COMPARISON ANALYSIS OF CHF PARAMETRIC TRENDS IN VERTICAL TUBE AND 5x5 BUNDLE

Shumiao Wang, Jianqiang Shan[*], Bo Zhang
School of Nuclear Science and Technology, Xi'an Jiaotong University
Xi'an, Shaanxi, China
[*].jqshan@mail.xjtu.edu.cn

Xuemei Lang
CNNC Key Laboratory on Nuclear Reactor Thermal Hydraulics Technology, NPIC
Chengdu, Sichuan, China

ABSTRACT

Heat transfer is maximized at the CHF (critical heat flux) point and sharply reduced after that. CHF has a significant effect on the integrity, safety or economic efficiency of components and systems. Therefore, it's of vital importance to predict CHF accurately for given conditions. An accurate prediction of CHF requires a good understanding of physical mechanisms, parametric trends, as well as adequate experimental databases. A study on parametric trends of CHF has been carried out for water flow upward in vertical uniform heated round tubes. The study is based on the UO (University of Ottawa) database which is one of the largest tube CHF databases containing 78 data sets compiled from worldwide sources, more than 30,000 data points in all. The data in the range of conditions of practical interest is selected and unreliable data are removed according to the slice method, heat balance requirement and other screening criteria. The parametric trends of normalized CHF are explored with respect to variations in pressure, mass velocity and local quality. In addition, more than 2500 CHF experiment data points of uniform heated 5×5 bundle are picked out from Columbia University bundle CHF databases, which are used in comparison analysis of CHF trends in tube and bundle with respect to pressure, mass velocity and local quality obtained from subchannel code COBRA. It turns out that the two are largely consistent in terms of parametric trends. The research lay a solid foundation of better understanding, accurately predicting and enhancing CHF in tubes and bundle.

KEYWORDS

CHF, parametric trends, CHF database, comparison analysis

1. INTRODUCTION

The new generation of nuclear reactor requires fuel assembly with larger thermohydraulic margin and core with more uniform thermohydraulic characteristics. CHF, as a safety limit, plays a significant role in design and accident analysis of PWR (pressurized-water reactor). Thus, it's of critical important to enhance and accurately predict CHF for economics and safety.

The prediction of bundle CHF is fairly complex and difficult. Over the last five decades, the CHF phenomenon has been extensively investigated from both theoretically and experimentally mainly with the development of water-cooled nuclear reactors. Many empirical predictors have been proposed such as W-3 correlation (Tong, 1967), Columbia correlation (Reddy and Fighetti, 1983) and WRB-1 (Weisman .et

al, 1985). However, the weak points of the existing prediction approach lie in the narrow validity range and unsatisfactory accuracy outside the range. It means that further study is still needed. An accurate prediction of CHF requires a good understanding of physical mechanisms, parametric trends, as well as adequate experimental databases. Empirical correlations are usually used to predict CHF in rod bundles. In order to develop a more reliable correlation, a systematic deep research of the parametric trends of CHF with respect to main influencing factors should be developed.

The mechanism of bundle CHF remains unclear. No general agreement has been reached so far. Meanwhile, systemic analysis and study is lacking in bundle CHF parametric trends. CHF phenomenon is related with various parameters and the parametric trends are also complex. Nevertheless, CHF in vertical round tubes has been extensively investigated all over the world, resulting in over 30,000 experimental data for wide operating conditions. Some extensively used mechanistic models and empirical correlations for tube CHF have been developed, such as Weisman & Pei model (1983), Lee & Mudawar model (1988), Bowring correlation (1972) and Hall & Mudawar correlation (2000).

Firstly, the paper carried out a deep study on parametric trends of CHF for water flow upward in vertical uniform heated round tubes. The parametric trends of normalized CHF with pressure, mass velocity and local quality in tube are summarized. After that, the paper compares CHF parametric trends in vertical tubes with 5x5 bundle. The results lay a solid foundation for better understanding, accurately predicting and enhancing CHF in tubes and bundle, as well as in more flow conditions for the further research.

2. Parametric Trends of CHF in round tube

2.1. Data Preparation

The study is based on the UO (University of Ottawa) database which is one of the largest tube CHF databases containing 78 data sets for vertical tubes with upward water flow compiled from worldwide sources. Due to the particularity of CHF tests, different research institutes collect data through different channels independently. As a consequence, it leads to the existence of (i) bad data sets, (ii) bad data, (iii)data duplication, (iv) data unsatisfied the heat balance and (v) unreasonable inlet temperature . Data screening become very necessary.

Slice method needs to be introduced at first.

2.1.1. Slice method

Durmayaz et al. (2004) first proposed the slice method. The slice method assigns all the experimental data to an appropriate slice. Useful information (e.g. identification of outliers, duplicate data and bad data sets) can be obtained from an amount of experimental data through slice visual inspection and observation.

The 2006 CHF LUT (look-up table) (Groeneveld et al., 2007) which consist of 11040 entries provides CHF values at 24 pressures, 21 mass fluxes, and 23 qualities for a vertical 8mm water-cooled tube, covering the full range of conditions of practical interest. In this study, referring to the 2006 LUT matrix, the experimental data is divided into 504 pressure-mass flux, 552 pressure-dryout quality and 483 mass flux-dryout quality slices, 1539 slices in all.

Shan (2005) explained the slice method clearly. For each nominal LUT pressure matrix, $\frac{p_{k-1}+p_k}{2} < p < \frac{p_{k+1}+p_k}{2}$, and nominal mass flux matrix,

$\dfrac{G_{j-1}+G_j}{2} < G < \dfrac{G_{j+1}+G_j}{2}$, the experimental CHF values $CHF(X_0,G_0,P_0)$ pertaining to a slice of CHF vs. X for $G=G_j$ and $P=P_k$ as follows:

$$CHF(p_k,G_j,x) = CHF(p_0,G_0,x) + \Delta CHF_{j,k} \tag{1}$$

where

$$\Delta CHF_{j.k} = \frac{\partial CHF}{\partial p}(p_k - p_0) + \frac{\partial CHF}{\partial G}(G_j - G_0) \tag{2}$$

This permits us to generate the 2-dimensional graphics for $CHF = CHF(x)$ slice at $p=p_k$ and $G= G_j$. A similar approach is applied to generate the graphics for $CHF = CHF(G)$ at x_i, p_k and for $CHF = CHF(p)$ at G_j, x_i .

For the reason that the experimental data comes from tubes of different diameter, the following formula is used to account for the diameter effect.

$$\frac{CHF_D}{CHF_{D=8}} = \left(\frac{8}{D}\right)^{1/2} \tag{3}$$

Figure 1 shows an example of normalized CHF vs. x slice. Figure 2 shows how to identify a bad data set. Different colors in the figure represent different data sets. It's obvious that data set Bertoletti et al. 1964 is outliers. Experiment data in this set are influenced by intensive flow oscillation. In trend analysis, bad data sets like Bertoletti et al. 1964 is not considered.
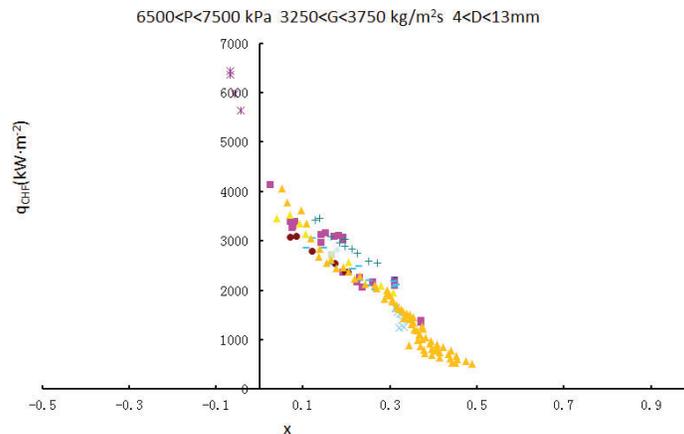
Figure 1. An Example of Slice at P=7MPa and G=3500kg/m^{2}s.
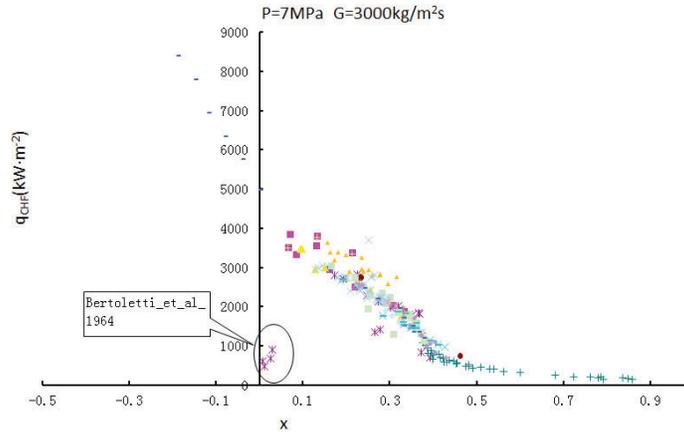
Figure 2. Bad Data Set Bertoletti et al. 1964

2.1.2. Data screening

The databases are subjected to the screening criteria identified in Table I. To ensure that the data satisfied the heat balance, the experimental data will be excluded when the relative error between reported power and calculated power is larger than 5%.

After data screening, a total of 26065 experimental data are used in the following study of parametric trends.

Table I. Data screening criteria and results

Parameter	2006 LUT screening criteria	Number of data removed due to the criteria
# of data in database	33175	
# of data sets in database	82	
D, mm	2<D<16	1948
P, kPa	100<P<21000	37
G, kg m^{-2} s^{-1}	0<G<8000	912
x	-0.5<x<1	368
Inlet temperature	>0	10
L/D, x$_{in}$<0	L/D>50 for x$_{cr}$>0, L/D>25 for x$_{cr}$<0	2214
L/D, x$_{in}$>0	L/D>100	154
Heat balance	out by >5%	619
Outliers	Outliers identified by slice method	326
"Bad" data sets removed	Bertoletti et al., 1964 ; Ladislau 1978	522
# of data accepted for the study	26065	(total of above:7710)

2.2. Parametric Trends of CHF in Tubes

The study of parametric trends of CHF in tubes in this paper is aimed to lay a foundation for bundle CHF. Therefore, by reference to the parameter range of target bundle CHF correlation, detailed analysis of an amount of slices is carried out within the range of interest: $2MPa<P<17MPa$, $1000kg/m^2s<G<5000kg/m^2s$, and $-0.2<x<0.45$.

2.2.1. CHF Trend with Pressure

By analyzing the CHF vs. P slices of experimental data of tubes, the variation trend of CHF with an increasing pressure can be summed up in three forms: monotone decrease, single peak form, or double peak form, as shown in Figure 3. Black line in Figure 3 is used only to make the trend clearer. Which form to present depends on the mass flux and quality. Usually, the first peak is located in 2-4MPa while the second peak in 16-20MPa. In addition, at a certain mass flux, with quality increase the variation trend of CHF over pressure presents monotone decrease, single peak form and double peak form in turns.

(a) monotone decrease

(b) single peak

(c) double peak
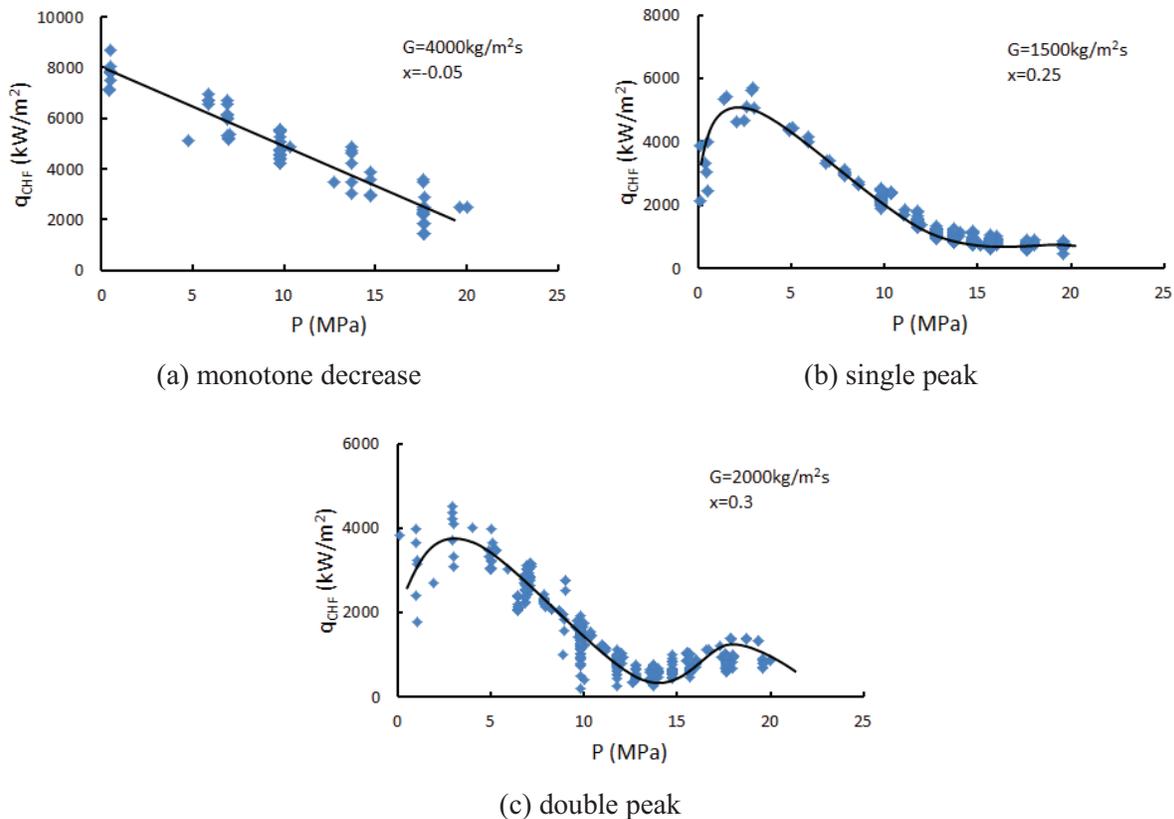
Figure 3. CHF Trend with Pressure

Table II shows the detailed CHF trend with pressure in the parameter range of interest.

Table II. CHF Trend with Pressure

G\x	-0.2	-0.15	-0.10	-0.05	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45
1000			2	2	2		2			2	2	2	3	3
1500			2	2	2				2	2	2	3	3	3
2000		2	2	2	2		3	3	3	3	3	3	3	3
2500			2				3	3	3	3	3	3	3	3
3000		1					3	3	3	3	3	3	3	3
3500		1					3	3	3	3	3	3	3	
4000				1			3	3	3	3	3	3		
4500		1	2	2				3			3			
5000		1	1	2	2	3	3	3	3	3	3	3		

1-monotone decrease, 2-single peak, 3-double peak, Blank-lack of experimental data
G: kg/m^2s

2.2.2. CHF Trend with Mass flux

When pressure and quality is certain, CHF has two kinds of tends with the mass flow increasing: monotone increase and decrease first then increase, which is shown in Figure 4. Black line in Figure 4 is used only to make the trend clearer. Usually, CHF will monotonically increase with mass flux under condition of subcooled boiling and high pressure while decrease first and then increase in saturated boiling. For the trend that decrease first and then increase, the inflection point will move left with the increase of pressure and quality, that is to say, moving to lower mass flux.

(a) monotone increase   (b) decrease first and then increase
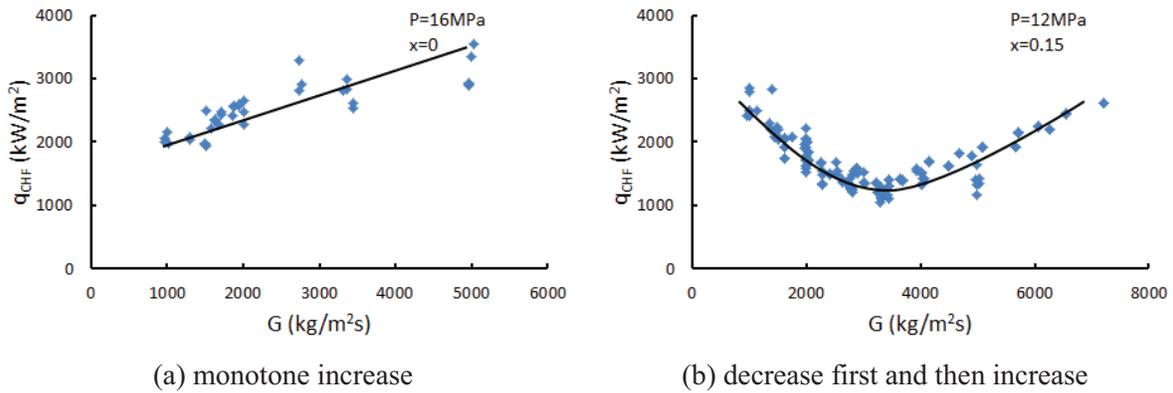
Figure 4. CHF Trend with Mass Flux

Table III shows the detailed CHF trend with mass flux in the parameter range of interest. Actually the form 2 in the table will convert to form 3 if a wider range of mass flux is considered. It is just caused by the inflection point locating above 5000kg m^{-2} s^{-1}.

Table III. CHF Trend with Mass Flux

P\x	-0.2	-0.15	-0.10	-0.05	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45
2	1	1	1	1	1					2		2	2	2
3	1	1	1	2				2	2	2	2	2	2	2
4														
5						2	2	2	2	2	2	2	2	2
6			2	2	2	2	2	2	2	2	2	2	2	2
7			2	2	2	2	2	2	3	3	3	3	3	3
8			2	2	2	2	2	2	3	3	3	3	3	3
9							3	3	3	3				
10			1	1	2	3	3	3	3	3	3	3	3	3
11					2	3	3	3	3					
12	1		1	1	1	3	3	3	3	3	3	3	3	
13				1	1	1	3	3	3	3	3	3		
14	1	1	1	1	1	1	3	3	3	3	3	3	3	
15	1		1	1	1	1	1	1	3	3	3	3	3	3
16	1	1	1	1	1	1	1	1	3	3	3	3	3	
17														

1-monotone increase, 2-monotone decrease,
3-decrease first and then increase, Blank-lack of experimental data
P: MPa

2.2.3. CHF Trend with Dryout quality

The variation trend of CHF with an increasing dryout quality can be simplified into three zones: Linear segments I and II, nonlinear segment III, as shown Figure 5. LQR (limiting quality region) is included in the zone III.
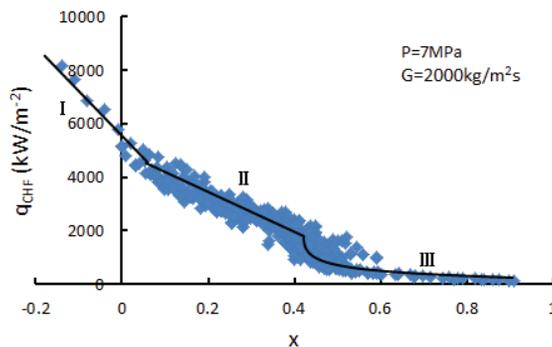
Figure 5. CHF Trend with Dryout Quality

CHF decreases monotonously with the quality increasing. Conjecturing that the zone I and II correspond to different flow regimes. The flow regime when CHF occurs is identified by calculating using regime map. Show the regime in the slices, as indicated Figure 6. After visual inspect and observe lots of slice, a

conclusion can be made that zone I represent bubble flow or slug flow while zone II is already annual flow.
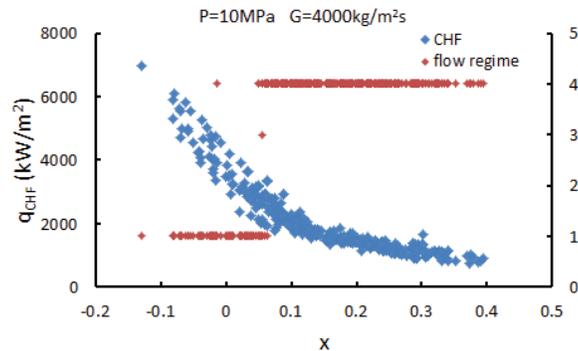
Figure 6. Flow Regime and CHF Change with Qualiy

1-bubble flow 2-slug flow 3-transition flow 4-annua-mist flow

3.   Comparison Analysis of CHF in Vertical Tubes and 5x5 Bundle

Bundle CHF experimental data used in the study come from Columbia University bundle CHF databases. More than 2500 CHF experiment data points of uniform heated 5x5 bundle without guide tube are picked out from the database. Subchannel analysis code COBRA is used to obtain local pressure, local mass flux and local quality.

Slice method is also applied to bundle experimental data to generate the 2-dimensional graphics. However, the bundle data is not normalized because no appropriate empirical equation can be used to modify while ensure the real parametric trends. CHF experimental data in tube and bundle is putted together to study parameter trends for the reason that bundle experiment data is much less than tube data. It leads to that some slices have no or little data which makes trend identification incapable.

3.1. Pressure Effects on Bundle CHF

Figure 7 shows how CHF change with pressure at certain mass flux and quality. In Figure 7a, the variation trend of bundle CHF is generally coincident with tube CHF. But the double peak form is not exist in bundle CHF. Only monotone decrease and single peak form can be observed. Bundle CHF value is usually lower than tube CHF under low pressure. However, these two are close when pressure is relatively high. Figure 7b and 7c are also in accord with the rule above.

(a)

(b)

(c)
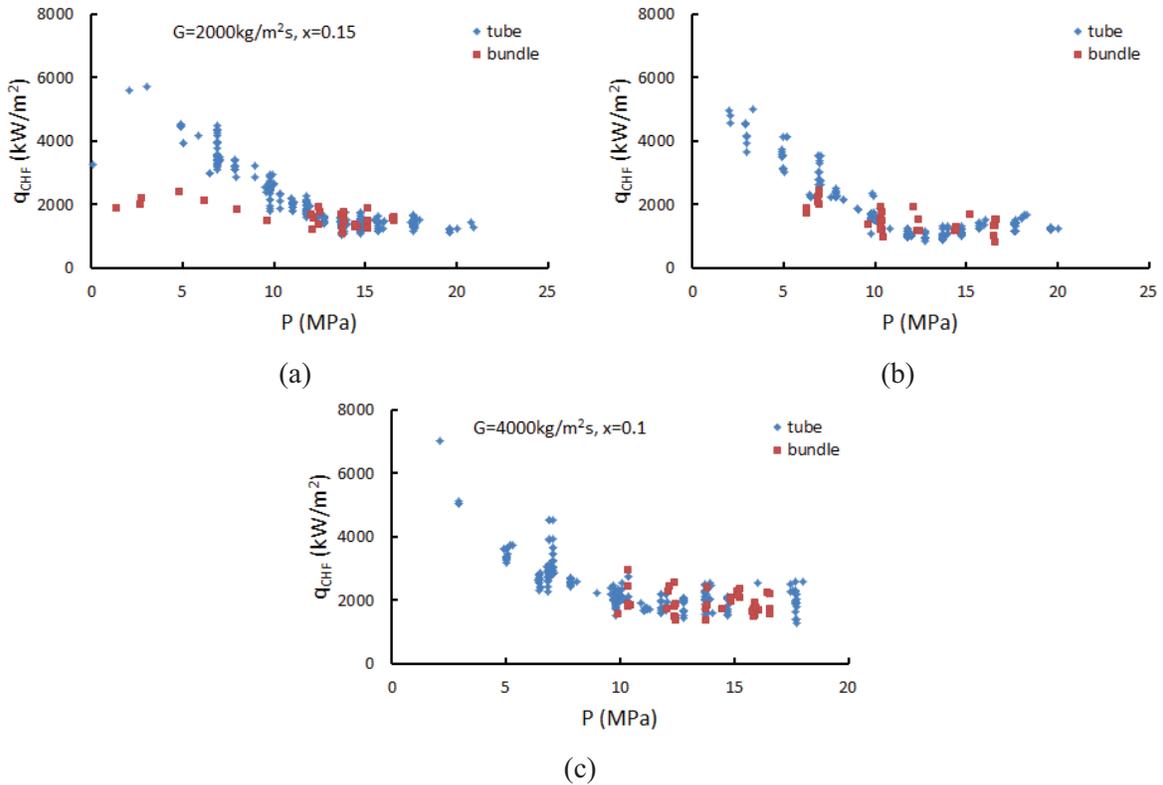
Figure 7. Comparison of CHF Trend in Tube and Bundle with Pressure

3.2. Mass Flux Effects on Bundle CHF

Figure 8 shows how CHF change with mass flux at certain pressure and quality. The conclusion that the variation trend of bundle CHF is approximately coincident with tube can be made from the following four pictures. However, for bundle CHF, decrease with the increasing of mass flux cannot be observed. The bundle CHF increase with mass flux with different slopes under different pressure and quality.

In addition, it can be seen that there is little tube CHF data in the slice in Figure 8d. But bundle CHF data is relatively more. In this case, bundle CHF data can think of as complementary to tube data. It can provide data support for the study of tube CHF within this parameter range.

(a)

(b)

(c)

(d)
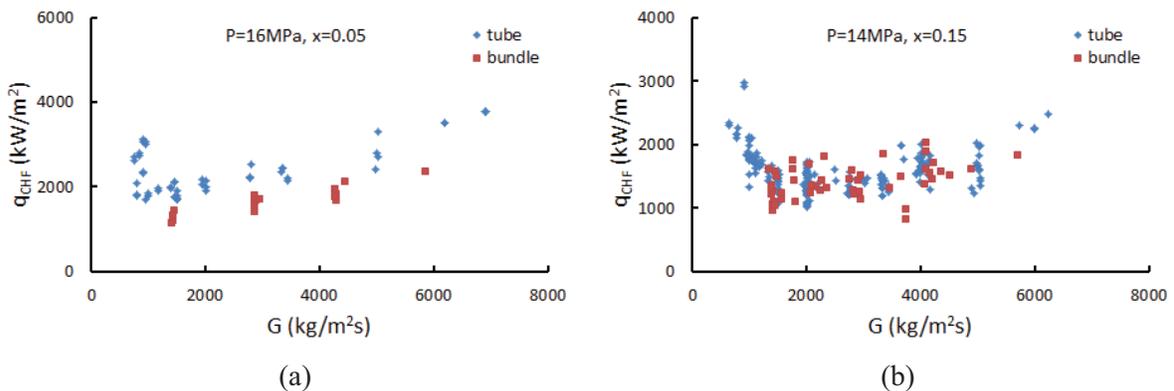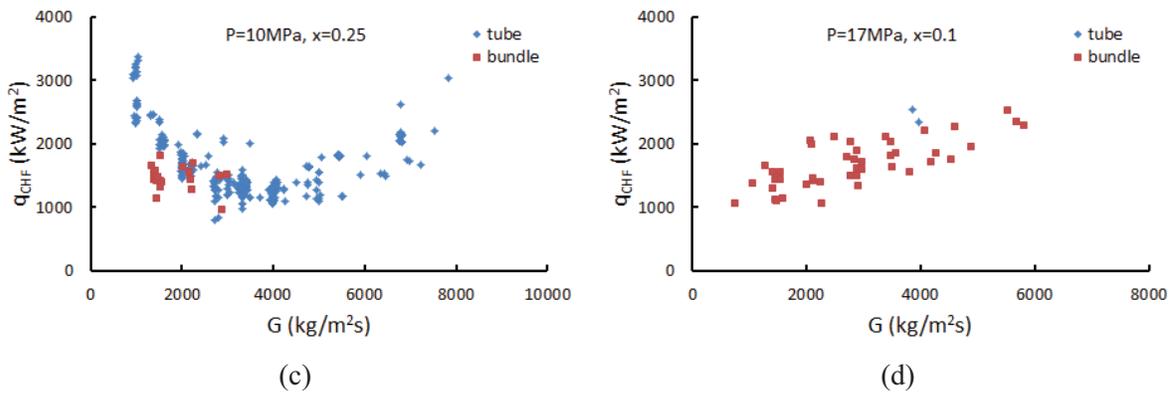
Figure 8. Comparison of CHF Trend in Tube and Bundle with Mass Flux

3.3. Dryout quality Effects on Bundle CHF

Figure 9 shows how CHF change with dryout quality at certain pressure and mass flux. The variation trend of bundle CHF with quality is also generally coincident with tube CHF. There is only some difference in numeric value. Under some condition, the value is close too.

(a)

(b)

(c)
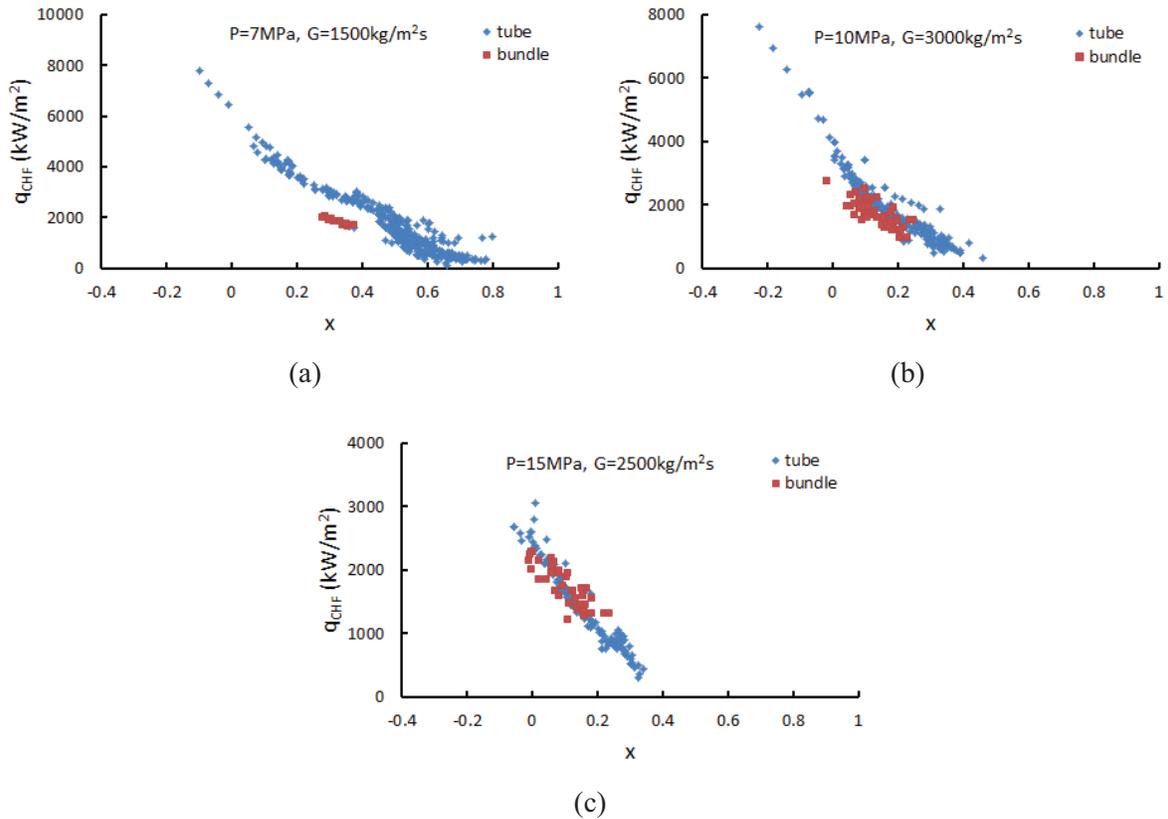
Figure 9. Comparison of CHF Trend in Tube and Bundle with Dryout Quality

4. CONCLUSIONS

In this paper, tube CHF database is analyzed using the slice method. Detailed trends of tube CHF with respect to variations in pressure, mass flux and dryout quality have been carried out for parameter range of interest. In addition, the study compares and analyzes the parametric trends of CHF in tube and bundle. It turns out that the two are largely consistent. The conclusion is as follows:

(1) The variation trend of tube CHF with an increasing pressure has three forms: monotone decrease, single peak form, or double peak form. Double peak form cannot be observed for bundle CHF.
(2) Tube CHF has two kinds of tends with the mass flow increasing: monotone increase and decrease first then increase. For bundle CHF, only monotone increase with the increasing of mass flux can be observed.
(3) CHF decreases monotonously with the quality increasing for both tube and bundle. However, LQR is not observed in bundle CHF.

The result lay a foundation for studying parametric trends of bundle CHF. It also proves that tube CHF prediction method applied in bundle CHF is feasible to some extent by introducing some correlation factors. Actually, Lee (2000) has proposed some correction factors (e.g. bundle factor, grid spacer factor and cold wall factor) for 1995 look-up table to apply it in bundle CHF prediction , and the result is acceptable.

Parametric trends of CHF in tube and bundle are both very complex. Further research is needed on parametric trends and change mechanism to better understand, accurately predict and enhance CHF.

REFERENCES

1. L.S. Tong, "Prediction of Departure from Nucleate Boiling for an Axially Non-uniform Heat Flux Distribution," *J. Nuclear Energy*, **21**(3), pp. 241-248 (1967).
2. D.G. Reddy and C.F. Fighetti, "Parametric study of CHF data: A Generalized Subchannel CHF Correlation for PWR & BWR Fuel Element Assembles," *EPRI Report NP-2609*, Vol. 2 (1983).
3. J. Weisman and S.H. Ying, "A Theoritically Based Critical Heat Flux Prediction for Rod Bundles at PWR conditions, "*Nuclear Engineering and Design*, **85**(2), pp. 239-250 (1985).
4. J. Weisman and B.S. Pei, "Prediction of Critical Heat Flux in Flow Boiling at Low Qualities," *International Journal of Heat and Mass Transfer*, **26**(10), pp. 1463-1477 (1983).
5. C.H. Lee and I. Mudawar, "A Mechanistic Critical Heat Flux Model for Subcooled Flow Boiling Based on Local Bulk Flow Conditions," *International Journal of Multiphase Flow*, **14**(6), pp. 711-728 (1988).
6. R.W. Bowring, "A Simple But Accurate Round Tube, Uniform Heat Flux, Dryout Correlation over the Pressure Range 0.7-17 MN/m^2(100-2500 psia)," *No. AEEW-R-789*. Atomic Energy Establishment, Winfrith, England (1972).
7. D.D Hall, I. Mudawar, "Critical heat flux (CHF) for water flow in tubes—II.: Subcooled CHF correlations," *International Journal of Heat and Mass Transfer*, **43**(14), pp. 2605-2640 (2000).
8. A. Durmayaz and D.C. Groeneveld, "Assessment of Critical Heat Flux Look-up Tables, Experimental Data and Selected Correlations," *Proceedings of 6th Int. Conference on Simulation Methods in Nuclear Engineering*, Montreal, October 12-15, 2004 (2004).
9. D.C. Groeneveld and J.Q. Shan, "The 2006 CHF Look-Up Table," *Nuclear Engineering and Design* **237**(15), pp. 1909-1922 (2007).
10. J.Q. Shan and D.C. Groeneveld, "Methodology of CHF Look-up Table Derivation," *Proceedings of 13th International Conference on Nuclear Engineering*, Beijing, China, May 16-20, 2005(2005).
11. D.G. Reddy, C.F. Fighetti, "Parametric study of CHF data: Critical heat flux data," *EPRI Report NP-2609*, Vol. 3 (1983).

12. M. Lee, "A critical heat flux approach for square rod bundles using the 1995 Groeneveld CHF table and bundle data of heat transfer research facility," *Nuclear Engineering and Design*, **197**(3), pp. 357-374 (2000).