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CRITICAL HEAT FLUX IN CONVECTIVE BOILING IN NUCLEAR REACTORS

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ABSTRACT

To asses the safety margin of a light water reactor during the postulated loss of coolant accident(LOCA) it is important to predict the peak clad temperature.To perform such a task thermohydraulic codes have been developed.Among the inputs to the computer codes,heat transfer equations which are used to determine the heat transfer coefficient in various heat transfer modes.Prediction of the critical heat flux (CHF) - as a limiting condition - is therefore of vital importance. The purpose of this paper is to recommend -based on the current state of knowledge - a set of correlations which are used to estimate the CHF in convective boiling.Also,for the present work a computer program is developed for the prediction of CHF.

1. INTRODUCTION

It is convenient to define the CHF-condition as follows:
A. For a heat-controlled surface the CHF-condition corresponds to that condition in which a small increase in heat flux from the particular surface gives an inordinate increase in wall temperature.
B. For a wall temperature-controlled surface the CHF -condition corresponds to that condition in which a small rise in wall temperature gives an inordinate decrease in heat flux.

In letrature [2,3,5-8] many mechanisme which can cause inordinate temperature rise in steady-state heat flux-controlled situation have been discussed. They may be broadley classified into two basic mechanisms which are discussed in the following:
I. Departure from nucleate boiling(DNB).This mechanism is proposed for the subcooled and low quality region.In the DNB-type the growth of a subcooled bubble boundary layer can give rise to bubble crowding near the heated surface. A great deterioration of the cooling effect can occur,perhaps by bubble coalescence near the surface and formation of a vapor film with low thermal conductivity,or perhaps by very large bubbles growing rate which inhibits rewitting of the surface. This film boiling in forced convection is essentially similar to that observed in pool boiling.
II. Dryout(DO).This mechanism is proposed in the annular high quality region. As the quality increases through the saturated nucleate boiling a point may be reached where the process of **boiling** (ie. bubble formation) is replaced by the process evaporation.Here the thickness of the thin film on the heating surface is often such that the thermal conductivity is sufficient to prevent the liquid in contact with wall being superheated to a temperature which would allow bubble nucleation. Heat is carried away from the liquid-vapor interface,where evaporation occur. At some critical value of the quality the complete evaporation of the liquid film occurs,leading to dryout, reduction of the cooling efficiency and by definition ,critical

heat flux condition(Fig.1).

The Dryout mechanism may be extended to include the subcooled low pressure flows,where the formation of a large slugs of vapor is possible.In this case,formation of a large dry spot during the passage of a large sluge of vapor is responsible for dryout [3]. The DNB-type CHF is generally fast and dramatic,often leading to physical destruction of the heater.On contrary,the DO-type CHF is slower and the resulting change in wall temperature less pronounced.

During the postulated LOCA in light water reactors,the reactor undergoes the blowdown,refill,and reflood stages.The blowdown phase is charectrized by highly transient thermohydraulic processes.Due to coolant depressurization flashing occurs,resulting in a large void in a very short time(≈0.7 s) as shown in Fig.2. At the same time, coolant rapidly leaves the reactor core,sometimes going through reversal and rereversal as shown in the same figure.The CHF-condition that occur in a LOCA under the previously mentioned rapidly varying conditions is called transient-CHF (T-CHF).

In T-CHF during a LOCA, both DNB and DO types can be present.Because of the predominance of the high-quality region in fast blow-down, it is unlikely that the DNB-type of CHF can be applied.However,if the flashing does not occur very fast and if the original subcooling is high,the DNB-type of CHF should be considerd as a possibility.

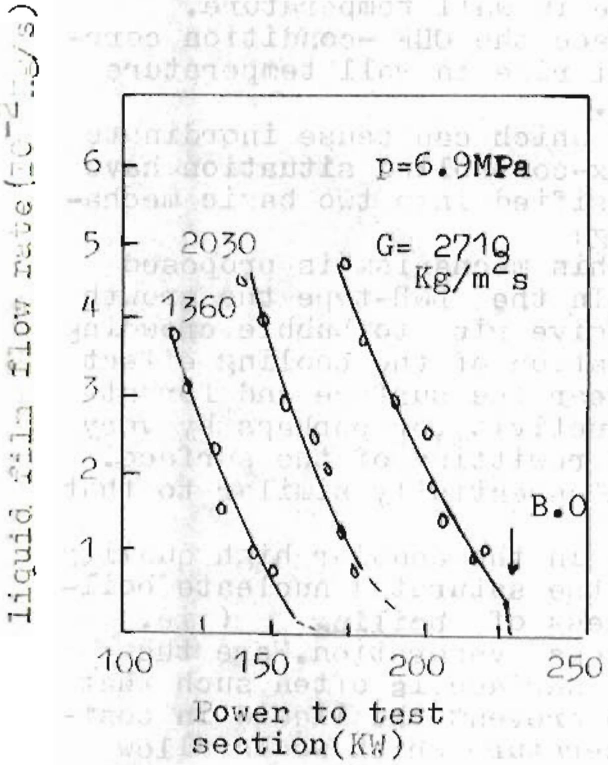

Fig.1 Film flow rate data for evaporation of water in a vertical tube [2]

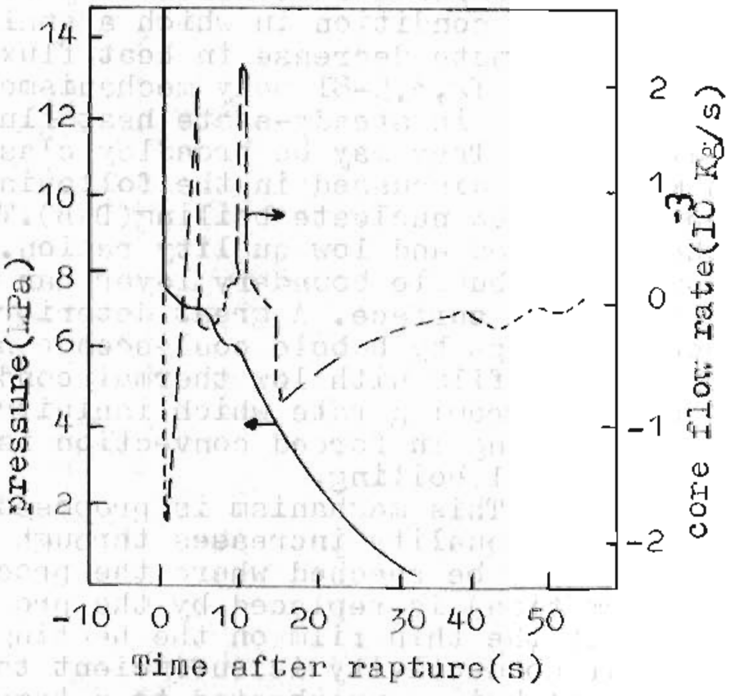

Fig.2 Pressure and flow history during blowdown of a PWR [3]

For transient conditions a third possible mechanism has been proposed, which postulated the formation of a vapor blanket in the region where there was no boiling during the steady-state operation prior to blowdown [2] . In other words, it was postulated that instantaneous flashing occurs in the region where there were no preexisting nucleation sites, resulting in early CHF-condition, while in the region where ebullition already is ongoing, flashing would not cause vapor blanketing.

2. CHF-CORRELATIONS

Analytical explanation of the CHF-condition in pool boiling based on hydrodynamic instability considerations have been proposed by Kutateladze(1951) and Zuber(1958) [2,5]. Kutateladze's original formulation is based on similarity arguments concerning the hydrodynamic stability of the counter-current vapor-liquid flow and takes the form:

$$K = U\sqrt{\rho_L}\ [g\,\sigma(\rho_L - \rho_g)]^{-1/4} \qquad (1)$$

In Eq.(1) U is the critical relative velocity for the Helmholz instability which is comparable to the volumetric flux of vapor($q_{cr}/\rho_L H_{Lg}$). The stability criterion K was determined from the data to be constant value. Thus analytical correlations usually takes the form:

$$\frac{(q_{cr})_{zuber}}{\rho_g\ H_{Lg}} = (\Pi/24).\left[\frac{g\sigma\ (\rho_L - \rho_g)}{\rho_g^2}\right]^{1/4} .\ f(\rho_L/\rho_g) \qquad (2)$$

The factor f in Eq.(2), which is a function of the ratio of densities, is usually very close to unity [2,9,10].

Most recently Griffith et al. [3,5] found that the CHF-condition in rod bundles with slow two-phase flow (approaching pool boiling) could be simply correlated in terms of the Kutatelaze-Zuber formulation and the void fraction as follows:

$$q_{cr}/(q_{cr})_{zuber} = 0.9\ (1-\alpha) \qquad (3)$$

In addition, due to the absence of comprehensive analytical models of the CHF-condition in flow-boiling, emperical correlations or CHF data must be used for design purpose. While the form of some correlations is based on analytical developments, some of the most widely used correlations were obtained as numerical fits of a large number of data points [1-8]. The most acceptable correlations are presented in the following sections.

A. Correlations for prediction of the DNB-type CHF.

W-3 correlation [2,5,8]

$$q_{cr} = 3.16[(2.02-0.0625\ p) + (0.172-0.000143\ p) .\ EXP(18.177-0.6\ p)] .\ (1.157-0.869\ x).[(0.11-1.178\ x + 0.1275\ x|x|)(G/1000)+1.037] .[0.2664+0.8357EXP(-124D_e)] .\ [0.826+0.00034(h_{sat} - h_{in})] \qquad (4)$$

B. Correlation for prediction of the DO-type CHF.
GEs correlation [2,5]

$$q_{cr} = 3.15\times10^{6}(0.84-x) \tag{5}$$

C. Correlation to predict the CHF of the DNB-DO-combination.
Biasi correlation [8,10]

$$q_{cr} = 2.764(10^{7-2n}).(De)^{-n}.G^{-1/6}.1.468(.681\,F_p.G^{-1/6} - x) \tag{6}$$

$$q_{cr} = 1.505(10^{8-2n}).G^{-0.6}(De)^{-n}\,.H_p.(1-x) \tag{7}$$

where

$F_p = 0.7249 + 0.99\,p\,EXP(-0.032\,p)$ and

$H_p = -1.159 + 0.149\,p\,EXP(-0.019\,p)+8.99\,p(10+p^2)^{-1}$

p in bars and
$n=0.4$ for $De \geq 0.01$
$n=0.6$ for $De \leq 0.01$

For $G \geq 300\ Kg/m^2s$ the higher value of q_{cr} obtained from Eqs.(6) and(7) is used,while for $G < 300\ Kg/m^2s$ Eq.(6) is always used.The correlation is applied over a wide range of pressure,massflux,and hydraulic diameter.

3. CHF CALCULATION AND RESULTS

Determination of the CHF is very important for thermohydraulic calculations in nuclear reactors.For this r purpose,the computer program CRIHF was developed for this work.The correlations used in this program are:

a) Zuber-Griffith correlation-Eq.(3)- for low flow,that is for $G < 100\ Kg/m^2s$.

b) Biasi correlation-Eqs.(6) and(7) - for high flow.

The above two correlations were selected since they account for both DNB and DO mechanisms,and they are applicable over a wide range of parameters.

Pressure,local quality,mass flux,and equivalent hydraulic diameter are input data.Water and steam properties are calculated in the subroutine STOFF using the IFC-correlations [9,10].

Figures 3,4,and 5 show an example for CHF-calculation.Fig.3 represents the effect of the local quality and mass flux on the CHF.As shown in the figure,as the local quality increase the CHF decreases which can be explained by the poor conductivity of the vapor.Experimental results obtained by Shiralkar [3] for various axial flux shapes show the same trend.

In Fig.4 the effect of system pressure on the CHF is shown.The CHF passes through a maximum at low pressures(≈ 4 MPa) and falls as the pressure is increased.This effect is the reflection of the change in vapor and water properties.The obtained pressure effect on the CHF is supperted by the experimental results presented in [8].It is important to note that for pool boiling the CHF increases with increasing pressure up to a maximum then falls sharply [3],which is the same trend as in convective boiling.

The relationship between the CHF and mass velocity is shown in Figs. 3 and 5 . In the subcooled region, the CHF increases with increased mass velocity [8].In contrary,the CHF decreases with increased mass velocity in the region with possitive value of quality-as shown in Fig.5. However the experimental results presented in [8] show very good agreement for the effect of mass velocity on CHF.Fig.3 shows that as the mass velocity increases the critical local quality required to cause the CHF-condition decreases,which is not the case in subcooled boiling.

4. CONCLUSIONS

a) DNB and DO mechanisms still the most accepted explanation of the CHF-condition

b) Emperical correlations developed for calculation of CHF in steady-state conditions are applicable for transient CHF calculations.

c) The results obtained using the computer program CRIHF,which is developed for this work,show that in flow boiling with possitive quality the CHF decreases with increased local quality,mass velocity,and system pressure.

NOMENCLATURE

De	Equivalent hydraulic diameter	(m)
G	Mass velocity(mass flux)	(Kg/m^2s)
h	Specific enthalpy	(J/Kg)
H	Latent heat of vaporization	(J/Kg)
g	Gravitational acceleration	(m/s^2)
K	Constant	
p	Pressure	(Pa)
q	Heat flux	(w/m^2)
x	Quality	
ρ	Density	(Kg/m^3)
σ	Surface tension	(N/m)
α	Void fraction	

SUBSCRIPTS

cr	critical
in	inlet
sat	saturated
L	liquid
g	vapor
Lg	liquid-vapor

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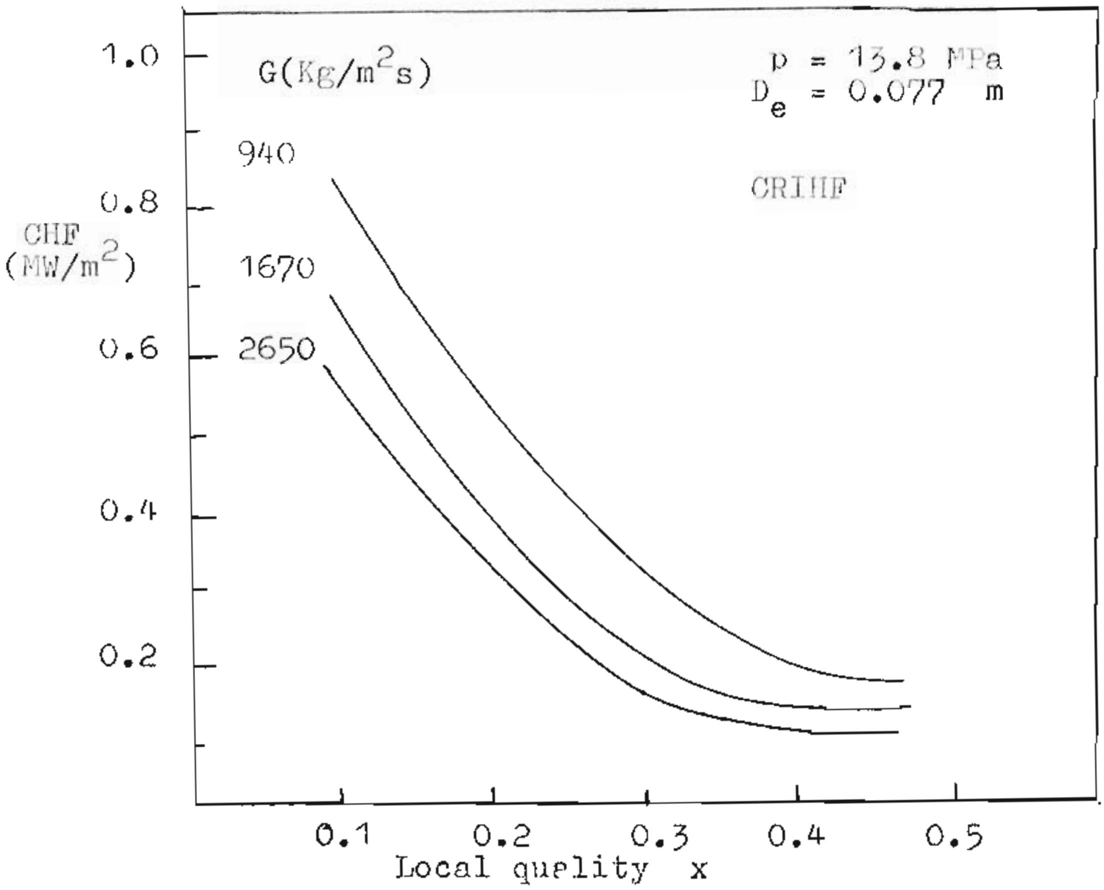

Fig.3 CHF-Quality relationship in flow boiling

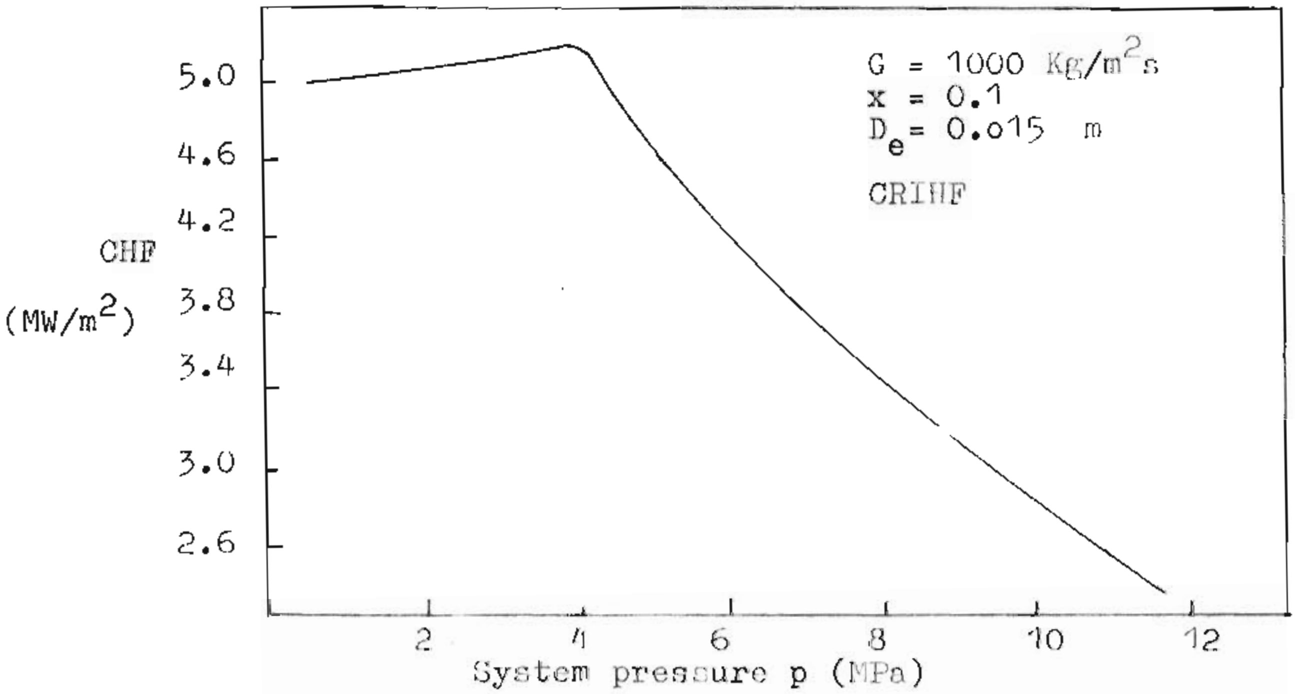

Fig.4 Effect of system pressure on CHF

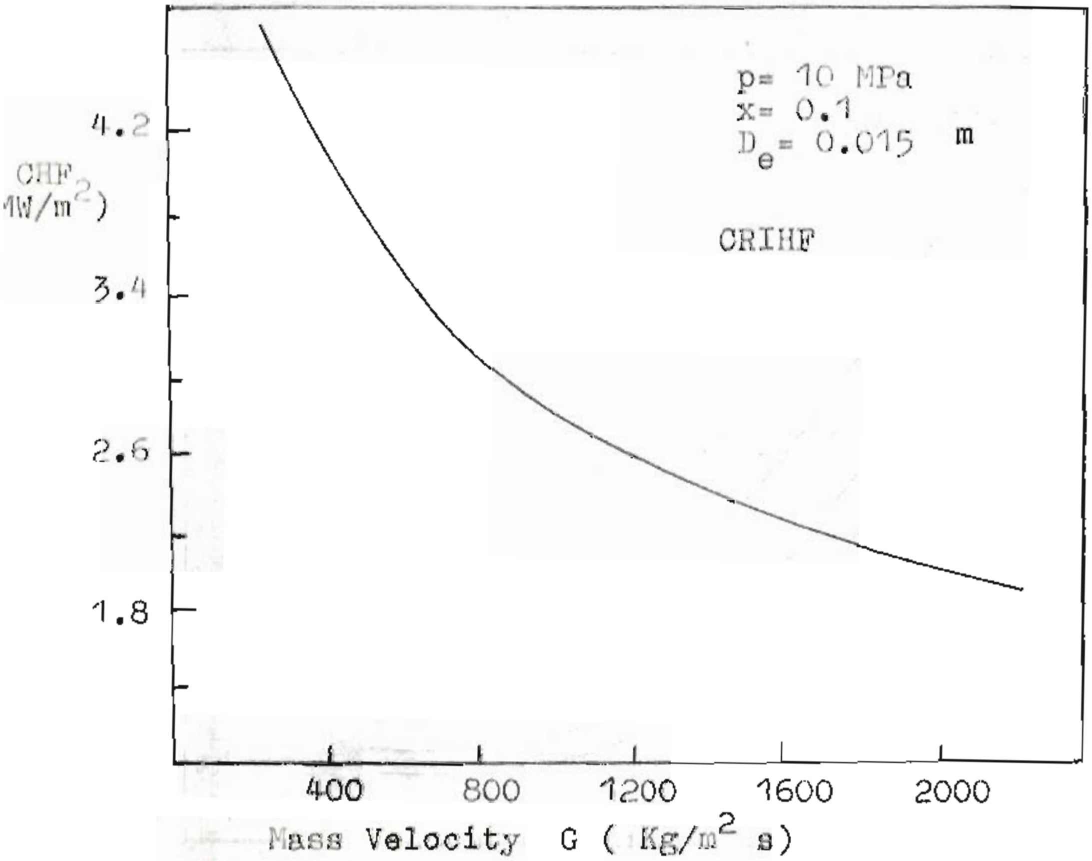

Fig.5 CHF-Mass velocity relationship in flow boiling with possitive quality