3. HEAT TRANSPORT SYSTEM THERMALHYDRAULICS

3.1 Introduction

[GAR96]

3.2 Energy Production and Transfer Parameters

The energy production in the nuclear reactor is expressed in a variety of terms that depend on the discipline.

a) Volumetric energy (heat) generation rate, q''' (kW/m^3)

This term is mostly used by reactor physicists because they deal with fission reaction rate, that results in volumetric energy generation rate. This term does not provide any information about the heat transfer in the core, nor it indicates any level of core margins. The triple-prime notation represents the fact that it is energy generation rate per unit volume of the fuel material.

b) Surface heat flux, q'' (kW/m^2)

The thermal-hydraulics engineer deals with heat transfer from the surface of the fuel elements to the coolant. This parameter is most importance to the thermal designer. The double-prime notation represents the fact that it is heat transferred per unit surface area of the fuel element in contact with the coolant.

c) Linear heat-generation rate, or power rating, q' (kW/m)

Both, the thermal designer and the metallurgical designer express fuel performance characteristics in terms of linear power rating. The single-prime notation represents the fact that it is heat generated per unit length of the fuel element in the core.

d) Rate of energy generation per fuel element, q (kW)

This parameter is useful in expressing heat generated separately in fuel element, which is usually used in modeling heat transfer phenomena in the core.

e) Core power, Q (kW)

Used in global calculations of the energy output from the core.

f) Core power density, Q''' (kW/m^3)

Used as a figure of merit for the core thermal performance.

g) Core specific power, Q/mass of heavy atoms

Used in a figure of merit for core thermal performance form the nuclear physics perspective.

3.2.1 Thermal Design Limits and Margins

Figure 3.1 shows a typical change of the heat flux and critical heat flux along the fuel element. The critical heat flux (CHF) is the heat flux at the surface of the fuel element that results in a sudden change of the heat transfer regime from single-phase liquid to bubbly flow, with the bubbles blanketing the fuel element surface. This phenomenon leads into severe reduction of the heat transfer coefficient and the heat flux from the fuel element to the coolant.

The objective of the thermalhydraulics design of the reactor core, for a desired core power Q, to ensure that the heat flux at all fuel elements in the core will be below CHF by a sufficient margin. CHF is the most important parameter in the core thermalhydraulic design. Note that the local power in the core will vary with position along the fuel channel, including the end flux peaking at bundle ends, and from channel to channel in the radial direction of the calandria.

The required thermal margins of the core are shown in Figure 3.2. The variations in the neutron flux, and power generation in the core in the radial and axial directions are represented by the corresponding peaking factors. Also, uncertainties in the calculated parameters and other engineering uncertainties are stacked on top of the peaking factors to arrive at the maximum peak steady state condition.

In transients, appropriate overpower factor needs to be stacked on top of the maximum peak steady state power to get the limit value for design transients. On top of this limit, there should be a margin for all uncertainties in calculating the CHF values and the uncertainties in monitoring global and local reactor parameters.

It is obvious from Figure 3.2 that core power can be enhanced by flattening the shape of the power-generation rate, optimizing the power-to-flow ratio in every channel of the reactor, and by using on-power refueling that allows for fine adjustments in the bundle local power. Also, power flattening can be achieved by having the flux adjusters and zone controllers in the core that provide an effective means for control of the local neutron flux.

In CANDU, adding fresh fuel at the inlet side of the channel is useful in achieving effective “flattening of the thermal margins”.

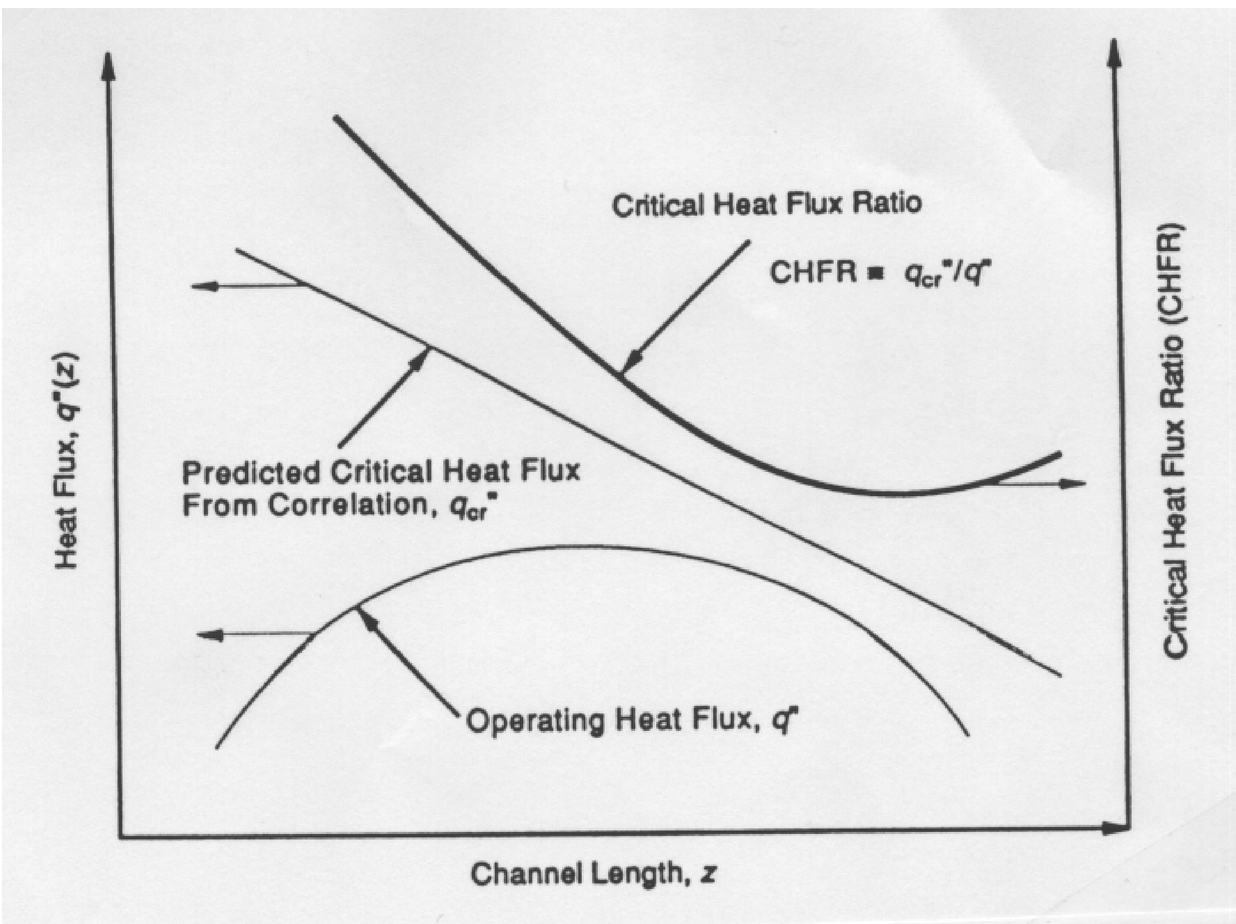

Figure 3.1: Critical Heat Flux Ratio

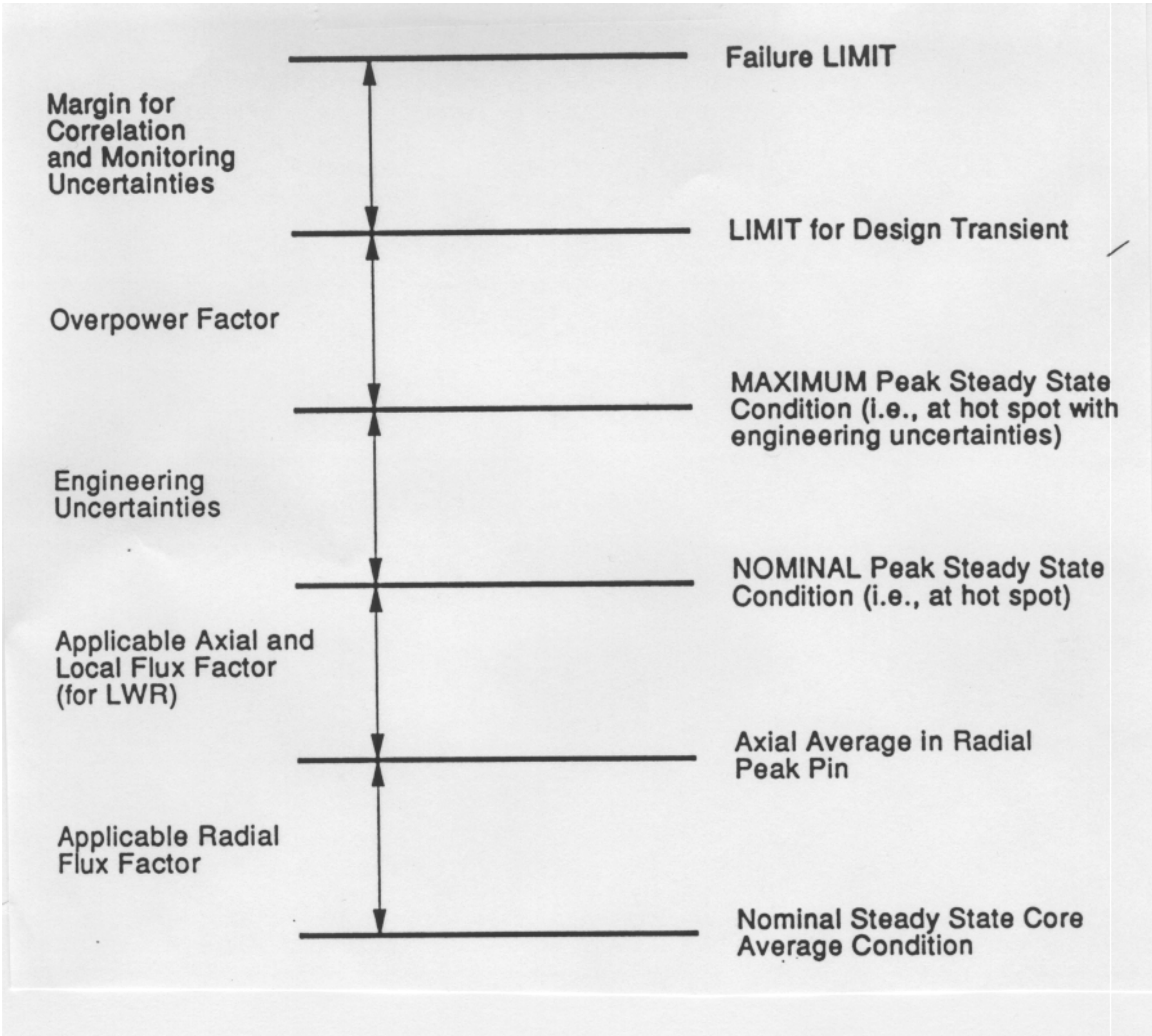

Figure 3.2: Thermal Design Margins

3.3 Steam Generator Heat Transfer

[GAR96]

3.4 Primary Side Flow

[GAR69]

The primary pumps are the vital component in the reactor Heat Transport System (HTS) because the primary function of the reactor HTS is to provide continuous cooling of the reactor core in normal operation, transient and during reactor shutdown. HTS pump start-up and shut-down is a routine operation of the reactor HTS. Pumps failures, due to loss of power or inadvertent operator action, are events of relatively common occurrence in all nuclear power plants.

Accurate prediction of pump performance includes specification of its head (H), torque (τ), discharge or volumetric flow rate (Q), and rotor speed (ω). The pump motor, by exerting a torque on the rotating shaft, provides energy to the impeller which creates the flow associated with a head increase from the suction to the discharge side.

During any transient, the pump motor provides torque for:

- overcoming frictional resistance and any local losses in the loop (piping, valves, core, etc.)
- overcoming frictional losses in the pump rotating parts
- acceleration of fluid in the loop
- acceleration of pump rotating parts (including the flywheels)

For a pump, only two parameters can be considered independent among, H, Q, τ and ω. The other two are determined from the pump characteristics. It is commonly assumed that the pump steady-state characteristics also hold for transient conditions. The pump characteristics are described by the specific relationships, called homologous relationships):

$$\frac{H_1}{\omega_1^2} = \frac{H_2}{\omega_2^2}, \text{ and, } \frac{Q_1}{\omega_1} = \frac{Q_2}{\omega_2}, \text{ which leads to } \frac{H_1}{Q_1^2} = \frac{H_2}{Q_2^2} \tag{3-1}$$

A more realistic relationship, usually available from tests, relates the head to both volumetric flow and the angular velocity of the pump:

$$\frac{H_1}{\omega^2} = a_1 + a_2\left(\frac{Q}{\omega}\right) + a_3\left(\frac{Q}{\omega}\right)^2 \tag{3.2}$$

The common approach is to use non-dimensional parameters with respect to the rated conditions (rated conditions refer to the rated quantities, which represent the point of pump best performance):

$$h \equiv \frac{H}{H_R}; \quad \nu \equiv \frac{Q}{Q_R}; \quad \alpha \equiv \frac{\omega}{\omega_R}; \quad \beta \equiv \frac{\tau}{\tau_R} \tag{3.3}$$

The above non-dimensional parameters are used to express pump homologous relationships in a similar form as shown by Eq. (3.2), in which the actual parameters are expressed by their non-dimensional forms. Homologous relationships of this forms are used in the computer programs describing pump behavior.

Figure 3.3 shows the four possible types of operation of a pump, e.g., the four quadrants of pump operation. Normally, the pump computer models are capable of simulating pump performance in any of the four quadrants. During a coastdown transient the pump may pass from the normal pumping region, quadrant I, through reverse flow but positive rotation region, quadrant II, to reverse flow and rotation, quadrant III, unless the rotor is equipped with anti-reverse ratchet to avoid this quadrant (such as in most reactor HTS pumps).

In postulated events with breaks at the pump suction or discharge side, and different logic of the pump operation control, pump can operate in any of the first three quadrants. Thus pump tests are performed to develop pump homologous relationships for all four possible operating quadrants.

Pump characteristics under severe transient flow conditions have been tested and investigated. One of the most important conditions that needs to be avoided in operation of the reactor HTS pumps, is the bubbly flow regime. Figure 3.4 shows pump characteristics in forward flow operation with bubbles present in the flow. Obviously pump characteristics deteriorate dramatically following initiation of bubble formation in the pump suction.

One of the most important objectives of the HTS flow design is to make sure that the pump suction pressure does not fall below the Net Positive Suction Head Required (NPSHR). In order for a pump to deliver its rated output it is necessary that the absolute pressure (including the velocity head $V^2/2g$) of the fluid at the pump inlet exceeds the vapor pressure by an amount sufficient to overcome any entrance or frictional losses between the point of entry into the pump and the impeller. Thus, the NPSH is defined as the absolute pressure at the pump inlet expressed in meters of liquid, plus the velocity head, minus the vapor pressure of the fluid at pumping temperature, and corrected to the elevation of the pump centreline in the case of horizontal pumps, or to the entrance of the first-stage impeller for vertical pumps.

NPSHR (required) is determined by the pump manufacturer and is a function of both pump speed and pump capacity. NPSHA (available) represents the energy level of the fluid over the the vapor pressure at the pump inlet and is determined entirely by the system preceding the pump. Unless NPSHA$\geq$NPSHR at any condition of operation, some of the fluid will vaporize in the pump inlet and bubbles of vapor will be carried into the impeller. These bubbles will collapse violently at some point downstream of the pump inlet (usually at some point at the pump impeller surface) as the pressure is increased in the pump, and produce a very sharp, crackling noises, frequently accompanied by physical damage of pump impeller surface. This phenomenon is know as cavitation and is very undesirable (in fact represents a micro water hammer effect on the impeller surface). The net mechanical effect of the cavitation is pump vibration and damage of the impeller, whereas the net effect of pump performance is loss of pump efficiency and pump head.

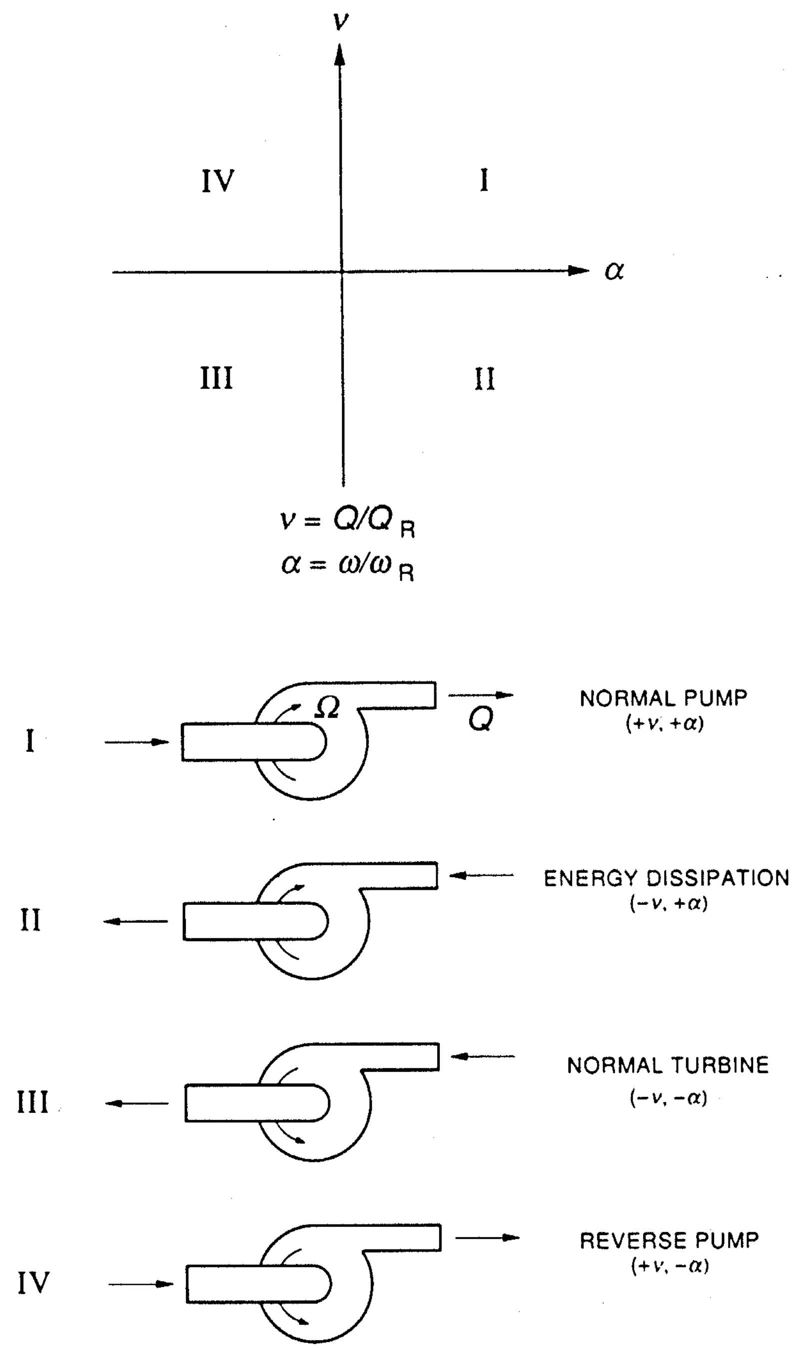

Figure 3.3: Pump Different Regimes of Operation

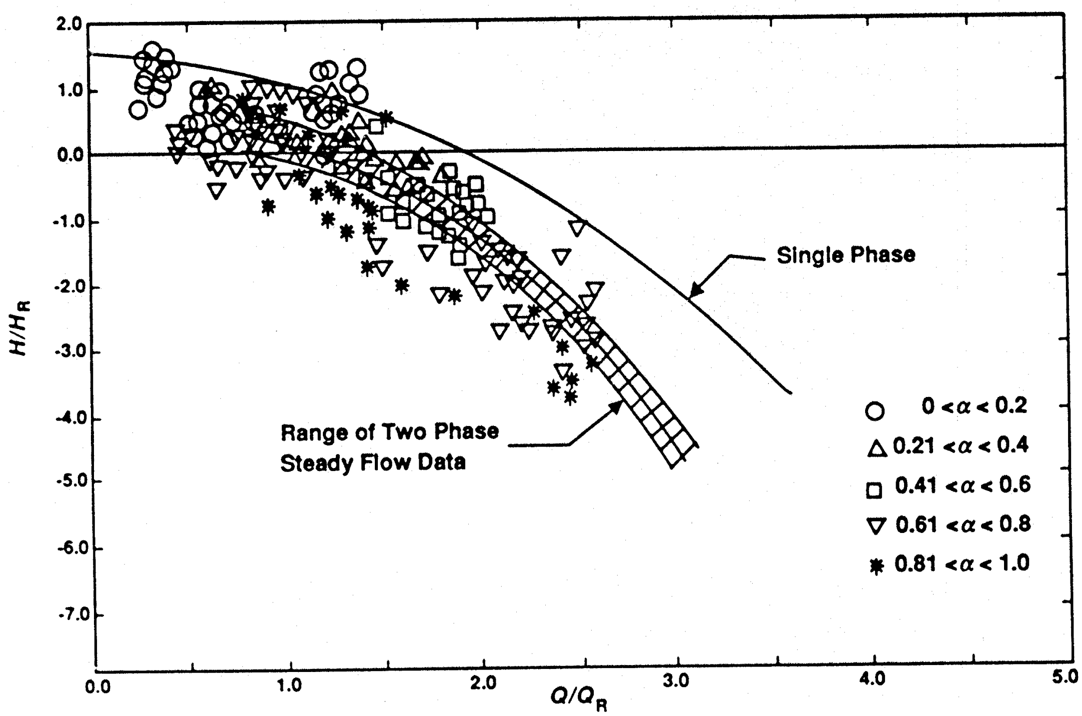

Figure 3.4: Pump Characteristics in Two-Phase Flow Operation