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THE FILM BOILING LOOK-UP TABLE: AN IMPROVEMENT IN PREDICTING POST-CHF TEMPERATURES

by

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ABSTRACT

During the past 50 years more than 60 film boiling prediction methods have been proposed (Groeneveld and Leung, 2000). These prediction methods generally are applicable over limited ranges of flow conditions and do not provide reasonable predictions when extrapolated well outside the range of their respective database. Leung et al. (1996, 1997) and Kirillov et al. (1996) have proposed the use of a film-boiling look-up table as an alternative to the many models, equations and correlations for the inverted annular film boiling (IAFB) and the dispersed flow film-boiling (DFFB) regime. The film-boiling look-up table is a logical follow-up to the development of the successful CHF look-up table (Groeneveld et al., 1996). It is basically a normalized data bank of heat-transfer coefficients for discrete values of pressure, mass flux, quality and heat flux or surface-temperature.

The look-up table proposed by Leung et al. (1996, 1997), and referred to as PDO-LW-96, was based on 14,687 data and predicted the surface temperature with an average error of 1.2% and an rms error of 6.73%. The heat-transfer coefficient was predicted with an average error of -4.93% and an rms error of 16.87%. Leung et al. clearly showed that the look-up table approach, as a general predictive tool for film-boiling heat transfer, was superior to the correlation or model approach. Error statistics were not provided for the look-up table proposed by Kirillov et al. (1996).

This paper reviews the look-up table approach and describes improvements to the derivation of the film-boiling look-up table. These improvements include: (i) a larger data base, (ii) a wider range of thermodynamic qualities, (iii) use of the wall temperature instead of the heat flux as an independent parameter, (iv) employment of fully-developed film-boiling data only for the derivation of the look-up table, (v) a finer subdivision and thus more table entries, (vi) smoother table, and (vii) use of the best of five prediction methods for areas where data are unavailable.

The look-up table is based on 20,785 film-boiling data points, which were carefully selected from a data bank compiled by the University of Ottawa. These data were all believed to be obtained in the fully developed film-boiling region. A comparison of the fully developed film-boiling look-up table with the fully developed film-boiling database shows an overall rms error in heat-transfer coefficient of 10.58% and an average error of 1.71% (the corresponding errors of the previous heat-flux controlled look-up table with the updated data base are: 20.65% rms and 6.87 % average error).

A comparison of the prediction accuracy of the look-up table with other leading film-boiling prediction methods clearly demonstrates the superiority of the present look-up table.

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NOMENCLATURE

A	area (m^2)
Cp	heat capacity (J kg^{-1} K^{-1})
D	tube inside diameter (m)
D_h	hydraulic diameter (m)
f	friction factor (-)
g	acceleration due to gravity (m s^{-2})
G	mass flux (kg m^{-2} s^{-1})
h	heat-transfer coefficient (kW m^{-2} K^{-1})
H	enthalpy (J kg^{-1})
H_{fg}	heat of evaporation = H_g - H_f (J kg^{-1})
k	thermal conductivity (kW m^{-1} K^{-1})
P	pressure (Pa = N m^{-2}, bar = 10^5 N m^{-2})
q	surface heat flux (kW m^{-2})
t	temperature (℃)
T	absolute temperature (K)
T_{mfb}	minimum film-boiling temperature (K)
ΔT	temperature difference = T_w - T (K)
u	fluid velocity (m s^{-1})
v	specific volume of fluid (m^3 kg^{-1})
X_{th}	thermodynamic quality = (H - H_f) / H_{fg} (-)
X_a	actual quality = α ρ_v u_v/ G (-)

Greek

α	void fraction
ρ	fluid density (kg m^{-3})
μ	dynamic viscosity N s m^{-2} = kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})

Dimensionless Groups

Bo	Boiling number = q / (G H_{fg})
Fr	Froude number = G^2 (L – L_{do})^2 / (ρ g D)
Pr	Prandtl number = μ Cp / k
Re	Reynolds number = G D / μ

Subscripts

a	actual
bulk	bulk-fluid conditions
DFFB	dispersed-flow film boiling
do	dryout or CHF condition
e	equilibrium conditions
exp	experimental
f	saturated liquid
g	saturated vapour
hom	homogeneous
IAFB	inverted annular-flow film boiling
MFB	minimum film boiling
pred	predicted
sat	saturation
TB	transition boiling
th	thermodynamic
table	PDO look-up table value
v	vapour
vf	vapour-film temperature
i	inside
o	outside
w	evaluated at wall conditions

Abbreviations

CHF	Critical heat flux
DC	direct current
DFFB	dispersed-flow film boiling
EPRI	Energy Power Research Institute
ID	inside diameter
IAFB	inverted annular-flow film boiling
LW	light water
LUT	look-up table
NSERC	Natural Sciences and Engineering Research Council
OD	outside diameter
PDO	post dry-out conditions
rms	root-mean-square
UO	University of Ottawa

1.0 INTRODUCTION

This paper describes the derivation and application of film boiling look-up table. The film-boiling look-up table represents a significant improvement in the prediction of film boiling heat transfer and is also a logical sequel to the development of the successful CHF look-up table (Groeneveld et al., 1996). It is basically a normalized data bank of heat-transfer coefficients for discrete values of pressure, mass flux, quality and heat flux or surface-temperature.

An earlier version of the film boiling look-up table proposed by Leung et al. (1996, 1997), and referred to as PDO-LW-96, was based on 14,687 data and predicted the surface temperature with an average error of 1.2% and an rms error of 6.73%. The heat-transfer coefficient was predicted with an average error of -4.93% and an rms error of 16.87%. Leung et al. clearly showed that the look-up table approach, as a general predictive tool for film-boiling heat transfer, was superior to the correlation or model approach.

This paper describes a major revision to the PDO-LW-96 look-up table. The following significant improvements were made:

- The database has been expanded significantly. The present database, compiled by the University of Ottawa (Vasic' et al., 2000), contains 77,234 film-boiling data points obtained from 36 sources; 36.64% of the film-boiling data were obtained in the fully developed film-boiling region.
- The range of thermodynamic quality has been expanded from –0.2 to +2.0. The previous upper limit in thermodynamic quality was 1.2. A wider range was needed as non-equilibrium effects at low flow can extend well beyond the point where the thermodynamic quality equals unity.
- The wall heat-flux has been replaced by the surface-temperature as an independent parameter. This change was needed because (i) in safety analysis the surface-temperature rather than heat flux is the independent parameter, and (ii) the surface-temperature uniquely defines the heat-transfer mode (see also section 3.1).
- The new look-up table is based only on fully developed film-boiling data.
- A finer subdivisions has been used resulting in a much larger number of table entries and less error due to interpolation.
- The method for smoothing the data in the look-up table (to remove unrealistic fluctuations) has been enhanced.
- Table entries, at flow conditions where no data are available, are based on the best of five selected film-boiling prediction methods.

In this paper the expanded database of the table, the stages of the development of this new table, and its final form are described. This paper presents also a comparison of the predictive capability of the look-up table and that of several leading prediction methods vis-à-vis the extensive film-boiling database compiled at the University of Ottawa.

2.0 DATA BASE

2.1 General

Earlier film-boiling look-up tables by Leung et al. (1996, 1997) had access to approximately 20,000 film-boiling data of which 14,687 were used for the development of the PDO-LW-96 look-up table. Since then thousands of additional data have become available. The current film-boiling data bank compiled at the University of Ottawa is the largest known film-boiling database available anywhere and is described in detail by Vasic' et al. (2000). It currently contains over 77,000 data points obtained in water-cooled vertical tubes. The majority of these PDO heat-transfer data have not been used for the development of the earlier PDO-LW-96 film-boiling look-up table. These data have been scrutinized carefully prior to adding them to the University of Ottawa film-boiling database, Vasic' et al. (2000). Sources of uncertainty beyond the usual measurement uncertainties were identified. The most common additional uncertainties are due to (i) not including the impact of the variation of test section tube resistivity with temperature for resistance-heated test sections (this is especially important for stainless steel tubes where the temperature coefficient of resistance is significant), and (ii) extracting temperatures directly from graphs provided in the reports or papers. In addition many of the data were obtained in the "developing film boiling" region, where some or most of the heat transferred from the wall is used for increasing the vapour superheat, rather than for evaporation of the liquid.

2.2 Data Screening

Many of the data in the data bank are questionable and were not used for the development of the new look-up table. Reasons for rejecting data or qualifying them as "secondary data" are listed below:

- The data within a given data set displays significant scatter and do not follow a smooth trend. This suggests the presence of unstable flow conditions or the employment of an inferior measurement technique;

- At locations near the inlet, outlet or hot patch, the temperature distribution suddenly changes. This is usually due to significant axial conduction due to the presence of a nearby heat source or heat sink, e.g. (i) copper power terminals (clamped to the test section) with large power cables, (ii) a high contact resistance (poor electrical contact) of the power terminals, which can result in additional local heat generation, or (iii) a high-temperature hot-patch;
- The data demonstrate some obvious inconsistencies, i.e. dryout qualities > 1.0, or reported local quality or outlet qualities that cannot be reproduced from a simple heat balance;
- Significant liquid-wall interaction takes place because the temperature of the wall is below the minimum film-boiling temperature, e.g. $T_w - T_{sat} < 50$ and/or $T_w < T_{mfb}$; Such data are representative of the transition boiling regime;
- Data obtained at roughly similar conditions do not result in similar film-boiling temperatures;
- The experimenter provided inadequate documentation, e.g., (i) no error analysis, (ii) no correction to the heat-flux due to heat-loss, (iii) the dryout quality or the quench front location were not reported (e.g., Bishop et al. (1965));
- Only the maximum film-boiling temperatures measured along the tube surface were reported (e.g. Bailey and Lee (1969) tabulated only the maximum wall temperatures, while all other temperatures were presented in graphical form);
- The data were reconstructed from graphs;
- The data were obtained in the developing film-boiling region and are strongly dependent on the location where CHF occurred;
- The flow conditions were outside the range of the look-up table.

To track the qualifications associated with each data point, an axial-temperature-distribution index J was added to each data entry. Table 1 below provides the definitions of index J. A graphical illustration of the differences in film-boiling data based on the J-value is shown on Figure 1. The basic definition is the same as was initially used by Leung and Groeneveld (1985); it is expanded to cover the additional cases covered by the enlarged database.

Note that if the quality at dryout, X_{do}, is unknown, it will be evaluated from the CHF look-up table (Groeneveld et al., 1996) for a given D, P, G and q, and the J-index is changed from J = 1 to 5 to J = 11 to 15. This permitted the inclusion of the data sets by Doerffer (1997), Miropolskiy (1962) and Subbotin et al. (1973) into the database.

3.0 TABLE DERIVATION

3.1 Choice of Independent Parameters

The film-boiling look-up table is considerably more complex than the CHF look-up table (Groeneveld et al., 1996): the CHF look-up table is based on three independent parameters, $CHF = f(P, G, X_{th})$, while the film-boiling look-up table has at least four independent parameters. The previous film-boiling look-up tables were all based on $h = f(P, G, X_{th}, q)$. The choice of the heat-flux q as an independent parameter was considered logical as q was normally independently controlled during experiments. However in safety analysis of reactor cores or other heat-transfer equipment, the temperature is generally known or evaluated from the previous time step and the heat-flux q is the unknown parameter. In addition the boiling curve demonstrates that if $q_{mfb} < q < q_{CHF}$ then three heat-transfer modes are possible (see Fig. 2) of which only one is film boiling (at point C). Hence it was decided to replace the heat flux q by wall superheat $(T_w - T_{sat})$ as the independent parameter in the current version of the look-up table.

In two-phase flow, upstream history is considerably more important than in single-phase flow. This is particularly true for the region just beyond the CHF location where film-boiling heat-transfer is "undeveloped" and the vapour superheat increases. Eventually the vapour superheat becomes fully developed and at this point there will be a balance between the heat-transfer from the wall to the vapour, and the heat transfer from the vapour to the liquid. In practice this point corresponds to a maximum in the axial temperature profile (Köhler and Hein (1986) e.g. see J = 2 in Figure 1). Hence for the developing film-boiling region an additional parameter is needed, which is related to the film-boiling length or $(X_{th} -$

X_{do}). *Since* such parameter is particularly difficult to evaluate during safety transients, it was decided to concentrate our efforts on first deriving a look-up table for fully developed film-boiling and treat the developing region as a special case for which the fully-developed film-boiling look-up table represents a logical upper limit in wall temperature.

3.2 Range of the Film Boiling Look-up Table

The updated film-boiling look-up table covers water flow conditions relevant to reactor safety analysis. The range of these flow conditions are: pressure from 0.1 to 20 MPa, mass-flux from 0 to 7 Mg m^{-2} s^{-1}, thermodynamic-quality from –0.2 to 2.0 and wall superheat (T_w – T_{sat}) from 50 to 1200 K. The subdivisions over the range of these parameters were selected to reduce the uncertainty introduced by the linear-interpolation procedure but at the same time minimize the size of the look-up table. The corrected film-boiling look-up table tabulates the overall heat-transfer coefficient (including conduction, convection and radiation) for the following conditions:

Pressure: 100, 200, 500, 1000, 2000, 5000, 7000, 9000, 10 000, 11 000, 13 000, 17 000, 20 000 kPa;
Mass flux: 0, 50, 100, 200, 500, 1000, 1500, 2000, 3000, 4000, 5000, 6000, 7000 kg m^{-2} s^{-1};
Thermodynamic quality: -0.2, -0.1, -0.05, 0.0, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0;
Wall superheat: 50, 100, 200, 300, 400, 500, 600, 750, 900, 1050, 1200K.

The look-up table is thus a four-dimensional matrix and contains 29,744 entries for the heat-transfer coefficient.

3.3 Methodology

The updated film-boiling look-up table was developed following a similar method used by Leung et al. (1996) in deriving the PDO-LW-96 film boiling look-up table derivation. Their approach creates first a "skeleton" table of heat-transfer coefficients at discrete values of pressure, mass-flux, thermodynamic quality and heat flux, based on predictions from a leading model and correlation. Leung et al. used the Hammouda model (Hammouda, 1995) for the IAFB region at low void fractions ($\alpha < 0.5$), the Groeneveld-Delorme (1976) correlation for DFFB region at high void fractions ($\alpha > 0.8$) and a linear interpolation between the two for $0.5 > \alpha > 0.8$. Their table values were initially based on an 8 mm diameter tube and were subsequently "updated" using experimental data. Finally the table was smoothed using various spline functions.

In the present approach the following steps were taken:

<u>A. Creation of a New Skeleton Table for an Expanded Film-boiling Look-up Table.</u>
Five preliminary skeleton tables containing heat-transfer coefficients *($h = f(P, G, X_{th}, Tw\text{-}Tsat)$)* were created based solely on the following models or correlations:

1. The Groeneveld-Delorme (1976) equation has been used for thermodynamic qualities > 0.0. This equation was derived based on the data sets available 28 years ago. Since then many more data have become available which have caused this equation to become somewhat dated.

2. The Köhler-Hein (1986) model is a semi-empirical model based on an energy balance between phases. The model assumes that a thermal non-equilibrium develops between the liquid and vapour phase downstream of the dryout location. This non-equilibrium will eventually reach a maximum at a given point: beyond this point the thermal non-equilibrium is considered "fully developed" and the wall and vapour temperature no longer depend on the CHF quality. This point is characterized by a maximum wall-temperature or a minimum heat-transfer coefficient as was shown in Figure 1. The main contributions of the Köhler-Hein model are: the predictions of (i) the boundary of the fully developed non-equilibrium region and (ii) the vapour temperature in the fully developed region. After the vapour temperature has been found, the wall temperature can be calculated using Gnielinski (1976) equation for single-phase flow. To determine the boundary of the fully developed non-equilibrium region, X_{do} is required.

The recommended parameter ranges are

P: > 3000 kPa;
G: > 300 kg m^{-2} s^{-1};
X_e: > 0.2

3. The IAFB model by Hammouda (1995) is a robust model that predicts the axial variation of all flow parameters using relatively few assumptions. It was tested thoroughly against experimental data of various fluids. It may be used for a homogeneous void-fraction α_{hom} less than 0.5.

$$\alpha_{hom} = \frac{x_e \rho_f}{x_e \rho_f + (1 - x_e) \rho_f} \quad (1)$$

4. The Chen-Chen (1998) method uses a tabular method to find the thermal non-equilibrium factor k. Plummer's (1974) equation was adopted to represent the degree of thermal non-equilibrium, defined as

$$k = \frac{x_a - x_{do}}{x_e - x_{do}} \quad (2)$$

The tabulation of k by Chen-Chen was based on their data bank, which includes vapour temperature measurements. Knowing the actual quality (X_a), the heat-transfer coefficient was calculated using a method similar to the one used in the Shah-Siddiqui (2000) model. In the Chen-Chen model, the convection heat-transfer coefficient for pure steam was calculated with their own correlation (Chen-Chen, 1996). The independent parameters of the Chen-Chen model are: thermodynamic quality (X_{th}) and the critical quality (X_{do}). Chen-Chen's method covers the following ranges:

P: 100 - 5800 kPa;
G: 23 - 1462 kg m^{-2}s^{-1};
X_{th}: 0 - 1.36.

Some extrapolation beyond these ranges was permitted, as the non-equilibrium is known to disappear at high flows.

5. The Shah-Siddiqui (2000) model is basically an updated version of the Shah (1980) graphical approach, using equations instead of graphs. To evaluate the non-equilibrium, the actual quality (X_a) was first predicted from empirical correlations. The vapour temperature was then determined, and the wall temperature was subsequently calculated by assuming pure convective heat-transfer between the heated wall and the superheated vapour. The Dittus-Boelter (1930) equation and the Hadaller-Banerjee (1969) equation were used to evaluate the vapour single-phase heat-transfer coefficient.

Four input parameters were required for this method: Boiling number *(Bo)*, Froude number *(Fr)*, equilibrium quality (X_{th}) and critical quality (X_{do}). The prediction method was applied to several fluids and provided credible results over a wide range of conditions. The recommended range of application for film boiling in water-cooled tubes is:

P: 100 – 21500 kPa;
G: 4 – 5176 kg m^{-2}s^{-1};
D: 1.1 – 24.3 mm;
X_{th}: 0.1 – 2.4.

The Shah-Siddiqui model, Chen-Chen model and Köhler-Hein model all depend on the critical quality (X_{do}). The impact of X_{do} disappears in the fully developed film-boiling region. To minimize the dependence on X_{do} and make the skeleton tables more representative of fully developed film boiling conditions, the tables were generated for $X_{do} = 0$. The required steam-water properties for predictions at temperatures less than 1,000℃ were evaluated using NIST/ASME property code, Harvey et al. (1997), and for temperatures greater than 1,000℃ using UO High Temperature property code, Vasic' (1993), Vasic' et al. (1992).

Each of the skeleton tables was divided into 64 sub-regions, based on intervals of pressure, mass flux and quality or void fraction. Subsets of experimental heat-transfer coefficients, corresponding to the conditions of each sub-region, were compared with the prediction of each of the above models and the rms and average errors were tabulated. The model that gave the best prediction in a specific sub-region was subsequently selected to evaluate the heat-transfer coefficients for that specific sub-region of the final skeleton table.

The skeleton table values must also satisfy an additional condition that it is at least equal to the heat-transfer coefficient for laminar flow of the vapour.

$$h_{table} = Max\left(h_{model},\ 4.3636\frac{k_{vf}}{D} \right) \tag{3}$$

The vapour-film properties were evaluated at the vapour-film temperature defined as

$$T_{vf} = \frac{T_W + T_{bulk}}{2} \tag{4}$$

where

$T_{bulk} = T_{sat}$ for $X_{th} \le 1$, and
$T_{bulk} = T_{v,eq}$ for $X_{th} > 1$.

The final skeleton table was used as the basis for the development of the look-up table for fully developed film boiling.

B. Manual Smoothing of the Skeleton Look-up Table.
The table generated from the above procedure contains values from different model predictions. Sharp transitions between values predicted with different models need to be removed. After visual inspection, some manual smoothing was applied at a few conditions.

C. Updating of the Skeleton Table with Experimental Data.
To improve the prediction accuracy of the film-boiling look-up table, the skeleton table values were modified using the data bank compiled by the University of Ottawa. Only fully developed film-boiling data from the data bank (J=2-5 and J=12-15) were used in the updating process. Section 2.3 described the selection process that was used to select 21,116 fully developed film-boiling data from a database containing a total of 77,234 data points.

The selected data were normalized with respect to the reference table diameter of 8 mm by applying the diameter correction factor proposed by Groeneveld et al. (1999):

$$\frac{h_{table}}{h_{\exp}} = \left(\frac{8}{D_{\exp}} \right)^{-0.2} \tag{5}$$

Subsequently the process of correcting the table entries was started. The basic premise is that each experimental data point affects the 16 (=2^4) adjacent look-up table entries. For example experimental point $h_{P,\ G,\ X,\ Tw\ -\ Tsat}$ affects the table entries at the adjacent matrix conditions; pressure $P_i < P < P_{i+1}$, mass flux $G_j < G < G_{j+1}$, quality $X_k < X < X_{k+1}$ and wall superheat $(T_w - T_{sat})_l < (T_w - T_{sat}) < (T_w - T_{sat})_{l+1}$. The data point closest to a look-up table matrix condition will be given the highest weight. After being given the appropriate weight and after adjusting for local gradients all experimental data surrounding a single table entry (e.g. all data falling within the range P_{i-1} to P_{i+1}, G_{j-1} to G_{j+1}, X_{k-1} to X_{k+1} and wall superheat $[T_w - T_{sat}]_{l-1}$ to $[T_w - T_{sat}]_{l+1}$) were used in a statistical averaging process to obtain a new empirically-derived table entry. Next, the new table was used for predicting the fully developed film-boiling heat-transfer coefficients for the complete database and the rms and average error were evaluated.

D. Four-Dimensional Smoothing of the Updated Table.

The table generated from the above procedure is partially based on experimental data and partially on values from model predictions. This will result in unwanted fluctuations in the look-up table values, e.g. the variation of h vs. X for constant P, G and $T_w - T_{sat}$ can be highly irregular with various spikes or discontinuities. To remove unwanted fluctuations in the table values, the four-dimensional table-smoothing method by Huang and Cheng (1992) was initially employed. For each table entry the smoothing procedure fits a curve through the six adjacent values in the pressure, mass flux, quality and wall superheat direction, and replaces the original table value for that entry with a new value that has been adjusted to partially reflect the smoothing process. To further reduce fluctuations in table values, steps C and D were repeated several times. The rms and average error were evaluated after completing each stage. This process was completed after the look-up table was updated with experimental data and smoothed three times (in an effort to derive an even smoother table this process is currently being modified, see section 5.0). The errors after each step are recorded in Table 2.

As a final check 3-D plots of the look-up table were produced. As can be seen from the six 3-D graphs presented in Figure 3, the parametric trends (i.e. h vs. p, G, X or T_w-T_{sat}) of the film-boiling look-up table have become reasonably smooth.

3.4 Final Film Boiling Look-up Table

A section of the present film-boiling look-up table is shown in Table 3. The complete look-up table containing 29,744 table values for the heat-transfer coefficient at the flow conditions listed in Section 3.2, can be accessed via the internet (http://www.magma.ca/~thermal/).

Three levels of shading have been applied to highlight regions of uncertainty. The un-shaded table entries represent areas that are derived directly from the experimental data and hence their uncertainty is least. The lightly shaded (yellow) regions represent calculated values based on the prediction from the selected prediction methods found to give superior predictions at neighboring conditions. The uncertainty in this region depends on the level of extrapolation from regions where data are available. It is expected to be smaller at conditions slightly beyond the range of data but becomes larger as the extrapolation is further beyond this range. The heavily shaded (red) regions represent predictions that are often impossible to obtain. They include; (i) conditions where critical flow may exist, (ii) conditions where the expected vapour superheat is higher than the wall superheat ($T_v - T_{sat} > T_w - T_{sat}$), (iii) conditions where the bulk temperature is lower than zero, solid phase ($T_{bulk} < 0$) and (iv) conditions where the wall temperature is lower than the minimum stable film-boiling temperature ($T_w < T_{mfb}$). These heavily shaded entries are included only to improve interpolation accuracy of the lightly shaded regions. Extrapolation into the heavily shaded regions should be avoided.

4.0 PREDICTION ACCURACY

4.1 General

The prediction accuracy of the look-up table was assessed by comparing the predicted and experimental heat-transfer coefficients. The predicted heat-transfer coefficient was calculated as

$$h_{pred} = h_{table}\left[P, G, X, (T_w - T_{sat})\right]\left(\frac{0.008}{D}\right)^{0.2} \qquad (13)$$

The experimental heat-transfer coefficient was calculated as

$$h_{\exp} = \frac{q}{T_w - T_{bulk}} \tag{14}$$

(Note that $T_{bulk} = T_{sat}$ for $X_{th} < 1$.)

In the comparison, the average error for the data set is defined as

$$Avg\ Error = \frac{1}{n}\sum_{i=1}^{n}(Error)_i \tag{15}$$

The Root-mean-square (rms) error for the data set is defined as

$$Rms\ Error = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Error)_i^2} \tag{16}$$

where n is the total number of data and the error is

$$Error = \frac{h_{pred}}{h_{\exp}} - 1 \tag{17}$$

4.2 Comparison With Fully-Developed Film-Boiling Data

Table 4 compares the Rms and average errors of the two film-boiling look-up tables (the new look-up table and the heat-flux-based look-up table PDO-LW-00, Rudzinski et al. (2001)), and the errors of leading film-boiling models or equations (Shah-Sidiqui (2000) model, Chen-Chen (1998) model, Hammouda (1995) model, Köhler-Hein (1986) model, Groeneveld-Delorme (1976) correlation, Dougall-Rohsenow (1963) correlation and Miropolskiy (1963) correlation) using only the fully developed film-boiling data points. All models are applied for data points with X >0 except for the Hammouda (1995) model which was applied to X < 0.1 only. The large rms error of the selected prediction methods is primarily due to the fact that none of these methods can be applied universally to all conditions. The new look-up table approach appears to be the only method available that provides a credible prediction over a wide range of conditions as is demonstrated by the significant improvement in prediction accuracy over the other prediction methods tested.

In total about 20,785 data points from 36 data sets were used in the error assessment. A comparison of the errors for the prediction methods of Table 4 for each individual data set was also made. For nearly all the data sets, the temperature-based film-boiling look-up table again provided the lowest Rms and average error.

4.3 Discussion

An examination of the error distribution of for the present look-up table for fully developed film boiling showed that 96.3% of experimental data points are predicted in the range of ±20%, 91.8% of ±15%, 81.7% of ±10% and 60.1% of ±5%. The distribution of the prediction-error with respect to various flow parameters was also examined: no clear systematic trend could be identified although the error appears higher at low flows, high pressures, low heat flux levels and low wall superheats. The look-up table should not be extrapolated to temperatures less than the minimum film boiling temperatures (T_{MFB}). For the wall temperature range $T_{CHF}<T<T_{MFB}$, which corresponds to transition boiling, the approach recommended by Groeneveld and Snoek (1986) should be followed:

$$\frac{q_{TB}}{q_{MFB}} = \left(\frac{CHF}{q_{MFB}}\right)^m \quad \text{where} \quad m = \frac{\ln\left(\frac{T_{MFB} - T_{sat}}{T - T_{sat}}\right)}{\ln\left(\frac{T_{MFB} - T_{sat}}{T_{CHF} - T_{sat}}\right)} \tag{18}$$

This will ensure the correct asymptotic trends at low wall superheats. Note that the prediction error is independent from the film-boiling length or $(X - X_{do})$, which was expected since only fully developed film-boiling data were used in the look-up table development.

5.0 CONCLUSIONS, RECOMMMENDATIONS AND FINAL REMARKS

This paper described the development of a temperature-based film-boiling look-up table. As a basis for developing this table, 20,785 film boiling data points were carefully selected from the film boiling data bank compiled by the University of Ottawa. These data were all believed to be obtained in the fully developed film-boiling region. A comparison of the fully developed film-boiling look-up table with the fully developed film-boiling database (20,785 data points) shows an overall rms error in heat-transfer coefficient of 10.58% and an average error of 1.71%. The corresponding errors of the previous heat-flux controlled look-up table are: 20.65% rms and 6.87 % average error.

A comparison of the prediction accuracy of the look-up table with other leading film-boiling prediction methods clearly demonstrates the superiority of the present look-up table.

Look-up tables have been used in safety analysis codes such as RELAP, CATHARE, ASSERT and CATHENA. One potential concern is the smoothness of the look-up table: irregular trends of the heat transfer coefficient vs. flow, quality, wall superheat or pressure can lead to convergence problems. The main cause of the irregular trends is the discontinuities of the skeleton table that was based on different models, and imposes a strong weight factor on the table points, especially at conditions where experimental data are scarce. These discontinuities become very noticeable when plotting the heat transfer coefficient against the independent variables. The smoothing approach developed by Huang and Cheng (1992) was initially applied but this may not mitigate the effect of these discontinuities sufficiently. Improvements to the smoothing approach are currently being made at the University of Ottawa to reduce these irregularities. To quantify the smoothness an expression for the smoothness index was derived. The net effect of a smoother table is a decrease in prediction accuracy. This can be partially balanced by using a table with greater subdivisions, which will reduce the error introduced by interpolation between table values.

The film boiling look-up table is based on fully developed film-boiling data obtained in vertical round tubes (normalized to an 8mm ID tube) cooled by light water at steady state conditions. The results may be applied to other configurations and fluids provided appropriate correction factors and scaling laws are applied, e.g. see Groeneveld et al., 1999, and Groeneveld et al., 1997.

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REFERENCES

Bailey N.A. and Lee D.H. (1969), An Experimental and Analytical Study of Boiling Water at 2000 to 2600 psi, Part I: Dryout and Post-Dryout Heat Transfer, AEEW - R 659.

Bishop A.A., Sandberg R.O. and Tong L.S. (1965), Forced Convection Heat Transfer at High Pressure After the Critical Heat Flux, ASME-65-HT-31.

Chen Y. and Chen H. (1998), A Tabular Method for Prediction of the Heat Transfer During Saturated Film Boiling of Water in a Vertical Tube, Proc. of 11th Int. Heat Transfer Conf., Korea, Aug. 23-28.
Chen Y., Xu H. and Chen H. (1996), Experimental Results of Steady-State Film Boiling of Forced Flow Water, China Institute of Atomic Energy, Beijing, China, Presented at 2nd Research Coordinated Meeting of IAEA, CRP on Thermalhydraulic Relationships for AWCR, Vienna.
Chen Y. and Chen H. (1996), Forced convection heat transfer to steam in tubes with different diameters, Chinese J. Engineering Thermophysics, Vol. 17, pp. 107-110.
Dittus F.W. and Boelter L.M.K. (1930), Heat Transfer in Automobile Radiators of the Tubular Type, Univ. of California Pub. In Eng., Vol. 2, No. 13, pp. 443-461, reprinted in (1985), Int. Comm. Heat Mass Transfer, Vol. 12, pp. 3-22.
Doerffer S. (1997), AECL, unpublished data, private communication.
Dougall R.S. and Rohsenow W.M. (1963), Film Boiling on the Inside of Vertical Tubes with Upward Flow of Fluid at Low Qualities, MIT-TR-9079-26.
Gnielinski V. (1976), New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow, Int. Chem. Eng., Vol. 16, No. 2, pp. 359-368.
Groeneveld D.C. and Leung L.K.H. (2000), Evolution of CHF and Post CHF Prediction Methods, Invited paper, #8626 Proceedings, *ICONE-8*, Baltimore USA, April
Groeneveld D.C., Leung L.K.H., Zhang J., Cheng S.C. and Vasic' A. (1999), Effect of Appendages on Film-Boiling Heat Transfer in Tubes, Proceedings of Ninth International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-9), San Francisco, California, October 3-8, Log #235, 17 pages.
Groeneveld,D.C., Doerffer, S.D., Tain, R.M., Hammouda, N., and Cheng, S.C., 1997,"Fluid-To-Fluid Modelling Of The Critical Heat Flux And Post-Dryout Heat Transfer",Proceedings, 4th World Congress on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Brussels, Vol 2, pp 859-867, June 2-6
Groeneveld D.C., Leung L.K.H., Kirillov P.L., Bobkov V.P., Smogalov I.P., Vinogradov V.N., Huang X.C. and Royer E. (1996), The 1995 Look-Up Table for Critical Heat Flux in Tubes, Nucl. Eng. Des., 163, 1-23.
Groeneveld D.C. and Delorme G.G.J. (1976), Prediction of Thermal Non-Equilibrium in the Post-Dryout Regime, Nucl. Engng. Design, Vol. 36., pp. 17-26
Groeneveld D.C. and Snoek, C.W. (1986), A Comprehensive Examination of Heat Transfer Correlations Suitable for Reactor Safety Analysis, Multiphase Science and Technology, Volume II, pp 181-274.
Hadaller G. and Banerjee S. (1969), Heat Transfer to Superheated Steam in Round Tubes, AECL, WDI-147.
Hammouda N. (1995), Subcooled Film Boiling in Non-Aqueous Fluids, Ph. D. thesis, Univ. of Ottawa, Ottawa, Canada.
Harvey A.H., Peskin A.P. and Klein S.A. (1997), NIST/ASME Steam Properties, Version 2.1, NIST Standard Reference Database 10, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, Maryland.
Huang X.C. and Cheng S.C. (1992), A Simple Method for Smoothing Multi-Dimensional Experimental Data with Application to CHF and Post-CHF Tables, Numerical Heat Transfer, Part A: Applications.
Kirillov, P.L., Smogalev, I.P., Ivacshkevitch, A.A., Vinogradov, V.N., Sudnitsina, M.O., Mitrofanova, T.V. (1996), The Look-Up Table for Heat Transfer Coefficient in Post-Dryout Region for Water Flowing in Tubes (the 1996-Version), Preprint FEI-2525, Institute of Physics and Power Engineering, Obninsk, (Rus.).
Köhler W. and Hein D., (1986), Influence of the wetting state of a heated surface on heat transfer and pressure loss in an evaporator tube, Report NUREG/IA-0003.
Leung L.K.H., Hammouda N. and Groeneveld D.C., (1997), A Look-up Table for Film-Boiling Heat Transfer Coefficients in Tubes with Vertical Upward Flow, Proceedings of the 8th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-8), Kyoto, Japan, Sept. 30–Oct. 4.
Leung L.K.H., Hammouda N. and Groeneveld D.C., (1996), Development of a Look-Up Table for Film-Boiling Heat Transfer Covering Wide Range of Flow Conditions, Proceedings of the 5th International Conference on Simulation Methods in Nuclear Engineering, September 8-11, Montreal, Canada, Vol. II, 1996.
Leung L.K.H. and Groeneveld D.C. (1985), Tabulation of Experimental Tube Post-Dryout Data for Water, AECL internal report APRP-TD-17.
Miropolskiy Z.L. (1963), Heat Transfer at Film Boiling Steam-Water Mixture in Tubes, Teploenergetika, No 5, pp. 49-52 (Rus.).

Miropolsky Z.L. (1962), Investigation of Temperature Conditions of Steam Generating Surfaces, (In Russian), RUENIN Institute, Dissertation.
Plummer D.N. (1974), Post-Critical Heat Transfer to Flowing Liquid un a Vertical Tube, Ph.D. Thesis in Mech. Eng., M.I.T., May.
Rudzinski K.F., Vasic' A..Z., Leung L.K.H. and Groeneveld D.C. (2001), A Revision of the Post-Dryout Table for Fully-Developed Film-Boiling Heat-Transfer Coefficients (PDO-LW-00), AECL Report COG-00-192/FFC-FCT-313.
Shah M. M. and Siddiqui M.A., (2000), A general correlation for heat transfer during dispersed-flow film boiling in tubes, Heat Transfer Engineering v.21, pp. 18-32.
Shah M. M. (1980). A general predictive technique for heat transfer during saturated film boiling in tubes, Heat Transfer Engineering 2, pp. 51-62.
Subbotin V.I., Remizov O.V. and Vorobiev V.A. (1973), Temperature Regimes and Heat Transfer in the Region of Degraded Heat Transfer, (In Russian), IPPE Institute, J., TVT, 11, 6, 73.
Vasic' A.Z., Cheng S.C., Renon O., Guo Y.J. and Antoshko Yu. (2000), Compilation and Assessment of Post-Dryout Heat-Transfer Data Sets, Report No. UO-MCG-TH-2000-008, 39 pages, prepared for AECL, November.
Vasic' A.Z. (1993), High Temperature Properties and Heat Transfer Phenomena for Steam at Temperatures up to 5000K, M.A.Sc. thesis, Univ. of Ottawa, Ottawa, Canada.
Vasic' A., Cheng S.C. and Groeneveld D.C. (1992), A Comparison of Predictions of High-Temperature Steam Properties, Nucl. Eng. Des., Vol. 132, No. 3, pp. 367-379.

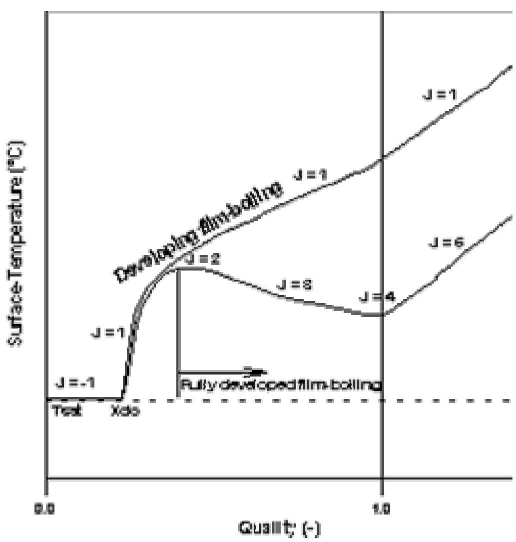

Figure 1 Schematic representation of J-Index

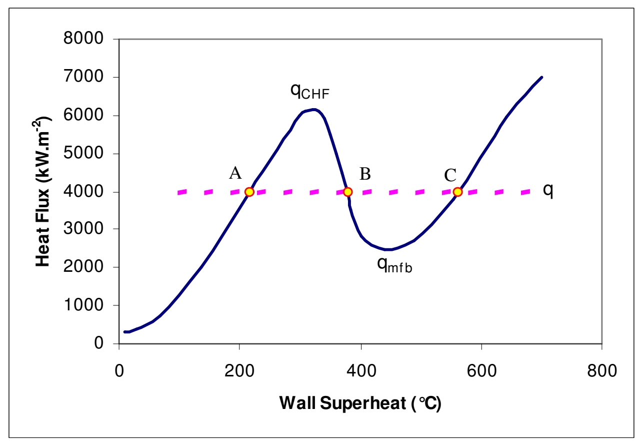

Figure 2 Boiling Curve

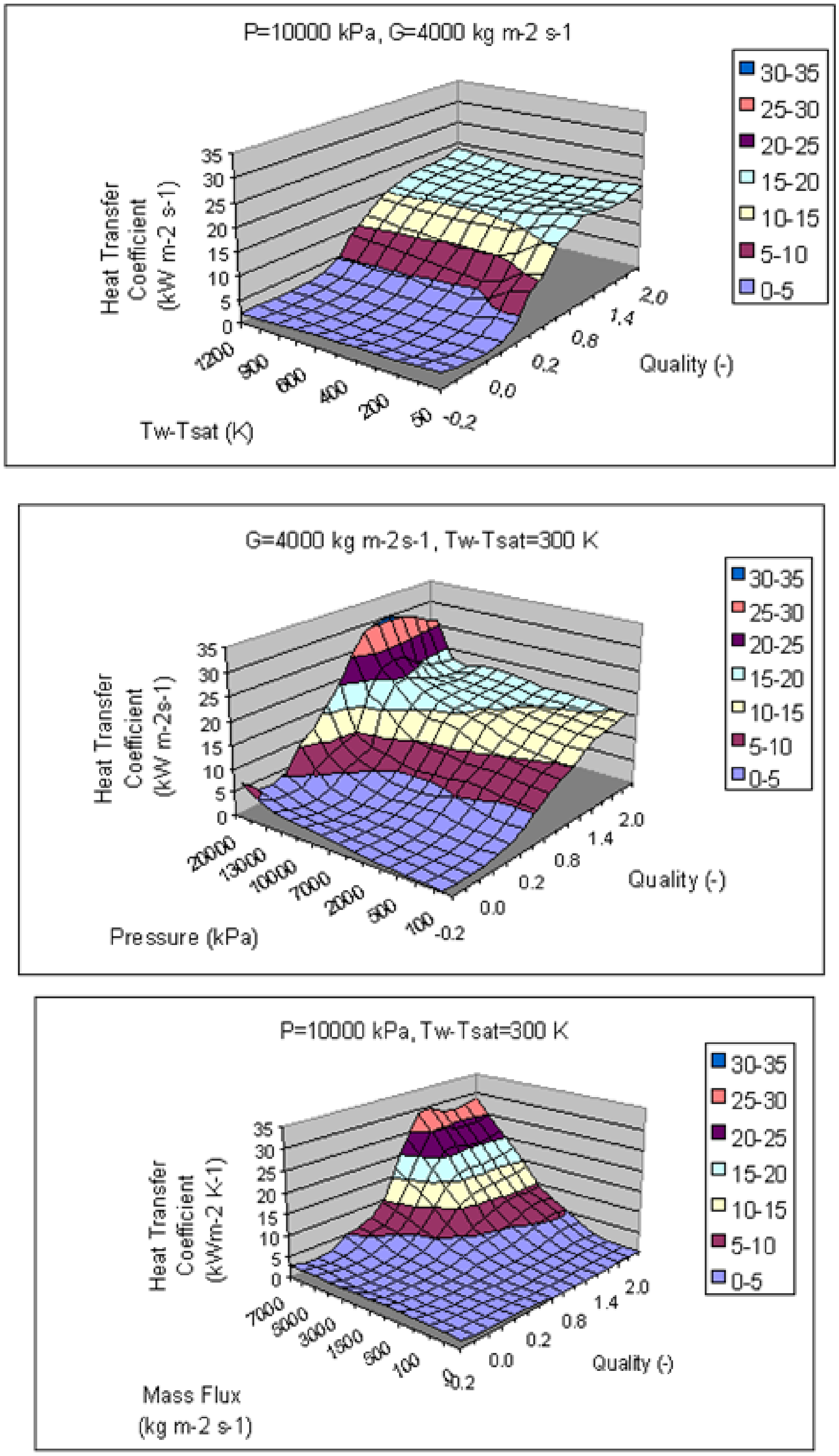

Figure 3a Variation of PDO Heat-Transfer Coefficient with Pressure, Mass-Flux, Quality and Wall-Superheat

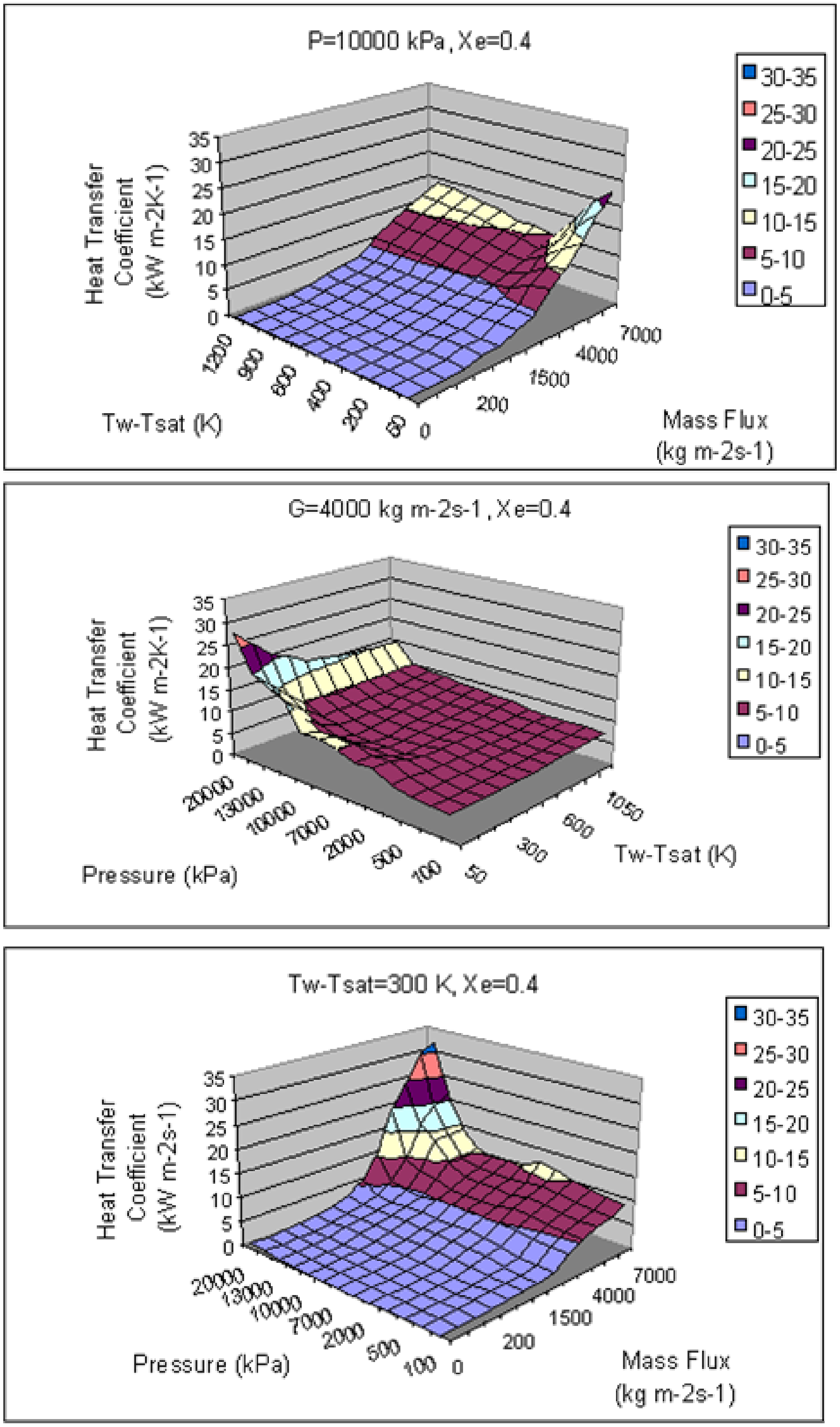

Figure 3b Variation of PDO Heat-Transfer Coefficient with Pressure, Mass-Flux, Quality and Wall-Superheat

Table 1 Values and Definitions of the Axial-Temperature-Distribution Index J

Direct Heating				Indirect Heating	Definition
Long tube		Hot-patch and tube			
Exp. X_{do}	Calculated X_{do}	Copper Block	Notch in Tube Wall		
-1	-10	-20	-30	-40	Pre-CHF temperatures or CHF temperature.
0	10	20	30	40	Information about temperature trend is not available.
1	11	21	31	41	Temperature increases after CHF (may extend to Xe>1.0).
2	12	22	32	42	Temperature reaches a maximum.
3	13	23	33	43	Temperature decreases after reaching maximum.
4	14	24	34	44	Temperature reaches a minimum at Xe $\geq$ 1.0.
5	15	25	35	45	T increases after Xe > 1.0 (superheated steam) following J=4.
-	-	26	36	-	Temperature decreases after hot patch.
9	19	29	39	49	Suspicious data, not recommended for use.

Table 2 Prediction Errors of the Film-Boiling Look-up Table at Various Stages of Table Development

STAGE	DESCRIPTION	DATA USED	ERROR (%)	
No.		Number	Avr.	Rms.
1	LUT formed by combination of five correlations/models: Groeneveld-Delorme (1976), Köhler-Hein (1986), Hammouda (1995), Chen-Chen (1998) and Shah-Siddiqui (2000).	-	3.98	21.52
2	Manual and visual smoothing	-	6.81	22.87
3	Updating of the LUT with data	21,131	1.30	9.82
4	4-D smoothing in decimal scale	-	2.24	10.98
5	4-D smoothing in log scale	-	1.68	10.41
6	Updating of the LUT with data	21,131	1.31	9.95
7	4-D smoothing in log scale	-	1.71	10.55
8	Manual and visual smoothing	21,131	1.71	10.56

Table 3 Section of the Film Boiling Look-up Table

P (kPa)	G (kg $m^{-2}s^{-1}$)	Xe (-)	T_w-T_{sat}= 50K	100K	200K	300K	400K	500K	600K	750K	900K	1050K	1200K
			Heat Transfer Coefficient (kW $m^{-2}K^{-1}$)										
10000	3000	-0.20	3.102	3.069	2.990	2.917	2.816	2.740	2.647	2.541	2.437	2.339	2.239
10000	3000	-0.10	1.762	1.648	1.397	1.322	1.215	1.181	1.349	1.486	1.728	2.001	2.243
10000	3000	-0.05	1.471	1.391	1.252	1.176	1.119	1.095	1.253	1.343	1.551	1.781	1.997
10000	3000	0.00	1.414	1.334	1.230	1.174	1.123	1.113	1.224	1.304	1.470	1.646	1.805
10000	3000	0.05	1.714	1.648	1.557	1.533	1.508	1.554	1.584	1.628	1.661	1.709	1.725
10000	3000	0.10	2.445	2.381	2.181	2.119	2.099	2.122	2.074	2.044	2.006	2.006	1.948
10000	3000	0.20	4.086	4.055	3.376	3.004	2.949	3.030	3.018	3.029	3.042	3.105	3.089
10000	3000	0.40	8.134	7.441	5.737	4.892	4.727	5.100	5.090	5.494	5.709	5.952	6.144
10000	3000	0.60	11.253	10.486	8.513	7.135	7.007	7.337	7.439	7.790	8.061	8.342	8.618
10000	3000	0.80	12.542	12.324	11.227	10.700	10.311	10.037	9.837	9.912	10.059	10.173	10.333
10000	3000	1.00	13.404	13.108	12.320	11.992	11.692	11.599	11.465	11.481	11.622	11.735	11.887
10000	3000	1.20	13.554	13.150	12.600	12.300	12.197	12.169	12.284	12.408	12.610	12.808	13.023
10000	3000	1.40	13.346	13.232	12.974	12.810	12.752	12.655	12.686	12.803	13.011	13.215	13.449
10000	3000	1.60	13.490	13.354	13.169	12.984	12.862	12.786	12.790	12.937	13.176	13.402	13.671
10000	3000	1.80	13.803	13.697	13.483	13.276	13.099	13.005	12.982	13.140	13.409	13.652	13.952
10000	3000	2.00	14.322	14.172	13.925	13.701	13.534	13.445	13.432	13.613	13.920	14.205	14.550
10000	4000	-0.20	3.038	3.007	2.950	2.867	2.791	2.714	2.640	2.534	2.429	2.329	2.228
10000	4000	-0.10	2.247	2.140	1.832	1.776	1.682	1.697	1.840	1.917	2.000	2.089	2.162
10000	4000	-0.05	1.627	1.535	1.286	1.288	1.272	1.313	1.419	1.563	1.719	1.896	2.048
10000	4000	0.00	1.407	1.338	1.177	1.252	1.248	1.301	1.396	1.523	1.690	1.877	2.043
10000	4000	0.05	1.816	1.710	1.574	1.596	1.612	1.674	1.749	1.887	2.035	2.214	2.327
10000	4000	0.10	3.713	3.918	2.680	2.414	2.576	2.579	2.732	2.806	2.859	2.966	2.986
10000	4000	0.20	8.778	7.637	5.054	3.709	4.006	4.143	4.740	4.528	4.620	4.771	4.822
10000	4000	0.40	10.877	9.914	7.274	5.908	6.213	6.670	7.240	7.541	7.865	8.269	8.599
10000	4000	0.60	15.821	14.430	11.550	9.872	10.234	9.462	10.246	10.533	10.897	11.331	11.730
10000	4000	0.80	17.300	16.943	15.536	13.820	13.967	13.496	13.469	13.510	13.707	13.893	14.124
10000	4000	1.00	18.891	18.130	17.284	16.664	16.074	15.689	15.440	15.422	15.583	15.712	15.899
10000	4000	1.20	18.352	17.798	17.328	16.853	16.519	16.275	16.169	16.240	16.453	16.646	16.885
10000	4000	1.40	17.601	17.297	17.014	16.692	16.470	16.328	16.299	16.447	16.712	16.970	17.271
10000	4000	1.60	17.514	17.288	16.997	16.716	16.520	16.418	16.416	16.617	16.934	17.234	17.593
10000	4000	1.80	17.855	17.645	17.314	17.024	16.803	16.693	16.684	16.910	17.272	17.605	18.015
10000	4000	2.00	18.687	18.475	18.081	17.739	17.469	17.322	17.283	17.510	17.906	18.274	18.725

Table 4 Prediction Error for the Fully Developed Film Boiling Data

Prediction methods	No. of data used	Average error (%)	Rms error (%)
Miropolskiy eqn.	20,785	48.36	91.11
Dougall-Rohsenow eqn.	20,785	28.34	51.76
Groeneveld-Delorme eqn.	20,785	15.74	46.93
Kohler-Hein model	20,785	-7.63	28.61
Hammouda model	7,288	-6.19	34.65
Chen-Chen model	20,785	3.11	78.73
Shah-Siddiqui model	20,785	11.73	33.24
q-based table (PDO-LW-00)	19,095	6.87	20.65
Present T-based table (2002)	20,785	1.71	10.58