Safety Limit Estimation of Natural Circulation Loop in EU-APR1400 Ex-vessel Core Catcher system

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1. Introduction

Since the early 2000s, in Europe, there has been a stronger demand for regulatory requirement for the rigorous safety of the nuclear power plant, the environment in the vicinity of the plant and the public. Instead of IVR, an ex-vessel strategy is adopted to meet the demand for the significantly improved safety. That is, a so-called ex-vessel core catcher system to cool down the molten core generating decay heat is required for the license. In such an ex-vessel strategy, the core catcher system is designed for retention and cooling of molten materials of nuclear fuels and structures. In the system, the molten materials spread on a large area, and experience more effective cooling by water flowing. The ex-vessel strategy has been internationally adopted in several nuclear reactors, such as EPR1600, ABWR, VVER1000, ESBWR, EU-APR1400.

On the basis of aforementioned core catcher designs in overseas, KAERI could develop an ex-vessel core catcher for EU-APR1400, having many positive features found in the existing core catcher designs. The potentially adopted layout of the ex-vessel core catcher concept is presented in Fig. 1.

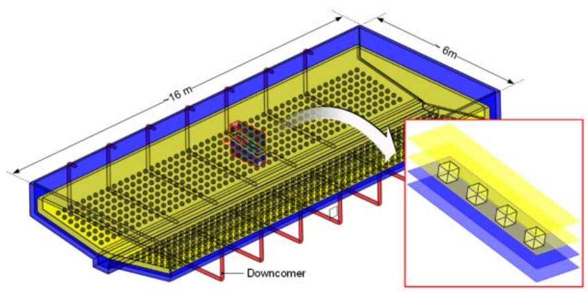

Fig. 1. Principal layout of EU-APR1400 ex-vessel core catcher concept.

Decay heat generated from the molten corium is removed by the boiling of water. The cooling system consists of a cooling channel and amid the core melt spreading compartment and inside wall of the reactor cavity. Many short columnar structures are placed at the cooling channel to provide coolant flow paths underneath the core catcher body. The channel consists of a vertical channel and a 10° inclined channel.

We should pay attention to a large dimension of the slightly inclined heated surface through which the decay heat is removed by boiling heat transfer. Based on the physical background, this paper suggests a trend in which the downward facing CHF varies along with heater size under pool boiling condition, as shown in Fig. 2. In Fig. 2, heater size can be classified into three types, such as small, medium, and large-sized heater. The small-sized heater is characterized by a weak bubble coalescence process, and corresponding wide path through liquid can be supplied to the heater surface easily. If the heater dimension is sufficiently large to form a large bubble at a heat flux level far lower than the CHF, the heater can be called as the medium-sized heater. The large-sized heater can be characterized by a frequent formation of very large bubbles elongated in the direction toward the exit, and their high velocity due to large buoyancy force exerted on them of large volume. Such speedy movement of the large bubble enhances the liquid entrainment from bulk region to the heater surface behind the bubble, and accordingly the CHF.

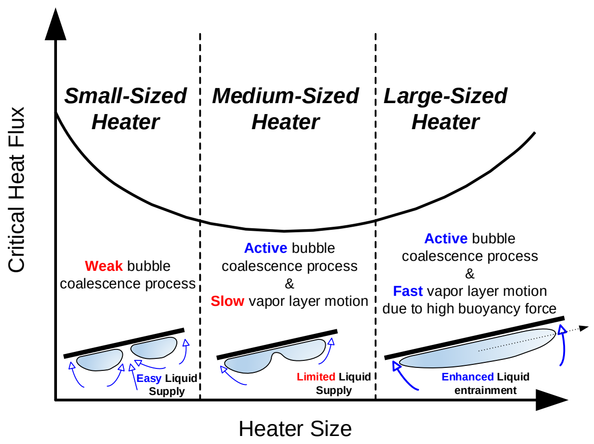

Fig. 2. CHF trend along with heater size for downward facing heater surface.

Even though the CHF values measured in the small and large-sized heater can be apparently similar to each other, the physics involved in the CHF triggering mechanism are different in each heater types. For an adequate and conservative evaluation of thermal margin in EU-APR1400 ex-vessel core catcher, at least a heater configuration of the medium size should be used in production of the CHF database.

As pointed out in Fig. 2, for the large-sized type heater, the two-phase boundary layer moving along the heater surface can have a flow characteristics due to a large buoyancy force even under pool boiling condition. Such flow characteristics is maximized by introducing a natural circulation loop to enhance the thermal margin in EU-APR1400 core catcher cooling system.

Obviously, in a natural circulation boiling system, the rate of circulation depends strongly on degree of liquid subcooling. This is because the driving force for the natural circulation system is the density difference between the unheated water and the heated vapor-water mixture, and higher degree of the liquid subooling lead to a decrease in amounts of vapor in the heated section.

The objective of the present study is to provide a forecast of a relation between CHF and liquid subcooling in EU-APR1400 ex-vessel core catcher cooling channel, and accordingly reasonable prediction of safety limit in the system. Experimental data of natural circulation flow rate from CE-PECS large-scale facility and the subcooled CHF model of Sulatskii et al. (2002) have been incorporated in the forecast as well as the present experimental data of the near-saturated CHF obtained under forced convective condition.

2. Experimental apparatus

In the present study, for the conservative estimates of CHF values, a heater configuration of the medium-sized type was designed. Heater length and width were determined as 216 mm and 108.5 mm, respectively. Channel height was also determined to be 30 mm to sufficiently minimize the direct interaction between the bubble and the unheated wall. The water boiling loop is shown in Fig. 3. More detailed information on the test section assembly, boiling loop, measurement uncertainties can be found in Ref. [1]. In all the present experiments, the absolute pressure at the outlet and inlet subcooling were maintained at 1.07 bar and 5 K, respectively.

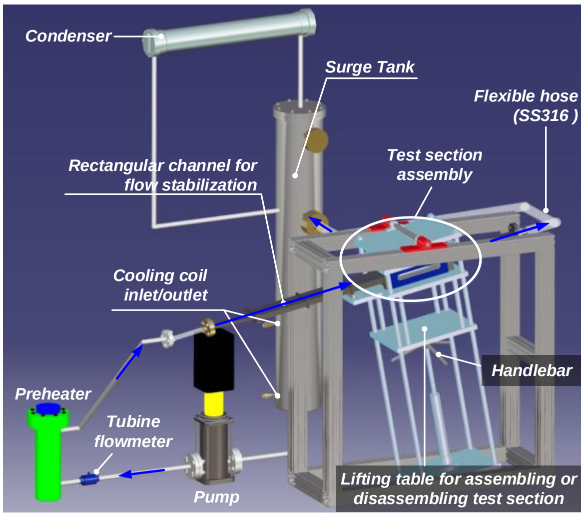

Fig. 3. 3D drawing of the forced convective water boiling loop.

3. Results and Discussion

The local heat flux was used to measure the CHF value, at which a sudden and continuous rise in the surface temperature beyond 200℃ appears simultaneously with an abrupt decrease in the local heat flux, following an incremental increase in the heater power.

3.1 Dependence of CHF on the mass flow rate

The relation between the mass flux and CHF was examined in the test section where studs were not installed. The results, shown in Fig. 4, present CHF variation with mass flux, and predicted CHF values from the existing pool boiling CHF models. A linear proportional relation was confirmed. It is noteworthy that the predicted CHF values from the models of Brusstar and Merte (1994) [2], Sulatskii et al. (2002) [3] are remarkably higher than the CHF value from the present experiment measured under pool boiling condition (G=40 kg/m^2-s). Note that a small-sized heater of 38.1 mm (width) x 19.1 mm (length) was used in the CHF experiments of Brusstar and Merte (1994), while Sulatskii et al. (2002) used a large-sized heater of 104 mm (width) x 2000 mm (length). Such deviation in CHF between them are well in accordance with the CHF trend presented in Fig. 2.

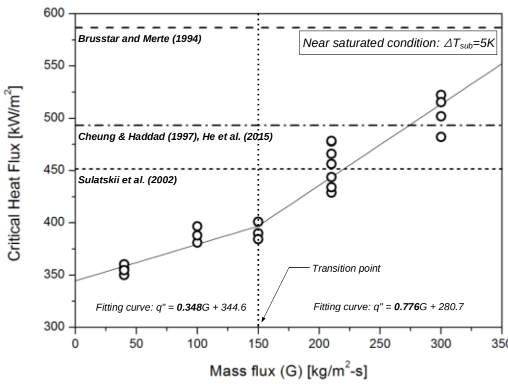

Fig. 4. Dependence of CHF on the mass flux under near saturated condition.

3.2 Natural circulation flow rate data from CE-PECS facility

As a first step for the adequate prediction of CHF with consideration of the subcooling and mass flow rate, the relation between subcooling and natural circulation flow rate was investigated to know the flow rate for a given degree of liquid subcooling. The results on the relation could be found in Song's Ph.D thesis (2017) [4], who utilized the natural circulation facility, called CE-PECS, constructed by a research team at KAERI. Figure 5 presents the natural circulation flow rate as a function of liquid subcooling at a heat flux level of 250 kW/m^2, which is quite smaller than the CHF. The graph clearly shows that the flow rate inversely proportional to the liquid subcooling. Note that the natural circulation flow rates, correspond to the quite low heat flux level, are obviously lower than that of the heat flux level near the CHF. Therefore, the natural circulation data versus the subcooling would lead to conservative estimation of CHF in the prototypic core catcher cooling system.

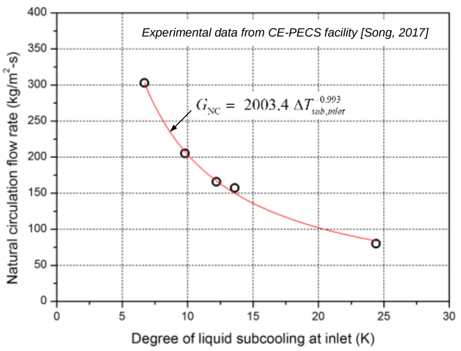

Fig. 5. Natural circulation flow rate versus inlet liquid subcooling at a constant heat flux level of 250 kW/m^2 [Song, 2017].

3.3 Procedures for forecast of a relation between CHF and liquid subcooling

(1) Determination of liquid subcooling at which CHF is desired to be known

(2) Calculation of natural circulation mass flow rate by using an empirically obtained equation, expressed as follow:

$$G_{NC}\left(\Delta T_{sub}\right) = 2003.4\ \Delta T_{sub}^{-0.993} \quad (1)$$

(3) Calculation of CHF value by using Eqs. (2) and (3) obtained based on the present experimental results, shown in Fig. 4, at a mass flux obtained from Eq. (1)

$$q''_{CHF} = 0.348G + 344.6 \quad \left(G < 150kg/m^2\text{-}s\right) \quad (2)$$

$$q''_{CHF} = 0.776G + 280.7 \quad \left(G \ge 150kg/m^2\text{-}s\right) \quad (3)$$

(4) Quantification of the subcooling ratio (R_{sub}) representing the CHF enhancement over the CHF value calculated from the process (3) due to subcooling excluding its effect on the natural circulation flow rate. Such quantification could be done on the basis of a CHF model of Sulatskii et al. (2002). Detailed description on it will be covered below

(5) Calculation of the CHF value at a specific degree of the subcooling by getting the product of the CHF value at subcooling of 5 K and the value of the subcooling ratio (R_{sub}) plus unity as following:

$$q''_{CHF,subM}\left(G\right) = q''_{CHF,sub5}\left(G\right)\left[1 + R_{subM}\right] \quad (4)$$

R_{sub} can be obtained from the CHF model of Sulatskii et al. (2002). They performed CHF experiments under conditions of boiling on an inclined extended (1 to 2m) surface facing downward and immersed in a large pool of water. Their modeling on the subcooled CHF incorporates the effect of the subcooling on vapor mass flow rate along the heater surface by adding a term representing single phase heat transfer to the subcooled liquid in calculation of vapor mass flow rate. Such modeling of the subcooled CHF can be mathematically described as following equation, which consists of dimensionless parameter.

$$Q''_{CHF,sub} = \sqrt{\left(Q''_{CHF,sat}\right)^2 + C_1 Fr_*^2 + C_2\left(\frac{c_{pl}\Delta T_{sub}}{h_{fg}}\sqrt{\frac{\rho_l}{\rho_v}}\right)^2} \quad (5)$$

where

$$Q''_{CHF,sat} = \frac{q''_{CHF,sat}}{q''_{CHF,Kuta}} = \frac{q''_{CHF,sat}}{0.16h_{fg}\sqrt{\rho_v}\sqrt[4]{\sigma g\left(\rho_l - \rho_v\right)}} \quad (6)$$

$$Fr_*^2 = \sin\theta\left(C_3\sqrt{\frac{\rho_l}{\rho_v}} - C_4\frac{\rho_l}{\rho_v}\frac{c_{pl}\Delta T_{sub}}{h_{fg}}\right) \quad (7)$$

$Q''_{CHF,sub}$ and $Q''_{CHF,sat}$ are the dimensionless critical heat fluxes under subcooled and saturated boiling conditions, respectively. $q''_{CHF,Kuta}$ is the CHF correlation derived by Kutateladze (1948). Fr_*^2 is the modified Froude number, and used for the modeling of the inversely proportional relation between the liquid subcooling and the vapor mass flow rate in the two-phase boundary layer. C_1, C_2, C_3, and C_4 are the constants empirically determined based on the CHF data. The explicit equation for the CHF can be expressed as follows:

$$q''_{CHF,sub}\left(\theta\right) = q''_{CHF,Kuta}\sqrt{\sin\theta}\ \sqrt{f_1 - f_2 + f_3} \quad (8)$$

where

$$f_1 = 0.50 + 0.0047\sqrt{\frac{\rho_l}{\rho_v}} \quad (9)$$

$$f_2 = 0.0057\frac{\rho_l}{\rho_v}\left(\frac{c_{pl}\Delta T_{sub}}{h_{fg}}\right) \quad (10)$$

$$f_3 = 0.07\frac{\rho_l}{\rho_v}\left(\frac{c_{pl}\Delta T_{sub}}{h_{fg}}\right)^2 \quad (11)$$

f_1 is a dimensionless parameter responsible for the saturated CHF. f_2 represents the term responsible for the change in the vapor mass flow rate along the heater surface according to variation of the liquid subcooling. f_3 represents the term responsible for the CHF enhancement with increase in the subcooling via reduction of the net rate of vapor generation due to introduction of the sensible energy and increased amount of condensate at vapor/liquid interfaces.

Among them, f_1 and f_3 are of interest because we can already estimate the change in the vapor mass flow rate along with variation of the subcooling by using Eq. (1).

The subcooling ratio (R_{sub}) for a given degree of liquid subcooling of M is defined as following:

$$R_{subM} = \frac{f_{3,subM}}{f_1 + f_{3,sub5}} \qquad (12)$$

Under a gauge pressure of 0.46 bar which corresponds to a specific water level of 5 m, the subcooling ratios were calculated, and then used in Eq. (4) for calculation of the subcooled CHF values. The results are plotted in Fig. 6. Note that such predictions of the subcooled CHF, applicable to EU-APR1400 core catcher cooling channel, are based on the conservative approximations and assumptions. Thus, the results, shown in Fig. 6, should be utilized in examining the tendency of the relation between the liquid subcooling and corresponding CHF rather than quantitative characteristics of them.

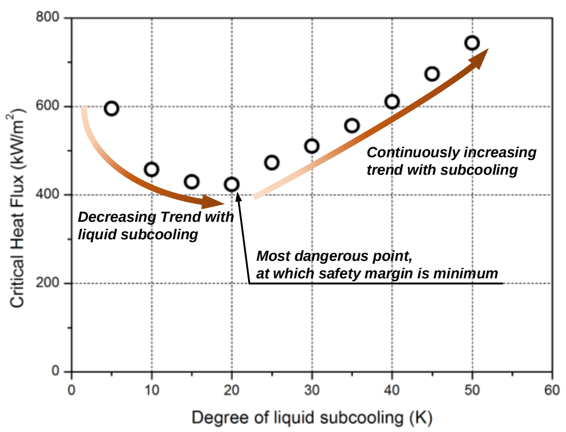

Fig. 6. Non-linear relation between degree of liquid subcooling and critical heat flux, expected in the inclined cooling channel of EU-APR1400 ex-vessel core catcher.

By utilizing both the experimental results of this study and the CHF model of Sulatskii et al. (2002) together, we could show that the non-linear dependence of liquid subcooling on the CHF is expected in the inclined cooling channel of EU-APR1400 ex-vessel core catcher system, having lowest safety margin at around 20K of liquid subcooling.

Notable feature was observed in Fig. 6, showing the rather rapid decrease in the CHF value with change of the liquid subcooling from 5 to 20K. Such rapid decrease can be explained by examining the characteristics of natural circulation and the effectiveness of the subcooling on the CHF via change in the net rate of vapor generation, quantified by R_{sub}. It can be seen from Fig. 5 that the natural circulation flow rate continuously decreases as the subcooling increases, rapidly up to 20K and gradually beyond 20K. By contrast, R_{sub} continuously increases as the subcooling increases, gradually up to 20K and rapidly beyond 20K. This means that, up to 20K of the subcooling, the variation of the natural circulation flow rate would dominantly affect the CHF. In this way, the decreasing trend presented in Fig. 6 can be explained.

It is noteworthy that the cooling system of EU-APR1400 core catcher is likely to face the most dangerous situation when degree of liquid subcooling approaches a specific value of around 20K. Accordingly, the safety limit in the cooling system should be investigated in the natural circulation loop by controlling the liquid subcooling to be 20K, not saturated state.

The imposed downward facing heat flux on the core catcher cooling channel under the severe accident scenario is estimated approximately as 200 kW/m^2. This means that the current design of EU-APR1400 core catcher cooling system provide a sufficient thermal margin even under the most dangerous state where the subcooling is around 20K.

4. Conclusions

By utilizing the experimental results of the present study and Song (2017), and the CHF model of Sulatskii et al. (2002) together, we could show that the non-linear dependence of liquid subcooling on the CHF is expected in the inclined cooling channel of EU-APR1400 ex-vessel core catcher system, having lowest safety margin at around 20K of liquid subcooling.

Despite the conservative approximations in prediction of the subcooled CHF, we could confirm a sufficient thermal margin of EU-APR1400 core catcher cooling system even under the most dangerous state.

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