VALIDATION OF THE DRYOUT MODELING CODE, FIDOM

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ABSTRACT

A Methodology, FIDOM (FIlm DryOut Modeling) has been developed in BARC to predict CHF due to dryout of liquid film in annular two phase flow. The FIDOM has been validated earlier in BARC using in-house experimental data on CHF (125 data points) under BWR conditions and some of the models of the deposition and entrainment were found to result into very good prediction. Subsequently, the code has been further validated against various CHF databases (2170 data points) available in the literature. The prediction of FIDOM was found to be excellent when compared to these experimental data. The models for the entrainment and deposition have been validated for the prediction of the dryout and these models have potential for the application to the nuclear fuel assembly for the evaluation of critical power.

KEYWORDS
Annular flow, CHF, dryout modeling, entrainment, deposition.

1. INTRODUCTION

Critical Heat Flux (CHF) is an important consideration for the thermal design of nuclear reactor and other thermal systems. The thermal system must be operated well below the CHF limit to allow for the operating flexibility and uncertainty in the prediction. Enormous amount of CHF data has been generated in the past and a number of empirical correlations on CHF have been developed for various experimental conditions. The applicability of these empirical correlations is within the range of their experiments. As of now, there exist more than 1000 correlations [1] just for a tube cooled by water which is due to the complex underlying mechanisms. Under the reactor conditions, the generation of the full-scale experimental data is indispensable due to the limitations posed by the empirical approach as any change in geometry and operating conditions causes profound impact on the value of CHF. Since the CHF phenomenon is very much dependent on the two-phase flow pattern; it is possible to develop mechanistic models to achieve wider range of validity. Even for the complex geometry like rod bundle and the spacer, the mechanistic approach would be very much useful provided adequate understanding of the mechanism responsible for the influence of these geometries on the CHF is attained. No additional treatment is required for the axially non-uniform heat flux profile in the film analysis. This would be one of the advantageous points of the film flow analysis, compared with empirical methods. Under the BWR conditions (high quality), the CHF is caused due to the progressive depletion of the liquid film over the heated surface (Fig.1). This phenomenon is generally referred to as Liquid Film Dryout (LFD). The phenomenological (mechanistic) models for LFD have been suggested by various investigators. Representative models [2-5] are available in literature with different level of success. Over the years there have been improvements in the prediction of dryout. Hong et al. [6] predicted the CHF in an annulus within ±20% under wide range of mass flux (189-3300 kg/m2 s), pressure (1-12 Mpa) and quality (more than10%). Okawa et al. [7,8] predicted the CHF data within ±30% for 1893 data points over wide range of operating conditions.

These mechanistic approaches make use of the constitutive correlations for the droplet entrainment and deposition. The success of the dryout model has a strong bearing on these correlations including the criterion for the dryout inception.

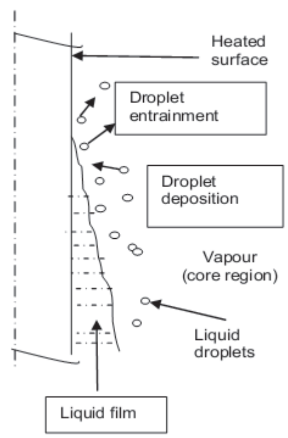

Figure 1. Progressive depletion of liquid film and three fluid streams (liquid droplet, liquid film and vapor core)

The prediction of onset of droplet entrainment in the annular flow regime and corresponding initial entrainment fraction is also important which the starting point for the film dryout analysis is. There are various models proposed in the literature for the droplet entrainment and deposition calculations. Most of the models are developed for the adiabatic condition and a few are based on the diabatic condition also.
This paper uses phenomenological model developed by Chandraker et.al. [9]. The model was earlier validated against a limited set of experimental data. This validation exercise is being extended to a wider range of data. The experimental data generated at AERE Harwell [10, 11] and Atomenergi, Sweden [12] have been used for the current exercise. The results obtained in the present studies substantiate validity of FIDOM. In section two the model is discussed in brief.

2. DESCRIPTION OF THE METHODOLGOY FOR FILM DRYOUT ANALYSIS (FIDOM)

The important aspects of film dryout model are the mass exchanges at the interface between the liquid film and the vapour core region. The wavy characteristic of the interface leads to the entrainment of the droplet from the liquid film to the vapour core. The droplet deposition on to the liquid film also takes place causing the buildup of the liquid layer which enhances the film thickness. In the code, FIDOM, the constitutive correlations for the entrainment, deposition and onset of annular flow have been considered which are same as that followed by Utsuno and Kaminaga [13].

2.1. Inception of Entrainment of Droplets

When a gas phase is flowing over the liquid film, the interfacial wave grows with the increase of gas velocity. As the gas phase velocity is increased, a roll wave with large amplitude is generated. The droplet entrainment starts when the retaining force of the surface tension is exceeded by the interfacial shear force exerted by streaming gas flow. Ishii and Grolmes [14] have suggested a simple model for $Re_{lf} > 1635$ as follows:

$$\frac{\mu_l j_{gc}}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}} = N_\mu^{0.8} \quad \text{For} \quad N_\mu^{0.8} < \frac{1}{15} \tag{1}$$

$$\frac{\mu_l j_{gc}}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}} = 0.1146 \quad \text{For} \quad N_\mu^{0.8} > \frac{1}{15} \tag{2}$$

Where N_μ viscosity number is given by

$$N_\mu = \frac{\mu_l}{\left(\rho_l \sigma \sqrt{\frac{\sigma}{g\Delta\rho}}\right)^{\frac{1}{2}}} \tag{3}$$

The onset of entrainment criterion is given as follows

$$j_g > j_{gc} \tag{4}$$

Where j_g is the volumetric gas flux and j_{gc} is the critical volumetric flux for gas for the entrainment inception. The initial entrainment fraction right after the transition to the annular-mist flow is assumed to be at equilibrium.

$$E = E_{eq} \tag{5}$$

Here, the droplet entrainment fraction is the fraction of liquid entrained in the gas core defined by

$$E = \frac{w_{ld}}{w_l} = \frac{j_{ld}}{j_l} \tag{6}$$

Where w_{ld} is the droplet mass flow rate and w_l is the total liquid mass flow rate. Also j_{ld} is the droplet volumetric flux and j_l is the total liquid volumetric flux.

2.2. Description of Models for the entrainment and deposition rates

The two-phase annular flow is modelled with the three fluid streams with liquid film, entrained droplet and gas. The basic assumption is that the droplet and the gas travel as a homogeneous mixture with no slip between them. The effect of momentum on the system pressure is regarded to be negligible. Mass balance of the liquid film is given by

$$\frac{dw_{lf}}{dz} = P(m_d - m_e - m_{ev}) \tag{7}$$

For the entrained droplets

$$\frac{dw_{ld}}{dz} = P(m_e - m_d) \tag{8}$$

For the gas

$$\frac{dw_g}{dz} = P(m_{ev}) \tag{9}$$

Energy balance in the liquid film region is

$$m_{ev} = \frac{q''}{h_{gl}} \tag{10}$$

The mass transfer correlations proposed by Whalley et al. [15] is given as

$$m_e = KC_{eq} \tag{11}$$

$$m_d = KC \tag{12}$$

The droplet mass per unit volume is given by

$$C = \frac{\rho_l j_{ld}}{j_g + j_{ld}} = \frac{\rho_l j_l E}{j_g + j_l E} \tag{13}$$

$$C_{eq} = \frac{\rho_l j_l E_{eq}}{j_g + j_l E_{eq}} \tag{14}$$

Entrainment fraction at equilibrium (E_{eq}) modified by Utsuno and Kaminaga[13] is given below

$$E_{eq} = \tanh(0.16 W_e^{0.08} R_{el}^{0.16} - 1.2) \tag{15}$$

For the Mass transfer coefficient or deposition coefficient (K) modified form by Utsuno and Kaminaga[13] has been considered.

$$K = 41.2 \frac{\mu_g}{\rho_g D} R_{eg}^{0.15} \left(\frac{C}{\rho_g}\right)^{-0.36} \tag{16}$$

The detailed calculation procedure is described in Ref [9]

3. RESULTS AND DISCUSSION

The model discussed above was used to predict the experimental conditions listed in table I. The present experimental database covers a very wide range of pressures including a substantial amount of data which are relevant to BWR conditions. The heated length also varies substantially. This allows contrasting the model performance in short and long length tubes.

Fig. 2 shows that the model tends to over-predict at short lengths and under-predict at longer lengths. Further the deviation from experimental data is very large for short length tubes. This signifies the importance of the history effect in annular flows. For length above 2m, the data fall within ±30%.

Table 1: Data used for validation

Experimental Conditions			
	AERE-M-2216[11]	AE-177[12]	AERE-R-5055 [10]
Pressure(bar)	68.94	10- 99	66.89-74.82
Mass flux (kg/m^{2}s)	1329-4136	218-3478	623- 5512
Exit quality	0.15-0.779	0.302-0.938	0.082-0.948
Inlet sub-cooling (KJ/kg or deg C)	945-1182 kJ/kg	29.4 to 240.2 ^{0}C	746- 1233 kJ/kg
Heat flux (kW/m$^{2)}$	429.7471 to 2645.125	556 to 4555	589.048 to 2591.057
Heated length (m)	0.9144 to 5.5118	0.96 to 3.75	1.828 to 5.562
Tube diameter (mm)	6.1722	3.93 to 24.95	12.624
Data points	74	2008	93

With mass flux (fig. 3), the deviation is pretty large for low mass flux but predictions are reasonably good for mass flux above 1000 kg/m^{2}s. Thus the model predictions would be reasonable for BWR operating flow range.

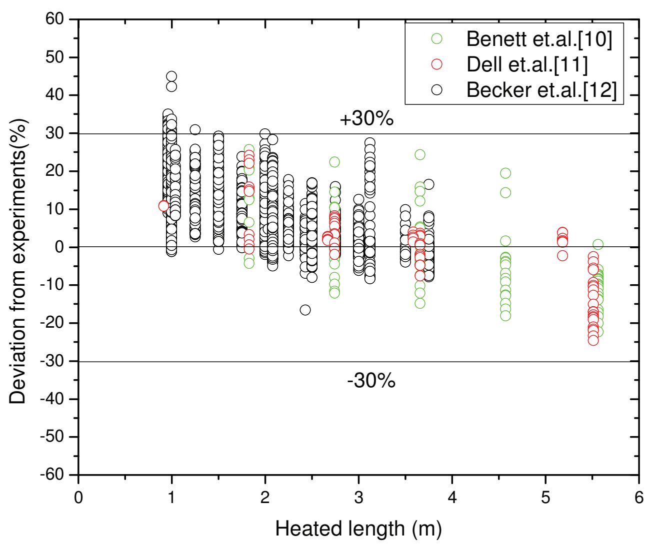

Figure 2. Deviation of FIDOM prediction with heated length

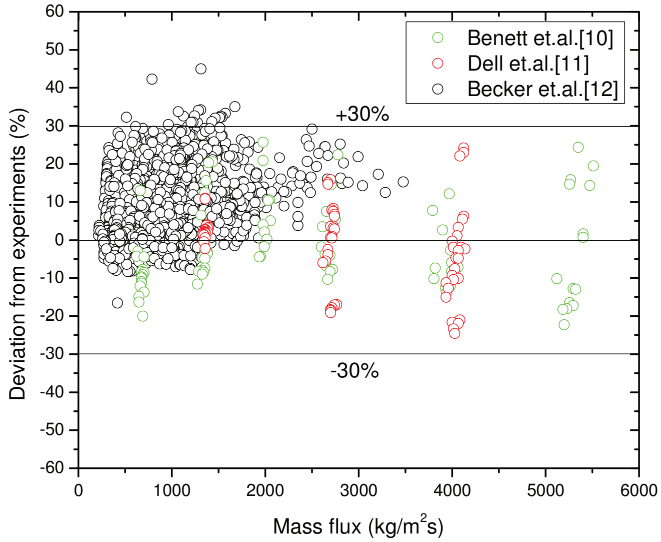

Figure 3. Deviation of FIDOM prediction with mass flux

The prediction trends with pressure (fig. 4) also show poor predictions at low pressure. But improvement is seen beyond 30 bar pressure. At ~70 bar, data are seen to lie equally around the parity line. This signifies that the model does indeed give better results in BWR conditions.

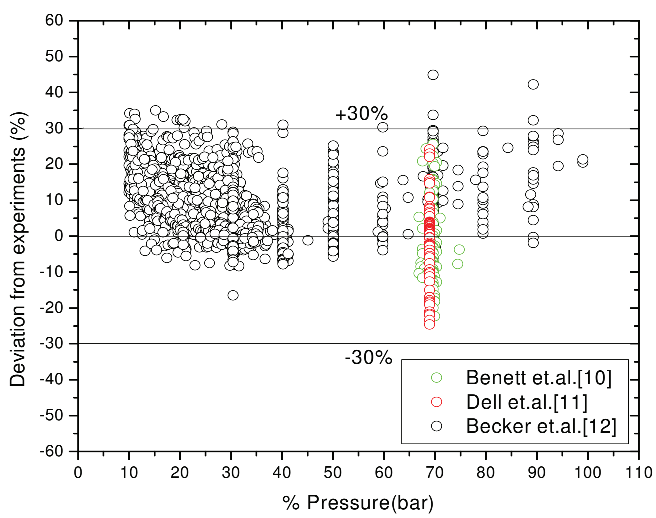

Figure 4. Deviation of FIDOM prediction with pressure

The model is seen to predict better at high qualities (fig. 5). In fact, for qualities in excess of 70%, barring a few data points, FIDOM is able to predict most of the experiments within ±10%. This is to be expected since as quality increases, the history effects diminish and the uncertainties in the model due to assumption of initial entrainment fraction reduce.

Finally, though it is obvious from the figures 2 through 5, for the purpose of clarity, fig. 6 shows a plot of predicted versus experimental CHF. It is seen that the predictions are on the higher side. One of the reasons for this might be the assumption of equilibrium entrainment as the Initial Entrainment Fraction (IEF). This actually gives low values of IEF resulting in higher CHF. An improvement in this aspect of the model may aid in better predictions.

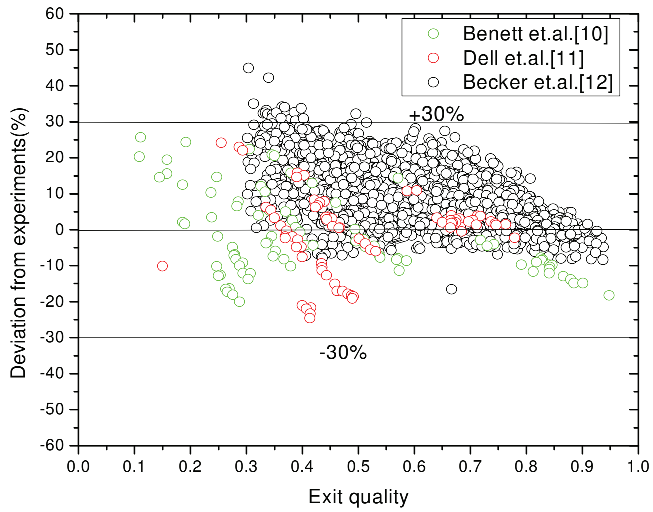

Figure 5. Deviation of FIDOM prediction with exit quality

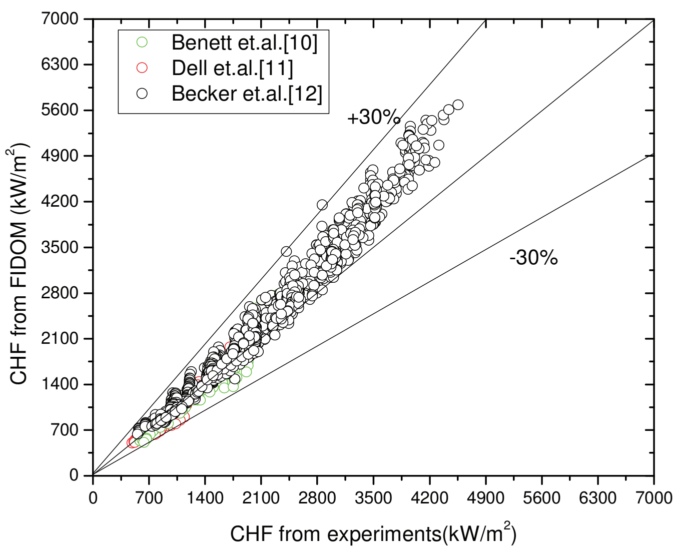

Figure 6. Comparison of FIDOM prediction and measurements

Table 2 shows the average, R.M.S. and standard deviation of the prediction as compared to the experimental data from three sources [10, 11, and 12]. AERE-M-2216 data was found to be predicted by FIDOM with a good agreement. Predictions for other two sources were also close to the experimental data as shown in table 2. Most of the data are predicted within ±10% of agreement.

Table 2: Error statistics on FIDOM prediction

Data Source			
	AERE-M-2216[11]	AE-177[12]	AERE-R-5055 [10]
Average error	-1.18	12.1	-0.35
R.M.S.	10.76	17.55	14.08
S.D.	10.69	12.7	14.08
Error range			
	±10%	±20%	±30%
No. of data points (total 2170)	1287	1911	2150
	59.31%	88.06%	99.08%

4. CONCLUSIONS

Dryout prediction code FIDOM was validated against a large number (~2500) of experimental dryout data. It was seen that FIDOM is capable for predicting CHF over large ranges of operating and geometrical parameters. The prediction accuracy is reasonably good for BWR conditions. The results of FIDOM are particularly good for higher exit quality and longer heated lengths. For shorter heated lengths, the history effects dominate and results are sensitive to initial value of entrainment fraction. Further it was seen that FIDOM mostly over-predicts Critical Heat Flux (CHF). In addition, the Utsuno's models for the rates of deposition and entrainment have been found to be applicable under BWR conditions. This can be further improved by incorporating appropriate model for the initial entrainment fraction. However, literature does not have adequate recommendation for the appropriate initial entrainment model for a shorter heated length. This aspect of the model will be improved in future. Thus, the phenomenological approach of FIDOM has potential to replace the existing CHF correlations. The advantage of the dryout model over empirical correlations is that the phenomenological modeling approach of dryout has the potential to capture the effect of various geometrical configurations of the rod bundles.

NOMENCLATURE

P	Perimeter of the heated surface(m)
C	Droplet concentration (kg/m^3)
D	Diameter (m)
L	Length (m),
E	Entrained fraction
G	Gravitational constant (m/s^2)
J	Volumetric flux (m/s)
K	Deposition coefficient (m/s)
m	Mass transfer rate (kg/m^2 s)
N_μ	Viscosity number
q"	Heat flux (MW/m^2)
Re	Reynolds number
We	Entrainment Weber number
W	Mass flow rate (kg/s)
X	Quality
Z	Distance (m)
ρ	Density (kg/m^3)
μ	Viscosity (Ns/m^2)
σ	Surface tension (N/m)

Subscripts

ld	Liquid droplet
d	Deposition
e	Entrainment
ev	Evaporation
eq	Value at equilibrium
lf	Liquid film
l	Liquid phase

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