20\ kW\ m^{-2}$, $p_0^* = 0.1$, $R_{a0} = 0.4\ \mu m$
$\alpha_{0.1}$	$=\alpha_0$ for $R_a = R_{a,exp} \neq R_{a0}$
β	contact angle (deg)
Δ	difference
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
η	dynamic viscosity (Pa s)
ν	kinematic viscosity ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension of saturated liquid ($N\ m^{-1}$)

Subscripts:

0	normalizing value
c	critical state
conv	convective
Cu	copper
exp	experimental
f	fluid or finned
g	saturated vapour
ℓ	saturated liquid
M	material of wall
nb	nucleate boiling
one	single tube
R	roughness of wall
ref	reference value
s	saturated state
u	lowest row of tubes
VPC	vapour pressure curve
w	heated wall

1. Introduction

Prediction of pool boiling heat transfer existing e.g. on the flooded bundle of horizontal tubes in large evaporators of refrigeration units should be as accurate as possible for the successful operation of the entire plant. The predictive methods used at present are empirical or semi-empirical, particularly for the heat transfer conditions relevant in practice, because theoretically consistent calculation of the heat transfer coefficient α in nucleate boiling is not yet possible (see e.g. the reviews in Stephan and Fuchs (2009), Kenning et al. (2009), Dhir (2006), Kenning (1999), Gorenflo et al., 1998). Most of the methods have been established as power laws in the past, containing separate factors for the main parameters that are of influence in nucleate boiling heat transfer.

One of these is included in the VDI Heat Atlas since 1984 (Gorenflo, 1984) and has been updated recently. It will be presented in the first main part of the paper and compared with experimental data for 55 fluids. In the second, eight more prediction methods from the literature will be tested using the same experimental database, and the deviations between measurement and calculation will be discussed in detail together with the different results calculated with the various methods.

2. Update of the heat atlas prediction method

2.1. Outline of the method

In the Heat Atlas prediction method (Gorenflo and Kenning, 2010; Gorenflo, 2013), the main groups of variables that are of influence on the heat transfer coefficient α are considered in separate factors to establish a reduced heat transfer coefficient α/α_{ref} of the form

$$\alpha/\alpha_{ref} = F_q(q/q_0) \cdot F_{p^*}(p^*/p_0^*) \cdot F_f(P_{f0}/P_{f,ref}) \cdot F_w \tag{1}$$

The reference heat transfer coefficient α_{ref} is a *constant* reference value for *all* fluids, independent of the influences on the right hand side of Eq (1). The functions F are *independent nondimensional* functions,

- F_q and F_{p^*} for the relative increases of the heat transfer coefficient α with rising heat flux q and reduced pressure $p^* = p/p_c$ (p_c = pressure in the critical state),
- F_f for the influence of the thermophysical properties of the fluid at the reference pressure p_0^*, and
- F_w for the influences of surface roughness and material of the heating wall.