Nahrain University, College of Engineering Journal (NUCEJ) Vol.15 No.2, 2012 pp.169 - 177

Effect of Mass Flow Rate on Critical Heat Flux in Vertical Tube

Muthana L.Abdullah / Assis. Lecturer / Institute of Technology/ Baghdad

Abstract:

The critical heat flux (CHF) in forced convective up flow has been investigated in a uniformly heated vertical steel tube of 18 mm internal diameter and 3.66 m length, with water as the working fluid. The CHF was determined by the sudden rise in the wall temperature of the electrically heated tube. Experiments were performed at nominal pressure 50 bar over three mass flux values 0.11kg/s, 0.055kg/s and 0.027 kg/s, and heat flux with up to 400 kW maximum power. The CHF results in the present experimental ranges rise linearly as the mass flux increases.

Finally, a comparison of the experimental data with available fluid correlations has been performed. The present results of CHF are found to be an acceptable agreement with those predicted by using (Bowring Correlation) and are slightly higher when compared with those predicted by Katto and Ohne Correlation .

Introduction

The critical heat flux (CHF) condition is characterized by a sharp reduction of the local heat transfer coefficient that results from the replacement of liquid by vapor adjacent to the heat transfer surface. The occurrence of CHF is accompanied by an inordinate increase in the surface temperature for heat-flux-controlled systems, and an inordinate decrease in the heat transfer rate for temperature-controlled systems [1].

High heat fluxes can be sustained in boiling heat transfer to water at moderate temperatures and for moderate temperature differences. This method is attractive when considering methods of extracting the heat from a high heat flux device such as a nuclear reactor. There are, however, other features of boiling heat transfer which limits its range of usefulness. The most important is the condition termed burnout [2].

The burnout condition occurs in more than one form. The form which might arise in most of the contemplated designs of water cooled reactors corresponds to a sudden inhabitation of the relatively efficient boiling heat transfer process and establishment of a relatively inefficient single phase heat transfer process through the vapor phase. The result, in a heat generating device is a large and rapid increase in the temperature of the heating surface. Such an increase is likely to raise the temperature of the heating surface above the melting point of materials that suitable use in a nuclear reactor and to have other equally unwanted consequences. Through investigation of the conditions promoting these undesirable features must precede the confident design and operation of the reactors.

Critical heat flux (CHF) mechanism and estimation is one of the most important issues for safe operation of power plant equipment. Since CHF depends upon many parameters, its prediction is based on correlation, which is generally valid within narrow ranges of parameters. Geometry and local conditions e.g. void, turbulence play very important role, forcing most vendors of power plant equipment to perform full or large scale experiments, at the conditions of operation to develop correlation for their own use [3]. Experiments have been carried out the last several decades in order to establish competent knowledge base of this phenomenon, [4].

Knowledge of the pressure drop, heat transfer coefficient and parametric behavior can reduce costs by avoiding both under-design and over-design of evaporators, boilers and other two-phase process equipments. For a given mass flux, CHF decreases, as expected, as the system pressure increases and show considerably lower critical heat flux at higher pressures as in the case of pure fluids, [5].

CHF mechanisms are usually studied by optical techniques to understand the liquid – vapor flow condition near the wall and in the bulk region and by wall temperature measurements which recorded the temperature excursion are associated with CHF, [6]. The maintained that at CHF, a very thin layer beneath a coalescent bubble or vapor slug can be evaporated in a few milliseconds while the passage time of a vapor slug is about 0.1 sec.

(Mudawwar et. al, 1987)[7] present strong evidence that just before CHF, a very thin liquid sublayer is trapped beneath a blanket formed by the coalescence of several bubbles at the heated wall. The CHF occurred due to dryout of the sublayer, causing unsteady rise of wall temperature.

The CHF in nuclear reactors is one of the important thermal hydraulic parameters limiting the available power, because the inordinate rise of reactor fuel surface temperature under CHF conditions is sometimes sufficient to cause melting of the fuel materials, then (Se – Young Chun et. al.) [8] indicates by experiments the CHF data under a zero mass flux condition, that both the effects of pressure and inlet subcolling on the CHF were smaller, compared with those on the CHF with net water upward flow.

Okawa et al. [9] predicted CHF in annular flow using a film flow model. Their predicted results agree with the experimental data fairly well when the flow pattern at the onset of critical heat flux condition is considered annular flow. The description of CHF phenomena under low pressure and low flow conditions is further complicated by the large specific volume of vapor and the effect of buoyancy that are inherent in the condition, (Shim, W.J. Jae Hyok Lim, 2003)[10].

Chang H. et. al, 2005 [11] found the experimental results of C H F using R-134a in uniformly heated vertical tube, coincided well with the data predicted with Bowring correlation and Katto correlation were used in the present investigation that demonstrates the R-134a can be used as the CHF modeling fluid of water for the investigated flow conditions and geometric condition.

Cheng L. and Xia G., 2002 [12] shows by experimental results in a smooth tube and a four – head spirally internally ribbed tube when compared with each other, that CHF can be enhanced by the four- head spirally internally ribbed tube in the test rang.

Finally, critical heat flux causes many serious problems to the operation and performance of power plants requesting a lot of attention. South-Baghdad power plant is a typical example. Since this problem is manifested in many aspects in that location. The objective of this present study is to obtain C H F data for water in vertical upflow at high pressure value, three different mass flux and heat flux values with a different inlet subcooling. The results are compared with two well known correlations that have been used in the literature throughout the following conditions fluid: steam – water systems only, Flow direction: vertical up flow, Pressure (p) = 2 – 190 bar, Tube diameter (d) = 2 – 45 mm, Tube length (L) = 0.15 – 3.7 m, Total mass flux (G) = 136 – 18600 kg/ m^2. s.

Experimental Set - Up

The schematic diagram of the experimental set-up is shown in Fig. 1.a. The test rig was assembled accordingly to satisfy the intended experimentations. Also, the test section was designed and built to fulfill the requirements for the critical heat flux measurement, and to investigate mass flow rate effects in the tube test section. The test section is constructed with tube of (18mm) inside diameter. It is heated with a (D C) current over a length of (3660 mm) and cooled with an upward flow of water. Seven Chromel – Alumel (K – type) thermocouples fast response (response time less than 0.5 sec) are brazed inside the tube wall. Details of the instrumentation on the test section are shown in Fig. 1.b.

Experimental Procedure

The heated channel (AB) discharges through a fitting (BC) into a riser (CD). From here the water (or water and steam) flows to a collector (E). Between two collectors (E) and (F) there is a heat exchanger consisting of a variable number of pipes in parallel. Water in (F) is returned to the inlet (M) by a down comer (GH), which feeds the pump (I). An inlet fitting (MA) is situated at the bottom of the heated channel. Pump (I) is optional and any component of the circuit between (B) and (A) can effectively be eliminated by specifying zero length for it. The number of pipes of the heat exchanger is an input quantity as well as localized pressure drop coefficients (Ki), introduced to account for elbows, flanges, fittings and valves eventually present in each of the main components of the circuit.

Different diameter may be specified for test – section (heated channel (AB), riser (CD), and heat exchanger pipes (EF), cold leg (GM). The pressure rise across the pump is determined from a specific pump characteristic. At the beginning of the experimental work on the system, calibrate all instruments were carrying out by used data collection. Experimental procedure is detailed in the following steps: The piston pump of the loop that contains the test section was switched – on, and the required water flow adjusted by the delivery valve, and system pressure controlled by control system. The circulation pump of the cooling water of the heat exchanger was switched – on, the preheater of the loop was switched – on to raise inlet water temperature required. When the power of the electrical heat supply was switched – on, the power was then gradually raised to the required output level and then recorded pressure drop in the test section and temperature distribution along the test section. Repeat the forth step until the power reached to C H F state which is known by shutdown of the system automatically, in this test the power increased until the C H F state was occurred with different inlet water temperature and recorded the experimental C H F with inlet temperature.

An electrical burnout detector acting on Wheatstone bridge principle is provided to detect the burn out region and to act as a safety device. The bridge unbalance due to the onset of the dry out on a part of the heated tube, promotes a power switch off. A (D.C) electrical supply system can heat the test section with up to 400 kW maximum power. For set values of flow rate, heat flux and inlet subcooling, the rise in the tube wall temperature is monitored. If a sudden rise in the wall temperature at any location is not detectable, the heat flux value in terms of the product of (V · I) power input is increased and the other flow parameters are adjusted if necessary and the wall temperature is again observed. This process is continued until one of the thermocouples shows a significant rise in wall temperature. The power supply is automatically shut-off when one of the measured wall temperatures exceeds a given limiting value. These experiments are repeated for different flow conditions.

Theoretical Aspects

To compare present results, the following correlations have been used:
Bowring correlation makes use of basic equation (1) where (Φc) is expressed in W /m^2. The correlation was derived from data covering the following parameter ranges [13],[14],[15]:

pressure (p)	tube diameter (d)
tube length (L)	mass velocity (G)
2-1 90 bar	0.002 -0.045 m
0. 1 5-3.7 m	1 36- 1 8,600 kg/m^2. s

$$\Phi c = [A + 0.25\ d\ G\ \Delta h_s] / [C + L] \tag{1}$$

(A) and (C) are given by:

$$A = [0.5792\ h_{fg}\ d\ G\ F_1] / [1 + 0.143\ F_2\ d^{0.5}\ G] \tag{2}$$

and:

$$C = [0.077\ F_3\ d\ G] / [1 + 0.347\ F_4\ (G / 1356)^{\ n}] \tag{3}$$

Where: F_1, F_2, F_3, F_4 and (n) are functions of a non – dimensional pressure (p),

p = (p / 69) where (p) is the system pressure in {bar}, n = 2 – 0.007 p

For p ≥ 1

$$F_1 = p^{-0.368} \exp [0.648\ (1 – p)]\ \ - \tag{4}$$

$$F_2 = p^{-0.448} \exp [o.245\ (1 – p)] \tag{5}$$

$$F_3 = p^{-0.219} \tag{6}$$

$$F_4 / F_3 = p^{1.649} \tag{7}$$

The other is that of Katto and Ohne [15],[16], which employed different fluid in vertical tube . The experiment is carried out to obtain data in heated tube with following conditions:
L = 0.01 – 8.8 m, d = 0.001 – 0.038 m.

Katto and Ohne correlated the (Φc W/ m^2) by the basic equation [15],[16]:

$$\Phi\ c = X\ G\ (hfg + k\ \Delta\ h_s) \tag{8}$$

where (X) and (K) functions of three dimensionless groups.
$L = L / d$, $R = \rho_g / \rho_L$, $W = \sigma\ \rho_L / (G)^2\ L$

Five values of (X) can then be :

$$X_1 = C\ W^{0.043} / L \tag{9}$$

$$X_2 = [0.1\ R^{0.133}\ W^{0.333}] / [1+ 0.0031\ L] \tag{10}$$

$$X_3 = [0.098\ R^{0.133}\ W^{0.433}\ L^{0.27}] / [1 + 0.0031\ L]\ X_4 =[0.0384\ R^{0.6}\ W^{0.173}] / [1 + 0.28\ W^{0.233}\ L] \tag{11}$$

$$X_5 = [0.234\ R^{0.513}\ W^{0.433}\ L^{0.27}] / [1+ 0.0031\ L] \tag{12}$$

Where the value of (C) is given for: L > 150 then C = 0.34. Three values of (K) can be calculated:

$$K_1 = 0.261 / C\ W^{0.043} \tag{13}$$

$$K_2 = \{0.833\ [0.0124 + (1 / L)]\} / R^{0.133}\ W^{0.333} \tag{14}$$

$$K_3 = \{1.12\ [1.52\ W^{0.233} + (1 / L)]\} / R^{0.6}\ W^{0.173} \tag{15}$$

Then the applicable values of (X) and (K):
For $R < 0.15$, $X_1 > X_2$ and $X_2 < X_3$ then $X = X_2$
$K_1 > K_2$ then $K = K_1$

Results And Discussions

Experiments were carried out to predict CHF [shutdown state of the system automatically] at a nominal pressure of 5.0 MN/m^2 and three mass flow rates of 0.11 kg/s, 0.055 kg/s and 0.027 kg/s covering arrange of inlet water subcooling of about 280 °C these results shown in figure(2).

It shows that for the same inlet water subcooling , a higher a heat flux are required to set the burnout condition as the water flow rate is increased that subcooling temperature or as the inlet subcooling temperature increased for a fixed flow rate value . This is expected as more heat is required to create the single phase blanket of vapor at the inside tube wall as the water mass flow rate or inlet subcooling is increased, then the C H F increases according to the decrease in the inlet water temperature.

The results are compared with two well known correlations that have been used in the literature to predict CHF situation of the present work , the first is that of Bowring [13],[14],[15], which employed only steam and water in vertical tube as a working fluids and Katto and Ohne [15],[16], which employed different fluid in the system.

The geometry and working conditions of present system lay within the geometrical range and working conditions of both correlations.

A comparison between present results and the two correlations are shown in fig.(3) , (4) and (5) for 0.11 kg/s , 0.055 kg/s and 0.027 kg/s data respectively. These figures show the difference between present C H F and empirical C H F calculated by Bowring correlation, which decreases according to the increase in the inlet water temperature, but the difference between present C H F and empirical
C H F Calculated by Katto and Ohne correlation increases according to the increase in the inlet water temperature.

The absolute percentage error [A.P.E] between present C H F and empirical C H F calculated by Bowring correlation and empirical C H F calculated by Katto and Ohne correlation such as:
For m = 0.11kg/ s, figure (3) [A.P.E] between present C H F and empirical C H F calculated by Bowring correlation is (0.025) at inlet water temperature from (220 – 240 ^{o}C) and (0.023) at inlet water temperature from (240 – 280 ^{o}C). On the other hand, [A.P.E] between present C H F and empirical C H F calculated by Katto and Ohne correlation is (0.04) at inlet water temperature from (220 – 240 ^{o}C) and (0.054) at inlet water temperature from (240 – 280 ^{o}C). For m = 0.055kg/ s, figure (4) [A.P.E] between present C H F and empirical C H F calculated by Bowring correlation is (0.046) at inlet water temperature from (220 – 240 ^{o}C) and (0.041) at inlet water temperature from (240 – 280 ^{o}C) while [A.P.E] between present C H F and empirical C H F calculated by Katto and Ohne correlation is (0.25) at inlet water temperature from (220 – 240 ^{o}C) and (0.26) at inlet water temperature from (240 – 280 ^{o}C).

It can be seen that the present data agrees well with Bowring correlation specially at the two high flow rate (0.11 kg/s , 0.055 kg/s) , that may be due to the fact that both systems has been using steam and water only as a working fluids . While the present data show, generally, trend when it compared with Katto and Ohne correlation. This may be explained that Katto and Ohne correlation used different working fluids in the system while the present data used only steam and water as working fluids.

Conclsions:

Step by step method for thermal hydraulic design of tubes is applied in this study to predict C H F in this system. A computer program for the simulation of the boiling state in tube is used to study the variation of pressure, quality and CHF.

The analytical results of this work yield the following conclusions:

1) Maximum power can be obtained from fuel rod, without reaching the CHF state ,by decreasing inlet water temperature, but this decrease requires a big heat exchanger in the system.

2) Increasing mass flow rate inside cooling channel, by increasing number of channels or area , causes an increase in maximum power which can be obtained from fuel rod.
3) The average percentage error between experimental CHF and theoretical CHF when Bowring correlation is used equal to [0.035]. On the other hand, when Katto correlation is used the percentage error becomes equal to [0.15] for the range [Tin = 220 – 240 ^{o}C].
4) The percentage error between experimental CHF and theoretical CHF when Bowring correlation is used equal to [0.032]. On the other hand, when Katto correlation is used the percentage error becomes equal to [0.16] for the range [Tin = 240 – 280 ^{o}C].

Recommendations:

The following recommendations for future studies are made:

1- Other methods and other new computer programs to calculate CHF in the vertical tube can be used to know the accuracy of the results according to the experimental results obtained from this study.

2- Many correlations to calculate the CHF in vertical tube can be used to know accuracy of the results with respect to the correlations used in this study.

REFERENCES

1. SoonH.&Won-Pil B."Understanding,Predicting,and Enhancing Critical Heat FLUX" The International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Seoul, Korea, October 5- 9, 2003.
2. Hino, R. & Ueda, T. " Studies on Heat Transfer and Flow Characteristics in Subcooled Flow Boiling " *Int. J. Multiphase Flow*, Vol. 11, pp, 283-297. 1985 .
3. Jasiulevicius, A. and Sehgal, B.R. " Vipre 02 Code Assessment for CHF and Post – CHF Heat Transfer Modes in Long Tubes" Nuclear Power Safety Division, Royal, institute of technology, Stockholm, Sweden, 2002.
4. Katto, Y. " Critical Heat Flux " Int. J. of Multiphase flow, Vol.20, pp. 53-90, 1994.
5. Sindhuja R., Balakrishnan A.R.& Srinivasa Murthy S.,"Critical heat flux of R – 407C in upflow boiling in a vertical pipe" Int. J. Applied Thermal Engineering , Vol.28.pp.1058 – 1065,2007.
6. Lee, C.H. and Mudawwar "A Mechanistic Critical Heat Flux Model for Subcooled Flow Boiling Based on Local Bulk Flow Condition" Int. J. Multiphase Flow, Vol.6, pp.711 – 728, 1988.
7. Mudawwar, I.A., Incropera, T.A. & Incropera, F.P. " Boiling Heat Transfer and Critical Heat Flux in Liquid Films Falling on Vertically – Mounted Heat Sources" Int. J. Heat and Mass Transfer, Vol. 30, pp. 2083 – 2095, 1987.
8. Se – Young Chun, Heung – June Chung, Sung – Deok Hong, Sun – Kyu Yang and Moon – Ki Chung,"Critical heat flux in uniformly heated vertical annulus under a wide range of pressures 0.57 to 15.0 mPa", Int. J. The Korean Nuclear Society, Vol.32.Number 2, pp. 128 – 141, April 2000.
9. Okawa T., Kotani A., Katako I., and Naito M., "Prediction of Critical Heat Flux in annular flow using a film flow model", J. Nuclear Science and Technology, Vol. 40, N0. 6, pp. 388-396, 2003.
10. Shim W. J., Jae H.L. & Gyoo D. J.," C H F for Uniformly Heated Vertical Tube Under Low Pressure and Low Flow Conditions" Energy Conversion Engineering Conference and Exhibit, [IECEC] 35th, Vol.1, PP.411-419,2002
11. Chang H.K. and Soon H.C., " C H F Characteristics of R- 134a Flowing Upward in Uniformly Heated Vertical Tube "Int. J. Heat and Mass Transfer, Vol. 48, pp. 2242 –2249, 2005.
12. Cheng L. & Xia G. " Experimental Study of C H F in a Vertical Spirally Internally Ribbed Tube Under the Condition of High Pressures " Int. J. Thermal Sciences , Vol. 41, Issue 4, pp. 396 –400, 2002.
13. Bowring, R.W."A simple but accurate round tube, uniform heat flux, dryout correlation for Pressure in the range 0.7 – 17 MN/m2" AEEW – R789, 1972
14. Tong L.S. & Tang Y.S. " Boiling Heat Transfer and Two – Phase Flow " Taylor & Francis Book Company, pp. 417 – 419,1997.
15. John G. & John R., " Convective Boiling and Condensation" Oxford Science Publications, pp. 353 –357,1994.
16. Katto, Y. and Ohne, H."An Improved Version of The Generalized Correlation of Critical Heat Flux for Convective Boiling in Uniformly Heated Vertical Tubes" Int. J. Heat and Mass Transfer, Vol. 27, pp. 1641 –1648, 1984.

Nomenclature:

CHF	critical heat flux (kW)
d	diameter (m)
G	mass flux (kg / m^2 s)
h	enthalpy (kJ / kg)
K	loss coefficient (/)
L	length of the tube (m)
n	number of bubbles (/)
P	pressure (bar)
R	two phase multiplier (/)
X	quality

Greek symbols

ρ	density (kg / m^3)
Φ	heat flux (kW / m^2)
σ	surface tension (N / m)

Subscripts

g	steam
K	C H F calculated by Katto correlation.
f	liquid

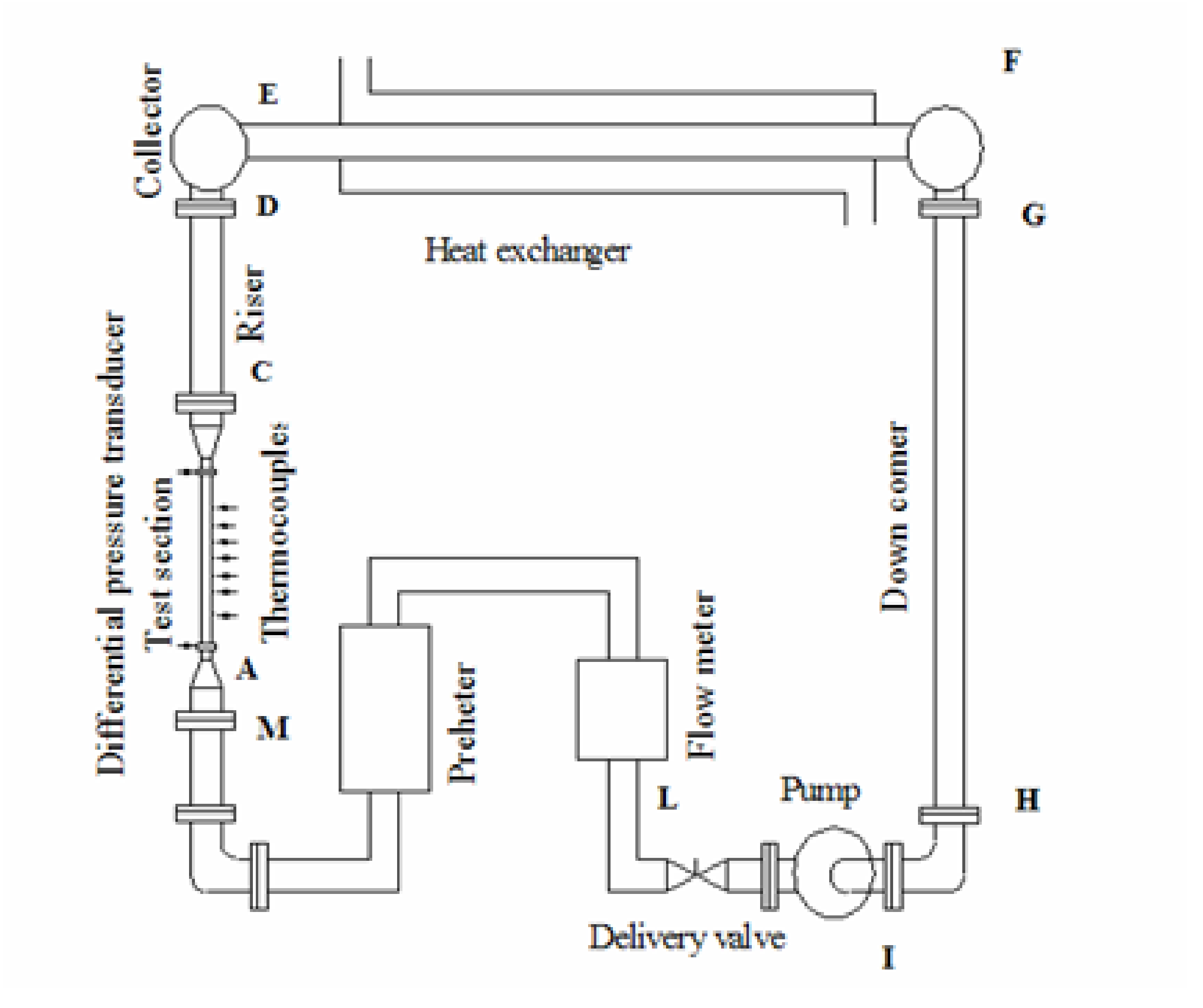


Fig.1.a. Schematic diagram of the experimental set-up: 1) Heated channel (AB), 2) Fitting (BC),(MA), 3) Riser (CD), 4) Collector (E),(F), 5) Heat exchanger (EF), 6) Down comer (GH), 7) Pump (I).

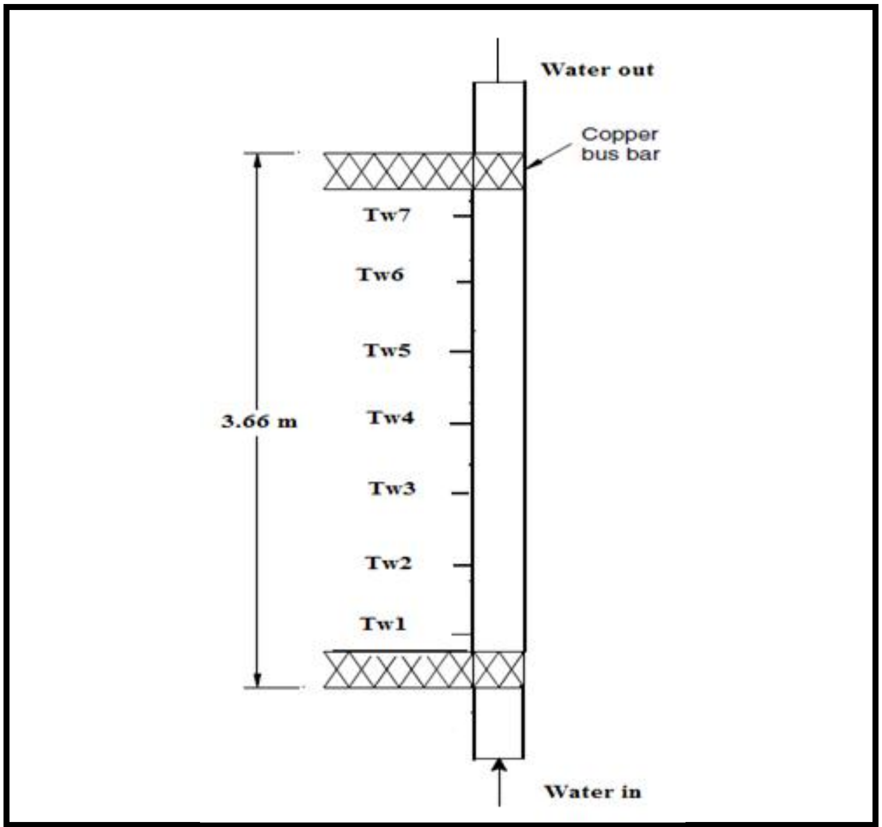
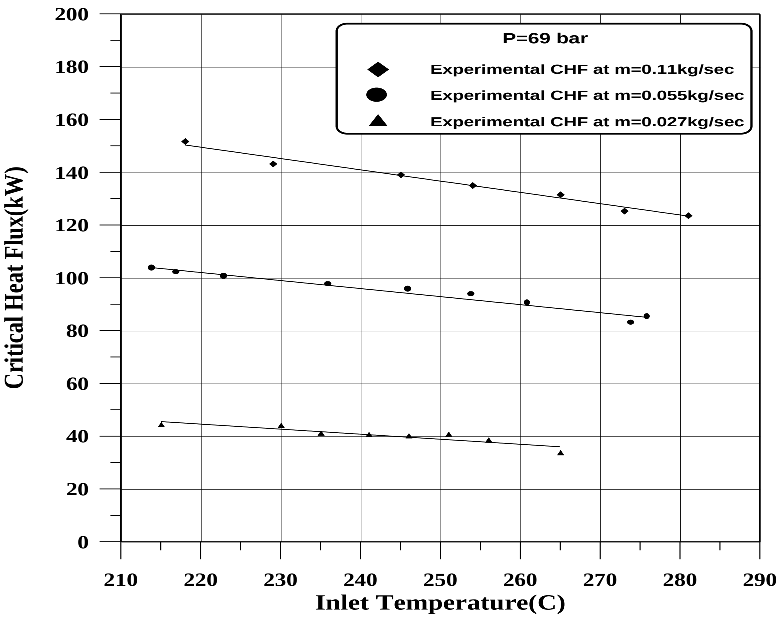
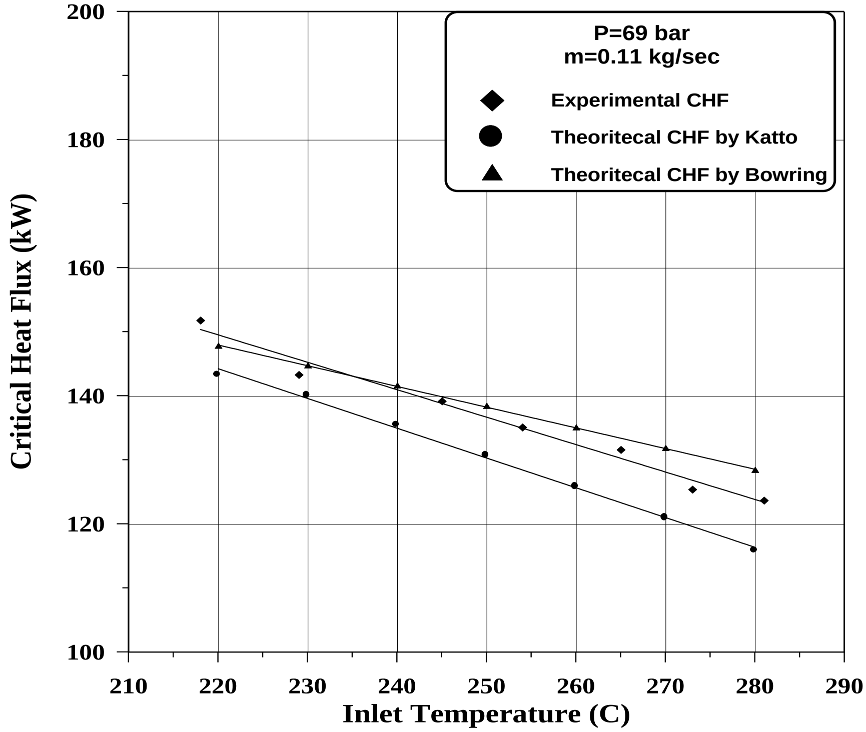


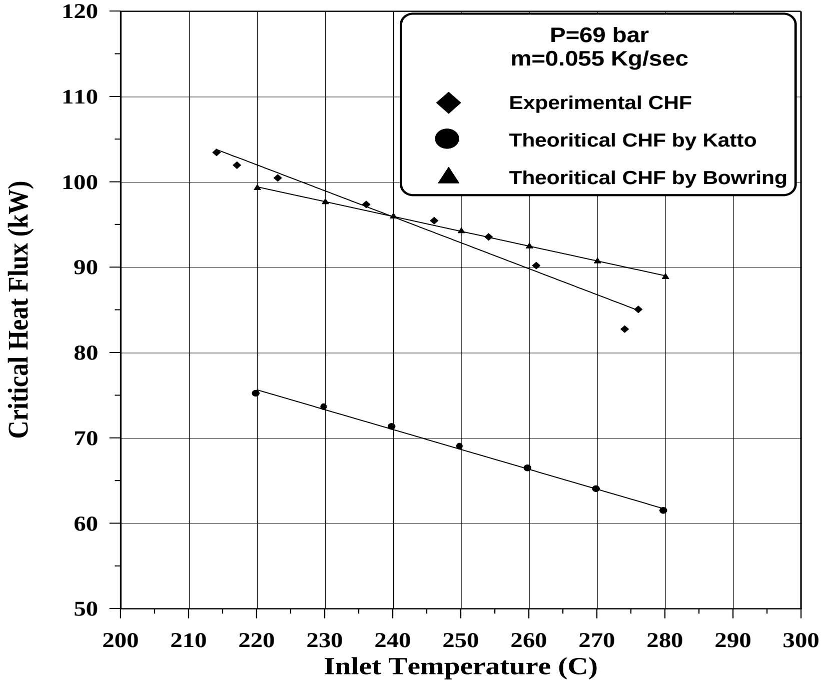
Fig.1.b. Schematic diagram of the vertical upflow test section



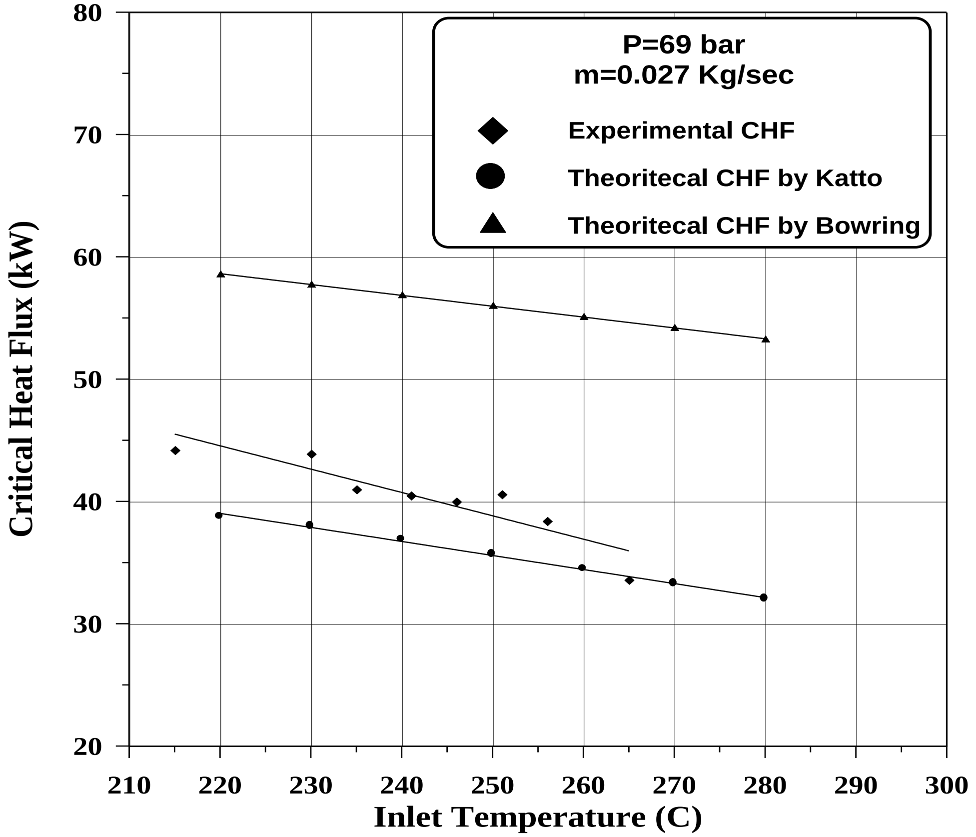
Fig(2)Effect of mass flow rate on experimental CHF



Fig(3)Comparison between two correlations with experimental
CHF of water flow rate of 0.11 kg/ s



Fig(4)Comparison between two correlations with experimental CHF
of water flow rate of 0. 055 kg/ s



Fig(5)Comparison between two correlations with experimental CHF of water flow rate of 0.027 kg/ s

تأثير معدل الجريان على الفيض الحراري الحرج في الأنبوب العمودي

مثنى لطيف عبد الله / مدرس مساعد / معهد التكنولوجيا – بغداد

الخلاصة:

تم إجراء التجارب العملية للفيض الحراري الحرج (CHF) لجريان ذو انتقال حرارة بالحمل القسري ونحو الأعلى في أنبوب عمودي مسخن بصورة منتظمة(على طول الأنبوب) بقطر داخلي 18 mm وطول 3.66m والمائع المستخدم هنا هو الماء. لقد تم تحديد الفيض الحراري الحرج عند الارتفاع المفاجئ في درجة حرارة جدار الأنبوب المسخن كهربائيا.أجريت التجارب عند ضغط معلوم قيمته 50 bar وعند ثلاث قيم لجريان الماء هي 0.027 kg/s, 0.055kg/s, 0.11kg/s ، ولحرارة مضافة إلى حد قدرة قصوى قيمتها 400KW . كانت النتائج تشير إلى أن قيمة الفيض الحراري الحرج تزداد خطيا عند زيادة شدة جريان الماء. أخيرا تمت مقارنة النتائج المستحصلة من التجارب قيد البحث مع معادلات المائع التجريبية. إن قيم الفيض الحراري الحرج المستحصلة من الدراسة الحالية أظهرت توافق جيد مع النتائج المستحصلة باستخدام معادلة (Bowring) التجريبية ، كما أظهرت نتائج هذا البحث توافق أقل بقليل عندما قورنت مع النتائج المستحصلة باستخدام معادلات (Katto وOhne) التجريبية.