LOOK-UP TABLE ESTABLISHMENT OF SUPERCRITICAL WATER HEAT TRANSFER IN VERTICAL UPWARD FLOW AND TUBE-SIZE EFFECT INVESTIGATION

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Abstract

The paper describes the derivation of a supercritical water heat transfer look-up table, which may be used for predicting the heat transfer behavior (wall temperature) for supercritical water upward flow in vertical tubes. With an exhaustive open-literature-reported test data collection of vertically upward-flowing water heat transfer under supercritical pressures in vertical tubes, related evaluation on supercritical water heat transfer characteristics is performed. With reasonable data screening and processing, a comparatively small look-up table of supercritical water heat transfer in vertical tubes is constructed by applying the techniques which has ever been used in CHF look-up table development. Further, assessment of the look-up table and several correlations are carried out and delivered. Meanwhile, based on the established look-up table, tube size effect on supercritical water heat transfer in vertically upward flow is preliminarily correlated and investigated. With the increase of test data in various other practical engineered regimes, the look-up table is expected to be further extended.

Keywords: Supercritical water, Heat transfer, Look-Up Table, Size effect

1. Introduction

Based on the advantage of relatively high operation thermodynamic parameters, supercritical water-cooled reactor (SCWR) is expected to achieve high efficiency up to 45-50%, which demonstrates its obvious attraction for nuclear power industry. Among the challenges for SCWR design, operation and safety assessment, the unique heat transfer characteristics of supercritical fluid under certain conditions, such as flow flux, heat flux and channel geometries, remain to be a fundamental subject that needs extensive investigation. When water works at above critical pressure, however, it is characterized by extremely nonlinear variation of all properties in the vicinity of pseudo-critical line which is defined by the maximum of specific heat for pressures above the critical value. Therefore, knowledge of heat transfer characteristics of water in heating ducts at supercritical pressure conditions becomes one of the key fundamental issues for the present preliminary development stage of SCWR.

Up to now, fairly many tests on supercritical fluid heat transfer within several geometries have been conducted among which those for vertical upward flow are the most common. Various predictive correlations are derived, mainly using empirical approaches ([1], [2], [3], [4]) and having relatively limited range of data validity for each correlation. As reviewed by Cheng and Schulenberg ([5]) and by Pioro and Duffey ([6]), most correlations, among others, are of Dittus - Boelter type**,** in which correction factors accounting significant effect of transverse/radial property variations between bulk and wall surface is used. However, due to extreme complexity of factors affecting heat transfer for various conditions, most of such empirical correlations still can not meet acceptable accuracy requirement within the parametric range far beyond. The current proliferating prediction correlation deduction status itself reflects the lack of understanding on heat transfer of supercritical fluid for the present and makes it rather difficult to choose one suitable correlation in specific application. Some authors made efforts to cover more wide a parametric range in their correlation development. By identifying as comprehensive controlling mechanisms as possible and applying certain statistical processing method, Kuang, Zhang and Cheng ([7]) developed a wide-ranged correlation for SCW heat transfer of vertically upward flow in tubes. Their correlation is based on over 8000 data points collected in open literature. Moreover, in the framework of recent development of SCWR, application of system analysis codes for system design and safety analysis is on the schedule. Since many correlations applied are based on local parameters, even on system parameters, it is inevitable for us to face the problem of iteration when they are applied in simulation and calculation codes.

Moreover, with more and more parameters included in the correlations for accurate prediction, they are on the one hand too complicated in form and inefficient in calculation, on the other hand might lead to challenges on convergence. For simplifying correlation structure, Cheng et al ([8]) proposed a simplified method for heat transfer prediction of supercritical fluids in circular tubes. However, for comprehensive validity of the correlations in a wide-spanning parametric space, there is still a long way to go.

To overcome above-mentioned problems in heat transfer prediction through various empirical correlations, esp. for code development application, a way, namely Look-Up Table (LUT) method, which provides simple mapping relations between SCW heat transfer characteristic quantities and controlling parameters seems to be a good choice. It has been successfully applied for CHF prediction in several computer codes such as CATHENA, CATHARE, RELAP5/MOD3, etc ([9]). Besides its high accuracy and wide range of parameters, it is simple to use and easy to extend for further test data added. This enlightens one rather a good approach in pragmatically predicting SCW heat transfer features in a wide parametric range, meanwhile, with acceptable accuracy.

As for SCW heat transfer LUT development, Loewenberg et al ([10]) has for the first time practiced in studying on the construction a look-up table for the condition of vertical upward flow of supercritical water in smooth tubes. In the pioneering work of Loewenberg et al, rather detailed discussion on the applicability of SCW LUT has been presented. On the basis of dimensional analysis, Loewenberg suggested that mass flux, pressure, tube diameter and bulk enthalpy be selected as primitive variables for construction of the wall temperature LUT framework. While developing the LUT for SCW heat transfer, Leowenberg et al adopted, under certain selection criteria, 5744 test data points of vertically upward water flow in different parameter regimes of mass flux, heat flux, pressures and tube diameters.

It is necessary to mention that LUT method, as stated by Leowenberg et al, is usually applied for describing local phenomena. Therefore, they excluded data of deteriorated heat transfer (DHT) from the database for LUT establishment, following Jackson’s criterion ([10]). Principally this is the case. However, with exclusion of DHT data, applicability is limited in possible relatively wide-ranged use of LUT in thermal-hydraulic design and analysis of SCWR. Actually, such kind of data is possible to be included in the formation of LUT to predict DHT mode for the reasons which are to be discussed in following part of the paper.

Moreover, in the process of LUT formation, Leowenberg et al applied a “best-correlation” method for interpolation of some grid points in making the LUT. This is to a extent a possible approach, for it is based on existed mechanistic achievement in correlation development and reflects somewhat controlling effects and factor interactions on SCW heat transfer such as heat flux, mass flux, bulk enthalpy, pressure etc. However, from viewpoint of the authors, it still seems to have not made fully advantages of the information provided by experimental data itself. Instead test data acts only as criterion that judge the accuracy of certain correlation in specific range. And as stated by Lowenberg, "in some cases, correlations which are outside their range of validity showed even better predictions than correlations within their recommended range".([10]) Some confusion might still rise here about interpolation, though it turns out to make no significant problem. It is suggested in this paper that other systematic interpolation or regression method which mainly based on experimental data without any prior trend applied in the making of LUT**.**

In this paper, based on open-literature test data collection, the authors' practice on derivation of a new supercritical water heat transfer LUT for upward flow in vertical channels is presented, along with related accuracy assessment. Size effect is preliminarily discussed as well.

2. Data collection and processing for LUT

2.1 Design of LUT framework

It has been pointed out by Loewenberg ([10]) that, after dimensional analysis, a lot of dimensionless parameters have to be introduced for complete description of SCW heat transfer, considering extremely nonlinear variation of properties near the pseudo-critical line which causes very complex heat transfer features. This means theoretically tremendous experiments are needed to adjust the constants for perfect correlations. Fortunately, these numerous dimensionless parameters are actually expressed by very limited physical parameters. Therefore, Loewenberg (2007) recommended 5 dimensional parameters for prediction of heat transfer in vertical up-flow of supercritical water in smooth tubes, namely, mass flux *G*, heat flux *q*, pressure *p*, bulk enthalpy *H*, and tube diameter *d*. So Loewenberg's LUT ([10]) takes the form as Table 1.

Table 1. Loewenberg's sample LUT

G	*q*	*p*	*d*	Bulk enthalpy (kJ/kg)														
(kg/m^{2}s)	(kW/m^2)	(MPa)	(mm)	1200	1400	1600	1800	1900	2000	2050	2100	2150	2200	2250	2300	2400	2500	2700
				Wall temperature (°C)														
1000	300	24	8	299	337	366	384	387	391	391	391	392	393	394	396	401	409	433
1000	300	24	10	300	337	367	385	388	391	392	392	392	393	395	397	402	410	434
1000	300	24	15	302	339	369	386	388	393	393	393	394	395	396	398	404	412	437
1000	300	24	20	303	340	370	386	390	394	394	394	394	395	397	399	405	413	438
1000	300	25	8	299	337	367	386	390	393	394	395	396	397	399	401	406	414	438
1000	300	25	10	300	338	368	386	390	393	395	396	397	398	399	401	407	415	439
1000	300	25	15	302	339	369	387	391	395	396	397	398	399	401	403	408	417	441
1000	300	25	20	303	341	370	388	392	396	397	398	399	400	401	404	409	418	443
2250	1200	22.5	8	328	362	388	396	400	403	404	405	406	408	411	415	424	430	462
2250	1200	22.5	10	331	364	390	403	408	409	409	409	411	413	417	420	426	432	464
2250	1200	22.5	15	330	366	393	400	405	407	408	408	409	411	414	418	430	436	470
2250	1200	22.5	20	333	368	393	398	401	405	406	407	407	408	412	416	426	440	474
2250	1200	23.5	8	325	361	388	397	402	404	406	407	410	411	414	417	423	434	466
2250	1200	23.5	10	326	363	390	401	407	410	411	412	413	415	417	419	425	437	469
2250	1200	23.5	15	330	366	393	401	406	409	410	411	413	414	417	420	429	441	474
2250	1200	23.5	20	333	369	394	400	404	407	409	411	412	413	417	421	432	444	478

In this paper, we adopt the same structure as Loewenberg's, only that tube diameter *d* is not chosen as one of the dimensions of LUT. A close look at the collected test data shows that they are not well-distributed on tube diameter, though we have data on altogether 9 tube diameters. Therefore, introduction of *d* dimension is considered unfavorable for accuracy of present LUT. Hence, for each specific diameter a table is made, one of the tables which contains relatively enough and well-distributed data and the *d* value is close to practical SCWR core channel, is considered as a "main LUT". When predicting heat transfer for a diameter other than the main table, one might either interpolate among main LUT and tables of neighboring diameters (for the present), or multiply the main LUT prediction with a diameter modifying factor, if possible.

It should be also mentioned that the main LUT is, for the present, a local-concept-based primitive T_w - (G, q, p, H) type table applicable for limited conditions. The present main LUT alone might not be considered as the final table for all practical and more complex applications. Instead, it is intended to be used as a basic table rather than an independent, integral one, which needs further development of multipliers accounting for such other effects as those of tube diameter, rod buddle geometry, power shape, boundary layer changes from inlet and spacers, etc. Unfortunately, current test data are still far from sufficient for developing these multipliers. However, the authors believe that this problem will be gradually solved with further tests conducted.

Tables for other diameters are also completed with the same method and using the same p, G, q, h_b grids, which might provides convenience for interpolations between tube sizes before proper diameter modifying multiplier is available. Yet since data for some of the tables other than the main one are relatively less or poorly parametric distributed, improvement on their accuracy and applicable range is open for further data supplement.

Anyway, the tables of different diameters are for the present given as appendix tables for accounting tube diameter effect in this paper, and thus do we design the task of an open-type LUT group development for further extension.

2.2 Data preparation

Through open literature survey and data collection, a databank which consists of heat transfer data of water under various conditions is implemented, in which test data for vertical upward flow of supercritical water in smooth tubes for the present LUT are included. Altogether 11564 data from 11 publications ([2-4], [12-19]) are selected, which are listed in Table 2. Parametric distribution of the data for water heat transfer of vertical upward flow under supercritical pressures is overviewed in Figures 1 and 2. In summary, working condition of selected data ranges: pressure: 22.5 ~ 31.03 MPa; mass flux: 407 ~ 3500 kg/m^{2}s; heat flux: 157.6 ~ 2000 kW/m^2; bulk enthalpy: 72.73 ~ 3084.6 kJ/kg; tube inner diameter: 7 ~ 26 mm.

Table 2. Source of selected data

No.	Authors	Number of data
1	Ackerman	163
2	Swenson	157
3	Hu	227
4	Zhu	89
5	Yamagata	253
6	Griem	166
7	Shitsman	11
8	Vikhrev	281

9	Xu	5411
10	Styrikovich	207
11	Herkenrath	4599

Figure 1. G, q distribution on the pressure range of the data collected

Figure 2. *q*, *p* distribution on the bulk enthalpy range of the collected data

2.3 Data Screening

Considering data reliability for the LUT making and various conditions of the tests carried out by different authors, not all the selected data can be used for LUT construction. The following procedure is followed for data screening:

• Data duplication checking: Limited number of duplicated data are identified and 162 such data are simply removed.

• Heat balance checking: All experimental data are checked for consistency in heat balance, following the criterion as

$$\frac{q\cdot(\pi\, d\, L)}{(H_{out}-H_{in})\cdot G\cdot(\pi\, d^2/4)}-1.0\le 0.03 \qquad (1)$$

with which 191 data are dropped.

• Inlet effect checking: The present LUT describes heat transfer in fully developed flow. Inlet effect which is to be ignored or left for inlet effect multiplier should not be considered in this table. Therefore, using the following criterion

$$x/d>50 \qquad (2)$$

447 data are eliminated.

• About DHT data: Other than Loewenberg's simply removing, DHT data are included in construction of the present look-up table.

Detailed survey of the existed DHT mechanism studies (eg. [11], [20]) shows that strong buoyancy effect, among some other factors, contribute most to DHT onset. Several successful CFD simulations of DHT conditions (both first and second peak of wall temperature) applying certain low-Reynolds turbulence model ([21], [22]) also indicate that DHT from buoyancy effect basically originates from specific near-wall turbulence production law and related turbulence structures that cause local laminarization. The present data after screening are all under conditions of fully developed flow (large length - to - diameter ratio) with uniform heating and thin tube wall. Thus, local parameters are considered to dominate heat transfer feature for the present test conditions, even for DHT. The present LUT development is based on a local concept. For heat transfer under conditions other than the above-mentioned ones, multipliers accounting for size (hydraulic), wall dynamics, heated length and non-uniform heating effects, etc. (and even for bundle and grid spacer effects) are expected to be developed to modify the present LUT predictions. From this viewpoint, DHT data are preserved.

Therefore, through above-mentioned data screening, number of data for LUT construction is reduced to 10764. That is, 93% of the total data are preserved for further research.

2.4 Data smoothing

Some of the data in databank are questionable for random error which is known as data noise or data scatter. Therefore, experimental data with great random error should be smoothed by a suitable smoothing method. A simple mathematical method, which is introduced by Huang and Cheng ([23]), is applied case by case in this paper for smoothing the multidimensional tabulated test data subject to random errors. Applying this method, scatter of data can be reduced significantly while remaining good agreement with original ones. Figure 3 shows several examples of data smoothing.

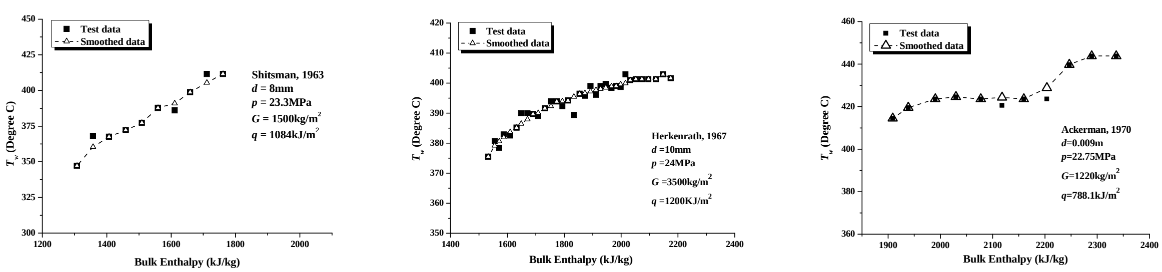


Figure 3. Examples of data smoothing

3. LUT derivation

Having carefully examined data and test conditions, skeleton of a four-dimensional table is formed, which contains 7 discrete values of pressure, 8 of mass flux, 9 of heat flux and 31 of bulk enthalpy as dimensional grids. Considering that distribution of the applied data for tube diameter are quite non-uniform (eg. data number for diameter of 8mm is only 10, while 5229 data are for diameter of 12mm) and conditions covered by respective diameter's data are rather uneven, we give up using tube diameter *d* as a dimension of the LUT, rather, for each diameter a “table” is made whilst the one for 10mm diameter case (2174 data relatively well-distributed and covering the widest parametric range) is seen as the “main table”.

For the main table, as well as other ones for other tube diameters, unified grids are designed covering the whole parametric range for all data. Further, bulk enthalpy grids give a finer resolution around pseudo - critical point allowing for strong property variations (of course, certain blank regions are observed in each table for the present due to databank limitation). The gird design is summarized as following:

7 grid values for pressure: 22.5, 23, 24, 25, 27, 30, 31 (MPa);

8 grid values for mass flux: 600, 700, 800, 1000, 1200, 1500, 2250, 3500 (kg/(m^2s));

9 grid values for heat flux: 200, 300, 500, 800, 1000, 1200, 1400, 1600, 2000 (kW/m^2);

31 grid values for bulk enthalpy: 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2050, 2100, 2150, 2200, 2250, 2300, 2400, 2500, 2600, 2700, 2800, 2900, 3000 (kJ/kg)

Altogether 9 tables are constructed, one for each diameter value (7, 8, 9, 10, 12, 18, 20, 24, 26mm). However, due to the scarcity of available data and unevenly distribution, tables of 7, 8, 18, 24mm diameters contain too small amount of values for practical use, while tables of 9, 26mm diameters is limited in use for part of the parameter ranges.

As for determination of tabulated wall temperature value on table grid points, Leowenberg et al applied a “best-correlation” method for interpolation in the LUT making ([10]). This method is essentially dependent partially on experimental data and partially on existed correlations. Accuracy of the LUT is dependent, to some extent, on current knowledge about SCW heat transfer mechanism or accuracy of the correlations.

To make full use of test data information, a pure regression over all experimental data within each bulk enthalpy interval is applied for wall temperature T_w prediction. In each interval, T_w (or heat transfer) is independent function of parameters of p, G, q and h_b, and perhaps also their interaction and cooperation. To this point, Response Surface Methodology (RSM) is adopted for regression. Response Surface function (RS function) is introduced to account for functional relation among the primitive variable T_w and independent ones (ie. p, G, q, h_b) within each interval, which takes following polynomial form

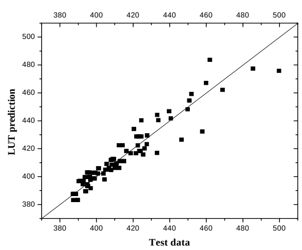
$$\hat{Y}\left(X_1, X_2, \cdots, X_k, \cdots, X_M\right) = a_0 + \sum_{i=1}^{M} \cdots \sum_{l=1}^{M} \cdots \sum_{m=1}^{M} a_{i \cdots k \cdots m} X_i^{N_1} \cdots X_l^{N_l} \cdots X_m^{N_m} + \varepsilon \quad \left(i \neq l \neq m\right) \qquad (3)$$

where, X_1, X_2, …, X_k, …, X_M are independent variables (ie. p, G, q, h_b), while $\hat{Y}$ is estimation of primitive variable (T_w here), and ε is fitting error. Moreover, $0 < N_i + \ldots + N_l \ldots + N_m \leq L$; L is the highest order of the regression polynomial.

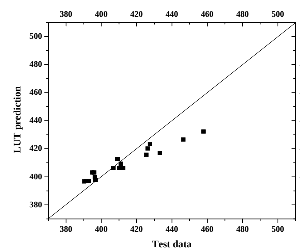
In RS function of this form, the coefficients of exponential terms represent the linear, quadratic, cubic effects of independent variables…… and so on, and those of cross product terms represent linear-by-linear, linear-by-quadratic, linear-by-cubic, quadratic-by-cubic interaction between independent variables…… and so on. This is considered somewhat a reasonable for regression accounting various effects of parameters on heat transfer behavior.

In present LUT making, at highest 3rd-order of the polynomial RS function is assumed for each intervals using the professional software, Design Expert. And the accuracy is later proved to be acceptable. Thus are the RS functions regressed and then T_w grid values calculated.

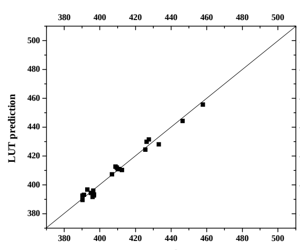
During case-by-case re-evaluation, such phenomena are observed that overall accuracy of RS function prediction is acceptable for the entire bulk enthalpy interval while for “test data vs prediction value” diagrams they are poorly-distributed or some data are poorly-regressed in certain sub-regions. Then parametric sub-regions in intervals with relatively too large error is identified, a new RS function right for the sub-region is deduced and specific grid values are renewed. Figure 4 presents a typical example of LUT prediction result before and after RS function re-evaluating and renewing procedure. Figure 4(a) gives the original LUT prediction vs. test data within the bulk enthalpy interval corresponding to 2050kJ/kg grid in the main LUT. With a new regression for sub-regions of A[22.25-25.25 MPa (*p*), 400-1200 kg/m^{2}s (*G*), 150-800 kW/m^2 (*q*)] and B[22.25-25.25 MPa (*p*), 1200-2000 kg/m^{2}s (*G*), 800-1450 kW/m^2 (*q*)], as shown in Figure 4(b)~(e), the new RS functions are substituted for related grid value calculation. The final LUT prediction vs. test data diagram is presented in Figure 4(f), which demonstrates obviously better prediction.



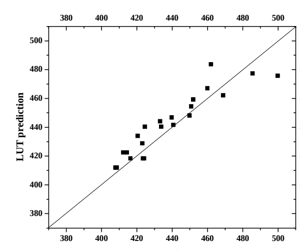
(a) original for whole interval



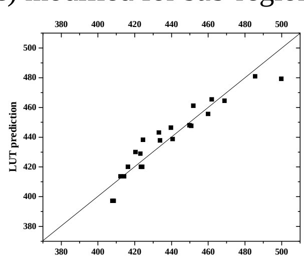
(b) original for sub-region A



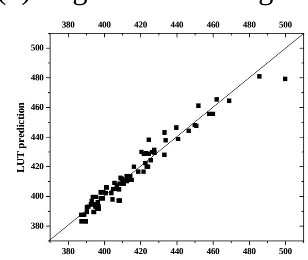
(c) modified for sub-region A



(d) original for sub-region B



(e) modified for sub-region B



(f) modified for whole h_b interval

Figure 4. Comparison of prediction result before and after re-evaluating and renewing response surface functions

Figure 5 presents several examples of response surfaces at the grid point of h_b=1700kJ/kg along with comparison to test data falling in the corresponding interval (1650-1750kJ/kg).

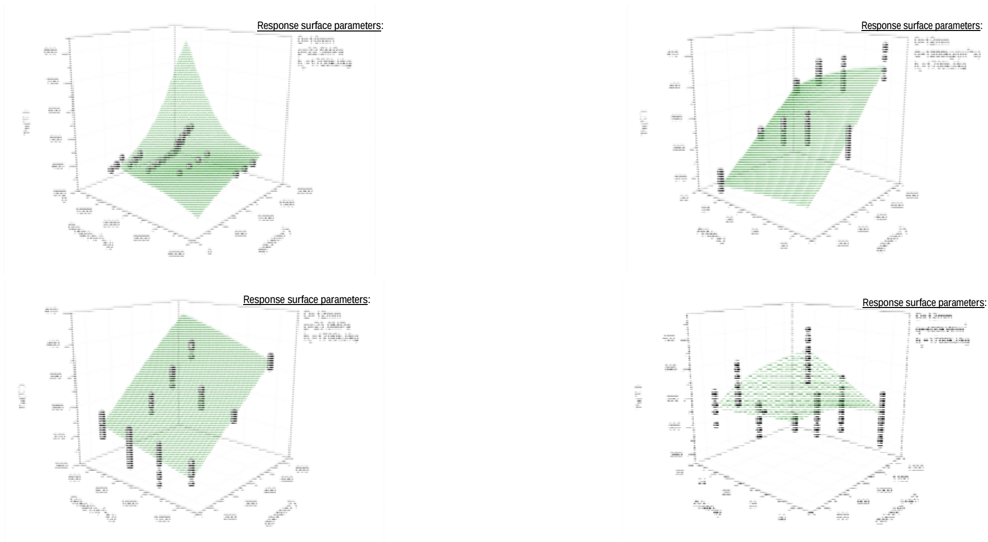


Figure 5. Examples of response surfaces and related test data falling in related h_b intervals

If one of the parameters for a grid point is out of range of test condition, the corresponding LUT interval is then printed blue, which means that predictive accuracy inside and the grid value is not assured for it is obtained through some kind of "extrapolation".

Specifically, it is possible that only one or very few test data fall in a certain interval and RS regression is no longer valid. Then the unknown grid value is for the present simply treated through linearly interpolating or extrapolating the datum with the nearest next known grid points. The linearly crossed interval is then painted green (interpolation) while the linearly extended edge interval is painted blue (extrapolation), which means that predicting error inside might be a bit larger (for green) or the precise is not assured (for blue).

Therefore, extrapolation outside the experimental range is usually not recommended. Use of grid values in blue areas of LUT is considered extrapolation operation, which is normally invalid or one should be careful. Also, since linear interpolation has been used in determining grid values since they are subject to data scarce, it might bring relative a bit larger error in green areas for prediction.

A few more words about the blue intervals in the LUT, though error of prediction within them might be possibly unreasonably large, they are still preserved in the LUT waiting for future "revival" when more reliable test data filled in. Improvement of accuracy in green region is also expected for more test data.

A sample table extracted from the final main LUT (d = 10mm) is shown in Table 3. The last row of the table gives standard deviation between wall temperature predictions and experimental data in each interval. The averaged accuracies within the bulk enthalpy intervals seem rather satisfactory. Tables of related polynomial coefficients of RS functions are obtained as well.

Table 3. Example of the main look-up table (d = 10mm)

P	G	Q	Bulk Enthalpy(kJ/kg)

MPa	kg/(m²s	kW/m²	1400	1500	1600	1700	1800	1900	2000	2050	2100	2150	2200	2250	2300	2400	2500	2600	2700	2800
			Wall temperature(degree C)																	
22.5	800	400	492.9	364.2	361.8	390.4	347.6	399.5	398.6	399.4	396.2	394.5	405.6	399.3	400.7	407.9	416.8	432.2	449.9	470.5
22.5	800	600	507.1	385.1	396.5	402.9	379.5	430.2	412.6	434.6	434.7	429.2	424.3	424.7	422.8	421.1	434.6	454.8	470.9	505.7
22.5	800	800	521.3	408.4	453.1	433.9	416.2	457.3	441.7	469.7	473.1	463.9	452.1	450.1	444.8	434.2	452.4	477.3	492	568.4
22.5	800	1000	535.5	436	484.2	484.2	480.5	484.7	483.3	477.7	474.9	462.3	475.8	465.9	471	476.3	471.4	495.1	513	556.7
22.5	800	1200	549.8	469.8	535.1	542.2	517.9	522.3	517.7	512.5	504.7	483.1	511.9	486	502.2	509.7	490.8	512.3	534.1	585.4
22.5	1000	400	447.7	358.6	371.9	385.4	386.8	389.5	375	379.8	373.1	373.8	396	380.5	384.9	398.1	401.4	424.2	439	458.7
22.5	1000	600	461.9	376	395.5	402.9	411.7	416.9	412.6	409.4	403.9	399.7	407.9	405.9	406.9	411.3	419.2	436.3	460	474.3
22.5	1000	800	476.1	395	440.9	433.9	441.5	443.9	441.7	439	434.8	425.6	435.8	431.3	429	424.5	437	448.5	481.1	537
22.5	1000	1000	490.3	417.5	453	454.1	460.4	464.6	463.9	459.3	457.8	448	458.1	454.3	455.7	461.3	463.2	484.1	502.1	540.1
22.5	1000	1200	504.5	445.4	494.2	500.5	494.4	498.9	495.4	491.1	485.4	467.5	490.9	474.4	484.7	492.3	483	502.6	523.2	567.3
23	1200	600	398.6	401.1	497.2	492.4	771.2	405.4	417.7	390.1	381.4	378	396.4	396.4	399.4	409.6	414.6	427	466	448.5
23	1400	600	374.5	395.4	376.9	382.8	385.1	388.5	390.5	390.1	389.9	390.4	391.1	389.2	390.3	394.1	399.7	414.4	453.6	466.6
23	1400	800	385.4	410.4	386.4	393.2	397.8	400.8	401.6	401.2	402.3	401.9	402.3	405.5	408.9	416	425	442.2	474.7	490.7
23	2250	1000	293.8	402.8	416.2	497.4	394.7	397.4	399.3	399.3	398.5	399.5	400.7	402.6	403.5	405.3	401.6	415.7	474.1	481.9
23	2250	1200	304.6	410.5	425.3	497.4	402.1	407.3	410.1	410	410.2	412.2	413.3	415.4	418.3	426.1	430.5	440.5	474.1	481.9
23	2250	1400	315.5	420.3	440.2	497.4	409.6	417.3	421	420.7	421.9	424.8	426	428.2	433	446.8	459.4	465.3	474.1	481.9
23	3500	1200	153.9	401.3	382.7	389.5	393.7	395.8	396.6	397	397.6	400.5	397	409.5	410	419.2	382.2	375.1	386.6	348.6
23	3500	1400	164.8	407.8	386.3	393.8	398.1	400.9	401.6	401.1	404.6	404.5	405.2	409.5	413.3	423.5	406.5	407.5	407.7	356.2
23	3500	1600	175.7	413.1	389.3	397.6	403.5	404.7	406.1	406	406.3	408.4	405.6	410.9	413	420.2	439.4	474.3	428.8	363.8
23	3500	1800	186.5	419	393.4	402.9	411.1	412.5	414.1	414.7	414.3	412.4	412.6	417.3	421.6	428.9	448.3	474.3	449.8	371.4
24	1200	1000	370.9	399.2	431.7	431.1	447.9	450.8	452.9	449.3	449.4	449.8	443.5	450	445.3	452	470.3	490.4	511.5	546.5
24	1200	1200	375.1	420.1	464.5	468.7	478.5	481.8	481.6	478.2	474.7	470.9	469.9	467.3	468	474.1	490.4	510.3	532.6	572.1
24	1400	400	376.5	354	368.3	373.2	372.4	377.6	383.5	383.6	380.7	382.1	380	372.9	371.7	376.3	381.6	392.6	433	457.8
24	1400	600	380.6	364.9	377.8	383.6	385.1	389.9	394.5	394.6	393.2	393.6	391.1	389.2	390.3	398.2	406.8	423.7	454	481.9
24	1400	800	384.8	375.6	387.3	393.9	397.8	402.2	405.6	405.6	405.6	405.2	402.3	405.5	408.9	420.1	432.1	451.5	475.1	505.9
Error Std in Intervals (°C)			**2.763**	**2.313**	**6.062**	**4.665**	**3.902**	**4.584**	**3.89**	**3.179**	**4.741**	**2.527**	**5.185**	**5.448**	**4.851**	**5.843**	**3.823**	**3.719**	**9.019**	**8.678**

In practical application, such a procedure is recommended to be followed:

(1) Firstly check the p, G, q parameters for the prediction case:

(a) If they encounter grid parameters in the main LUT, simply choose the T_w grid value;

(b) Otherwise, find neighboring grids and interpolate among them to get the T_w value;

(2) Secondly, check the tube diameter parameter d of the prediction case:

(a) If d = 10mm, then simply use the T_w value obtained from the main LUT as final T_w prediction;

(b) Otherwise, check whether d is right the size parameter for the appendix tables:

(i) If d of prediction case encounters either of the appendix table d values, then follow the same procedure as (1) in the appendix table to obtain T_w for prediction (Unluckily, some appendix tables are almost unfit for practical use due to data scarcity and needs future supplement).

(ii) Else if d of prediction matches none of the appendix table d values, calculate corresponding T_w values using both appendix tables whose diameters are the nearest larger and smaller, following the same procedure as (1). Then simply interpolate the two T_w values as per d to get the predicted T_w. Another possible way is to multiply the T_w value main LUT with a size effect multiplier. Unfortunately, this multiplier is not satisfactorily acquired yet.

For predictive cases with additional conditions, eg. non-uniformly heating, inlet effect, or bundle geometries, no corresponding multipliers allowing for such effects is for now available. One might simply locally use the LUT for the time being until related test conducted and corresponding multipliers developed.

4. Accuracy of the look-up table

To assess accuracy of the LUT constructed in this paper, three error evaluation quantities, namely averaged relative error σ_1, averaged absolute of relative error σ_2 and standard deviation of relative error σ_3, are introduced, which are defined respectively as

$$\begin{cases} \sigma_1 = \sum_{i=1}^{N} e_i \Big/ N \\ \sigma_2 = \sum_{i=1}^{N} |e_i| \Big/ N \\ \sigma_3 = \sqrt{\sum_{i=1}^{N} (e_i - \sigma_1)^2 \Big/ (N-1)} \end{cases} \tag{4}$$

where $e_i = (T_{w,i,\mathrm{pre}} - T_{w,i,\mathrm{exp}}) / T_{w,i,\mathrm{exp}}$ with $T_{w,\,i,\,\mathrm{pre}}$ represents wall temperature predicted by LUT (using corresponding RS function), and $T_{w,\,i,\,\mathrm{exp}}$ is related original test data.

Table 4 delivers both the overall accuracy of the LUT and accuracies of separate tables for different tube diameter, which presents fairly good features for error analysis.

Furthermore, applicability of heat transfer trend for the current LUT in some typical cases (non-deterioration and deterioration cases) is qualitatively evaluated and demonstrated as in Figure 6(a), (b) respectively. For non-DHT case, as in Figure 6(a), the LUT presents rather obvious advantage over most correlations, while for typical DHT case as shown in Figure 6(b), the best prediction in region around pseudo-critical point is also obtained by the LUT.

Table 4. Error analysis for different correlation

Tables \ Error Index	σ_1	σ_2	σ_3
7 mm-diameter table (149 pt.s)	-1.35089×10^{-4}	18.67116×10^{-4}	26.11868×10^{-4}
8 mm-diameter table (10 pt.s)	-28.17364×10^{-4}	60.21861×10^{-4}	103.01783×10^{-4}
9 mm-diameter table (209 pt.s)	14.80415×10^{-4}	145.79386×10^{-4}	339.28461×10^{-4}
10 mm-diameter table (2174 pt.s)	3.61264×10^{-4}	128.93139×10^{-4}	181.56377×10^{-4}
12 mm-diameter table (5229 pt.s)	0.702235×10^{-4}	34.50983×10^{-4}	46.84112×10^{-4}
18 mm-diameter table (34 pt.s)	0.791×10^{-4}	49.67297×10^{-4}	89.33019×10^{-4}
20 mm-diameter table (2686 pt.s)	-37.97392×10^{-4}	160.34597×10^{-4}	318.31556×10^{-4}
24 mm-diameter table (64 pt.s)	9.48113×10^{-4}	153.00022×10^{-4}	281.36437×10^{-4}
26 mm-diameter table (209 pt.s)	49.67063×10^{-4}	425.34324×10^{-4}	675.55322×10^{-4}
LUTs overall (10764 pt.s)	-7.2×10^{-4}	95.24×10^{-4}	211.76×10^{-4}

(a) non-DHT case (b) DHT case

Figure 6. Comparison of test data with values predicted by the LUT and other for typical heat transfer cases

5. Effect of tube diameter Parameter

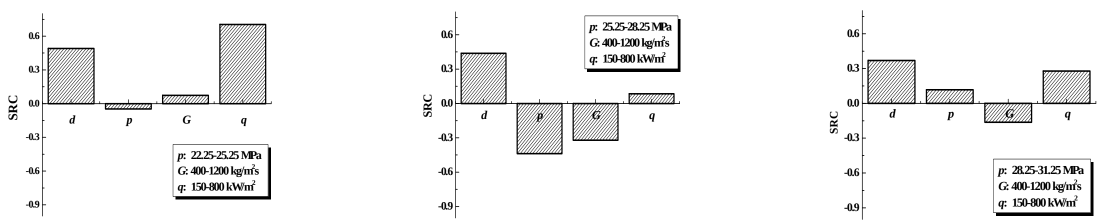
According to data distribution, we divide whole affecting parameter (pressure *p*, mass flux *G* and heat flux *q*) range into several sections to form a parametric space consisting of several sub-regions, in which the parameter ranges are:

Pressure, *p*, regions: (I) 22.25-25.25 MPa, (II) 25.25-28.25 MPa, (III) 28.25-31.25 MPa;

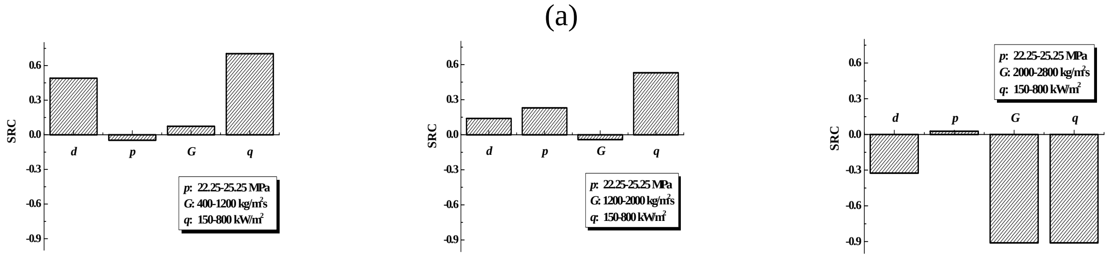
Mass flux, *G*, regions: (I) 600-1200 kg/m^{2}s, (II) 1200-2000 kg/m^{2}s, (III) 2000-2800 kg/m^{2}s, (IV) 2800-3600 kg/m^{2}s;

Heat flux, *q*, regions: (I) 150-800 kW/m^2; (II) 800-1450 kW/m^2; (III) 1450-2100 kW/m^2.

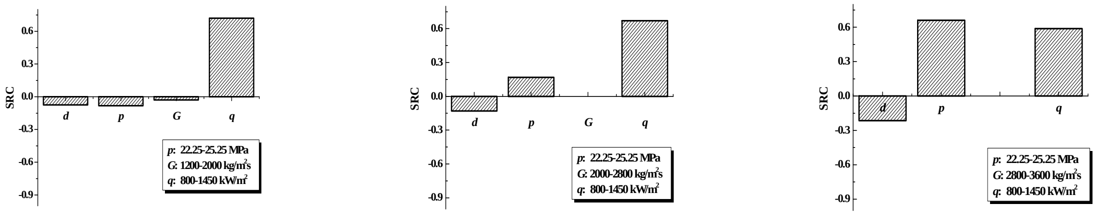
Sensitivity analysis about parametric effects of tube diameter (*d*), pressure (*p*) and heat flux (*q*) on wall temperature T_w are statistically conducted in various sub-regions based on related test data, using Standardized Regression Coefficient (SRC). Some SRC results are demonstrated in Figure 7, which qualitatively determine relative importance of the explanatory variables for SCW heat transfer. And the relative importance (SRCs) of the parameters *d*, *p*, *G* and *q* as well as their varying trends across the parametric sub-regions are summarized in Table 5.



(a)

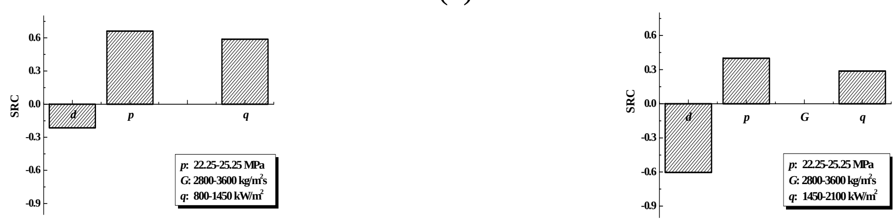


(b)



(c)

(d)

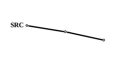
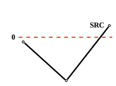
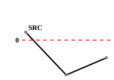
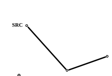
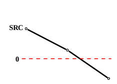
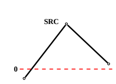
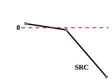
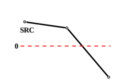


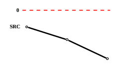
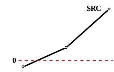
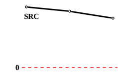
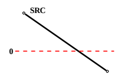
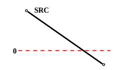
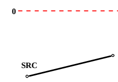
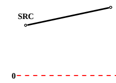
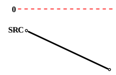
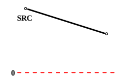
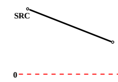
(e)

Figure 7. Standardized regression coefficients of *d*, *p*, *G*, *q* on T_w in different parametric sub-regions

Reminding that SRC is actually partial correlation coefficient between primitive variable T_w and affecting parameters *d*, *p*, *G* and *q*, it is observed that influences of *p*, *G* and *q* on wall temperature seem rather complicated (monotonously increasing or decreasing with *p*, *G*, *q* increase, or being non-monotonous). Instead, SRC values of tube diameter *d* effect drop monotonously with increasing of *p*, *G* or *q*, which implies that either positive dependence of T_w on *d* is weakened, or T_w drops simply with *d* increasing when *p*, *G*, *q* increases. From Table 5, therefore, it is seen that there exist some sub-regions where T_w increases with *d* increasing, esp. for relative low mass flow and low heat flux; however, when *G* or *q* increases to high enough, T_w turnover to drop with *G* or *q* increasing.

Table 5. Relative importance of the parameters on wall temperature and their varying trends across the parametric sub-regions

Sub - Regions	**Varying Parameter**	**SRC values (relative importance on T_w)**			
		d	***p***	***G***	***q***
***G*I-*q*I**	***p*: I→II→III**				
***p*I-*q*I**	***G*: I→II→III**				

***p*I-*q*II**	***G*: II→III→IV**			**N/A**	
***p*I-*G*II**	***q*: I→II**				
***p*I-*G*IV**	***q*: II→III**			**N/A**	

It should be mentioned that the SRCs only give fairly rough impression on parametric sensitivity trend for complex heat transfer features. Due to interaction among parameters and even poor data distribution of present databank in some sub-regions, possibilities of introducing any distortion is conceivable.

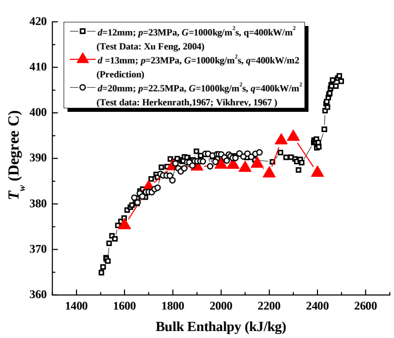
A prior guess of linear-log type formula for approximate diameter effect estimation is assumed, which reads

$$\ln\left[\frac{T_{w,\text{pre}}(h_b, d; p, G, q)}{T_{w,\text{LUT}}(h_b, 10\text{mm}; p, G, q)}\right] = k_1 \ln\left(\frac{d}{10\text{mm}}\right) + k_2 \tag{5}$$

in which, $T_{w,\text{LUT}}(h_b$, 10mm; p, G, $q)$ represents wall temperature looked up in the main LUT (d = 10mm) under related conditions of p, G, q and h_b, while $T_{w,\text{pre}}(h_b$, d; p, G, $q)$ stands for wall temperature under the same condition but for a different tube diameter d. k_1 and k_2 are regressed constant from test data and the main LUT. And with the above eq. (5) and very limited data for different diameters, coefficient table of k_1 and k_2 for very limited conditions is obtained. Therefore, for the diameter effect prediction, we have

$$\frac{T_{w,\text{pre}}(h_b, d; p, G, q)}{T_{w,\text{LUT}}(h_b, 10\text{mm}; p, G, q)} = k_2'\left(\frac{d}{10\text{mm}}\right)^{k_1} \tag{6}$$

in which, $k_2' = \exp(k_2)$. Figure 8 gives a prediction of T_w of a 13mm tube diameter (p=23MPa, G=1000kg/m^{2}s, q=400kW/m^2) using the coefficient table, as well as data under neighboring conditions for comparison. And Figure 9 presents T_w predictions for several diameters (d=13, 15, 17mm) under the same p, G, q conditions.



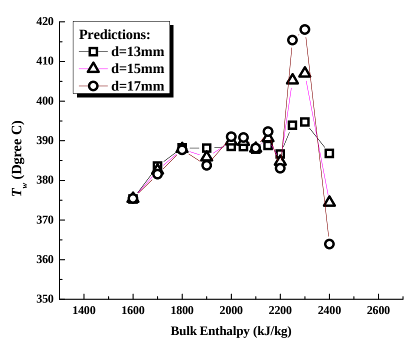


Figure 8 Prediction of T_w for d =13mm with comparison of neighboring test data

Figure 9 Prediction of T_w for d=13, 15 and 17mm

It should be mentioned that this is for now, with limitation of data collection, a rough overview on the effect but still far from obtaining practical size effect multipliers. With more data for various diameters added, both formulation and accuracy of modification should be improved.

6. Conclusions

Look-up table seems to be a good method in predicting heat transfer of supercritical water for its easy-using, relatively high accuracy, and readiness to update as well. Besides, it avoids approximating and extrapolating concerning physical flow phenomena or fluid properties. Based on local concept of SCW heat transfer, in this paper, a LUT for inner wall temperature of heating tubes for vertically upward flowing supercritical water heat transfer has been derived with 10764 test data collected, applying response surface methodology as well as reasonable data selection and processing method.

Assessment carried out for the deduced LUT demonstrates that such good features as possible wide-range applicability, relatively low error, and satisfactory prediction ability under special conditions are preliminarily achieved. A preliminary size effect case investigation, which might be a first step for further development towards diameter modifying multiplier for LUT prediction, is also conducted. Further efforts and improvements are still necessary in database enlargement, data regression optimization and parametric effect study.

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