TRANSIENT CRITICAL HEAT FLUX UNDER FLOW COASTDOWN IN VERTICAL ANNULUS WITH NON-UNIFORM HEAT FLUX DISTRIBUTION


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Abstract
An experimental study on transient critical heat flux (CHF) under flow coastdown has been performed for water flow in a non-uniformly heated vertical annulus under low flow and a wide range of pressure conditions. The objectives of this study are to systematically investigate the effect of the flow transient on the CHF and to compare the transient CHF with steady state CHF. The transient CHF experiments have been performed for three kinds of flow transient modes based on the coastdown data of the Kori 3/4 nuclear power plant reactor coolant pump. Most of the CHFs occurred in the annular-mist flow regime. Thus, it means that the possible CHF mechanism might be the liquid film dryout in the annular-mist flow regime. For flow transient mode with the smallest flow reduction rate, the time-to-CHF is the largest. At the same inlet subcooling, system pressure and heat flux, the effect of the initial mass flux on the critical mass flux can be negligible. However, the effect of the initial mass flux on the time-to-CHF becomes large as the heat flux decreases. Usually, the critical mass flux is large for slow flow reduction. There is a pressure effect on the ratio of the transient CHF data to steady state CHF data. Some conventional correlations show relatively better CHF prediction results for high system pressure, high quality and slow transient modes than for low system pressure, low quality and fast transient modes.

Introduction
Presently, many aspects of CHF phenomena are well understood and several reliable prediction methods are available for most of the operating conditions of nuclear reactors. However, the CHF behavior in low flow conditions is not well identified, which is of importance in the safety of nuclear reactors during operational transients and accidents such as LOCA (Loss-Of-Coolant Accident). The CHF under low flow conditions plays an important role in thermal hydraulic behavior for accident analyses of LWR, research reactors, and advanced nuclear reactors. However, most of the experimental studies for CHF under low flow conditions have been performed under atmospheric pressure conditions.

In a nuclear reactor core, the CHF is more likely to happen during abnormal transients or accident conditions rather than during normal or steady state conditions. Therefore, the understanding on the effects of transients on the CHF is very important for studying the CHF of nuclear power plants (Chang et al., 1998). The research on the transient CHF until now has been focused on the effect of the magnitude of transients and the prediction methods using correction factors to reflect the transient...
Recently, present authors have performed CHF experiment using a vertical annulus test section with non-uniform axial heat flux in low-flow and wide pressure conditions. As an extension of the steady state CHF experiments, the present paper shows the results of the flow transient CHF experiment. Flow coastdown of the reactor coolant pump of Kori 3&4 (PWR type Korean Nuclear Power Plant) have been simulated to investigate the flow transient effects on CHFs and compare the flow transient CHF data with the steady state CHF data. Three kinds of flow transients are simulated in the present experiments; normal, slow and fast modes according to the decreasing rate of the flow rate.

**Nomenclature**

- $G_0$: Initial mass flux
- $G_c$: Critical mass flux (at CHF)
- $L$: Heated length
- $P$: System pressure
- $Q_c$: Total power from inlet to exit
- $q(Z)$: Local heat flux at $Z$
- $q_c$: Average heat flux from inlet to exit
- $T$: Temperature
- $t$: Time
- $t_c$: Time-to-CHF
- $X_e$: Thermodynamic quality at exit (critical quality)
- $Z$: Axial location from inlet

**Greeks**

- $\Delta H_n$: Inlet subcooling

**Subscripts**

- $c$: CHF location or critical
- $ex$: Exit
- FT: Flow transient
- NU: Non-uniform
- ST: Steady state
- Wall: Heater surface

**Test Description**

Figure 1 shows a schematic diagram of the test facility where the present CHF experiments are performed. It consists of a main circulating pump, a preheater, a CHF test section, a steam/water separator, a condenser, a pressurizer and a cooler. The flow rate is controlled by the adjustments of the motor speed of the circulating pump, the flow control valve and the bypass control valve. The flow oscillations that are usually observed in low flow conditions are effectively suppressed by a throttle valve installed at the inlet of the test section. The preheater adjusts the degree of inlet subcooling at the inlet of the test section. The steam generated in the test section is condensed through the condenser attached in the steam/water separator. The system pressure is maintained at a setting value using a pressurizer with an immersion heater of 40 kW.

As shown in figure 2, the annulus test section consists of an outer pipe with a 19.4 mm inside diameter and an inner heater rod with a 9.53 mm outer diameter. The inner heater rod is heated indirectly by AC power. Six K-type thermocouples with a sheath diameter of 0.5 mm are embedded on the surface of the heater rod to measure the surface temperatures of the heater rod and detect CHF occurrence. The inner rod having a heated length of 1843 mm is uniformly divided into ten steps.
to simulate a symmetric chopped cosine axial heat flux profile, as shown in figure 3. Figure 3 also shows the thermocouple locations and the approximate axial heat flux profile. Using the test section with a non-uniform axial heat flux, a total of 118 CHF data for three kinds of transient modes have been collected for inlet water subcooling ranging from 86 to 353 kJ/kg, initial mass fluxes of 650 and 550 kg/m$^2$s, system pressure from 0.54 to 10.48 MPa, exit quality from 0.02 to 0.63, and time-to-CHF (time to the CHF condition from the start of flow transient) of 2.38 to 177.78 seconds. The initial mass fluxes chosen in the present experiments do not correspond to those at the typical PWR normal operating conditions. Therefore, we do not simulate the magnitude of mass flux but the coastdown trends only.

The uncertainties in measurement are less than $\pm 0.3\%$, $\pm 1.5\%$, $\pm 0.6\%$ and $\pm 1.0\%$ of the readings for pressure, mass flux, temperature and power, respectively. The measured data are recorded, processed and stored in a data acquisition and control unit. During each transient simulation, the system parameters are maintained within $\pm 0.048\%$, $\pm 0.004\%$, $\pm 0.018\%$, $\pm 0.058\%$ for given system pressure, inlet fluid temperature, heat flux, and inlet subcooling, respectively, with 95% confidence level.

The CHF experiments are performed by the following procedures. After setting the initial flow rate, inlet subcooling, pressure and total power to the test section at the desired values, the flow rate is decreased by speed control of the main coolant pump according to the required transient mode. This process continues until maximum wall temperature exceeds a predefined value. After that, the test section flow rate is increased to protect the test section failure due to CHF. CHF time is defined as the initiation time when the excursion of wall temperature of the heater rod starts. About 72% of CHFs are occurred at the thermocouple No. 2 located 200 mm upstream the exit of test section. Thus, CHF data analyses are approximately performed using the average heat flux from inlet to outlet and critical quality defined at the outlet of the test section.

Figure 4 shows the mass flux as a function of time based on the coastdown curve of the reactor coolant pump of Kori 3 and 4 nuclear power plants. The normal mode means the exact coastdown curve of the nuclear power plants. The fast and slow modes simulate the square and the square root of the normal coastdown curve. As shown in Figure 6, the fast and normal modes of the flow transient are not well simulated due to the limit of the speed control of the main coolant pump and the interactive effects between the flow rate and the pressure drop in the present experimental loop.

**EXPERIMENTAL RESULTS**

**Parametric Trends**

Figure 5 shows the measured heater wall temperature and the inlet mass flux. As shown in the figure, as the mass flux decreases, the heater wall temperature increases abruptly when the CHF condition is reached. When the flow regimes of the present data at CHFs are assessed with a rough estimate by the conventional flow regime map for round tubes, the flow regimes are revealed to be the annular-mist flow. It means that the CHF occurs when the liquid film is dried out by depletion of the liquid film on the surface of the heater rod.

Figure 6 shows the time-to-CHF for three flow transient modes at the same inlet subcooling test section power and system pressure. As shown in the figure, the CHF occurs most early in the fast transient and most lately in the slow transient. However, the critical mass fluxes at the CHF conditions have the largest values for the slow transient and the smallest values for the fast transient. These critical mass fluxes are lower than those of the steady state CHF conditions at the same system pressure, total power and inlet subcooling.

Figures 7 and 8 show the critical mass flux and the critical exit quality for three flow transient modes at the same system pressure and heat flux. As shown in these figures, the critical mass flux
decreases and the critical exit quality increases as inlet subcooling increases. The slow transient has the largest critical mass flux and the smallest critical exit quality. On the other hand, the fast transient has the smallest critical mass flux and the largest critical exit quality.

**Effect of Initial Mass Flux on the Flow Transient**

Figures 9 and 10 show the effect of the initial mass flux on the flow transient CHF. As the test section power increases, the critical mass flux increases and the exit critical quality decreases. Even if the initial mass flux of 550 and 650 kg/m$^2$s is somewhat different, the critical mass fluxes are not different as much. Because of the same test section power and inlet subcooling, the initial quality at the exit of the test section is 1.3 to 3 times larger for low mass flux of 550 kg/m$^2$s than the case of high mass flux of 650 kg/m$^2$s. However, the critical qualities at the exit of the test section show somewhat similar values for both conditions. The main difference by the difference of the initial mass flux is the time-to-CHF as shown in figure 11. The time-to-CHF for the lower initial mass flux is about 75.6% smaller than that for the higher initial mass flux. The figure also shows that the effects of transient mode on CHF disappear for high heat flux conditions, giving the similar critical mass fluxes. The effect of test section average heat flux on the time-to-CHF becomes small as the test section average heat flux increases.

**Comparison with Steady State CHF**

The flow transient CHF data have been compared to the steady state CHF data having the same geometry (Moon et al., 2000). Figure 12 shows the critical mass flux ratio against system pressure for three flow transient modes. Here, the subscripts FT and ST mean the flow transient and the steady state, respectively. As shown in the figure, at low system pressure, the critical mass flux for the flow transients has a higher value than that for the steady state CHF condition. This might be a premature CHF due to an instability that usually occurs in low pressure and low flow conditions. However, for the case of low system pressure, the critical mass flux for the flow transients has a lower value than that for the steady state CHF condition. As shown in figure 13, except for low system pressure, most of the critical exit qualities for the flow transient have higher values than the steady state CHF condition.

**Prediction Results Using Inlet Mass Flux**

In flow transient CHF experiments, it is difficult to obtain the outlet local parameters because the local mass flux is not the same as the inlet mass flux due to some delay. Therefore, we should use a transient thermal-hydraulic code to obtain local parameters. However, such a delay is observed only for very fast flow transient conditions. By preliminary analyses for the present CHF data, it was possible to assume that there is no significant delay in mass flux. Therefore, we can calculate local parameters for whole test section using inlet conditions such as temperature and mass flux. Based on this assumption, we compared the present CHF data with the conventional CHF correlations without using any thermal-hydraulic code.

Figures 14 through 16 show the prediction results for critical mass flux and time-to-CHF using Doerffer et al. (1994) correlation using AECL 1986 (Groeneveld et al., 1986) and 1995 (Groeneveld et al., 1995) Look-Up Tables, and Bowring correlation (1977). The flow transient CHF conditions are calculated as follows: Given the total power and the axial heat flux distribution, local parameters such as the local heat flux and local quality are calculated at each location $Z$ where the test section is divided into 100 locations from inlet to exit. By preliminary study, the step size (18.43 mm) was found not to affect the CHF prediction results. Using CHF correlations, a local CHF value is calculated at each time step and each location $Z$ using the local conditions calculated before. If the local heat flux is
equal to the local CHF value that is predicted by the correlations, it is judged that the CHF occurs at that point. Otherwise, the calculation proceeds to the next time step. If the CHF does not occur until the termination of the flow transient, the inlet mass flux is assumed to decrease following flow transient curves.

As shown in Figures 14 and 15, the critical mass flux is under-estimated and the time-to-CHF is over-estimated. Thus, the flow transient CHF conditions are predicted to occur later than the experimental data, regardless of the correlations. As shown in Figure 16, the three correlations show better prediction results as the system pressure increases. The worse prediction results at low system pressure might be due to the prediction capability itself at low system pressure and some flow instability. The prediction results become better at high quality, high system pressure and slow transient modes. As the flow transients become faster, in general, the outlet mass flux does not coincide with the inlet mass flux. Thus, for fast transients, there are some delays in local (outlet) mass flux and quality. This factor might be the cause of the worse prediction results for fast transients.

**Prediction Results Using System Code**

The experimental CHF data obtained under the flow transients are assessed with the thermal hydraulic system code, RELAP5/MOD3.2. The test section is non-uniformly nodalized to have 40 nodes in total. The upper region of the test section has more fine nodes than the lower region. It is evident that the liquid film in the annular geometry is split to exist on both walls, i.e., an inner heating rod and an outer cold wall. However, it was found out that the system code such as RELAP5/MOD3.2 does not show satisfactory results due to the film split. The predictions of RELAP5/MOD3.2 give much delay in time for the flow transient conditions. It means that the calculated critical mass flux is much lower than the experimental data.

In order to overcome the film split problem in the system code, the annular flow area is split to two regions based on the location in which interfacial shear stress becomes zero. Thus, the flow area simulating the liquid film on the heating rod is found to be 38.5% of the total area. Inlet mass flux is also reduced at the same ratio. This concept is based on the premise that liquid flow entering the test section is split to two regions and CHF would occur when the liquid film on the inner heating rod side is dried out. Local parameters such as local quality, mass flux and wall temperature of the heater rod are predicted using RELAP5/MOD3.2. Figure 17 shows the wall temperature trace and the excursion of wall temperature (i.e. CHF occurrence) coincides with those of experimental data. Therefore, it can be concluded that CHFs occurring in annular geometry can be reasonably predicted if the flow area and inlet mass flux are reduced according to the location of zero interfacial shear stress.

**Conclusions**

CHF experiments were conducted to observe the effects of flow transients on the CHF and to compare the flow transient CHF data with the steady state CHF data in an annulus having a non-uniform heat flux profile under low flow and a wide range of pressure conditions. From the experiments, the following conclusions have been obtained:

1. The CHF condition is reached early at fast flow transients and lately at slow flow transients. However, the critical mass fluxes have the smallest value at fast flow transients and the largest value at slow flow transients.
2. For the present experimental conditions, most of the critical mass fluxes at flow transients have smaller values than steady state CHF data. Thus, even if at the same system pressure, inlet subcooling and heat flux, the CHF is delayed at flow transients.
3. The effect of initial mass flux on the flow transient CHF is negligible.
4. Most of the flow transient CHF data occur in the annular-mist flow regime and the CHF
mechanism might be the liquid film dryout by depletion of the liquid film on the heater surface.

(5) As inlet subcooling increases, the critical mass flux decreases and the critical exit quality increases. The slow flow transients have the largest critical mass flux and the smallest critical exit quality.

(6) For low system pressure, the critical mass flux for flow transients has a somewhat larger value than the steady state CHF condition. However, for other system pressure, most of the critical mass fluxes for flow transients have smaller values than steady state CHF conditions.

(7) The Doerffer et al. and Bowring correlation show better prediction results for high system pressure, high quality, and slow transient modes rather than for low system pressure, low quality and fast transient modes.

(8) RELAP5/MOD3.2 shows good prediction results for the heater wall temperature trends. Therefore, it can be concluded that CHFs occurring in annular geometry can be reasonably predicted if the flow area and inlet mass flux are reduced according to the location of zero interfacial shear stress.

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References


Fig. 1. KAERI RCS loop schematics

Fig. 2. Test section geometry and thermocouple location
Fig. 3. Heat flux profile of the test section

Fig. 4. Flow transient modes

Fig. 5. Parametric trends of heater wall temperature and mass flux
Fig. 6. CHF occurrence time against flow transient mode

Fig. 7. Effect of inlet subcooling on critical mass flux

Fig. 8. Effect of inlet subcooling on critical exit quality
Fig. 9. Effect of initial mass flux on the critical mass flux

Fig. 10. Effect of initial mass flux on the critical exit quality

Fig. 11. Effect of initial mass flux on time-to-CHF
Fig. 12. Comparison flow transient CHF with steady state CHF

Fig. 13. Comparison flow transient CHF with steady state CHF

Fig. 14. Critical mass flux prediction results
Fig. 15. Time-to-CHF prediction results

Fig. 16. Critical mass flux prediction results

Fig. 17. Critical mass flux prediction results