Development of an Experimental Facility and Modeling Strategy for Jet Impingement Heat Transfer under i-SMR LOCA Conditions

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1. Introduction

Globally, various types of Small Modular Reactors (SMRs) are being developed to provide carbon-free energy with enhanced safety. Among them, Pressurized Water Reactor (PWR)-based SMRs typically adopt an integrated configuration in which the reactor core, pressurizer, steam generators, and reactor coolant pumps are housed within a single pressure vessel. In the Republic of Korea, the Innovative Small Modular Reactor (i-SMR) is being developed with such integrated features [1], as illustrated in Fig. 1.

The i-SMR safety strategy for a Loss-of-Coolant Accident (LOCA) involves accumulating the discharged coolant in the annular region between the Containment Vessel (CV) and the Reactor Vessel (RV). As the pressure equalizes, the Emergency Recirculation Valves (ERVs) located at the bottom of the RV open, allowing the coolant to return to the reactor core. This passive safety concept is intended to minimize the risk of core damage even in the event of a primary system break.

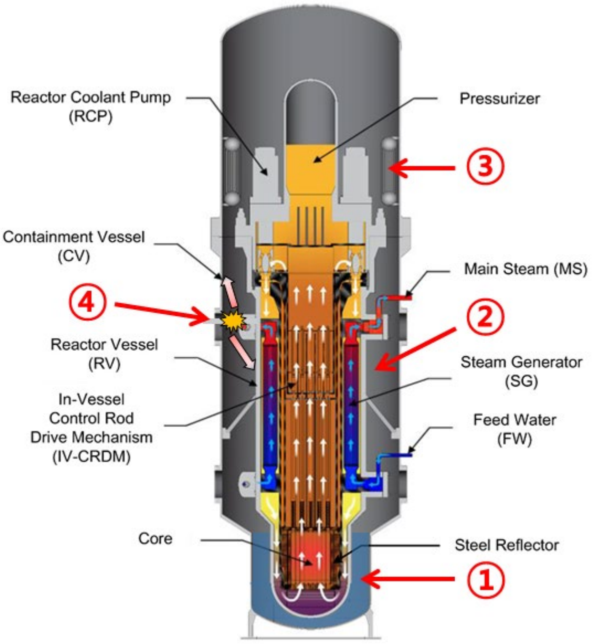

Fig. 1. Conceptual configuration of the i-SMR and its passive safety features during a LOCA

While this integrated design enhances safety and compactness, the reduced containment volume introduces new thermal-hydraulic challenges. Conventional large-scale PWRs possess massive containment volumes on the order of tens of thousands of cubic meters, which mitigates the rate of pressure rise during accident scenarios [2]. In contrast, the containment volume of modern SMRs, including the i-SMR, is significantly smaller, typically ranging from several hundred to a few thousand cubic meters [3]. Consequently, a LOCA in an i-SMR is expected to produce a rapid and pronounced pressure increase within the confined containment space. Accurate evaluation of this pressure transient is therefore essential to ensure containment integrity.

During a LOCA in an i-SMR, heat transfer between the discharged fluid and the surrounding structures can be categorized into four primary regions: ① heat transfer from the accumulated sump water, ② condensation and natural convection in the steam-filled upper region, ③ heat removal through the Passive Containment Cooling System (PCCS), and ④ heat transfer induced by impinging jets, as indicated in Fig. 1. Due to the proximity between the CV/RV walls and potential break locations in the integrated layout, high-velocity, high-energy jets are expected to directly impinge on vessel surfaces. Unlike in large-scale PWRs, the thermal interaction between the jet and the vessel walls in an i-SMR can become a dominant contributor to the overall containment thermal response. Therefore, a rigorous understanding of jet impingement heat transfer under these conditions is required.

Extensive research has been conducted on impinging jet heat transfer [4-6]. However, most previous studies were performed under relatively low-pressure conditions and primarily focused on surface cooling applications. In contrast, LOCA conditions involve high-pressure, high-temperature jets that may cause significant surface heating, particularly on containment walls. Such conditions fall outside the validated ranges of most existing correlations. Although impingement on RV walls may involve surface cooling, the extremely high Reynolds numbers associated with LOCA-induced jets substantially exceed those considered in conventional models. Therefore, the applicability of existing correlations to SMR LOCA conditions remains uncertain.

Furthermore, the early phase of a LOCA may involve flashing jets, in which subcooled liquid undergoes rapid phase change upon depressurization. Experimental data and heat transfer models for impinging flashing jets are very limited.

In the nuclear field, previous jet impingement studies have primarily focused on the mechanical impact of jets on Structures, Systems, and Components (SSCs) to prevent structural damage. These studies mainly addressed impingement loads and pressure distributions [7,8]. For flashing jets, analyses have largely relied on expansion models described in ANSI/ANS-58.2-1988 [9], and more recent efforts have refined the definition of the Zone of Influence (ZOI) [10]. However, these approaches provide limited information regarding the local heat transfer coefficient at the point of jet impact.

To address this research gap, the present study develops an experimental facility capable of reproducing jet impingement phenomena under representative i-SMR LOCA conditions. This paper describes the design range of the facility and outlines the methodology for establishing a heat transfer model applicable to high-pressure, high-Reynolds-number impinging and flashing jets.

2. Experimental Facility and Research Strategy

2.1 Experimental Facility

Fig. 2 shows the piping and instrumentation diagram (P&ID) of the experimental facility developed to investigate jet impingement heat transfer. Two pressure vessels, each with an inner volume of 27.4 L, are installed to supply heated and pressurized fluid. Electric heaters with a maximum power of 15 kW are installed in each vessel.

To generate the water jet, both vessels are first filled with water, and the remaining upper volume is pressurized using compressed air supplied by a compressor. Once the target water temperature and pressure are achieved, an on/off valve is opened to initiate discharge. The water then flows through a Coriolis mass flow meter (Rheonik RHM10) and two sets of thermocouples and pressure transmitters before being discharged through the nozzle.

Except for the mass flow meter, all instruments are designed to withstand pressures up to 200 bar and temperatures up to 300 °C. Due to the pressure limitation of the mass flow meter, the maximum allowable air pressure inside the vessel is 133 bar at 350 °C and 156 bar at 210 °C. The final discharge pressure is controlled by a pressure control valve (PCV), as indicated in Fig. 2.

The expected mass flow rate range is estimated using a proposed correlation for the critical flow rate of water [11], given as:

$$g_c\sqrt{2\left[P_0 - C_f P_{sat}(T_0)\rho_{f0}\right]} \qquad (1)$$

For example, under the conditions of a 3 mm nozzle diameter, 75 bar discharge pressure, and 200 °C water temperature, the mass flow rate calculated using Eq. (1) is approximately 0.72 kg/s. The overall experimental operating range is summarized in Table I.

Table I: Experimental Operating Range

Variable	**Range**
Working Fluid	Water (discharged using pressurized air)
Nozzle Diameter	$1 \leq D_{nozzle} \leq 3\ [mm]$
Test Pressure	1 atm (atmospheric environment)
Jet Discharge Pressure	$10 \leq p \leq 75\ [bar]$
Test Temperature	Jet Temperature: $50 \leq T_{Jet} \leq 280$ [℃] Wall Temperature: $20 \leq T_{Wall} \leq 280$ [℃]
Mass Flow Rate (Re)	$\dot{m} \leq 1\ [kg/s]\ \ (Re \leq 3 \times 10^6)$
L/D	$L/D \leq 100$

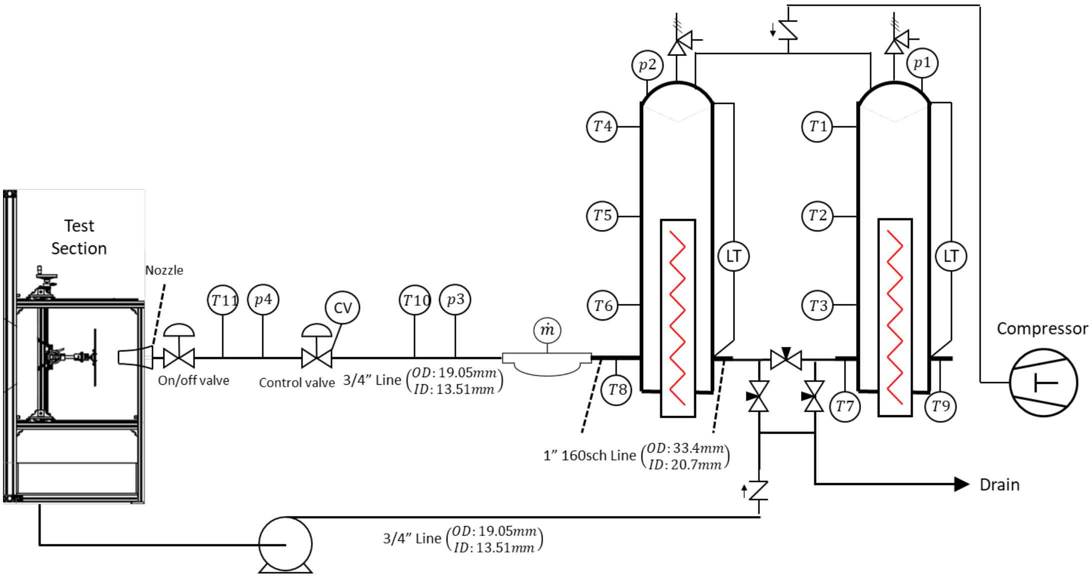

Fig. 2. Piping and instrumentation diagram (P&ID) of the experimental facility

2.2 Research Strategy

To ensure that the developed jet impingement heat transfer model contributes effectively to SMR safety analysis, it must be implemented in the one-dimensional (1D) system codes used for actual safety evaluations. Unlike three-dimensional CFD simulations, which employ fine computational grids and can continuously resolve local thermodynamic states, 1D system codes are limited to a small number of control volumes and can only access bulk thermodynamic states within each cell. Therefore, the model must be formulated in a manner consistent with the available variables in system codes.

To simulate jet impingement heat transfer during a LOCA within a system code framework, only limited information can be utilized, such as the thermodynamic state of the discharged fluid cell at the break location and the state of the heat structure cell at the impingement surface. A schematic representation of this modeling concept is illustrated in Fig. 3.

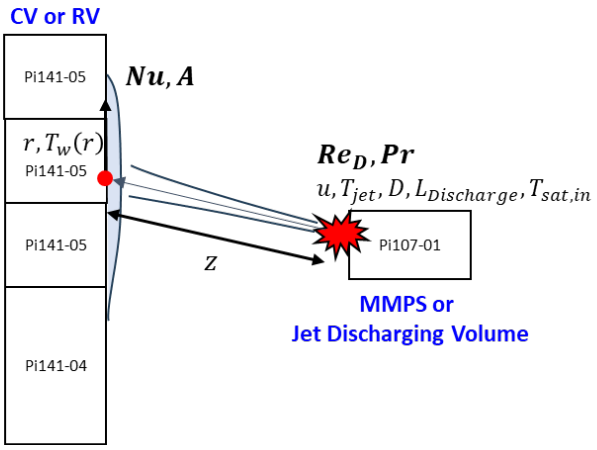

Fig. 3. Fraction of counts lost with voltage and charge sensitive preamplifiers as a function of the true count rate.

When the system code provides the jet temperature, break diameter, and mass flux calculated using a choked flow model, the corresponding jet velocity can be determined. Using these quantities, the Reynolds number defined with the nozzle diameter (Re_D) and Prandtl number (Pr) of the discharged jet can be evaluated. Based on these dimensionless parameters, a model must be developed to calculate the energy transferred to the heat structure surface maintained at temperature T_w.

The transferred energy can be expressed as shown in Eq. (2).

$$Q = hA(T_{jet} - T_{w,i}) \tag{2}$$

As indicated in Eq. (2), in addition to the jet temperature and wall temperature, the heat transfer coefficient h and the effective heat transfer area A must be determined. Accordingly, this study first aims to develop a model to predict the impingement or effective influence area A. Subsequently, a model for determining the heat transfer coefficient h under LOCA jet conditions will be established.

The effective heat transfer area is primarily governed by the expansion of the jet in ambient air and its subsequent spreading across the impinging surface. In single-phase jet impingement, the extent of spreading is typically determined by Re_D and L/D. under high-temperature surface conditions where boiling occurs, the wall superheat must be considered, as it influences the spreading extent through the onset of dry-out. Furthermore, the initial jet expansion is dictated by the jet superheat and nozzle geometry (length). Consequently, the model for the effective heat transfer area A can be formulated as shown in Eq. (3).

$$A = f\left(Re_D, \frac{z}{D}, \frac{L}{D}, T^*_{jet}, \Delta T_w\right) \tag{3}$$

Where, $\frac{z}{D}$: non-dimensional distance between the nozzle and impinging plate, $\frac{L}{D}$: non-dimensional length of the nozzle, $T^*_{jet}\left(= \frac{T_{jet} - T_{sat,amb}}{T_{sat,in} - T_{sat,amb}}\right)$: non-dimensional jet superheat, and $\Delta T_w(= T_w - T_{sat,amb})$: wall superheat

The Nusselt number Nu model for determining the heat transfer coefficient is formulated as shown in Eq. (4) consistent with previous studies that characterized impinging jet heat transfer using these variables [4-6]. However, when phase-change phenomena—such as boiling or condensation—occur on the surface, the heat transfer coefficient can no longer be accurately correlated solely with the variables defined in Eq. (4). Therefore, a modified heat transfer model must be developed to account for the specific mechanisms associated with phase-change heat transfer.

$$Nu(r) = f\left(Re_D, Pr, \frac{r}{D}, \frac{L}{D}\right) \tag{4}$$

Where, Pr: Prandtl number of jet

To develop the effective heat transfer area A model, two primary measurement approaches are currently being considered. The first approach involves high-speed camera imaging combined with image processing techniques to characterize the jet morphology and spreading behavior. The second approach focuses on analyzing the influence region through measurements of the liquid film thickness formed after jet impingement.

As discussed in the Introduction, existing models summarized in the ANSI/ANS-58.2-1988 standard and subsequent studies have already characterized the spreading extent of flashing jets [9,10]. Therefore, the present study aims not only to validate the existing flashing jet influence range model but also to propose modifications where discrepancies are observed under the current experimental conditions. Through this effort, a refined model describing the direct influence region of flashing jets can be established.

In cases where flashing or breakup is less severe and the jet impinges on the wall predominantly in the liquid phase, the classical impinging jet structure observed in previous studies appears [4-6]. However, the present operating conditions extend beyond the parameter ranges typically investigated in conventional impinging jet experiments. Therefore, a new model describing the spreading behavior under these extreme conditions will be developed.

To achieve this, a conductance sensor will be fabricated to measure the liquid film thickness generated by jet impingement [12]. The boundary of the effective heat transfer area will be defined based on a criterion where the liquid film thickness approaches negligible values. Using this definition, the effective heat transfer area can be quantitatively determined as the region where the jet significantly enhances heat transfer compared to the surrounding surface. In addition, it must be validated whether the suggested methodology in the previous study using the electrical current ratio from two different receiver electrodes to resolve the problem of film thickness dependence on the temperature [13].

3. Conclusions

This study presented the development of an experimental facility to investigate jet impingement heat transfer under representative i-SMR LOCA conditions. Due to the compact containment configuration of the i-SMR, high-pressure and high-temperature jets generated during a LOCA may significantly affect the thermal response of containment and reactor vessel walls. Since existing impinging jet correlations are not directly applicable to such extreme conditions, particularly in the presence of flashing, a dedicated experimental and modeling approach is required.

Accordingly, a high-pressure jet facility was designed, and a modeling framework compatible with one-dimensional system codes was proposed. The strategy focuses on determining the effective heat transfer area and heat transfer coefficient using measurable parameters and dimensionless groups. The proposed approach is expected to provide a physically consistent and system-code-applicable model for evaluating jet-induced heat transfer in SMR LOCA scenarios.

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