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Development of a new empirical correlation for the prediction of the onset of the deterioration of heat transfer to supercritical water in vertical tubes

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ABSTRACT

Heat transfer to supercritical water is relevant for modern power applications such as supercritical water reactors, supercritical boilers in fossil-fired power plants or future concepts for supercritical solar-thermal power plants. The phenomenon of deteriorated heat transfer (DHT), caused by the strong variation of fluid properties at pressures above the critical pressure is still not thoroughly understood to date. At the same time it is of great importance for plant design and operation. Disagreements exist regarding its definition, its prediction and the mechanisms leading to its occurrence. This study evaluates the performance of empirical correlations for the a-priori prediction of the heat flux causing the onset of DHT in heated vertical tubes with an internal upward flow of supercritical water and proposes a new correlation. Also, definitions from literature are discussed, and the most frequently used quantitative definition: $\alpha < 0.3 \cdot \alpha_{NHT}$ is selected for correlation analysis and development. It is emphasized that the predictive capability of a correlation for the deterioration of heat transfer is limited when no definition for this phenomenon is provided. For the evaluation of the existing correlations and the development of the new correlation, heat transfer data consisting of 4455 data points from 14 independent references is considered. This data set is reduced to 32 independent experiments reflecting the heat flux causing the onset of DHT. The newly developed correlation has a mean average relative deviation of 12.9% and predicts 78.1% of the DHT data within $\pm 20\%$. This is a significant improvement compared to the best existing correlation with a mean average relative deviation of 23.4% and which predicts 56.3% of the DHT data within $\pm 20\%$.

1. Introduction

Being relevant for supercritical conventional steam power plants, next generation supercritical nuclear power plants and future supercritical solar-thermal power plants [1], heat transfer to supercritical fluids in tubes and channels is and has been a heavily studied topic over the past five decades. The heat transfer and pressure drop at supercritical pressures have unique characteristics, caused by the large variations of fluid properties in the supercritical region. A vast number of past works have provided experimental data, correlations and look up tables for calculating the heat transfer coefficient. Other studies proposed correlations for the prediction of the heat flux causing the onset of the deterioration of heat transfer. Also there exists a large number of theoretical and numerical studies to explain the unique heat transfer behavior.

The phenomenon of deteriorated heat transfer (DHT), referring to unusually low values in the heat transfer coefficients between the wall and the bulk fluid flowing in a heated tube is important for the design of supercritical steam generators, as it leads to peaks in the wall temperature. Despite the large amount of efforts to investigate this topic there still remain disagreements on a precise quantitative definition of the phenomenon and especially its prediction and the mechanisms responsible for it [2,3]. This paper discusses the qualitative and quantitative definitions of DHT found in literature and the correlations used for its prediction. Heat transfer data for supercritical water flowing in vertical tubes is gathered and digitalized from 14 independent studies. Using the fraction of the available data corresponding to heat transfer deterioration, existing correlations for the a-priori prediction of the heat flux causing the onset of DHT are analyzed and a new correlation for the prediction of the onset DHT is developed.

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Nomenclature

Latin symbols

c	constant
c_p	specific heat capacity (J/kg K)
C	coefficient, regression parameter
d_i	inner diameter (m)
e	exponent, regression parameter
G	mass flux (kg/m^2 s)
n	number of points
N	total number of points
$\boldsymbol{Nu}$	Nusselt number
p	pressure in bar
$\boldsymbol{Pr}$	Prandtl number
$\dot{q}$	heat flux (W/m^2)
R	fraction of data
$\boldsymbol{Re}$	Reynolds number
T	temperature (K)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
β	thermal expansion coefficient (1/K)
η	dynamic viscosity (Pas)
λ	thermal conductivity (W/m K)
ν	kinematic viscosity (m^2/s)
ξ	friction factor

Subscripts

20	within 20%
b	at bulk conditions
calc	calculated
crit	critical
exp	experimentally determined
i	internal
NHT	normal heat transfer
opt	optimal
pc	at pseudo-critical conditions
w	at the internal tube wall

Abbreviations

DHT	deteriorated heat transfer
MARD	mean absolute relative deviation
MRD	mean relative deviation
NHT	normal heat transfer
RD	relative deviation
RMSRD	root mean squared relative deviation
SD	standard deviation

2. State of the art

This section discusses and evaluates the qualitative and quantitative definitions for the phenomenon of DHT and introduces the existing correlations that are available for its prediction.

2.1. Defining DHT

The deterioration of heat transfer in a heated tube is defined in its most general form as the phenomenon of lower heat transfer coefficients as compared to normal heat transfer and correspondingly higher values of the wall temperature in sections of the tube or even the entire tube [4]. Normal heat transfer is characterized by heat transfer coefficients similar to those of subcritical convective heat transfer [4]. To date, there is still some disagreement on the qualitative and quantitative definition of this phenomenon. Lee and Haller [5] and Ackerman [6] emphasized the abrupt nature of the phenomenon resulting in pronounced temperature peaks and sudden drops in the heat transfer coefficients. Licht et al. [7] defined the occurrence of heat transfer deterioration as any small or large, localized increase in wall temperature. For comparing experimental data and for the assessment of correlations predicting DHT, a quantitative definition in terms of its heat transfer coefficient is necessary.

The variation of the properties of a supercritical fluid with temperature is continuous, causing the temperature peaks from a deterioration of heat transfer to be smooth and often not very distinct. This leaves room for debate on the quantitative definition of DHT and several definitions have been proposed by various authors in the past. The definition used most frequently in literature is expressed by Eq. (1).

$$\alpha < c \cdot \alpha_{NHT} \tag{1}$$

α refers to the heat transfer coefficient, α_{NHT} is the heat transfer coefficient at normal heat transfer conditions. This definition has been proposed by Koshizuka et al. in 1995 [8] with $c = 0.3$ and has since been referred to and applied by several authors [9–15]. The authors proposed to calculate α_{NHT} with the well known Dittus–Boelter form [16] for subcritical single-phase, turbulent, convective heat transfer to a fluid flowing in a tube as given in Eq. (2).

$$\alpha_{NHT} = \frac{\lambda_b \cdot \boldsymbol{Nu}_b}{d_i} = \left(\frac{\lambda_b}{d_i}\right) \cdot 0.023 \cdot \boldsymbol{Re}_b^{0.8} \cdot \boldsymbol{Nu}_b^{0.4} \tag{2}$$

$\boldsymbol{Nu}_b$ refers to the local Nusselt number at bulk fluid conditions as defined in Eq. (3). $\boldsymbol{Re}_b$ refers to the local Reynolds number evaluated at bulk fluid conditions as defined in Eq. (4). $\boldsymbol{Pr}_b$ refers to the local Prandtl number evaluated at bulk fluid conditions as defined in Eq. (5). d_i represents the inner tube diameter, λ_b represents the thermal conductivity of the fluid at bulk conditions, G represents the mass flux in the tube, η_b represents the dynamic viscosity of the fluid at bulk conditions and $c_{p,b}$ represents the specific heat capacity of the fluid at bulk conditions

$$\boldsymbol{Nu}_b = \frac{\alpha \cdot d_i}{\lambda_b} \tag{3}$$

$$\boldsymbol{Re}_b = \frac{G \cdot d_i}{\eta_b} \tag{4}$$

$$\boldsymbol{Pr}_b = \frac{\eta_b \cdot c_{p,b}}{\lambda_b} \tag{5}$$

Wang et al. [2] proposed Eq. (6) to define the deterioration of heat transfer with $\alpha_{crit} = 8$ kW/m^2 K.

$$\alpha < \alpha_{crit} \tag{6}$$

Lee and Haller [5] considered the heat transfer to be deteriorated, when the measured wall temperature is more than 50 °F (27.8 K) higher than the predicted wall temperature.

$$\Delta T_{w,crit} < T_w - T_{w,NHT} \tag{7}$$

This can be expressed mathematically as Eq. (7) with $\Delta T_{w,crit} = 27.8$ K. This expression can be rearranged in terms of heat transfer coefficients and the heat flux as Eq. (8).

$$\frac{\Delta T_{w,crit}}{\dot{q}} < \left(\frac{1}{\alpha} - \frac{1}{\alpha_{NHT}}\right) \tag{8}$$