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Genetic optimization of heat transfer correlations for evaporator tube flows

Matheus P. Porto [a,b], Hugo T.C. Pedro [b], Luiz Machado [a], Ricardo N.N. Koury [a], Carlos U.S. Lima [c], Carlos F.M. Coimbra [b,*]

[a] Programa de Pós Graduação em Engenharia Mecânica, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil

[b] Department of Mechanical and Aerospace Engineering, Jacobs School of Engineering, Center of Excellence in Renewable Energy Integration, Center for Energy Research University of California San Diego, La Jolla, CA, USA

[c] Departamento de Engenharia Mecânica, Universidade Federal do Pará, Belém, PA, Brazil

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ABSTRACT

Two-phase heat transfer coefficients for internal flows play a critical role in the design and analysis of evaporators and condensers. Previous studies propose empirical relations that combine the effects of nucleate and convective boiling onto the overall heat transfer coefficient. Although these relatively simple empirical relations offer physical insight on the nucleation, boiling and flow processes, they come at the expense of some computational accuracy. In this work, we explored new techniques to determine two-phase heat transfer coefficients for refrigerants R-22, R-134a and R-404a. We used multiple functional forms for the heat transfer coefficients and considered multiple dimensionless parameters as inputs to the algebraic relations. We used genetic algorithms to search the solution space that consists of the input parameters plus the different functional forms, and obtained optimal empirical correlations that cover a wide range of heat transfer regimes. Then, we combined genetic algorithm and artificial neural networks to obtain a more universal correlation. Two versions were developed for each correlation: one that assumes a priori knowledge of the local heat flux and another that does not. Several error metrics were computed for all the correlations developed and compared against correlations from the literature. We conclude that substantial improvements can be achieved in both accuracy and robustness of the correlations by using advanced optimization techniques.

1. Introduction

The determination of the heat transfer coefficients (HTC) in phase-changing conditions is critical to the optimal design of refrigeration systems. The current level of computational technology allows for the use of computationally intensive tools to solve heat transfer problems that were beyond reach just a few decades ago. Two optimization tools that are particularly relevant to the optimal determination of two-phase flow coefficients are genetic algorithms (GAs) and artificial neural networks (ANNs). Recent works employing GAs for the solution of heat transfer problems are reviewed by Gosselin et al. [1]. Mojaraj et al.[2] reviewed the application of ANNs for refrigeration, air conditioning and heat pump systems (RACHP), highlighting the ANN ability to model and solve multivariable nonlinear problems. Considering the determination of HTC in particular, both ANNs and GAs have proven to offer substantial advantages over conventional methods for correlating experimental data [3–7]. Mohanraj et al. [2] conclude that there are substantial gains to be explored in the following areas:

- development of simplified correlations for predicting the performance of RACHP systems;
- hybridization of ANN with other expert systems;
- phase change behavior of newly developed refrigerant mixtures.

The present work introduces four different methodologies for obtaining two-phase flow HTC correlations, and these methodologies combine all three areas mentioned above. The first two are based on the optimization of strictly empirical algebraic expressions, the third results from the optimization of an HTC functional form currently in use (based on the asymptotic behavior of nonlinear superposition effects), and the last one is based on the ability of ANNs to function as a universal nonlinear approximator. With the exception of the third methodology, the other methodologies are applied to two distinct cases: (1) assuming that the heat flux is known, and (2) assuming that the heat flux is unknown. The second scenario has especial relevance in design applications for which both the heat fluxes and the wall temperatures are

* Corresponding author. Tel.: +1 (858) 534 4285; fax: +1 (858) 534 7599.
E-mail address: ccoimbra@ucsd.edu (C.F.M. Coimbra).

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Nomenclature

d	diameter, m
g	gravitational acceleration, m s^{-2}
G	mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient (HTC), W m^{-2} K^{-1}
i	enthalpy, kJ kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
Q	heat flow, W
Q''	heat flux, W m^{-2}
U	mass flow or bulk velocity, m s^{-1}
RMSE	root mean square error, W m^{-2} K^{-1}
MAE	mean square error, W m^{-2} K^{-1}
MBE	mean bias error, W m^{-2} K^{-1}
R^2	coefficient of determination

Greek

χ	Martinelli parameter
μ	viscosity, Pa s
ρ	specific mass, kg m^{-3}
σ	surface tension, N m^{-1}

Dimensionless numbers

Fr	Froude number, $G^2\rho^{-2}g^{-1}d^{-1}$
Pr	Prandtl number, $\mu c_p K^{-1}$
Re	Reynolds number, $\rho Ud/\mu$
We	Weber number, $G^2 d\rho^{-1}\sigma^{-1}$

Subscripts

cb	convective boiling
crit	critical properties
eq	equivalent property – linear proportion between saturation properties and quality
l	saturated liquid, $x = 0$
lv	difference between vapor from liquid saturated properties
nb	nucleate boiling
tp	two-phase flow
tt	liquid/vapor interface
s	saturated
v	saturated vapor, $x = 1$
w	tube wall

unknown. The selection of inputs to be considered for all the correlations was optimized via GA.

To develop the optimized HTCs, we used data from different refrigerants (R404a, R134a and R22), and different flow pattern conditions, that were obtained experimentally by varying the evaporation temperature, vapor quality, mass flow and heat flux.

2. Two-phase flow HTC correlations

The HTC in a horizontal tube can be determined experimentally through the convective heat transfer definition:

$$h = Q''/(T_w - T_s) \tag{1}$$

and

$$Q'' = Q/S, \tag{2}$$

where h is the HTC (W m^{-2} K^{-1}), Q'' is the heat flux (W m^{-2}), T_w is the tube internal surface temperature (°C), T_s is the bulk temperature of the fluid (°C), and S is the tube surface area (m^2).

Understanding the different phase change flow regimes is critical to the development of optimal HTC correlations. Phase changing has multiple roles in RACHP, and what is particularly relevant in our study is the enhancing mechanism for heat transfer capacity. In general, heat transfer rates during phase change can be 4 to 25 times higher than for equivalent single-phase forced convection [8]. Fig. 1 describes the most relevant flow patterns and HTC levels during the phase change process along an evaporator tube. The flow pattern presented in this figure is only illustrative and it will vary depending on the fluid characteristics and flow regimes (evaporation temperature, vapor pressure, heat flux, mass flow velocity, diameter and vapor quality, etc.). Observing the evolution of HTC regimes along the evaporator it is possible to recognize:

- a gradual increase in HTC due to the phase change phenomena, related to nucleate and convection boiling;
- a rapid decrease for high values of quality, more precisely in the region identified as dryout/mist flow.

The phase change mechanism can be further divided into two different processes: convection boiling, which is the phase change regime that occurs in the liquid/vapor interface; and nucleate boiling, which is the phase change regime related to bubble formation on a heated surface (liquid/solid interface). There is a group of correlations, called Strictly Convective, that considers only the convection term for the calculation of a two-phase flow HTC [9–14]. In general, Strictly Convective correlations use the well-known Dittus–Boelter heat transfer relation applied to saturated liquid flow and the Martinelli parameter [15], as expressed by

$$h_{tp} = h_l(1 + C_l\chi_{tt})^{-C_2}, \tag{3}$$

where C_1 and C_2 are constants obtained empirically, as proposed by Bandarra [14]. Another group of correlations, called Superposition Rule correlations, considers both processes: convection boiling (h_{cb}) and nucleation boiling (h_{nb}) [16–22]. These correlations determine the functional form of the HTC by weighing the contribution of each mechanism of heat transfer (h_{nb} and h_{cb}) as

$$h_{tp} = \left[(Fh_{cb})^n + (Sh_{nb})^n\right]^{1/n}. \tag{4}$$

where S and F are weighing factors for the two components. At high values of mass flow the temperature gradient near the wall

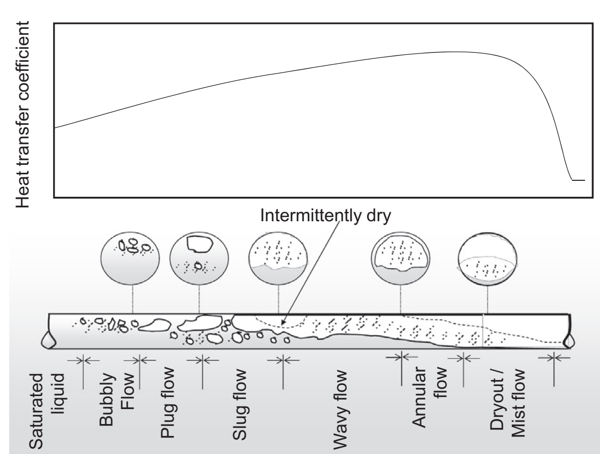

Fig. 1. Example of phase change HTC and flow patterns for a fluid passing through a tube evaporator.