Proceedings of the Korean Nuclear Society Autumn Meeting
Yongpyong, Korea, October 2002

Natural Convection and Heat Transfer in a Mini-SIGMA Experiment

Seung Dong Lee, Kune Y. Suh*

Seoul National University
San 56-1 Sillim-Dong, Kwanak-Gu, Seoul, 151-742, Korea
*Phone: +82-2-8808324, Fax: +82-2-889-2688, Email: kysuh@snu.ac.kr

Abstract

The experimental facility is of two-dimensional (2D) slice with the diameter, height, and thickness of the test section being 250mm, 125mm, and 50mm, respectively. The pool's sidewall, with a 23mm thick copper plate, was cooled by the regulated water loop. A water-cooling system was used to maintain the temperature of water surrounding the test section nearly constant with time. Four (4) thin cable-type heaters, with a diameter of 2.4mm and a length of 85cm, were used to simulate internal heating in the pool. They were uniformly distributed in the semi-circular section to supply a maximum of 1kW power to the pool. From theses data we obtained the Rayleigh number on the order of 10^{10}. The water loop temperatures were used to obtain the average heat flux on the sidewall and on the top of the pool. A total of 20 T-type thermocouples were fixed inside the copper wall at different angular locations in order to obtain local heat fluxes. Inside the pool, 27 T-type thermocouples were installed to measure the pool temperature distribution and variation. The thermocouple readings were all calibrated using the calibration box. The Mini-SIGMA experiment was conducted to test the performance of the water-cooling loop, cable-type heaters, thermocouples and the data acquisition system (DAS) against the available data on natural convection. We focused on the average heat transfer coefficients, angular heat flux, and peak values. The local heat fluxes were calculated from the temperature differences obtained from the thermocouple pair placed inside the wall and water pool. The maximum heat flux region corresponded to the upper part of the pool. The lowest heat transfer occurred at the bottom of the pool, which was the stagnation point. However, the highest value occurred at the upper corner of the pool.

1. Introduction

Accident such as loss-of-coolant accident (LOCA) that leads to core melt may be initiated in a number of ways involving the malfunction of components or safety system, or improper operator action. During a severe accident in nuclear power plants, melt formation and in the core region and relocation take place at various locations within a reactor core over a considerable period of time. Thus the molten core in the reactor vessel can relocate to the lower plenum, and form hemispherical shaped pools of molten core materials. If there is no effective cooling mechanism, the core debris may heat up and commence natural circulation. The high temperature pool of molten corium will threaten the structural integrity of the reactor vessel. The extent and urgency of this threat depend primarily upon the intensity of the internal heat sources and upon the consequent distribution of the heat fluxes on the vessel walls in contact with the molten corium pools. The feasibility of external vessel flooding as a severe accident management, and the phenomena affecting the success in retaining the molten corium inside the vessel, has received wide attention.

Recently attentions are being paid to the feasibility of external vessel flooding as a severe accident management, and to the phenomena affecting the success path in retaining the molten corium inside the vessel. The proposed experimental work Mini-SIGMA (Simulation of Internal Gravity-driven Melt Accumulation) is concerned with high Rayleigh number turbulent natural convection in a molten pool. The internal direct heater heating method will then be adopted in the test the by using the cable-type heaters. This study will concentrate on thermal load, angular heat flux distribution, and temperature distribution inside the molten pool.

Natural convection plays an important role in determining the thermal load from debris accumulated in the reactor vessel lower head during a severe accident. The heat transfer inside the molten corium can be characterized by the strong buoyancy-induced flows resulting from internal heating due to radioactive decay energy. The thermo-fluid dynamic characteristics of such flow depend strongly on the thermal boundary conditions. Several numerical and experimental programs were conducted to study the heat transfer in the molten pool. The spatial and temporal variation of heat flux on the pool wall boundaries and the pool superheat are mainly characterized by the natural convection flow inside the molten pool. In general, the natural convection heat transfer phenomena involving internal heat generation are represented by the modified Rayleigh number, Ra', which quantifies the internal heat source and hence the strength of the buoyancy force.

The previous works suffer from serious weakness to represent a molten corium behavior in the reactor vessel lower plenum involving specific conditions such as high Rayleigh numbers, turbulent boundary layers, a low height-to-diameter ratio, and a hemispherical geometry. Therefore any extrapolations to different geometries and convection conditions have to be considered carefully. In addition, whereas in many previous studies only the average heat transfer coefficients from liquid to surrounding walls have been correlated, the heat flux profiles and their peak values are also needed for safety assessments concerning the external vessel cooling.

Several numerical and experimental programs were conducted to study the heat transfer in the molten pool. Mayinger [1] carried out experimental and theoretical researches involving the natural convection heat transfer from a semicircular geometry. The investigation was implemented under the assumption of isothermal boundary conditions in the modified Rayleigh number range, $7\times10^6<Ra'<5\times10^{14}$. The COPO [2] experimental facility uses water as simulant and employs top and sidewall cooling to create crust at the boundaries. The BALI [3] experiments, conducted in a full-scale slice facility with water as simulant. The Mini-ACOPO experiments were transformed into ACOPO [4] experiment, employing a one-half scale 3D representation of the lower head. UCLA [5] experiments were conducted in Pyrex bell jars, using Freon-113 as the simulant.

2. In-Vessel Heat Transfer Phenomena

Molten corium would be in a state of volumetrically heated liquid pool with uniform boundary temperatures at the melting point of molten corium assuming that the outer surface of the upper vessel wall remained under nucleate boiling conditions. For a volumetrically heated pool, the heat removed from the boundaries of the pool must exactly balance the energy generated within the pool under steady-state conditions. Assuming a uniform volumetric heat generation rate, the energy generated in the pool is a monotonically increasing function of the pool depth. It follows that the surface heat fluxes at the pool boundaries must also increase with the pool depth although the upward and downward energy flow split may either increase or decrease. Otherwise, a steady-state natural convection process cannot be maintained in the pool. For highly turbulent natural convection flow, the convective heat transfer is expected to be independent of the physical dimensions of the pool. This is because the fine scales of turbulent mixing in the well-mixed region are considerably less than the pool depth.

In such a steady corium pool convection state, the thermal loads against the vessel would be determined by the in-vessel heat transfer distribution involving convective and conductive heat transfer from the decay-heated corium pool to lower head wall in contact with corium. The use of isothermal pool boundary conditions results in the convection of greater amounts of heat towards the upper horizontal boundary and adjacent areas of the curved boundary. Correspondingly, smaller amounts of heat are transferred to the lower curved regions of the semi-circular domain representing the lower head of the reactor vessel. That is, with isothermal pool boundaries, heat would be transferred by convection predominantly to upper and side surfaces, and the bottom surface would receive lower heat fluxes as may well be physically reasoned.

A number of physical situations involve natural convection heat transfer in a fluid layer cooled from the top. The situation in which the fluid is bounded by a hot surface at the bottom and a cold surface at the top is classically known as the Rayleigh-Benard problem. A situation of interest for nuclear reactor safety is slightly different in the sense that the fluid layer can be volumetrically heated with different boundary conditions. In case of uniform cooling, the pool can be divided in two parts depicted in Figure 1. A lower part, where temperature stratification is observed and an upper part, which can be considered as a volumetrically heated cavity cooled at the top with a virtual adiabatic surface at the bottom.

3. Dimensionless Parameters

The spatial and temporal variation of heat flux on the pool wall boundaries and the pool superheat characteristics depend strongly on the natural convection flow pattern inside the molten pool. The natural convection heat transfer phenomena involving internal heat generation are represented by the modified Rayleigh number, Ra´, which quantifies the internal heat source and hence the strength of the buoyancy force.

Natural or free convection phenomena can be scaled in terms of the Grashof number (Gr), the Prandtl number (Pr), and additionally, the Dammkohler number (Da) in the presence of volumetric heat sources. The dimensionless numbers are defined as follows

$$Gr = \frac{g\beta\Delta TL^3}{\nu^2}; \quad Pr = \frac{\nu}{\alpha}; \quad Da = \frac{qL^2}{k\Delta T^2} \qquad (1)$$

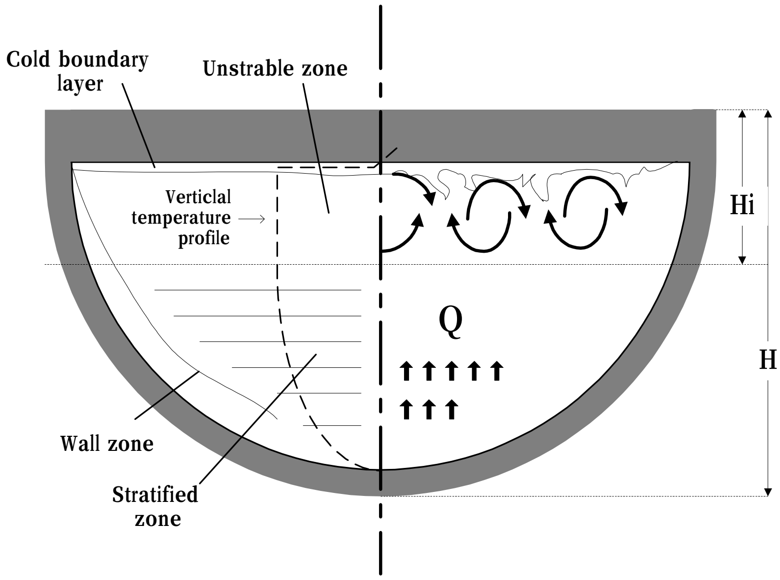

Figure 1. Severe Accident Nuclear Reactor Situation (Adapted from Bernaz et al. [6])

The Rayleigh number (Ra) can be used to characterize the heat transfer in natural or free convection problems, including those involving external heat sources or external heating such as heating from below. This dimensionless number is defined as follows

$$Ra = Gr\,Pr = \frac{g\beta\Delta TL^3}{\alpha\nu}; \quad \alpha = \frac{k}{\rho C_p}; \quad \nu = \frac{\mu}{\rho} \tag{2}$$

The preceding equation relates the buoyancy and viscous forces, which are linearly related via the factor, Gr/Re, but other dependencies are also present. The modified Rayleigh number, Ra´, is germane to free or natural convection problems with internal heat sources, and it is defined as follows

$$Ra' = RaDa = Gr\,Pr\,Da = \frac{g\beta\Delta TL^5}{\alpha\nu k} \tag{3}$$

In general, the natural convection heat transfer phenomena involving the internal heat generation are adequately represented by such dimensionless parameters as Ra´ and Pr, and physical dimensions of the pool. For the natural convection phenomena involved in reactor vessel molten corium flow, the predominant driving force for heat transport processes in the internal heating from the decay heat, while the conduction effects are relatively small. Thus, the heat transfer rates are primarily governed by the modified Rayleigh number, Ra´, and the flow geometry while the dependence on the Prandtl number, Pr, is fairly weak as is shown in Figure 2. Hence the average Nusselt number has been correlated reasonably well by the following relation, which incorporates the dependence on the modified Rayleigh number, Ra´, and the geometry parameter, H/R.

$$Nu = aRa'^n \left(\frac{H}{R}\right)^m \tag{4}$$

The constant value (H/R=1) of the geometric parameter corresponds to the situation where the vessel bottom head is filled up. For this case Equation (4) reduces to the following simplified power law expression for the Nusselt number as a function of the modified Rayleigh number, Ra´

$$Nu = aRa'^{m} \tag{5}$$

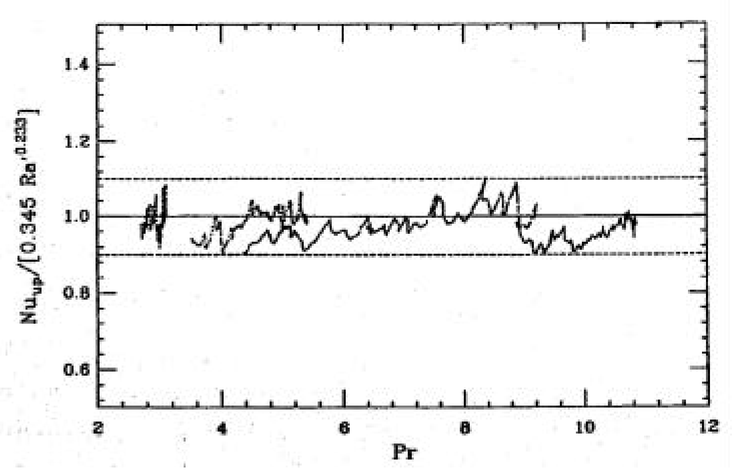

Figure 2. The Mini-ACOPO Results Showing the Prandtl Number Effect (Theofanous [7])

For low values of the modified Rayleigh number, Ra´, the turbulence intensity is small and the turbulent or eddy viscosity is negligible in comparison with the molecular viscosity. Such flows can be characterized as laminar and, furthermore, they would be steady if the internal heat source and boundary conditions vary slowly over the time scale of interest. However, the flow is characterized as turbulent and unsteady for large values of the modified Rayleigh number, Ra´, at least in domains of vigorous mixing and high turbulent intensity, and the molecular viscosity is small in relation to the eddy viscosity. Regions of laminar, transition and turbulent flow may coexist in the cavity according to the thermal stratification of the molten corium.

4. Experimental Facility

The experimental facility is of 2D slice-type and the diameter, height, and thickness of the test section are 250mm, 125mm, and 50mm, respectively as shown in Figures 3 through 5. The pool's curved wall, with a 23mm thick copper plate, is cooled by regulated water loop. A water-cooling system was used to maintain the temperature of water surrounding the test section nearly constant with time. Thermal insulator insulates the semicircular front and rear plates. Over the period of two hours, the maximum variation of water temperature in the outer pool was less than 2℃. Four thin cable-type heaters, with a diameter of 2.4mm and a length of 850mm, are used to simulate internal heating in the pool. They are uniformly distributed in the semi-circular section and thus they can supply a maximum of 1kW power to the pool. From theses data we obtained the Rayleigh numbers up to 10^{10}. The water loop temperatures were used to obtain the average heat flux on the sidewall and on the top of the pool.

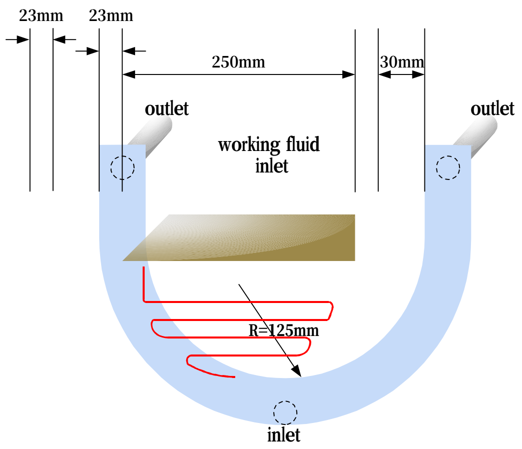

Figure 3. Schematic of the Mini-SIGMA 2D Test Section

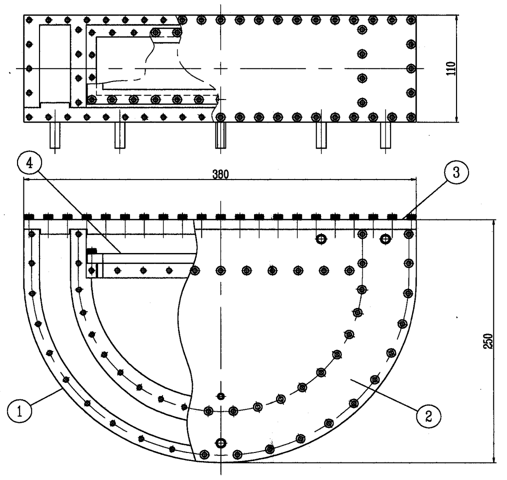

Figure 4. Detailed Drawing of the Mini-SIGMA 2D Test Section

Figure 5. Mini-SIGMA 2D Test Facility

A total of 20 T-type thermocouples were mounted inside the copper wall at different angular locations in order to obtain local heat fluxes as shown in figure 6. Inside the pool, 27 T-type thermocouples were installed to measure the pool temperature distribution and variation. Each thermocouple was calibrated before the tests. Table 1 shows the location of each thermocouple.

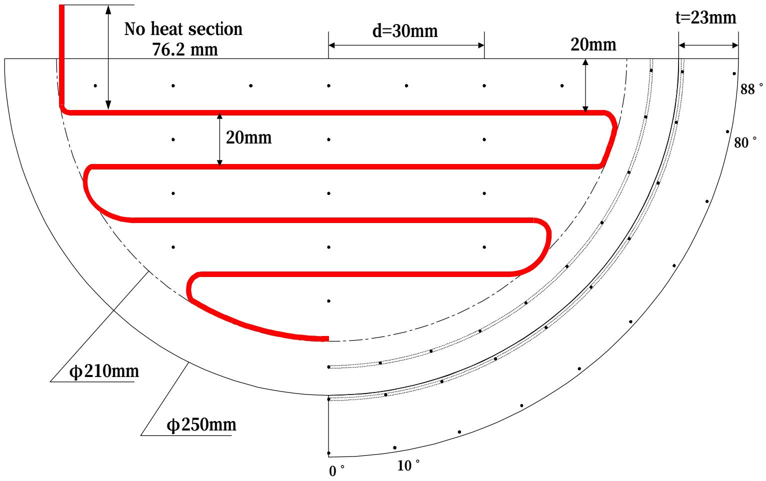

Figure 6. Schematic of the Mini-SIGMA 2D Heater and Thermocouple Installation

Table 1. Thermocouple Installation Location

	No.	Location	Note
Horizontal	7	-90, -60, -30, 0, 30, 60, 90	Z=115
Axial	4	95, 75, 55, 35	X=0
	6	95, 75, 55	X=60, -60
Azimuthal (Fluid)	10	0, 10, 20, 30, 40, 50, 60, 70, 80, 88	R=115
Azimuthal (Fluid)	20	0, 10, 20, 30, 40, 50, 60, 70, 80, 88	R=126, 147
Total	47	Unit: °	Unit: mm

Figure 7 shows the conceptual diagram of the Mini-SIGMA 2D test loop. This consisted of demineralized water system, test section, and chiller, which is a heat exchanger. Mini-SIGMA 2D water test was conducted to test the performance of the water-cooling circuit, cable-type heaters, thermocouples and the data acquisition system (DAS) against the available data on natural convection.

5. Experimental Procedure and Heating Method

Before the actual experiment was run, each thermocouple was calibrated using a calibrator. After every thermocouple was properly calibrated, all of the thermocouples were placed in their designated locations. Uniformity of the heat generation rate is one of the important conditions in the experiment. So we measured water temperatures at different locations. After the uniformity of the heat generation rate was identified the demineralized working fluid was pumped fully into test section through the heat exchanger, which is heat exchanger. So the working fluid in the test section and external cooling system temperature reached initial steady state. After assuring that everything was properly running, the power switch was turned on, and the pool was allowed to heat up. The HP Data Acquisition system was adjusted to record the temperatures.

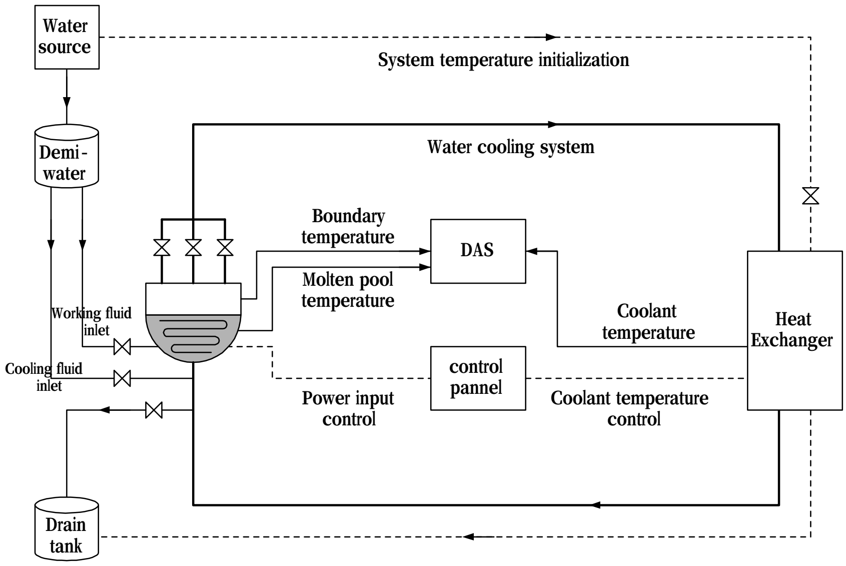

Figure 7. Conceptual Diagram of the Mini-SIGMA 2D Test Loop

Asfia et al. [8] conducted experiments related to the natural convection heat transfer in volumetrically heated spherical pools. Their experiments were conducted in pyrex bell-jars, using Freon-113 as the simulant liquid. Microwave heating was used in the experiment, and a surrounding water pool cooled the experimental system. It was concluded that a large variation in heat transfer coefficient existed along the vessel wall. The BALI (Bonnet and Seiler [3]) experiment has been designed to study the thermal-hydraulics of corium pool for in-vessel or ex-vessel situation. The corium melt is represented by salted water. The pool is cooled from the bottom and the top and heated electrically by the Joule effect with current supplies located on the sides. Gabor et al. [9] conducted natural convection experiment with hemispherical pool containers. The pool container served both as a heat transfer surface and as an electrode. $ZnSO_4$-H_2O was used as the heat generating liquid. The earliest study of natural convection in volumetrically heated layers is that of Kulacki and Goldstein [10]. Energy transport is measured in a layer of dilute electrolyte bounded horizontally by two rigid planes of constant and equal temperature. Joule heating by an alternating current passing horizontally through the layer provides the volumetric energy source. Kulacki-Emara [11], Kulacki-Nagle [12] used the same heating method. Kolb et al. [13] conducted in a semicircular slice with a vertical section to study the heat transfer at the boundaries of an internally heated molten salt pool with a boundary crust. Thin cable-type heaters, with a sheath diameter of 3mm and 4m in length, provide internal heating in the pool. Kymäläinen et al. [2] investigated experimentally the heat flux distribution from a large volumetrically heated pool for the Loviisa nuclear power plant in Finland. Their experimental approach is based on using a two-dimensional slice of the Loviisa lower head, including a portion of the cylindrical vessel wall. This allows well-controlled uniform heating using the flats as the electrodes. The pool is filled with a conduction $ZnSO_4$-H_2O solution and the current through each electrode can be individually adjusted.

6. Results and Discussion

Figure 8 shows typical results for the upward Nusselt number versus the Rayleigh number. In this experiments the Rayleigh number is small, so it is not enough to compare the results. From the results, we can compare previous analytical and experimental results and correlations such as Kulacki-Emara [11], Kulacki-Nagle [12], and Cheung [14] in the Rayleigh range from 10^8 to 10^{12}. But one of important objectives of the test was the feasibility of internal heating method with direct heater and we identified it. After this test we will conduct another experiments with the range of Rayleigh number is more than 10^{13}.

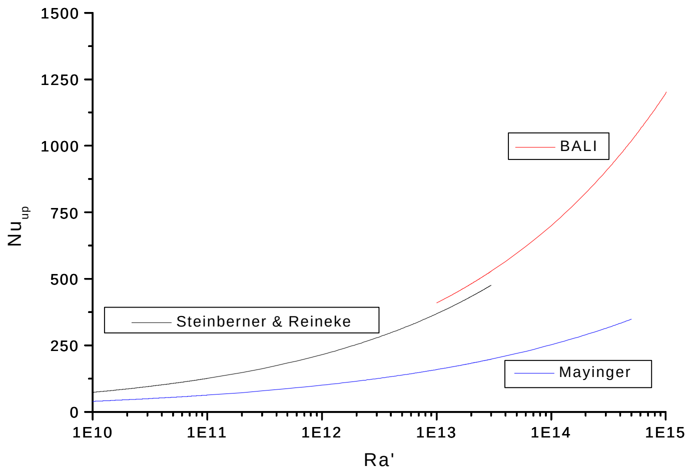

Figure 8. Upward Nusselt Number versus Rayleigh Number

7. Conclusion

Up to now, the different hypotheses formulated to explain the heat transfer coefficient have not been successful. The average Nusselt number along the upper flat surface of the test section was found to be very similar to those observed in previous experimental studies of Kulacki-Emara, Steinberner-Reineke, Mayinger, Kymäläinen, and Theofanous. Even though the experimental parameters such as geometry and thermal boundary conditions are different, the correlations are similar. Therefore, the average Nusselt number correlations along the upper flat surface are all relatively close over the modified Rayleigh number range of 10^{15}. However, the deviation among the average Nusselt number correlations increases over the modified Rayleigh number range greater than 10^{15}.

There exist several methods to simulate the uniform heat source in the molten pool such as microwave heating, direct current heating, cooldown, and direct heater heating. In the Mini-SIGMA experiment, we adopted the direct heater heating method. Uniformity of the heat generation rate is one of the important considerations in the natural convection experiments. Thus, in the first place, we identified the uniformity of heat generation rate by measuring the temperatures at different locations. After confirming the heating method in the Mini-SIGMA experiment, we will scale up the test section and power so as to obtain high Rayleigh numbers.

Nomenclature

C_p	specific heat (J/kg K)
Da	Dammkohler number
g	gravitational acceleration (m/s^2)
Gr	*Grashof number*
k	thermal conductivity (W/m K)
L	pool depth (m)
Pr	Prandtl number
Ra	Rayleigh number
Ra'	modified Rayleigh number
T	temperature (K)

<u>*Greek Letters*</u>

á	thermal diffusivity (
â	thermal expansion coefficient (K^{-1})
í	kinematic viscosity (m^2/s)
r	density (kg/m^3)
m	dynamic viscosity (N s/m^2)w

References

[1] Mayinger F., Jahn M., Reineke H., and Steinberner V., 1976, “Examination of thermohydraulic processes and heat transfer in a core melt," BMFT RS 48/1, Institute fur Verfanhrenstechnic der T.U., Hanover, Germany.

[2] Kymäläinen O., Tuomisto H., Hongisto O., Theofanous T.G., 1994, “Heat flux distribution from a volumetrically heated pool with high Rayleigh number,” Nuclear Engineering and Design, Vol. 149, pp. 401-408.

[3] Bonnet J.M., Seiler J.M., 1999, “Thermal hydraulic phenomena in corium pools: the BALI experiment," 7th International Conference on Nuclear Engineering, ICONE-7057, April 19-23, Tokyo, Japan.

[4] Theofanous T.G., Maguire M., Angelini S., Salmassi T., 1997, “The first results from the ACOPO experiment,” Nuclear Engineering and Design, Vol. 169, pp. 49-57.

[5] Frantz B., Dhir V.K., 1992, “Experimental investigation of natural convection in spherical segments of volumetrically heated pools,” ASME Proc. National Heat Transfer Conference, San Diego, CA, August 9-12, HTD Vol. 192, pp. 69-76.

[6] Bernaz L., Bonnet J.M., Spindler B., Villermaux C., 1998, “Thermalhydraulic phenomena in corium pools: numerical simulation with TOLBIAC and experimental validation with BALI,” Workshop on in-vessel core debris retention and coolability, Germany, NEA/CSNNI/R(98)18.

[7] Theofanous T.G., Liu C., Angelini S., Kymalainen O., Tuomisto H. and Additon S., 1995, “In-vessel coolability and retention of a core melt,” DOE/ID-10460, Vols. I & II, July.

[8] Asfia F.J., Dhir V.K., 1996, “An experimental study of natural convection in a volumetrically heated spherical pool bounded on top with a rigid wall,” Nuclear Engineering and Design, Vol. 163, pp. 333-348.

[9] Gabor J.D., Ellison P.G., Cassulo J.C., 1980, “Heat transfer from internally heated hemispherical pools,” 19th National Heat transfer Conference, Florida, July.

[10] Kulacki F.A., Goldstein R.J., 1972, “Thermal convection in a horizontal fluid layer with uniform volumetric energy sources,” Journal of Fluid Mechanics, Vol. 55, pp. 271-287.

[11] Kulacki F.A., Emara A.A., 1977, “Steady and transient thermal convection in a fluid layer with uniform volumetric energy sources,” Journal of Fluid Mechanics, Vol. 83, pp. 375-379.

[12] Kulacki F.A., Nagle M.E., (1975). “Natural convection in a horizontal fluid layer with volumetric energy sources,” Journal of Heat Transfer, Vol. 97, pp. 204-211
[13] Kolb G., Theerthan S.A., Sehgal B.R., 2000, “Experiments on in-vessel melt pool formation and convection with NaNO3-KNO3 salt mixture as melt simulant,” 8th International Conference on Nuclear Engineering, ICONE-8639, April 2-6, Baltimore.
[14] Cheung F.B., 1977, “Natural convection in a volumetrically heated fluid layer at high Rayleigh numbers,” International Journal of Heat and Mass Transfer, vol. 20, pp. 499-506.