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Transient CHF in Rod Bundle under SMR Conditions

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1. Introduction

Under transient conditions in nuclear reactor core, the CHF phenomena is governed by various physics such as neutron physics coupled with reactivity feedback, fuel heat conduction, convective heat transfer and burnout at fuel rod surface, and so on. Considering the CHF mechanisms near the heater surface, a certain period of time must elapse before the liquid layer at the surface completely evaporated after the onset of CHF occurrence. In a power increase transient, for example, the surface heat flux continues to increase during this elapsing time. Thus, the surface heat flux at complete dryout is higher than the steady-state CHF in this case. This heat flux is referred to as the transient CHF.

True transient simulation of CHF is difficult due to complicated conjugate problem under two-phase flow conditions and insufficient understanding of CHF phenomena. Thus CHF under transient condition is usually predicted by the quasi-steady approach. The conjugate problem addresses the coupled equation set that combines fluid conservation equations with heat conduction equation within a bounding wall. The quasi-steady approach assumes that the wall-to-fluid heat transfer is known from the local-instantaneous fluid parameters. This assumption is valid when the fluid responds more quickly than the wall. The validity of quasi-steady approach is more restrictive at two-phase flow conditions because the response time in two-phase flow is much larger than that in single-phase flow. It is known that the quasi-steady approach yields erroneous results for fast transients where the transient time constant is smaller than the phenomena time constant[1]. In addition, some difficulties may be caused associated with the selection of time-step size when different phenomena are being analyzed simultaneously as usually appeared in multi-physics analysis.

Many studies have been conducted experimentally and analytically to investigate the characteristics of CHF under various power-flow-pressure transient conditions[2,3]. For power transients, nonquasi-steady analysis have been conducted on the basis of mechanistic CHF models. For a pool boiling system Serizawa[4] assumed that CHF occurs because of a balance between the consumption of a thin liquid layer formed between a vapor blanket and a heated surface, and the supply of liquid during the postulated transient. It was found that the liquid layer thickness is a primary influence on the transient burnout behavior as well as the liquid supply to the layer. Pasamehmetoglu[5] suggested a theoretical model at low quality DNB-type transient CHF under flow boiling by accounting for the near-wall bubble crowding mechanism. The rate-of-change of the liquid layer thickness underneath the bubbly boundary layer on the heater surface is the governing parameter in evaluating transient CHF.

Transient CHF in rod bundle for a water-cooled SMR is investigated in this study. In SMR the transient time constant is usually smaller than commercial PWRs. It is mainly due to a relatively large reactivity change in the small core for reactivity induced accidents, and a lower pump inertia that results in a rapid decrease of flow after pump trip. The appropriateness of a quasi-steady approach was examined by conducting transient CHF experiments for rod bundle which is applicable to a water-cooled SMR, named SMART. The CHF behavior under various flow and/or power transients were experimentally observed. The applicability of the steady-state CHF prediction model was examined through a quasi-steady analysis of the transient CHF data using a subchannel code.

2. Transient CHF Experiments

2.1 Description of Test Facility

The CHF experiment has been conducted in a high-pressure water test loop at Stern Laboratories in Canada. The test bundle simulates fuel assembly which is applicable to SMART core. As illustrated in Fig. 1, the major components of the test loop consists of test section, gas pressurizer, mixers, heat exchangers, condenser, main coolant pump, and preheater. The test section includes the pressure housing, flow channel, fuel simulators, spacer grids, and instrumentation. The test bundle consists of twenty-four indirectly heated rods with a 9.5 mm outer diameter, and one central unheated rod with a 12.24 mm outer diameter. The axial power shape is center-peaked non-uniform shape with a peaking factor of 1.51. The test section and test loop were instrumented to measure the power, flow rate, absolute/differential pressures, and coolant temperature during testing.

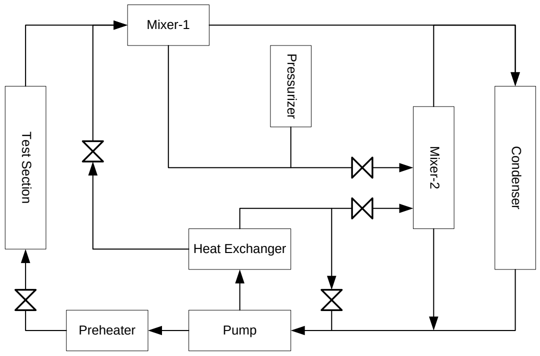


Fig. 1. Schematic of CHF test loop

2.2 Test Procedures

Three types of transient CHF experiments was conducted with various ramp rates for power and flow as summarized in Table I.

__Power transient tests__: For the power transient CHF tests, the power was increased from 50% of the steady-state CHF value to incrementally increasing values (repeated) until dryout was reached. Different time constants for the transients were achieved with two different time intervals, 5.0 seconds (slow) and 0.42 seconds (fast), to investigate how the power ramp rate affected CHF. This was performed for two different initial starting conditions to cover a range of mass flux.

__Flow transient tests__: For the flow transient CHF tests, the flow was decreased from about 180% of the target value to the target values (repeated) until dryout was reached. Two different time intervals, approximately 4.5 and 1.0 seconds, were considered to simulate slow and fast ramp rates. The influence of flow ramp rate on CHF was investigated for two different initial starting conditions.

__Combined power and flow transient tests__: Two series of combined power and flow transient CHF tests were performed for code validation under simulated accident conditions, a loss of flow accident and a reactivity insertion accident. For these tests, the initial pressure, inlet temperature and flow were set to the starting conditions as listed in Table I. Initially, the starting power was set to a value that did not result in dryout during the transient and was incrementally increased (repeated) until dryout occurred.

Table I. Transient CHF test conditions

Case ID	Pressure (MPa)	Tin (°C)	Flow (kg/m^2-s)			Power (kW)		
			Initial	Target	Δt	Initial	Target	Δt
Power Transients								
Q-1	14.3	300	500			0.5 Qc	Qc	5.0
Q-2						0.5 Qc	Qc	0.42
Q-3			1300			0.5 Qc	Qc	5.0
Q-4						0.5 Qc	Qc	0.42
Flow Transients								
G-1	15.6	300	1440	~800	4.0	Qc		
G-2			1440	~800	1.0	Qc		
G-3	12.0	260	1500	~800	4.7	Qc		
G-4			1500	~800	1.0	Qc		
Combined Flow/Power Transients								
QG-1	15.6	300	1430			1145		
QG-2	15.6	300	1430			921		

2.3 Test Results

CHF at steady-state condition (CHF_{SS}) was measured for comparison with the transient CHF (CHF_{TR}) at pre-determined target conditions. For the power or flow transient cases, CHF_{SS} was measured at the specified pressure, inlet temperature and (target) flow conditions. As shown in Fig. 2 the flow transients do not affect CHF significantly. For the power increasing transients, however, the transient effects are prominent at various ramp rates. In most cases, it was observed that the CHF_{TR} is greater than CHF_{SS}.

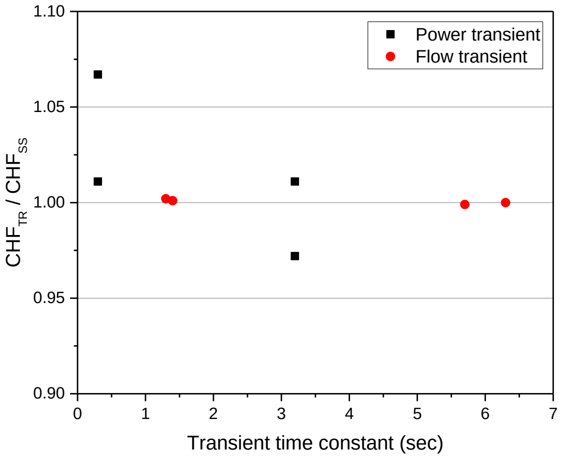
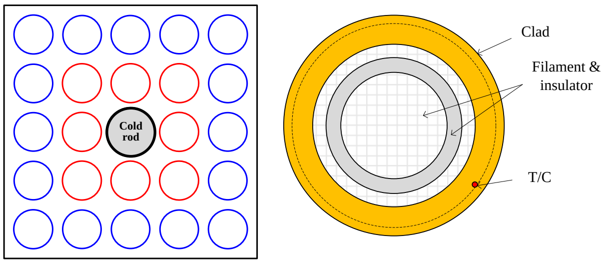


Fig. 2. Comparison of transient CHF with corresponding steady-state CHF at various transient time constants

3. Analysis of Transient CHF Data

3.1 Heater Rod Simulation

The transient CHF test was conducted using a 5x5 test bundle as shown in Fig. 3. The indirectly heated fuel simulator consists of Inconnel-718 resistance filament surrounded by boron nitride insulation and enclosed in clad tube. The K-type thermocouples are located at inner surface of the clad tube. The heat generated in the filament material is transferred to the clad surface by conduction. The surface heat flux variation during power transients are calculated by a quasi-steady analysis using the MATRA code[6] by homogenizing the interior region (i.e., filament and insulator region) of heater rod.



Test Bundle Heater Rod

Fig. 3. CHF test bundle and heater rod

3.2 Quasi-steady Analysis of Transient CHF

In the quasi-steady analysis of CHF, the local-instantaneous (actually, averaged over the channel cross-section and the time interval) values of CHF parameters are used in a steady-state CHF correlation. These parameters including the rod heat flux are computed by the MATRA code with a quasi-steady approach to the transient conjugate problem. That is, the local-instantaneous value of the convective heat transfer coefficient is used to solve the heat conduction equation.

Time variations of the rod heat flux and DNBR during a power-flow combined transient are illustrated in Fig. 4. At the early stage of the transient (until about 11 sec), the clad surface temperature increases due to a decrease of heat transfer coefficient mainly caused by a rapid reduction of flow rate at the initial pump coast-down region. This results in a decrease of surface heat flux more rapidly than the decrease of heater power. Thereafter a delay of heat flux variation is observed due to the heat capacity of heater rod. The clad temperature decreases when the flow decay curve is stabilized (elapsed about 11 sec), and then the heat flux varies in accordance with the power variation.

Time to CHF occurrence (t_{CHF}) during transients were predicted by a quasi-steady approach using the MATRA code with the EPRI CHF correlation[7]. It is determined at the time when the DNBR becomes minimum during the transient as shown in Fig. 4. From the analysis results shown in Fig. 5, it was revealed that the predicted t_{CHF} is smaller than experiments for the power related transients. This implies that the quasi-steady approach with steady-state CHF correlation conservatively predicts CHF under power increasing and/or power-flow combined transients.

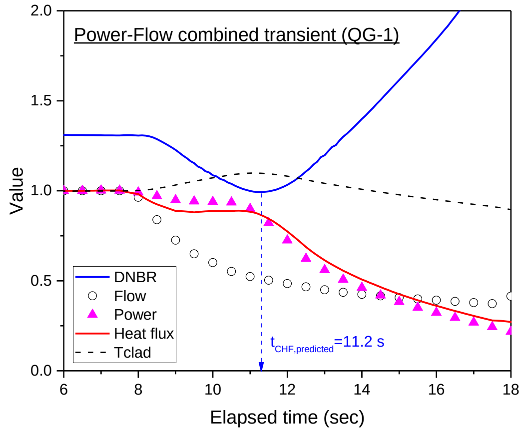


Fig. 4. Transient CHF analysis using MATRA code

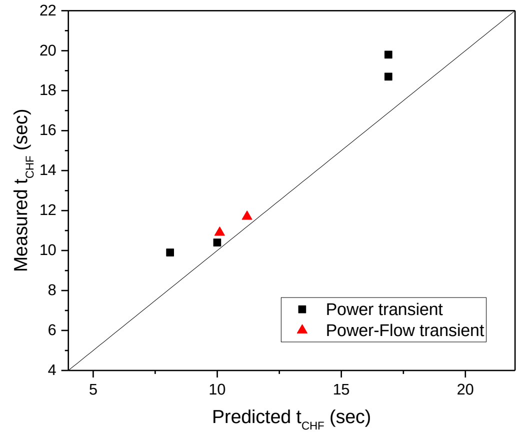


Fig. 5. Comparison of t_{CHF} for power related transients

4. Conclusions

Characteristics of transient CHF in a rod bundle was experimentally investigated under power, flow, and power-flow combined transient conditions. A quasi-steady approach was applied to predict transient CHF with a subchannel analysis code MATRA and a steady-state CHF correlation. From the analysis results for the time to CHF occurrence, a conservatism or adequacy of the quasi-steady approach was appeared.

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