Experimental Investigation on the Droplet Parameters in the Core under the LBLOCA Reflood Phase of PWR

Taeho Kim[1], Jinhoon Kang[1], Kyoungdoo Kim[2], Jae Jun Jeong[1], and Byongjo Yun [1*]
[1]*School of Mech. Engr., Pusan Nat’ l Univ., 2 Busandaehak-ro, 63-gil, Geumjeong-gu, Busan, 46241, South Korea.*
[2]*Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, 305-353, Korea*
[*]*Corresponding author:bjyun@pusan.ac.kr*

1. Introduction

In case of Large Break Loss-of-Coolant Accident (LB-LOCA) in a light water reactor, an Emergency Core Cooling System (ECCS) is operated to provide coolant into the core. In the reflood phase of the LB-LOCA, the injected coolant contacts with the high temperature fuel rod. In this flow condition, since the fuel cladding temperature is heated above the Leidenfrost temperature, the coolant filling up from the bottom plenum evaporates rapidly and forms a vapor blanket near the fuel rod. As a result, heat removal performance of the coolant from the fuel rod is deteriorated and the surface temperature can increase dramatically. At this time, the flow regime occurring in the core is expected to be inverted annular flow, inverted slug flow, and dispersed droplet flow. Therefore, precise prediction of the core heat removal rate according to each flow regime is required for the realistic safety evaluation of fuel rod.

In the reflood phase, liquid water exists in various topological forms which are generally classified as a slug, sheet, ligament, and droplet, and thus the velocity and interfacial area concentration of the liquid are changeable according to its shape. Previous investigators applied visualization technique with high-speed camera in the reflood test to understand flow phenomena, and proposed various physical models to predict the reflood phenomena [1-3]. However, due to the limitations of the measurement method, only variables such as interface shape, droplet size, and droplet velocity are obtained under limited flow conditions. Therefore, in this study, various droplet parameters are experimentally investigated at local locations by applying local optical fiber sensors developed by Kim and Yun [4].

2. Experimental setup

The schematic diagram of the reflood test facility is shown in Fig. 1. As shown in the figure, the apparatus consists of a test section, steam supply system, and cooling water supply system. At the center of the test section, a heating rod with a diameter of 9.5 mm and a total length of 2.785 m is installed to simulate nuclear fuel rod. The heating rod has a non-heating portion of 0.035 m at the top and 0.46 m at the bottom and heating portion of 2.29 m. The housing of the test section is made to have an inner diameter of 21.28 mm to maintain 11.78 mm of the hydrodynamic diameter of the annulus channel which is the same with that of a sub-channel consisting prototype reactor core, however the total length is reduced to 2.2 m.

An optical fiber sensor module is installed at the 3/4 axial elevation from the bottom of the heated section of the rod, which corresponds to a height of 1.72 m based on the thermocouple embedded in the inlet of the housing. In one module, six optical fiber sensors are installed radially, and each sensor measures the local droplet parameters such as a droplet fraction, droplet frequency, droplet velocity, and droplet diameter. The installation location of the thermocouple for measuring inner wall temperature and fluid temperature, and the pressure transmitter are shown in Fig. 2.

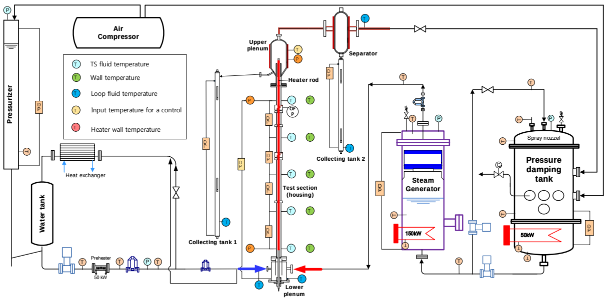

Fig. 1. Schematic diagram of the reflood test facility

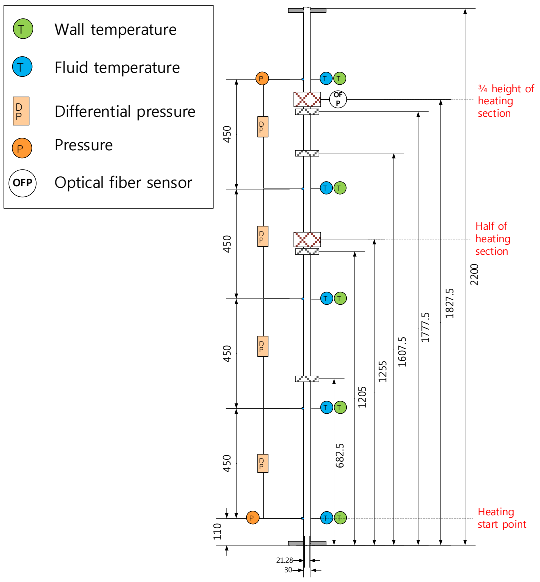

Fig. 2. Instruments in the housing of the test section

Since this experiment aims to obtain droplet parameters in the reflood phase, the experimental conditions are determined representing the accident condition as summarized in Table I.

Table I: Experimental conditions

Outlet pressure	1.7 bar
Heater wall temperature	600 ℃
Power	1.45 kW
Inlet mass flow rate (reflood rate)	6 g/s (2.21 cm/s)
Subcooled temperature	30 ℃

3. Experimental results

The coolant level in the test section increases after initiation of experiment in which the initial surface temperature of the heating rod is at 600 ℃The global variables measured according to time in the experiment are shown in Fig. 3. The output pressure of the test section was maintained at 1.7 bar, and quenching occurred sequentially along the axial direction at the wall of the heating rod as the coolant level increased.

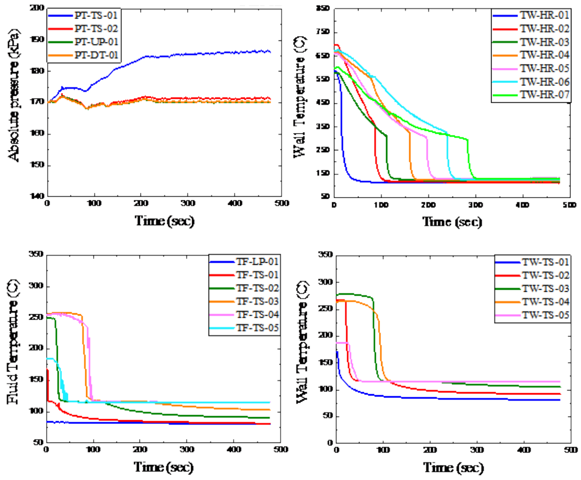

Fig. 3. Time variation of the global variables

In the present experimental condition, the diameter of stable spherical droplet is estimated as 1.47 mm according to Ishii's maximum droplet size model [5], which was utilized as a criterion for the classification of droplet flow and liquid slug flow in the measured experimental data by optical fiber sensors.

The local droplet parameters at a fixed elevation is shown in Fig. 4. At the beginning of the experiment (0 ~ 100 seconds), the droplet size is in the range from 0.6 mm to 1.1 mm, and the maximum droplet velocity is 12 m/s. The droplet velocity measured near the heater wall is faster than that near the housing wall, and the fast droplet velocity is biased toward the heater wall. This is because the droplets continuously evaporate near the heater wall and the generated vapor accelerates the droplets. Because of this fact, the smallest droplet fraction and frequency are observed at the heater wall region.

After 100 seconds of initiation of experiment, the droplet fraction and the droplet frequency in the vicinity of heater wall are three times larger than those of the outer wall region. Additionally, the local liquid fraction and liquid chord length show that most of the liquid phase exists as the form of a liquid slug or liquid film in outer of the annulus channel as shown in Fig. 5. At this time, the interface of liquid phase becomes unstable due to the interaction with the high-speed steam generated from heater wall surface, therefor the droplet entrainment occurs. The measured droplet size is around 1 mm or more, differently with the droplet size measured at the beginning of the experiment, and the droplet velocity is about 6 m/s because it is not reached to the terminal velocity. As the droplet fraction increases rapidly near the heater wall, the heat transfer from the heated wall is significantly increases by the droplets. When the quench front reaches to sensor elevation (295 s), the liquid fraction measured by the sensor element S1 increases drastically. After that, there is no significant change in liquid velocity, while the liquid chord increases rapidly.

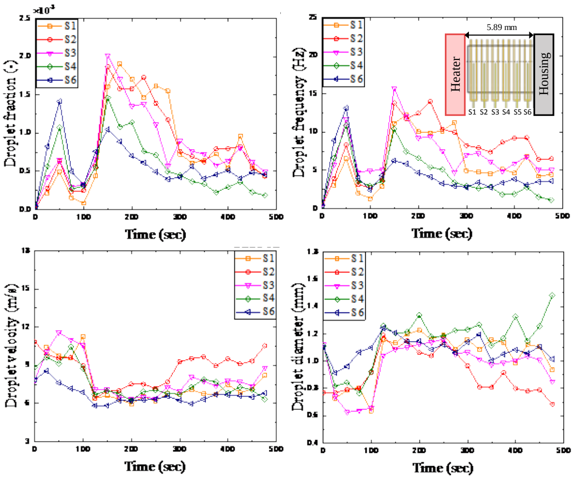

Fig. 4. Distribution of local droplet parameters

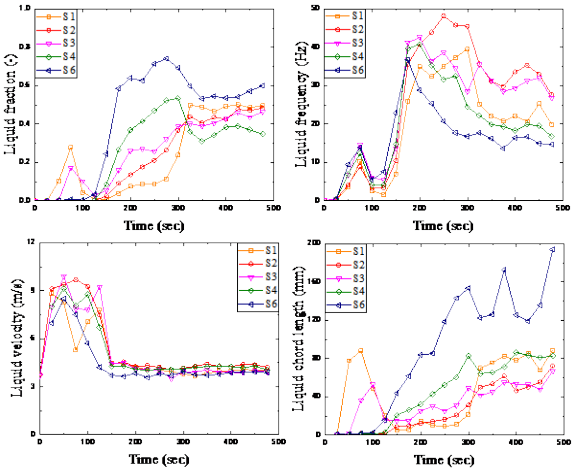

Fig. 5. Distribution of local liquid parameters

4. Conclusions

An experiment was conducted to investigate droplet behavior in a vertical annulus channel under reflood flow condition of LBLOCA. In order to establish an experimental database for droplet parameters, we introduced an optical fiber probe sensor technique. This allowed us to investigate the characteristics of the local droplet parameters during the reflood phase. It is expected that present data can be used for the benchmark of existing best estimate safety analysis code and model development for droplet parameters.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), a grant from the Nuclear Safety and Security Commission (NSSC) (Grant No. 2003001-0120-SB110), and a grant from the Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (MSIP), Republic of Korea (Grant No. 2017M2A8A4015059).

REFERENCES

[1] Lee, Naugab, PWR FLECHT SEASET unblocked bundle, forced and gravity reflood task data evaluation and analysis report. No. 10. The Commission, 1982.
[2] Ishii, M., and G. De Jarlais, Flow visualization study of inverted annular flow of post dryout heat transfer region, No. CONF-851007--7. Argonne National Lab., 1985.
[3] De Jarlais, G., M. Ishii, and J. Linehan, Hydrodynamic stability of inverted annular flow in an adiabatic simulation, pp. 84-92, 1986.
[4] Kim, Taeho, Taehwan Ahn, Byeonggeo Bae, Jae Jum Jeong, Kyungdoo Kim, and Byongjo Yun, Measuring local droplet parameters using single optical fiber probe, AIChE Journal, Vol. 65.6, e16591, 2019.
[5] Ishii, M., and G. De Jarlais, Hydrodynamics of post CHF region. No. CONF-8404146—1, Argonne National Lab., 1984.