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Experimental investigation of natural convection and gas mixing behaviors driven by outer surface cooling with and without density stratification consisting of an air-helium gas mixture in a large-scale enclosed vessel

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1. Introduction

The interaction behavior of heat and mass transfer is a significant issue in the discussion of thermohydraulic phenomena in nuclear containment vessels during severe accidents, such as the Fukushima-Daiichi nuclear power plant accident. In such an accident, a large amount of steam is discharged from the primary system, and several structures are directly heated, which can induce over-temperature damage to the containment vessel. Furthermore, since the temperature of the containment structure in the early phase of the severe accident is lower than the saturated temperature, part of the steam is condensed on the internal wall surface. An electrical power company in Japan proposed outer surface cooling as an accident management measure for preventing over-temperature damage. Owing to the outer surface cooling, natural convection can occur in the containment vessel. Therefore, the various types of fluid behavior, i.e., jet, steam condensation, conjugate heat transfer between the structure and inner fluid, and natural convection, should be investigated. Additionally, hydrogen combustion is a considerable hazard to containment integrity (hydrogen risk). Hydrogen transport behavior must be understood to elucidate the hydrogen risk. Since the density of gas mixtures containing hydrogen gas is generally lower than that of ambient gas, the buoyancy effect should be considered. In particular, density stratification is a typical behavior. Combined with the heat transfer behavior described above, the gas mixing behavior (mass transfer) in the containment vessel can become complicated. Moreover, during the operation of passive autocatalytic recombiners (PARs) for mitigating the hydrogen risk, natural convection is driven inside the containment because heat is produced by the chemical reaction in PARs (Studer et al., 2016). Hydrogen transport is significantly affected by ambient flow behavior, including natural convection. Since the natural convection itself is driven by the density difference, the mixing behavior of stratification and strength of natural convection interact with each other. In light of this, we focus on the interaction behavior of natural convection and gas mixing.

The nuclear research community has performed experimental and numerical studies on containment thermal hydraulics (e.g., Abe et al., 2018; Allelein et al., 2007; Andreani et al., 2016; Auban et al., 2007; Gupta et al., 2015; Kelm et al., 2019; Kumar

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et al., 2020; OECD/NEA, 1999; OECD/NEA Committee on the Safety of Nuclear Installations, 2012; OECD/NEA Committee on the Safety of Nuclear Installations, 2018; Studer et al., 2012; Studer et al., 2018). In particular, some characteristic stratification behavior driven by natural convection has been observed in experiments on large-scale facilities. In the NATHCO test on the MISTRA facility in the SETH-2 project (OECD/NEA Committee on the Safety of Nuclear Installations, 2012), the natural convection was driven by heating the inner component (called “condenser”) from 100 °C to 130 °C. Due to the natural convection, the helium (as mimic gas of hydrogen) molar fraction was homogenized in the stratification. In the TH22 test on the THAI facility in the German national project THAI-III (Gupta et al., 2015), the natural convection was driven by controlling the wall temperature of the test vessel, and this flow significantly enhanced the stratification breakup (gradual erosion of the stratification from the bottom with decreasing layer thickness). However, there has been no systematic investigation focusing on the difference in mixing modes by natural convection. Regarding numerical investigations, Kelin et al. (2016) used the experimental data of the NATHCO and TH22 tests to assess the ability of computational fluid dynamics (CFD) on buoyancy-driven mixing processes. This study concluded that experiments should aim to characterize buoyant flow and the mixing process. Additionally, experimental data may need further expansion because the convective behavior should change significantly during a real severe accident due to various conditions. Moreover, to gain added knowledge on the heat and mass transfer induced by the natural convection in the containment, the experimental data obtained by various experimental facilities should be systematically organized.

We, the Japan Atomic Energy Agency (JAEA), have been operating the Rig-of-safety Assessment—Severe Accident (ROSA-SA) project since 2013 to extend the experimental data on the thermohydraulic behavior of containments during severe accidents. In particular, we constructed a large-scale test facility named Containment InteGral effects Measurement Apparatus (CIGMA) (Hamdani et al., 2020; Ishigaki et al., 2020) and a small-scale test facility (Abe et al., 2020). This paper includes the CIGMA experimental results on the interaction behavior of the heat and mass transfer driven by the natural convection in the presence of density stratification consisting of a non-condensible gas mixture. This natural convection was driven by outer surface cooling. The CIGMA facility has a unique outer surface cooling system; the cooling section is divided into three parts, and the cooled region is controlled by selecting a part. The objective of this paper is to gain insights into the mixing mechanism of density stratification in this context.

There has been considerable research in various engineering fields on natural convection behavior. For instance, the convective velocity scale (Deardorff, 1970) should be estimated when discussing the airflow circulation between urban and rural areas. Many formulations have been proposed for the convective velocity scale, which is generally derived from the averaged kinematic turbulent heat flux in the vertical direction at the surface (e.g., Colomer et al., 1999; Fan et al., 2016; Lu et al., 1997a; Lu et al., 1997b). However, this velocity scale cannot be applied directly to examine the natural convection behavior in the CIGMA experiment due to the difficulty of estimating the averaged kinematic turbulent heat flux at the surface. Additionally, the natural convection in the CIGMA, MISTRA, and THAI experiments was driven by heating and/or cooling the sidewall, which means that the direction of the heat flux at the surface differed from that of the buoyancy. Regarding the natural convection in a rectangular cavity, which is the simplest geometry for investigating the buoyancy velocity $w_B = \sqrt{g \beta T \Delta T/D}$, where $g$ is the gravitational acceleration, $\beta$ is the thermal expansion rate, $\Delta T$ is the temperature difference between the hot and cold walls, and $D$ is the characteristic length scale. Previous experimental and numerical data (Ampofo and Karayiannis, 2003) indicate that the maximum magnitude of the velocity is approximately $0.2–0.25 \ w_B$. Kumar et al. (2020) adopted two-dimensional (2D) natural convective flow in a heated square cavity for CFD validation as an initial step toward the establishment of a CFD methodology for the buoyancy-driven flow in the containment. We consider the use of this buoyancy velocity to estimate the interaction Froude number, $Fr$, to explain the interaction behavior between natural convection and stratification. Originally, Studer et al. (2012) proposed $Fr$ to classify the interaction behavior between the stratification and a vertical jet from below. In this paper, we organize the stratification erosion rate on $Fr$.

This paper is organized as follows. In Section 2, we describe the CIGMA facility and its experimental conditions. Additionally, we introduce the formulation expressing the flow characteristic. In Section 3, the experimental results are reported. Finally, the main conclusions are summarized in Section 4.

2. CIGMA

2.1. Experimental facility

To investigate the containment thermohydraulic phenomena during severe accidents, we constructed the CIGMA facility after the Fukushima-Daiichi accident (Hamdani et al., 2020; Ishigaki et al., 2020). The test vessel consists of a cylindrical part, domes (upper and lower), and protruding bottom sump (see Fig. 1). The test vessel, covered with a thermal insulator made of rock wool, is 11 m in height and 2.5 m in diameter, resulting in a free volume of approximately 48 m³. The wall is 25 mm thick and withstands temperatures up to 300 °C. To conduct thermohydraulic experiments in higher temperature conditions than those in other experimental facilities, such as MISTRA (in CEA, France, Studer et al., 2007) and PANDA (in PSI, Switzerland, Paladino and Dreier, 2012), we installed a high-power heater unit in the injection system of the gas mixture of air, steam, and helium (as mimic gas of hydrogen). Therefore, the injected gas can be heated up to 700 °C. The CIGMA facility has a unique system for investigating...
the containment thermohydraulic behavior during outer surface cooling management. As described in Fig. 1, the cooling system is divided into three sections, namely, an upper pool, middle jacket, and lower jacket. That is, the cooling location can be selected under each experimental condition. A Type K thermocouple (TC) was inserted to measure the gas and wall temperatures, and the gas composition is measured by using a quadrupole mass spectrometer (QMS) system with a multipor-t rotating valve. Appendix shows the measurement locations and numbers of TCs and QMS capillaries used in this paper. The flow field was visualized using 2D particle image velocimetry (PIV). In this study, since statistical approaches could not be applied due to the instability of convective flow (Kumar et al., 2020), the PIV data were utilized only to qualitatively grasp an image concerning the natural convection driven by the outer surface cooling. The PIV system consisted of 135-mJ pulsed Nd:YAG laser, and a black-and-white Andor Neo 5.5 camera, which has a resolution of 2560 × 2160 pixels and a Nikon 35 mm-f/1.4 s lens. The field of view (FOV) is approximately 600 mm high and 700 mm wide. The FOV was set to EL = 7.2–7.8 m to observe the convective flow behavior driven by the outer surface cooling.

2.2. Experimental conditions

Eight experiments were performed to investigate the heat and mass transfer in the vessel during the outer surface cooling, and they are summarized in Table 1. The test vessel was preheated with superheated steam injection. The inner gas was replaced by dry air in the cases without density stratification (CC-PL-26, CC-PL-29, and CC-PL-33). The initial temperature in CC-PL-33 was lower than those in CC-PL-26 and CC-PL-29 (see Fig. 2). In the other cases (CC-PL-27, CC-PL-28, CC-PL-30, CC-PL-32, and CC-PL-34), after the air replacement from steam, the density stratification was formed by injecting binary gas of air and helium. The initial pressure and temperature distributions are shown by Table 1 and Fig. 2, respectively. Comparing the initial temperature distribution among the experimental data, we confirm the high reproducibility of the CIGMA facility. As an illustration, the initial distribution of CC-PL-26 is similar to that of CC-PL-29.

As shown by Fig. 3, the initial stratification was formed above about EL = 6 m. Note that the profile depended only on the height, and it was reproducible from test to test. The integration of this profile also allowed checking the helium mass balance while knowing the injection flow rate (1.0 ± 0.006 g/s in CC-PL-32 and 2.1 ± 0.013 g/s in the other cases) and the duration of injection (660 s). Under these initial conditions, the difference between these two values was less than 1%. The helium gas fraction of the whole test vessel is in Table 1. In this study, the completion time of the stratification breakup and dissolution is when the helium fraction at EL = 10 m decreases to the fraction of the whole vessel. The characteristic strength of density stratification is defined as Jirka (2004).

### Table 1

| Working gas | Outer surface cooling region | Initial temperature T<sub>ini</sub> (°C) | Initial Pressure P<sub>ini</sub> (kPa) | Initial Stratification | Helium fraction of the whole vessel (%) | Helium molar fraction at the top (%) | Initial stratification strength Ni (s<sup>-1</sup>) | Buoyancy velocity scale w<sub>B</sub> (m/s) | Interaction Froude number Fr<sub>i</sub> | Number of test |
|-------------|-------------------------------|----------------------------------------|--------------------------------------|-------------------------------|-------------------------------------|-------------------------------|----------------------------------------|----------------------------------|-------------------------------|----------------|
| No-stratification | No-stratification | No-stratification | No-stratification | No-stratification | No-stratification | No-stratification | No-stratification | No-stratification | No-stratification | No-stratification |
| Air | Air | Air | Air | Air | Air | Air | Air | Air | Air | Air | Air | Air | Air |
| CC-PL-26 | CC-PL-29 | CC-PL-33 | CC-PL-27 | CC-PL-28 | CC-PL-30 | CC-PL-32 | CC-PL-34 | CC-PL-34 | CC-PL-34 | CC-PL-34 | CC-PL-34 |
| EL > 8.1 m | EL > 4.2 m | EL > 8.1 m | EL > 8.1 m | EL > 4.2 m | EL > 8.1 m | EL > 4.2 m | EL > 8.1 m | EL > 8.1 m | EL > 4.2 m | EL > 8.1 m | EL > 4.2 m |
| 176 | 178 | 84 | 167 | 168 | 67 | 72 | 74 | 74 | 74 | 74 | 74 |
| 180 | 180 | 180 | 185 | 185 | 175 | 180 | 174 | 174 | 174 | 174 | 174 |
| 0 | 0 | 0 | 13 | 13 | 11 | 6 | 11 | 11 | 11 | 11 | 11 |
| 1.64 | 1.64 | 1.60 | 0.85 | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 |
| 3.0 | 3.1 | 1.9 | 3.0 | 3.0 | 1.9 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| 0.73 | 0.74 | 0.42 | 1.29 | 0.45 | 1.29 | 0.45 | 1.29 | 0.45 | 1.29 | 0.45 | 1.29 |
| TC, PIV | TC, PIV | TC, PIV | TC, PIV | TC, PIV | TC, QMS | TC, QMS | TC, QMS | TC, QMS |

### Table 2

| Property | Value |
|----------|-------|
| Density (ρ) | Ideal gas equation of state |
| Specific heat capacity C<sub>p</sub> (J/kgK) | Air: 1020, Helium: 5192 |

Fig. 2. Initial gas temperature at the center.
where $g$ means the gravity acceleration, $\rho$ means gas density, the subscript $s$ refers to the stratification, the subscript $0$ pertains to the ambient air, and $H_t$ means the height of the gradient layer of the stratification. The initial strength, $N_s$, is about 0.85–1.64 s$^{-1}$ in this study (see Table 1).

Regarding the cooled location, the upper pool and middle jacket were used in CC-PL-26, CC-PL-27, CC-PL-30, CC-PL-32, and CC-PL-33. Consequently, the test vessel was cooled above EL = 8.1 m. All the outer surface cooling system was used in all the other cases (CC-PL-28, CC-PL-29, and CC-PL-34), which meant that the cooled location was above EL = 4.2 m. Figs. 4–7 show the vertical distributions of the inner wall temperature at 0–1000 s in the all cases, where the time of 0 s means the start time of the outer surface cooling in this paper. The error bars in these figures are the standard deviations based on some measurement points at the same elevation. The existence of density stratification did not affect the inner wall temperature. Additionally, the effective temperature in the top head flange did not decrease due to its thick wall (120 mm). Thus, the cooled area, $S_c$, was approximately 14.5 m$^2$ in the cases with the upper pool and middle jacket (CC-PL-26, CC-PL-27, CC-PL-30, CC-PL-32, and CC-PL-33), and it was approximately 44.1 m$^2$ in the cases with all the outer surface cooling system (CC-PL-28, CC-PL-29, and CC-PL-34).

We performed three tests for CC-PL-26. Fig. 8 shows the time transient of the pressure in the test vessel. The error bars in this figure are the standard deviations from the independent experiments. A small value (less than 1.2 kPa) indicates good reproducibility of the CIGMA facility.

### 3. Results and discussion

#### 3.1. Overall behavior

The overall capability of the outer surface cooling was revealed by the time transient of the normalized pressure in the test vessel, as shown in Fig. 9, where $p_{ini}$ means the initial pressure. All the experimental data indicated a gradual decrease process. In CC-PL-28 and CC-PL-29, since the cooling area was wider, the time transients were faster than those of CC-PL-26 and CC-PL-27. Meanwhile, in the cases with low initial temperatures (CC-PL-30, CC-PL-33, and CC-PL-34), the time transients became slower than those in the high-temperature cases. The comparison of time transients between the cases with and without stratification did not show

#### 2.3. Flow characteristic

For a better understanding of the flow characteristic in the test vessel during the outer surface cooling, the velocity scale in the CIGMA experiments was estimated as

$$w_B = \sqrt{\frac{2gD}{\rho_0 + \rho_B}}$$

where $w_B$ is the buoyancy velocity scale, which is commonly used in studying heated square cavity flows (Ampofo and Karayianis, 2003); $D$ is the inner diameter (2.5 m), which is a characteristic length scale in this study; and $\rho_0$ and $\rho_B$ are the gas densities in the bulk and cooled near-wall regions, respectively. These gas densities were estimated based on the initial and boundary conditions described in Table 1. The convective velocity scales were 3.1–1.8 m/s under the high- and low-temperature conditions, respectively (see Table 1). From knowledge on heated cavity flows, we assumed that the cooled gas descended with 0.2 – 0.25$w_B$ in the near-cooled-wall region, and the hot gas ascended in the central region. The characteristic time scale, $t^*$, for the heat and mass transfer with the convection is given by $D/w_B$. The Reynolds number $Re = \frac{\rho_0 D^2}{\mu}$, where $\mu$ is the molecular viscosity, and it reached the order of $10^5$. The Rayleigh number $Ra = \frac{\rho_0 C_p D^3}{\mu_0 k}$, where $\nu$, $\lambda$, and $C_p$ denote the kinematic viscosity, thermal conductivity, and heat capacity, respectively, reached the order of $10^{12}$. On the basis of these dimensionless numbers, we regarded the convective flow in the test vessel as the fully developed turbulence flow in all the experimental cases.

#### 2.4. Interaction between convective flow and stratification

To describe the interaction behavior between the convective flow and the stratification, we referred to Studer et al. (2012). They proposed the interaction Froude number as

$$Fr = \frac{U}{NL}$$

where $U$ is a characteristic velocity scale, which is estimated with Eq. (2) in this study; $D$ is used as the characteristic length scale $L$. A Froude number that is lower than unity indicates that the buoyancy of the stratified layer dominates, and the convective flow erodes the stratification slowly. A large Froude number means that the convective flow dominates, and the erosion behavior becomes faster. The range of the Froude number, based on the initial and boundary conditions of the CIGMA experiments, was 0.45–1.29. The Froude numbers in the MISTRA-NATHCO and THAI-TH22 experiments were 0.3 and 0.6, respectively. On the basis of the Froude number, we compared the stratification erosion rates of CC-PL-28 and CC-PL-34 and TH22, as described in the following section.

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**Fig. 3.** Initial helium molar fraction—the error bars are the standard deviations from independent experiments.
Fig. 4. Time transients of the vertical distribution of the inner wall surface temperature in the cases without stratification and high-temperature conditions (CC-PL-26 and CC-PL-29) at 0, 250, 500, 750, and 1000 s—the error bars are the standard deviations based on some measurement points at the same elevation.

Fig. 5. Time transients of the vertical distribution of the inner wall surface temperature in the cases without stratification and low-temperature conditions (CC-PL-33) at 0, 250, 500, 750, and 1000 s—the error bars are the standard deviations based on some measurement points at the same elevation.
any clear difference in the early phase. However, the pressure transients indicated slight increases in CC-PL-27 and CC-PL-30 (at about 1600 and 6300 s, respectively), which were associated with the stratification behavior and the heat transfer between the inner gas and vessel structure (as discussed below in detail). Additionally, in the early phase, the time fluctuation in CC-PL-32 was larger than those in the other cases with stratification, exhibiting an evident difference in the gas mixing and containment cooling.

For a quantitative evaluation of the outer surface cooling ability, the heat loss rate of the inner gas, $H$, was roughly estimated based on the time transient of the inner pressure,

$$H = \frac{\Delta q}{\Delta t}$$  \hspace{1cm} (4)

where $\Delta q$ is the quantity of removal heat during $\Delta t$, which is set to 100$^\circ$C in this study. All the experimental data indicated the peak values of the heat loss just after the start of the outer surface cooling ($\sim$250 s), followed by exponential decreases in the time transients (see Fig. 10). The heat loss rate in the cases with high initial temperatures and wider cooled areas remarkably increased. For a better understanding of the outer surface cooling capability, we organized the heat loss coefficient, $Q$ (W/m$^2$ K), with the cooled area, $S_c$, and...
the temperature difference, $\Delta T$, between the inner gas and cooled wall as

$$ Q = \frac{H}{S \Delta T}. \quad (5) $$

Fig. 11 shows the time transients of the $Q$ value in all cases. In the cases without stratification, there was no significant difference in the peak value, and a similar decrease trend after the peak value was observed. The mean peak value around 250 s from CC-PL-26, CC-PL-29, and CC-PL-33 was 1.83 W/m² K, and the standard deviation among the tests was only 0.05 W/m² K (3% of the mean value). That is, the CIGMA apparatus can perform outer surface cooling uniformly. In the cases with stratification, Fig. 11 indicates a large difference in the peak value among the experimental cases. In CC-PL-30, the peak value of $Q$ just after the start of the outer surface cooling was 2.1 W/m² K, which was about 20% larger than the peak value in the cases without stratification. Meanwhile, in CC-PL-28, we confirm the about 17% decline from the $Q$ value in the cases without stratification. Fig. 12 organizes the normalized peak value of $Q$ based on $F_{ri}$, where $Q_{wo}$ is the peak value in the cases without stratification. The peak value reduced as $F_{ri}$ increased. Additionally, in the cases where the cooled region was wider than the initial stratification, the peak values of $Q$ were relatively small (see orange dots in Fig. 12). In the late phase, the experimental data for CC-PL-27 and CC-PL-30 indicated negative values at about 1600 and 6300 s, respectively (see Figs. 10 and 11), i.e., the reheating quantity of the inner gas from the noncooled vessel structure was greater than the heat removal quantity by the outer surface cooling. Below, we discuss the flow and temperature fields to elucidate the abovementioned cooling behavior.

3.2. Flow field

Fig. 13 shows some instantaneous flow fields in the cases without stratification. Overall, the velocity magnitude in the cases with
the high initial temperature (CC-PL-26 and CC-PL-29) was in the order of 10^{-1}, which agreed with the estimation based on the buoyancy velocity. In CC-PL-26, the FOV (EL = 7.2–7.8 m) located the interaction region between two convective flows, namely, one in the cooled part and the other in the noncooled part. The PIV measurement indicated various instantaneous flow fields, namely, strong upward and downward flows (see Fig. 13(a) and (b), respectively) and the compound upward and downward flows.

Fig. 9. Time transients of normalized inner pressure $P/P_{init}$.

Fig. 10. Time transients of heat loss rate $H$ (W).

Fig. 11. Time transients of heat loss coefficient $Q$ (W/m² K).
In this region, intense mixing of hot and cooled gases was performed, and it was inferred from the time fluctuation of the gas temperature, as explained below. In CC-PL-29, since the FOV was in the cooled region, the visualized flow was regulated upward (see Fig. 13(d), (e), and (f)). Due to the small temperature difference between the inner gas and the cooled wall, the velocity magnitude in CC-PL-33 was lower than those in the cases with the high initial temperature (see Figs. (g) and (h)), although the qualitative flow behavior was similar to that in CC-PL-26.

3.3. Gas temperature field

3.3.1. Cases without stratification

Figs. 14–17 show the spatial distributions of the gas temperature in the test vessel, constructed by means of 248 TCs. The figures for the cases without density stratification (CC-PL-26 and CC-PL-29) confirm the formulation of the cooled region (see Fig. 14). In this region, the convective flow—downward flow in the near-wall region and upward flow in the central region—was driven by the outer surface cooling. In the bottom part of the cooled region—$E_L = 8.1$ m and $EL = 4.2$ m in CC-PL-26 and CC-PL-29, respectively—part of the convective flow was entrained downward. Thus, the gas temperature in the bottom area became lower than the inner wall temperature of the noncooled region. Furthermore, in the noncooled region, the inner gas was heated by the residual heat of the CIGMA structure. Therefore, the flow direction was opposite that in the cooled region, meaning, i.e., upward flow in the near-wall region and downward flow in the central region; hence, for

Fig. 12. Relation of the interaction Froude number $Fr_t$ and heat loss coefficient $Q$ normalized by $Q_{wo}$; the peak value in the case without stratification.

Fig. 13. Instantaneous flow fields at $EL = 7.2$–$7.8$ m in the cases without stratification—the color contour shows the velocity magnitude derived with radial and vertical components.
evaluating the outer surface cooling capability, the secondary heat transfer from the containment structure to the inner gas should be considered.

For a detailed discussion of the inner flow and heat transfer behavior in the CIGMA test vessel, time transients of the gas temperature are shown in Fig. 18. The experiment data indicated a monotonic decrease with the time fluctuations, revealing intense gas mixing in the whole test vessel. The upper convective flow in CC-PL-26 was localized in the relative narrow region of EL greater than 8.1 m, and the high-temperature gas was entrained from the noncooled region. Therefore, the gas temperature fluctuated largely due to the conflict between the cooled gas and hot gas from below. Since the cooled region in CC-PL-29 was wider than that in CC-PL-26, the influence of the hot gas from below on the cooled region was mitigated. Hence, the gas temperature was distributed uniformly, as shown in Fig. 14. Although the cooling process in CC-PL-33 slowed due to the small temperature difference between the inner gas and the cooled wall, the temperature field and time transients in CC-PL-33 (see Figs. 15 and 18) exhibited a similar behavior to that in CC-PL-26.

3.3.2. Cases with stratification

In the cases with density stratification, the convective flow behavior was more complicated, as revealed by the spatial distribution of the gas temperature (see Figs. 16 and 17). In CC-PL-27, since the cooled region was narrower than the initial stratification, the experimental result indicated a significant temperature decrease above EL = 8.1 m. The mass and heat exchange between the upper and lower regions in the test vessel was suppressed due to the large density difference between the initial stratification and the lower region. This convective flow condition was maintained for more than 1000 s. Then, the flow changed rapidly; the cooled gas was transported downward, and another convective flow appeared in the lower part of the stratification (see 1140, 1340, and 1540 s in Fig. 16). This change in flow was related to the stratification behavior, called “stratification dissolution” as mentioned below in detail. The gas behavior of CC-PL-28, whose cooled region was wider than the initial stratification, was separated into the three sections. In the initial stratification (EL greater than 6 m), the cooled gas flowed downward in the near-wall region and then upward toward the central region. A similar flow occurred in the middle region (EL = 4–6 m). Thus, counterflow emerged between the two regions, i.e., the shear stress at the bottom of the stratification in CC-PL-28 would be larger than that in CC-PL-27. The gas mixing promoted by the shear flow played an important role in the stratification breakup. Another convective flow in the lower region (EL less than 4.2 m) was driven by the heat transfer between the noncooled wall and the inner gas.
Fig. 16. Spatial distributions of gas temperature in the cases with stratification and high-temperature conditions (CC-PL-27, CC-PL-28, and CC-PL-32).

Fig. 17. Spatial distributions of gas temperature in the cases with stratification and low-temperature conditions (CC-PL-30 and CC-PL-34).
The time transient of CC-PL-27 in the cooled region decreased sharply (see Fig. 19). However, the experimental data of EL less than 6.7 m did not confirm the significant temperature decrease and time fluctuation in the early phase. That is, this region did not have any active convective flow. After the gas mixing between the upper and lower regions started, the gas temperature in the upper part recovered, and that in the lower part rapidly decreased and fluctuated. Interestingly, the timing of the gas temperature recovery in the initial stratification was independent of the elevation. That is, the hot gas reached the top of the test vessel rapidly. The complicated temperature transient was related to the stratification dissolution, as mentioned below. Meanwhile, the experimental result in CC-PL-28 confirmed the different transients. Since the cooled region covered the whole initial stratification, the decrease of the gas temperature just after the start of the outer surface cooling was faster than that in CC-PL-27 (see Fig. 19). In addition, the temperature decrease in the stratification was more significant than that in the below part. The temperature transients below the stratification were similar to those in CC-PL-29. Thereafter, rapid recovery occurred orderly from the lower elevation in the initial stratification, which was different from that in CC-PL-27. As shown in Fig. 20, although the qualitative time transients of CC-PL-30 and CC-PL-34 were similar to those of CC-PL-27 and CC-PL-28, respectively, the temperature decreases just after the start of the outer surface cooling were small due to the small temperature difference between the inner gas and the cooled wall. Then, since the convective flows were moderate, the recovery of the gas temperature in the initial stratification was much slower than those in CC-PL-27 and CC-PL-28. Meanwhile, the time transients of CC-PL-32 differed from those of CC-PL-27 and CC-PL-30; the temperature decreases in the initial stratification were small, and the temperature recovery was not observed clearly (see Fig. 19). The time transient revealed that the gas mixing between the initial stratification and its lower part was not suppressed completely because the convective flow dominated ($Pr_t$ was larger than unity). That is, some of the hot gas from below penetrated the stratification.

### 3.4. Stratification behavior

Comparison of the time transient of the helium molar fraction revealed quite different behaviors between CC-PL-27 and CC-PL-28. Fig. 21 shows the time transients at seven measurement elevations and vertical distributions in CC-PL-27, CC-PL-28, and CC-PL-32. When the cooled region was narrower than the stratification thickness, the density-stratified region expanded to the lower part while decreasing in the helium fraction at the upper part of the test vessel (stratification dissolution). Meanwhile, when the cooling region was wider than the stratification thickness, the stratification was gradually eroded from the bottom with decreasing layer thickness (stratification breakup). These phenomena are described in detail below. The time transients in CC-PL-27...
indicated that the helium molar fraction decreased monotonically in the upper part of the test vessel, whereas they in the lower part of the initial stratification became complicated. Regarding the time transient at EL = 7.5 m, the helium molar fraction kept the initial value of about 40% during the about 300 s following the start of the outer surface cooling and then increased to about 46%, which was equal to that of the upper part. At EL = 7.0 m (which was only 0.5 m lower), the experimental data showed different transients. The helium molar fraction decreased linearly during the about 500 s and then increased significantly to a fraction equivalent to that of the upper part, indicating a homogenization of the stratification. Compared with previous experimental reports, a similar behavior was observed in the NATHCO test of the SETH-2 project (OECD/NEA Committee on the Safety of Nuclear Installations, 2012). In the lower part (EL = 5.4 m), a rapid increase in the helium molar fraction started at about 1000 s. Consequently, the helium gas distributed homogeneously with a molar fraction of 13% over the test vessel. The completion time of helium homogenization was about 2000 s, which was shorter than that in the NATHCO test. This difference between the two tests arose from the heating or cooling condition. In the NATHCO test, the stratification was heated by the condenser installed in the MISTRA test vessel. Thus, the gas density in the stratification remained lower than the ambient one for a long time. Meanwhile, in CC-PL-27, the density difference between the stratification and lower part gradually decreased. When the gas density in the cooled region exceeded that in the noncooled region, the gas in the stratification was transported downward, that is, the density stratification disappeared due to the outer surface cooling. The rapid increase in the helium molar fraction in the lower part also implied this dissolution behavior. Additionally, the timing of the gas temperature recovery (see Fig. 19) was associated with the stratification dissolution.

The experimental result from CC-PL-28 did not confirm any rapid increase as observed in CC-PL-27. The helium molar fraction in the initial stratification decreased orderly from the lower elevation of the stratification. In the upper region, the helium molar fraction decreased linearly until more than 1000 s, and then the fraction decrease became faster (see EL = 10.0 and 9.3 m in Fig. 21). The time transient at EL = 7.5 m was similar to that in the upper part, although the duration of the slow transient was shorter. Moreover, at EL = 7.1 m, the helium molar fraction decreased rapidly just after the start of the outer surface cooling. Compared with the time transient of EL = 7.1 m in CC-PL-27, the fraction decrease in CC-PL-28 was faster. As mentioned above, in CC-PL-28, counterflow appeared at the bottom of the initial stratification. Thus, the turbulence mixing at the bottom part was enhanced. This counterflow played a dominant role in the stratification breakup. A similar behavior was observed in the THAI TH22 test. In addition, similar transients were observed in previous studies on the stratification breakup by a jet from below (Abe et al., 2020; Andreani et al., 2016). In this transient, the turbulence mixing at the bottom of the stratification, induced by the interaction between a jet and the stratification, played a main role in enhancing the stratification breakup.

Fig. 19. Time transients of gas temperature at the center in the cases without stratification and high-temperature conditions (CC-PL-27, CC-PL-28, and CC-PL-32).
Fig. 20. Time transients of gas temperature at the center in the cases without stratification and low-temperature conditions (CC-PL-30 and CC-PL-34).

Fig. 21. Time transients of helium molar fraction at EL = 0.9, 2.9, 5.9, 7.1, 7.5, 9.3, and 10.0 m and the vertical distribution at 0, 500, 1000, 1500, and 2000 s in the cases with high-temperature conditions (CC-PL-27, CC-PL-28, and CC-PL-32).
In CC-PL-30, since the containment cooling was moderate due to the small temperature difference between the inner gas and the cooled wall, the time transient of the helium molar fraction was quite slow (see Fig. 22). The fraction at the top of the test vessel decreased linearly. Consequently, the density stratification dissolution consumed about 7000 s to complete. The time transient of CC-PL-32 indicated a faster behavior (see Fig. 21); the stratification dissolution was completed in only about 1000 s. Due to the penetrating hot gas from below, the stratification homogenization, as observed in CC-PL-27 and CC-PL-30, did not occur perfectly.

Fig. 23 shows the completion time of the stratification based on $Fr_i$, as defined by Eq. (3). We confirm that this Froude number is an important criterion for understanding the interaction behavior between the convective flow and stratification.

The time transients of the helium molar fraction in CC-PL-34 were much slower than those in CC-PL-28; the stratification breakup consumed about 6000 s to complete. Fig. 24 plots the erosion rate, $E$, based on $Fr_i$ to compare the erosion rate induced by the convective flow with that in the TH22 test. $E$ is defined as the time evolution of the stratification volume, $V_{\text{cloud}}$ (namely, $E = \frac{dV_{\text{cloud}}}{dt} \approx \frac{\Delta V_{\text{cloud}}}{\Delta t}$). In the CIGMA tests, $t_1$ and $t_2$ were defined as when the helium fraction at 7.0 and 8.0 m, respectively, decreased to a fraction equivalent to that of the lower part. The $t_1$ and $t_2$ in the THAI TH22 tests were derived with the time transient data at 7.0 and 7.7 m, respectively (acquired from Visser et al., 2014). Although additional data should be gathered via parametric studies, $E$ can be estimated by the function of $Fr_i$. This knowledge will help in the development of engineering models of the hydrogen transport in containments.

4. Conclusion

We performed eight experiments with CIGMA. In the experimental series, we focused on the heat and mass transport behavior driven by natural convection with and without density stratification. The stratification behavior was classified into two types, namely, dissolution and breakup. When the cooled region was narrower than the initial stratification, homogenization occurred due to the natural convection, and the gas in the stratification was
transported downward when the gas density in the stratification exceeded that in the lower part. That is, the density stratification was dissolved by the outer surface cooling effect. When the cooled region was wider than the initial stratification, the stratification was gradually eroded by the shear stress at the bottom of the stratification. Therefore, the helium molar fraction in the initial stratification decreased orderly from the lower elevation. Consequently, the stratification was broken up.

In both cases (with and without density stratification), the experimental data on the pressure transient confirmed the effective outer surface cooling capability. The PIV measurement indicated a velocity magnitude of $10^{-1}$, which was consistent with the estimation based on buoyancy velocity. In the cases without density stratification, the natural convection was driven in the cooled region, and a secondary convection occurred due to the entrainment of the cooled gas to the lower part. Therefore, the gas temperature of all measurement locations decreased monotonically. Meanwhile, in the cases with density stratification, the convective behavior was classified with the relative location between the cooled region and stratification. In cases where the cooled region was narrower than the initial stratification, due to the large density difference between the stratification and its lower part, the natural convection was limited in the stratification, and the gas mixing between the upper and lower regions was suppressed. Therefore, the decrease of the gas temperature in the initial stratification in the cases with stratification was faster than that in the cases without stratification; however, in the lower part, we did not confirm any temperature decrease or convection behavior in the early phase. After the stratification dissolution, natural convection was initiated also in the lower part. In cases in which the cooled region was wider than the initial stratification, two natural convections were driven by the outer surface cooling, and the secondary convection was observed in the noncooled region, which meant that natural convection occurred in the whole test vessel. Therefore, in all measurement locations, the gas temperature decreased. Particularly, the temperature decrease in the stratification was more significant than that in the lower part. As the stratification was eroded, temperature recovery occurred in the stratification. CFD analysis is currently being performed for a more detailed understanding of these findings.

**CRediT authorship contribution statement**

Satoshi Abe: Conceptualization, Investigation, Methodology, Validation, Data curation, Writing – original draft, Visualization. Ari Hamdani: Writing – review & editing, Visualization. Masahiro Ishigaki: Writing – review & editing. Yasuteru Sibamoto: Project administration.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Appendix A**

Tables A1 and A2 show the TC locations for the inner wall temperature and gas temperature shown in this paper, respectively. Table A3 shows the locations of the QMS capillaries shown in this paper; those with the asterisks were used for time transients at seven elevations in Figs. 21 and 22.

### Table A1

TC locations for inner wall temperature.

| Elevation (EL) | Number of TC |
|---------------|--------------|
| 10.0 m        | 6            |
| 9.7 m         | 14           |
| 9.3 m         | 8            |
| 8.4 m         | 6            |
| 7.5 m         | 8            |
| 6.7 m         | 6            |
| 5.9 m         | 8            |
| 4.9 m         | 5            |
| 3.9 m         | 6            |
| 2.9 m         | 8            |
| 0.9 m         | 11           |

![Diagram of TC locations](image.png)
### Table A2
TC locations for gas temperature.

| Elevation (EL) | Distance from center |
|----------------|----------------------|
| TCs for gas temperature around the central region | |
| 10.0 m        | 0.3 m                |
| 9.7 m         | 0.2 m                |
| 9.3 m         | 0 m                  |
| 8.4 m         | 0 m                  |
| 7.5 m         | 0 m                  |
| 6.7 m         | 0 m                  |
| 5.9 m         | 0 m                  |
| 4.9 m         | 0.5 m                |
| 3.9 m         | 0.3 m                |
| 2.9 m         | 0.3 m                |
| 0.9 m         | 0 m                  |

### Table A3
QMS capillary locations for gas concentration.

| Elevation (EL) | Distance from center |
|----------------|----------------------|
| QMS capillaries for gas concentration | |
| *10.0 m        | 0.3 m                |
| 9.7 m          | 0.7 m                |
| *9.3 m         | 0.9 m                |
| 8.9 m          | 0.9 m                |
| 8.4 m          | 0.0 m                |
| 8.0 m          | 0.0 m                |
| 7.7 m          | 0.9 m                |
| *7.5 m         | 0.9 m                |
| *7.0 m         | 0.9 m                |
| 6.3 m          | 0.9 m                |
| *5.9 m         | 0.9 m                |
| 5.4 m          | 0.9 m                |
| 4.3 m          | 0.9 m                |
| *2.9 m         | 0.9 m                |
| *0.9 m         | 0.9 m                |
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