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Consistency considerations on a large databank and wide range heat transfer prediction for supercritical water in circular tubes

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A B S T R A C T

The heat transfer coefficient (HTC) of supercritical water (SCW) shows abnormal behavior when compared with conventional fluids. This behavior is caused by steady variations of thermal–physical properties of SCW around the pseudo-critical point. A large database of heat transfer of SCW flowing in tube and rod bundles was proposed by the Karlsruhe Institute of Technology (Zhao et al., 2017). This databank contains 28,364 high quality experimental data points (nodes) for heat transfer of supercritical water flowing in tubes, covering a wide domain of flow parameters.

Additional consistency checks were made in this work on the experimental data using our own developed procedure. This procedure was able to provide hints on the intrinsic reliability of the data and also error levels for almost all experimental nodes.

The derived information on error levels made a high-performance methodology of data assimilation and model calibration (Cacuci and Ionescu-Bujor, 2010) subsequently accessible to this domain of experimental data. The BESTEST module (Badea et al., 2011) based on the methodology of data assimilation and model calibration (Cacuci and Ionescu-Bujor, 2010) was used in an iterative manner to optimize a new proposed correlation able to describe with good accuracy a large domain of the databank.

1. Introduction

The databank proposed by the Karlsruhe Institute of Technology (Zhao et al., 2017) contains 28,364 high quality experimental data points (nodes) for the heat transfer of supercritical water flowing upwards in tubes, covering a wide range of parameters (see Table 1).

The SCW heat transfer experimental data were collected out of 24 different sources. The largest numbers of data points are from Herkanrath et al. (1967) (~4000 data points), Xu (2004) (~5000 data points) and Zhao et al. (2012) (~10000 data points).

There are many heat transfer correlations in literature able to reproduce the experimental points of the databank with a certain degree of precision but only for sub-domains. The main goal is to have a correlation reproducing the experimental data for a large(r) domain. The errors of the experimental data, provided scarcely in previous works, have to be estimated as a first condition for unifying the results of the past in a correlation valid for a large domain. Actually, for achieving that, almost the entire collections of experimental data and proposed correlations over decades (describing only sub-domains of the experimental data) were used together in the procedure highlighted in Paragraph 2. The results of this procedure consist of: i) hints on the intrinsic consistency of the experimental databank; ii) estimated errors for almost all points (nodes) of the experimental databank. A new semi-empirical correlation was introduced in Paragraph 3 and then matched (optimized, calibrated) on the experimental data (data assimilation). Making use of the estimated errors from Paragraph 2, the BESTEST module (Badea et al., 2011) – based on the methodology of data assimilation and model calibration (Cacuci and Ionescu-Bujor, 2010) – was used in an iterative manner for the optimization. The new correlation was derived with two branches: for HTD (heat transfer deterioration) and no-HTD regimes. The accuracy of the correlation for the large domain of the available experimental data was than assessed in Paragraph 4.

2. Consistency considerations and error estimations

An own developed procedure was used to assess the intrinsic consistency of the experimental information (values of the Nusselt number at bulk Nu_b) contained in the databank. So called "contributions" of the neighboring (experimental) nodes were considered (whenever possible)

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Table 1
Ranges of parameters for the experimental data in the KIT databank for SCW heat transfer in circular tubes.

Internal diameter (mm)	Parameter Range		
	Pressure (MPa)	Mass flow density (kg/m^2s)	Heat flow density (MW/m^2)
1.3–46.0	22.3–41	100–3600	0.1–9.4

for each experimental node. The contributions are just scaled experimental values of the neighbors toward the node of interest. An experimental value (expressed as Nu_b) may be scaled from the node k into the node i using the local optimal correlation as vehicle:

$$\frac{e_k}{c_k} = \frac{e_i}{c_i} \Rightarrow e_i = e_k\frac{c_i}{c_k} \tag{1}$$

e_k – the experimental value in the node k
c_k – the value of the local optimal correlation in the node k
e_i – pseudo (i.e. extrapolated) experimental value (contribution of node k) for node i
c_i – the value in node i of the local optimal correlation for node k

For each node of the databank a number of 15 correlations from literature, proposed by different authors over almost 7 decades (1942–2011), i.e. McAdams (1942), Miropol'skii and Shitsman (1957, 1958), Bringer and Smith (1957), Krasnoshchekov-Protopopov (1959, 1960), Petukhov et al. (1961), Domin (1963), Swenson et al. (1965), Kondratev (1969), Ornatsky et al. (1970), Yamagata et al. (1972), Jackson and Fewster (1975), Gorban et al. (1990), Kitoh et al. (1999), Jackson (2002), Cheng et al. (2009) and Mokry et al. (2011) were considered to find the closest computed value to the experimental one for each experimental node. The correlations of Swenson et al. (1965), Ornatsky et al. (1970) and Cheng et al. (2009) were able together to describe (as closest correlations) almost 50% of the experimental nodes. The other half of the experimental nodes was described by the remaining correlations together.

Here are the conditions considered to ensure an undistorted scaling from node k towards node i:

i) Only a small change in the correlation value during scaling:

$$\frac{|c_k - c_i|}{c_k} < 7.5\% \Leftrightarrow \frac{|e_k - e_i|}{e_k} < 7.5\% \tag{2}$$

ii) It exits a "tool"/correlation to make the scaling:

$$\frac{|e_k - c_k|}{e_k} < 25\% \tag{3}$$

iii) The same HTD regime (existing or not), i.e. the same Boolean values for the double inequality

$$T_w > T_{pc} > T_b \tag{4}$$

for the two nodes involved in the scaling.

T_w – (internal) wall temperature
T_{pc} – pseudocritical temperature
T_b – bulk temperature

iv) The real physics to be almost similar for the two nodes, i.e. the flow parameters belong to the same sub-space of flow parameters:

$$|\Delta T_w| < 10°\mathrm{C}; |\Delta T_b| < 10°\mathrm{C}; |\Delta \dot{q}| < 0.1\frac{\mathrm{MW}}{\mathrm{m}^2}; |\Delta d_{int}| < 2.5\mathrm{mm}; |\Delta G| < 100\frac{\mathrm{kg}}{\mathrm{m}^2\cdot\mathrm{s}}; |\Delta p| < 2.5\mathrm{bar}; \tag{5}$$

$\dot{q}$ – heat flow density
d_{int} – tube (internal) diameter
G – mass flow density
p – pressure

For a given experimental node i one may have a number of experimental nodes (here denoted as *neighbors*) which allow successful scaling (towards i), i.e. fulfilling the conditions i–iv) above. There are 3119 nodes (from the total number of 28,364 experimental nodes of the databank) without neighbors; in other words, there are no experimental nodes fulfilling the conditions i–iv) in the case of the 3119 nodes. All 28,364 experimental nodes of the (full) databank will be said to have at least one *contribution* (the node itself); the minimum amount of contributions in a node is 1 (the experimental node itself). A node which doesn't contribute may receive (or not) contributions. Formally, for all nodes, the number of contributions is obtained by adding 1 to the number of neighbors. The databank obtained by excluding the 3119 nodes with no neighbors (number of contributions equals 1) will be denoted further as *restricted* databank.

The experimental nodes fulfilling the inequality (4) will be hereby denoted as HTD nodes, i.e. they are in the heat transfer deterioration regime. The no-HTD nodes are those simply not fulfilling the inequality (4). Table 2 resumes the distribution of the experimental nodes between the two regimes (no-HTD and HTD) for the full and restricted databanks, respectively.

All nodes in the *full* databank (the 3119 nodes without neighbors being included) were considered in Fig. 1. Left side of Fig. 1 shows a distribution of the number of nodes on the contributions. In the first bin (i.e. number of contributions is 1) of the 1D-histogram one may recognize the 3119 nodes without neighbors, in the sense of the conditions expressed by i–iv). There are some regions well populated (the multidimensional space of flow parameters is dense) by experimental data resulting in nodes having up to 80 neighbors, as seen in the right tail of the distribution. Mean values $\langle Nu_b \rangle$ and their relative standard deviations σ_{rel} were computed for all nodes of the *restricted* databank (nodes with at least one neighbor) by considering all contributions for each node (the pure experimental data itself and pseudo-experimental data as contributions from neighbors). The distribution of the number of nodes on the estimated relative standard deviations σ_{rel} of the mean values $\langle Nu_b \rangle$ is displayed on the right diagram of Fig. 1. The big majority of the nodes have estimated relative standard deviations of the mean values below 5%. The 3119 points without neighbors are also displayed with a dummy value of -1%, just for graphical representation. They appear only formally in the first bin of the histogram.

Fig. 2 contains all nodes of the *restricted* databank; the number of contributions was in this case at least 2 (the experimental node itself and one neighbor). The left side of Fig. 2 is a 2D-histogram showing the spread of experimental nodes in the two dimensional field of relative standard deviation σ_{rel} of the mean values $\langle Nu_b \rangle$ versus the number of contributions (in each node). The nodes with more contributions display lower relative standard deviations, going asymptotically towards zero with increasing number of contributions. This is the 1st proof of the intrinsic (experimental) consistency of the databank. The 2nd proof of consistency is the result from Fig. 2right): very limited and well balanced (with respect to zero-value) relative discrepancies between the mean values $\langle Nu_b \rangle$ computed out of contributions (experimental

Table 2
Statistics of no-HTD and HTD nodes in the full and restricted databanks, respectively.

Databank	Total nodes	No-HTD nodes	HTD nodes
full	28,364	12,414	15,950
restricted	25,245	11,134	14,111