CHAPTER 1

INTRODUCTION

1.1 Topic Statement

1.1.1 Critical Heat Flux

For a heated surface that is cooled by liquid, Critical Heat Flux (CHF) is defined as the heat flux that corresponds to a sudden deterioration of heat transfer coefficient. As shown in fig.1-1, the boiling process for pool and forced convection flow is usually expressed in a heat flux vs. heated surface superheat curve. In the figure, region BC is nucleate boiling region. At point C, the boiling mode suddenly changes from nucleate boiling to film boiling with the heated surface temperature suddenly jumping from T_C to T_D. The heat flux at point C is called CHF. In literature, the CHF is known by various names, such as: boiling crisis, departure from nucleate boiling (DNB), burnout or dryout.

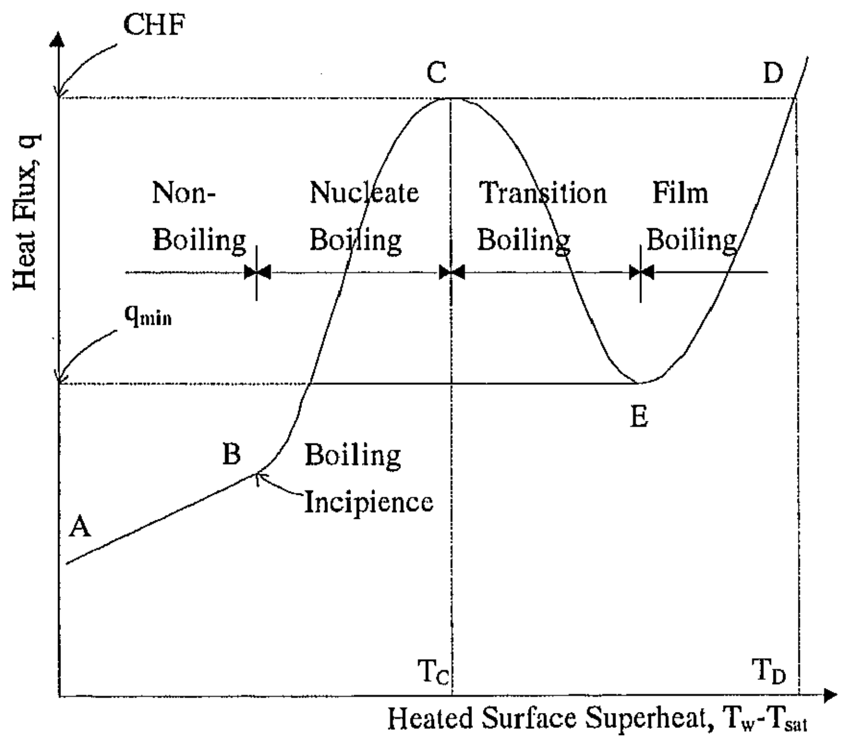

Fig1-1 Boiling Curve

Generally, the CHF can be categorized into two kinds: local and non-local. The former means that the CHF is only determined by the thermo-hydraulic condition at the CHF location and the latter means the CHF is determined not only by the CHF occurrence location, but also by inlet temperature and heated length.

1.1.2 Subcooled Flow Boiling

Subcooled flow boiling is the boiling that begins and develops even though the mean enthalpy of liquid phase is less than saturation. The subcooled flow boiling is characterized by the fact that thermodynamic equilibrium does not exist in the system.

For subcooled flow boiling, two kinds of flow pattern are found being reported. First one, as shown in fig.1-2, which is well encountered, includes single-phase flow, bubbly flow and slug flow regions. While the second one, as shown in fig.1-3, which is seldom encountered, includes single-phase flow, nucleate boiling flow and inverted annular flow regions. The first kind of flow pattern is characterized by obvious bubble detachment, movement and coalescence processes and happens under most working conditions. While the second kind of flow pattern is characterized by the appearance of explosive-like film boiling that begins suddenly at some point in the nucleate boiling region. As being reported in literature, the second kind of flow pattern happens easily only under some extremely high heat flux or high-pressure condition.

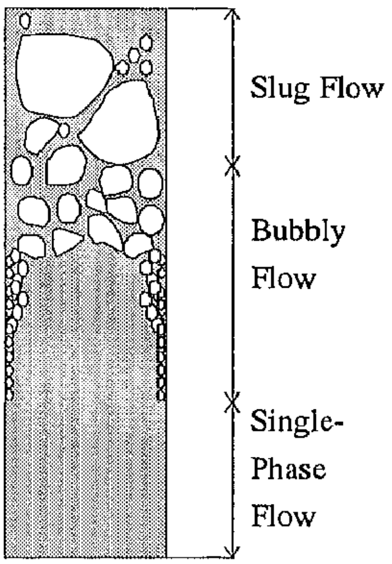

Fig.1-2: The First Kind of Flow Pattern of the Subcooled Flow Boiling

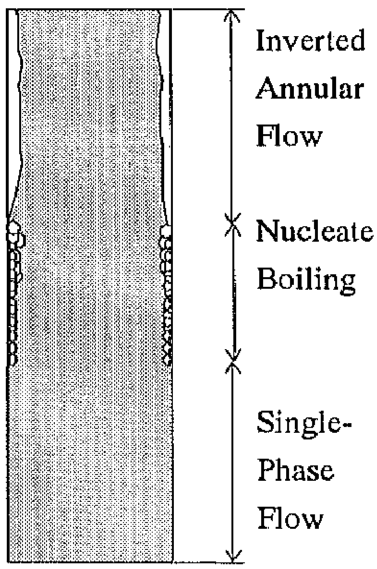

Fig.1-3: The Second Kind of Flow Pattern of the Subcooled Flow Boiling

Because the first kind of flow pattern happens under most working conditions, present paper mainly focuses on the research on the first kind flow pattern condition. In this paper, if not specified, the phrase "subcooled flow pattern" refers to the first kind of subcooled flow boiling.

Fig.1-4 shows important locations in the first kind of flow pattern condtion. Wall and fluid temperature variations along the tube are also shown out. Point B is the onset of nucleate boiling, or ONB. The region before point B is the single-phase region, in which the heat transfer coefficient is almost constant (neglecting property variation with temperature) and the wall temperature rises linearly. With the onset of nucleate boiling, the wall temperature begins to level off, as more nucleation sites are activated beyond the ONB. The region BC is partial boiling region, where C corresponds to the point at which the contribution to heat transfer from the nucleate boiling reaches maximum and the single-phase convective contribution diminishes. The region after point C is fully developed boiling region, or FDB. The tube wall keeps almost same temperature in the fully developed region and therefore it can be approximately assumed that the highest wall temperature is reached when the fully developed region is established. Point D is net vapor generation point (NVG point, also called as OSV point). From this point on, true quality and void fraction begin to develop obviously. Generally, The NVG is very near to the beginning point of the FDB. The subcooled flow boiling reaches thermo hydraulic equivalence at point E. But the flow is charged by subcooled flow boiling characteristics until the point F, at which the last drop of coolant in the core region is heated to the saturation, is reached. The first kind of flow pattern happens only when the exerted heat flux q is higher than q_{NVG}, which is defined as the heat flux needed for the establishment of the NVG point at the tube exit and is the lowest possible heat flux for the establishment of the first kind of subcooled flow boiling

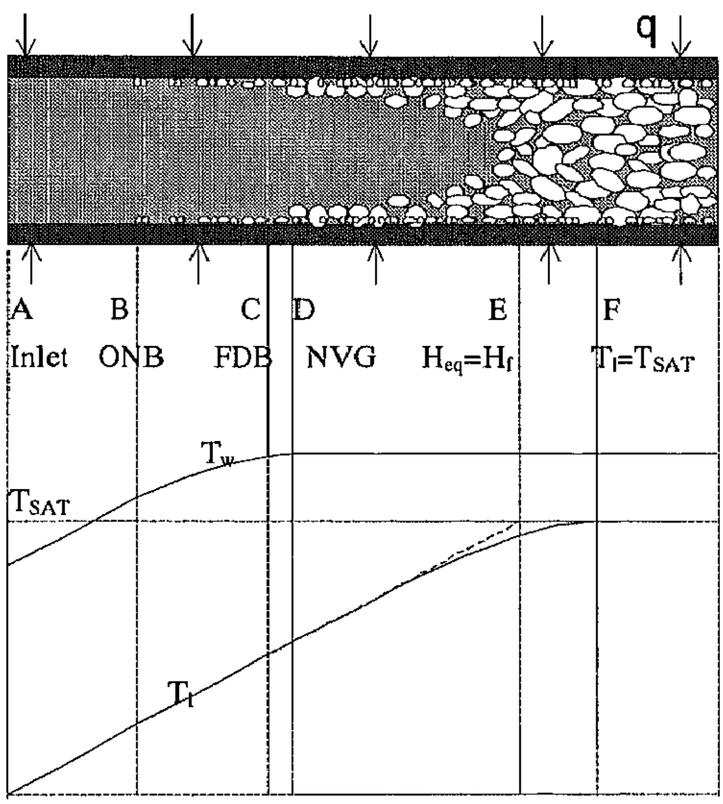

Figure 1-4 Schematic Representations of Flow Regimes and Wall Temperature Variation in Subcooled Flow Boiling

1.2 Significance of the Subcooled Flow Boiling CHF

Subcooled flow boiling is one of the most efficient ways for the removal of high heat flux. It is widely used in the equipments such as nuclear reactor cores, accelerator targets and advanced microelectronic modules. The operating conditions of these systems are restricted to be lower than a heat flux called CHF to prevent the danger of overheating or burnout. If the subcooled flow boiling CHF can be predicted with good accuracy, high heat flux equipments can be operated safely. The ability to predict Critical Heat Flux (CHF) well therefore is of considerable interest.

1.3 Research Objectives and Scope

1.3.1 Research Objectives

Although lots of approaches have been presented for the prediction of the CHF for the subcooled flow boiling, various investigations still strongly disagree on the following issues:

(1) The physical picture of subcooled flow boiling just before CHF;

(2) The condition that triggers CHF;

(3) The controlling factors determining the CHF variations with respect to pressure, mass velocity, subcooling and hydraulic diameter.

So the objectives of this research is:

(1) Propose CHF mechanism for the most often encountered first kind of subcooled flow boiling.

(2) Develop a mechanistic CHF model based on the proposed CHF mechanism and verify the model by comparison with experimental data.

(3) Analyze the CHF parametric trends and interpret the trends using the proposed model.

(4) Adapt the model to peripheral non-uniform heating, twist tape inserts, both presences of the peripheral non-uniform heating and the twist tape inserts condition and non-water system condition.

1.3.2 Research Scope

The research mainly focuses on the first kind of flow pattern condition. Although seldom encountered, the CHF mechanism for the second kind of flow pattern is also discussed a little in chapter 6.3.

Concretely, Chapter 2 reviews the existing methods for the CHF prediction. Tabular methods, empirical correlations are introduced simply while the CHF predictions from bubble crowding mechanism and liquid sublayer dryout mechanism are introduced much more. Based on the experimental observations from previous works, the liquid sublayer dryout mechanism is adopted by the present author as the CHF triggering mechanism for the most often encountered first kind of flow pattern.

Then, in chapter 3, a new mechanistic model for the prediction of the CHF for subcooled flow boiling is proposed with the model assumptions and CHF computation process introduced.

Chapter 4 gives the verification of the model. The proposed model is firstly tested with a big dataset. The comparisons between the proposed model and the Celata model on the predictions of the CHF and some important parameters, such as vapor blanket velocity, length, diameter and liquid sublayer thickness, are carried out. Consequently, the possible systematic effects in the model behavior are ascertained. Finally, the parametric trends of the CHF versus mass flux, pressure, inlet subcooling, inner diameter and the ratio of heated length to inner diameter are studied. This chapter also points out the deficiencies of the proposed model at low L/D condition and extreme conditions (extremely high pressure or high mass flux condition). The possible reasons are analyzed in first step.

Chapter 5 adapts the proposed model to peripheral non-uniform heating; twist tape inserting and non-water (liquid nitrogen and refrigerant 113) system. The model is also adapted to the both emergences of the twist tape and peripheral non-uniform heating conditions successfully.

Chapter 6 first gives out the discussions on the existing models for the predictions of the NVG point, true quality, void fraction and drag coefficient and then the model recommendations and sensitivity studies. Besides, Chapter 6 also gives out discussion on writing Helmholtz instability wavelength in finite system and discussion on the CHF triggering mechanism for the second kind of flow pattern. A criterion is developed to determine the flow pattern near the CHF. The reasons for the deficiencies at low L/D condition and extreme conditions are analyzed in detail in the chapter.

At last, chapter 7 gives out conclusion remarks.