ENERGETIKA. 2006. Nr. 1. P. 1–8

Experimental investigation of debris bed quenching with non-condensable gas release

Audrius Jasiulevičius*,

Bal Raj Sehgal

Nuclear Power Safety Division
Royal Institute of Technology
Dr. Kristinas väg 33A
S–10044 Stockholm, Sweden

A series of experiments were performed at the POMECO (Porous Medium Coolability) facility at the Nuclear Power Safety Division of the Royal Institute of Technology in Stockholm, Sweden. During the experiments, quenching of uniformly heated debris beds of different porosity with air injection from the bottom was investigated. These sets of experiments extend the earlier experiments performed on the POMECO facility and are applicable to ex-vessel coolability phase of a postulated nuclear power plant severe accident in which the attack on concrete generates non-condensable gases which traverse the debris bed. The beds had been heated up to ~500 °C before a water pool was established on top of the bed. Air was added from the bottom at different flow rates.

The results obtained for quench rates and flooding limits showed that for a very low porosity beds (ε = 0.26), the flooding limit is reached with modest air flow rates, while for a usual porosity (ε = 0.38) bed very high air flow rates would be required. The analysis of the experiments showed that the flooding correlations of Marshall–Dhir and Wallis could describe the measured data.

Key words: severe accidents, debris bed coolability, CCFL (Counter Current Flow Limitation) experiments, LWR

1. INTRODUCTION

Severe accidents of the Light Water Reactor (LWR), which are a subject of intensive research since the TMI-2 (Three Miles Island, USA) accident, are usually defined as accidents during which the meltdown of the reactor core occurs. The progression of the severe accident in the LWR may be classified into the in-vessel and ex-vessel phases. These phases involve extreme conditions and high temperatures. Investigations of this severe accident consequences require scaled experiments and numerical simulations in order to describe and assess the complex processes involved at various stages of the accident. The knowledge and understanding of these processes is needed to devise methods to prevent accidents and to mitigate their consequences through accident management.

The Reactor Pressure Vessel (RPV) is one of the main barriers against the release of the radioactive material into the environment during a severe accident in a LWR.

The RPV comes under severe thermal attack if the core melt drops from the original core boundary into the lower head during the later part of the in-vessel accident progression. The RPV lower head most probably will contain water at that time in the scenario, and the interaction of the melt discharged to the lower head with water would lead to the formation of a particulate debris bed. If the water supply is not restored, the lower head water will evaporate with time and a melt pool will be formed, which will circulate in the lower head and thermally load the vessel to fail it. If the vessel cannot be saved, the next and last barrier to the radioactivity release to the environment is the containment. The discharged melt from the vessel falls on the concrete in the reactor cavity and attacks the concrete basemat. This attack generates much non-condensable gases, and the containment will fail unless the melt pool can be cooled to temperatures below the concrete ablation temperature.

Ex-vessel melt (debris) coolability is a critical safety issue for the current and future nuclear power plants, with respect to the management and termination of a postulated severe (core melt) accident [1]. A particulate debris bed can be generated in the cavity of a PWR or the dry well of a Boiling Water Reactor (BWR), if water is already present prior to the melt release from the RPV. If no additional water is available in the cavity, the existing water will evaporate with time, resulting in a dry heat generating particulate debris bed which would start attacking the basemat concrete. Thus, it is most opportune to cool the debris bed in its particulate state before it rewets and becomes a melt pool.

The most convenient accident management measure is to cool the debris by establishing a water layer on

* Corresponding author, currently at Paul Scherrer Institute, Switzerland. E-mail: audrius.jasiulevicius@psi.ch

the top of the melt pool. The concrete ablation process induces the release of gases from the concrete, which may limit the quenching of the debris bed.

A number of tests were carried out throughout the world on the debris bed coolability issues (with and without gas addition). Schrock et al. [2] have studied the flooding of an isothermal particle bed by steam and water. Hu and Theofanous [3] investigated the deep volumetrically heated debris beds (up to 101.6 cm deep). Series of DCC tests were carried out at the Sandia National Laboratory [4] to verify the accuracy of existing coolability models. Kernforschungszentrum Karlsruhe (KfK) [5] carried out series of experiments to measure dryout heat fluxes and quenching in inductively heated small particle beds. Tung et al. [6] have performed coolability tests with volumetrically heated particle beds with top flooding and simultaneous air injection from the bottom, to simulate the gas release from concrete erosion at UCLA. The experimental test section consisted of stainless steel particles and Freon-113 was used as a coolant. More recently, SILFIDE tests were carried out at EdF [7] and at Royal Institute of Technology (RIT) in Stockholm [8].

The aim of the work presented in this paper was to investigate experimentally the possibilities to cool a hot particulate debris bed down to the saturation temperature having the additional gas flow from the bottom of the debris bed at atmospheric pressure. The experimental data support analytical predictions for the onset of the counter-current flow limitation (CCFL) for the debris bed porosity compositions expected to be formed during a LWR severe accident. The scenario investigated here is that with the gas release from the bottom of the debris bed, which corresponds to the quenching of the ex-vessel debris beds. The gas (air) supply system was installed in the POMECO facility below the debris bed. The gas flow rates through the debris bed corresponded to the gas release rates at the late stages of MCCI (several hours after the beginning of the process) from both basaltic and limestone-common sand concretes. A series of quenching experiments (adding the coolant from the top of the debris bed) were carried out at various gas flow rates. The dependence of the quenching time of the debris bed on the gas addition rates was investigated.

2. EXPERIMENTAL FACILITY

The idea of the experimental setup was to construct a test facility which simulates a unit cell of an ex-vessel debris bed. The debris bed during a severe accident is anticipated to be formed of particles of different sizes and varying porosity. The material for the bed to simulate the debris of reactor materials during the experiments was chosen to be sand, since the sand is a non-reacting material and the sand beds of various mean particle sizes and porosities could be easily accommodated and replaced in the test section. The flow of gas released in the concrete as a particulate bed ingresses during the severe accident scenario described above was to be simulated by the air supplied below the sand particle bed and flowing upwards through the sand bed in the test facility. To simulate the initial release of the particulate bed on the concrete basemat in the accident scenario, the sand bed was initially heated up in the test facility to the 450–500 ˚C (under atmospheric pressure of approximately 1 bar). Then the airflow was established through the test section to simulate the release of the gases from the concrete during the ingression of the hot particle bed. Finally, to simulate a severe accident management scheme, the hot debris bed was flooded from the top with water and a water layer of about 1 m height was established above the sand bed. The aim of the experiments was to measure the time which it takes for the water to completely penetrate the sand bed and to quench it down to the saturation (i.e. to cool the sand bed down from 450–500 ˚C to 100 ˚C). The flowrate of air supplied from the bottom of the test section during the test was selected according to the calculated gas release rate from two types of concrete commonly used in the western LWR construction: basaltic aggregate concrete and limestone aggregate – common sand concrete at the debris ingression rate of about 5 cm/hour. The aim of the test was to obtain the experimental data for the time until the debris bed is fully quenched for different porosity beds and at different air flow rates through the sand bed.

The schematic of the POMECO (Porous Media Coolability) facility designed and constructed at the Nuclear Power Safety Division of the RIT is shown in Fig. 1. The test section was a 350 mm square (500 mm high). The porous debris bed was assembled from sand. The porosity and mean particle sizes of the sand varied. The sand bed was supported from the bottom by a stainless steel net. Another stainless steel net covered the top surface of the bed to prevent the flying-off of the sand particles. Air, supplied from the

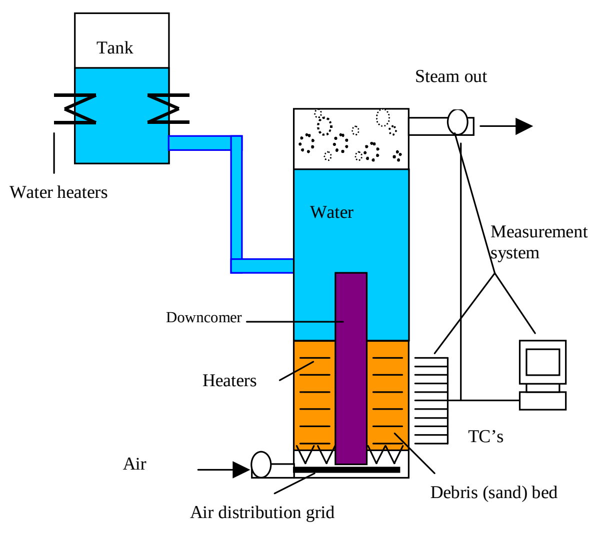

Fig. 1. POMECO test facility

bottom of the test section, passed through the stainless steel net and penetrated the sand bed from the bottom to simulate non-condensable gas release in the basemat concrete.

Thirty thin electrical heaters were distributed within the sand bed of the test section. The total power capacity of the heaters was 42 kW, which corresponds to the volumetric power of 0.98 MW/m^3. A number of thermocouples were embedded in the sand bed. The thermocouples were divided into five groups, each of the groups being inserted at various depths into the sand bed. The thermocouples were placed at 11 axial locations, at the same intervals, to facilitate the axial and radial temperature distribution readings from the test section.

A steam flowmeter of the capacity of up to 200 l/s was placed at the steam outlet line, on the top of the POMECO test facility. The heat removal rate from the test section during the experiments was estimated according to the steam flow rate at the outlet.

Pressurized air was supplied to the bottom of the test facility. The maximum capacity of the air which was possible to supply to the test section was up to ~150 l/min. A flowmeter was installed at the air line to measure the amount of air supplied.

A water tank was connected to the upper part of the POMECO facility. The tank supplied water to the top of the debris bed. The feedwater from the tank was heated up to a required temperature (~90 °C for the tests described in this paper).

2.1. Test section and instrumentation

The test section was a stainless steel vessel whose details are presented in Fig. 2, b. The cross-sectional area of the test section was 350 × 350 mm^2. The height of the lower (heated) part was 500 mm and the height of the upper part was 900 mm. The maximum height of 370 mm could be achieved for the sand bed in the lower part of the test section.

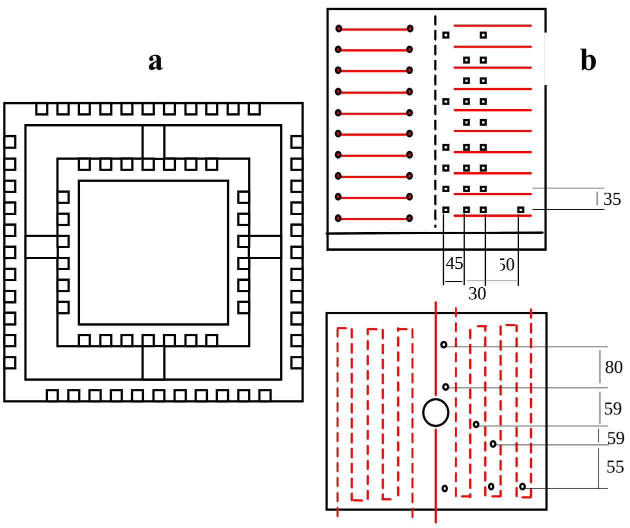

Fig. 2. POMECO test section design, heater and thermocouple distribution.
a – air supply grid,
b – distribution of thermocouples

The POMECO facility contained an annular pipe (outside diameter ¨124 mm) in the center of the sand bed. The annular pipe was of the same dimensions as the actual Control Rod Guide Tube (CRGT) in the BWR lower head. This test section configuration was the same as in previous POMECO experiments [8]. The annular pipe would allow evaluating the enhancement of the heat transfer in the porous medium in a severe accident scenario in BWR, where the additional coolant supply can be made available through the CRGTs. During experiments described in this paper the ex-vessel conditions were simulated, where the coolant supply though the CRGT is not relevant, hence the annular pipe was closed and no additional coolant was supplied through the downcomer.

Table 1. **Chemical composition of Default concretes (values in $^{w}/_{o}$)**

Species	Basaltic aggregate concrete	Limestone aggregate-common sand concrete	CRBR concrete
SiO_2	54.84	35.8	3.60
TiO_2	1.05	0.18	0.12
MnO	0.00	0.03	0.01
MgO	6.16	0.48	5.67
CaO	8.82	31.30	45.40
Na_2O	1.80	0.082	0.078
K_2O	5.39	1.22	0.68
Fe_2O_3	6.26	1.44	1.20
Al_2O_3	8.32	3.60	1.60
Cr_2O_3	0.00	0.014	0.004
CO_2	**1.50**	**21.154**	**35.698**
H_2O evap	**3.86**	**2.70**	**3.94**
H_2O bound	2.00	2.00	2.00

In Fig. 2, a presents the design of the air supply grid installed at the bottom of the POMECO test section. The air was distributed into two rectangular passage lines with openings on the sides of the lines. This allowed for more mixing and more homogeneous air distribution before the air entered the sand bed.

An most important measurement in the experiments was the temperature of the sand particle bed. Thirty-three thermocouples were distributed at different positions in the particle bed as shown in Fig. 2, b. The thermocouples were located at 11 axial elevations and at 5 radial positions. The quenching occurrences during the test series were recorded according to the readings of those thermocouples.

2.2. Experimental procedure

The experiments represent an ex-vessel situation of a severe accident scenario. After the melt is released from the Reactor Pressure Vessel (RPV) onto the containment floor, the corium starts interacting with the concrete material. The POMECO experiments represent the later stages of the process (i.e. several hours after the onset of MCCI). During the MCCI interactions in the later phases of the transient, the concrete ablation rate was assumed to be equal to 5 cm/h (i.e. corium continues to penetrate the concrete at this velocity). The heat generation in the debris bed of the POMECO facility was equal to 0.1 MW/m^3. This heat generation rate was equal to about 10% of the estimated decay heat rate for the corium mixture.

A series of quenching experiments were carried out. First the sand in the test section was heated up to about 500 ˚C. After the sand bed in the test section reached this temperature, an airflow from the bottom of the test section was established.

The flow rate of the air through the test section was calculated according to the amount of gas contained in and released from various default concrete types. The material content of some types of concretes used in the reactor technology is presented in Table 1. The gaseous components are typed in bold in Table 1. As is seen, the main contributors to gas release in the concrete are carbon dioxide (CO_2) and water vapor (H_2O). It was assumed that gases contained in the concrete are fully released during the MCCI scenario investigated at the POMECO test facility.

As is seen from Table 1, the amount of gases contained in the concrete differs with various concrete types.

During the experiments, gas amounts corresponding to the gas release rates from two widely used concrete types, basaltic and limestone concretes, were chosen to be simulated. The airflow at the flow rate, which corresponds to the amounts of the gas released, was supplied at the bottom of the POMECO test facility. The initial air temperature at the entrance to the test section was equal to the room temperature (about 20 ˚C). The air heated up to the porous bed temperature (about 450–500 ˚C) after traveling about 8 cm through the porous bed.

After establishing the airflow through the porous debris bed, the water (at a temperature of about 90 ˚C) was supplied to the top of the debris bed. Quenching experiments were carried out in order to determine the debris bed quenching time at various air flow rates.

Two configurations of the porous beds were used during the experiments: with porosities ε = 0.38 and 0.26 and corresponding mean particle sizes of 1.0 and 0.7 mm.

3. EXPERIMENTAL RESULTS

Four different experimental conditions were investigated:

- No airflow through the test section. Quenching experiments were carried out in order to determine the reference quenching time for the different bed configurations.
- Experiments with low airflow rate. These conditions correspond to the MCCI with a low gas content concrete (gas generation in basaltic concrete).
- High airflow rate experiments, which correspond to the MCCI with a high gas content concrete (gas generation in limestone concrete).
- Experiments with varying the airflow rate, which were carried out in order to determine the corresponding CCFL onset airflow rate in the porous debris bed.

The results of the experiments are presented in Fig. 3–5. These figures contain the temperature readings from the 30 thermocouples distributed within the test section sand bed. The quenching time for the debris beds was the key parameter to be determined during the experiments. The full quenching of the debris bed occurs when the temperature within the debris bed is equal to the steam saturation temperature at a given pressure (the pressure during the experiments was close to 1 bar), i.e. when the water ingresses though the whole height of the debris bed. Therefore, the main information presented in Fig. 3–5 is the time at which the temperature of the last thermocouple within the test section was reduced down to the saturation temperature.

3.1 Debris bed of porosity 0.26

Table 2 presents the experimental results for the quenching tests in the first test series, with a low porosity debris bed (the porosity of 0.26 and the mean particle size of 0.7 mm). The power supply to the test section was 4200 W (about 0.1 MW/m^3). The initial average sand bed temperature was about 450 ˚C. The temperatures (over 500 ˚C) were highest in the middle plane of the test section (about 20 cm deep in the debris bed). The temperatures at the top and the bottom of the debris bed were lower due to the heat losses to the environment. The temperatures at the locations of the

Table 2. **Quenching experiments for the low porosity debris bed (porosity 0.26, mean particle size 0.7 mm; power supply 4200 W, initial mean sand bed temperature 450 ˚C)**

Test No.	Air flow rate through the debris bed, l/min	Average steam discharge rate, kg/s	Quenching time, s
LP-1.1	–	~0.003	2400
LP-1.2	30.0	~0.002	5100
LP-1.3	142.5	0.0	No quenching
LP-1.4	Reduced in steps	Variable	Quenching at air flow ~93 l/min

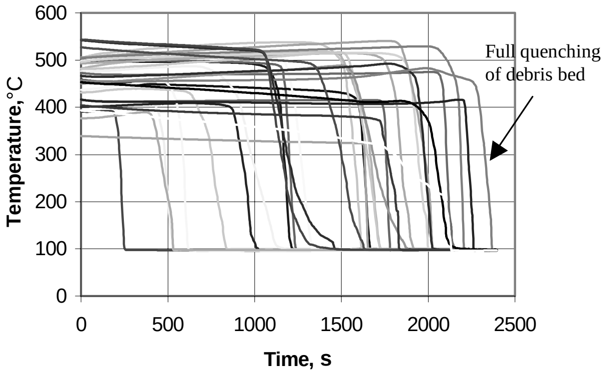

Fig. 3. Temperature distribution in the debris bed during LP-1.1 test

lowest and highest thermocouples embedded in the test section were about 430–450 ˚C.

The LP-1.1 test presented in Table 2 was carried out with no airflow through the debris bed. For this porous bed composition, the full quenching of the debris bed in the test section occurred at about 2400 seconds after the filling of the upper tank with water (Fig. 3). The average steam generation rate was about 0.003 kg/s, which corresponds to an about 6.5 kW heat removal rate from the debris bed by the top flooding (the power input during the test series was 4.2 kW). The third column in Table 2 shows only the steam flow rates (additional gas flow subtracted) for the tests LP-1.2, LP-1.3 and LP-1.4.

During the test LP-1.2 the airflow at the rate of 30 l/min was supplied to the test section. This additional airflow significantly increased the quenching time for the debris bed (5100 s vs. 2400 s with no airflow).

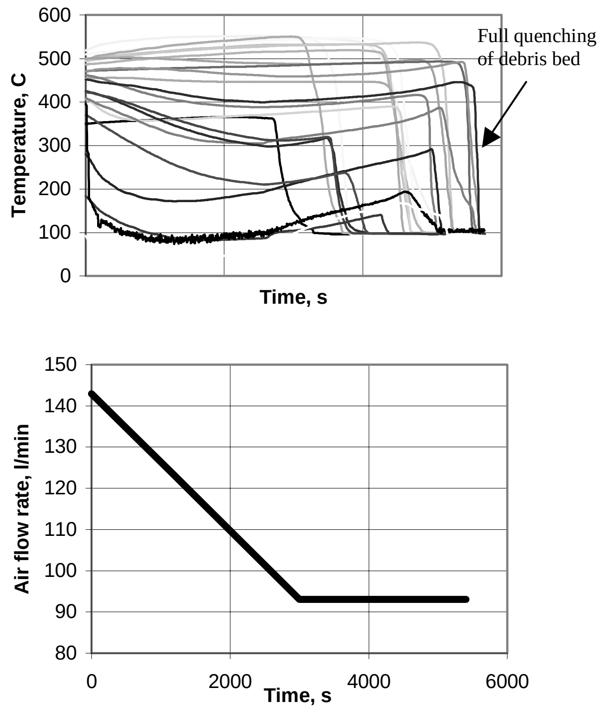

Fig. 4. Debris bed temperature and gas flow rate distribution during LP-11.4 test

During the test LP-1.3, the gas flow rate which corresponds to the gas generation rate in the limestone concrete (several hours after the onset of MCCI, when concrete ablates at the rate of about 5 cm/hour), was supplied through the test section. At this gas flow rate, the counter current flow limit (CCFL) was exceeded, and no water was able to penetrate the debris bed of the porosity 0.26.

The test LP-1.4 was carried out in order to determine the gas flow rate, at which the CCFL is reached. For this test, the initial gas flow at the rate of 142.5 l/min was established. After this, the gas flow rate was reduced in steps of 10 liters/every 10 minutes, until the quenching of the debris bed started (Fig. 4). After the start of the quenching process, the gas flow rate was not changed during the rest of the experiment. It was determined that for the porosity of 0.26 and the mean particle size of 0.7 mm the CCFL were reached at the flow rate of about 93 l/min. As is seen from Fig. 4, temperatures at the bottom of the debris bed reached rather low values at the very beginning of the transient. This was due to the fact that the inlet air was at the room temperature (about 20 ˚C). The air passed for about 8 cm into the sand bed cooling the debris bed from the bottom, before being heated up to the debris bed temperature.

3.2. Debris bed of porosity 0.38

The second series of experiments was carried out with the debris bed of porosity 0.38 and mean particle sizes of about 1.00 mm. The results of the experiments are presented in Table 3. As is seen, no CCFL was reached for the higher porosity debris bed configuration.

Table 3. **Quenching experiments for the higher porosity debris bed (porosity 0.38, mean particle size 1.00 mm; power supply 4200 W, initial mean sand bed temperature 450 ˚C)**

Test No.	Air flow rate through the debris bed, l/min	Average steam discharge rate, kg/s	Quenching time, s
HP-1.1	–	~0.003	1680
HP-1.2	30.0	~0.002	1740
HP-1.3	142.5		2220

During the test HP-1.1, no additional airflow was supplied into the test section. The quenching time (Table 3) for the debris bed was 1680 s, i.e. the debris bed was quenched in a shorter time, compared to the first experimental series (Table 2), due to a higher porosity of the debris bed, which results in a larger flow area and a smaller influence of the capillarity effects, compared to the porosity of 0.26 (during the first test series).

The test HP-1.2 was carried out with a 30.0 l/min air flow rate (which corresponds to the gas generation

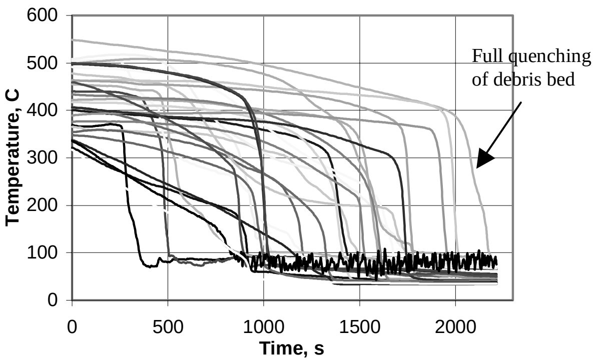

Fig. 5. Temperature distribution in the debris bed during HP-1.3 test

rate in basaltic concrete). The quenching time in this test was longer than in test HP-1.1.

At the high gas flow rates of 142.5 l/min (test HP-1.3) the quenching of the debris bed occurred about 540 s later (Fig. 5) compared to the reference case.

As the CCFL was not reached for the debris bed configuration of porosity 0.38, the last experiment of the test series (determination of the onset of CCFL) was not carried out for this debris bed configuration.

4. ANALYSIS

Dell and Pratt [9] found that for immiscible fluids the flooding velocities can be correlated as

$$j_1^{1/2} + j_2^{1/2} = C\,, \qquad (1)$$

where the constant C is a function of the particle diameter, bed porosity, surface area and phase densities (1 and 2 represent two phases or fluids). Later on, the C value was found to be affected also by changes in the viscosity and surface tension of the two phases [10].

For the flooding limit of the gas flow moving upward and the liquid flux downward, Wallis [11] proposed an empirical flooding correlation of the form:

$$j_g^{*1/2} + m\, j_f^{*1/2} = C, \qquad (2)$$

where m and C are the constants and j_k^* are the dimensionless superficial velocities defined as

$$j_k^* = j_k \left[\frac{\rho_k}{gD(\rho_l - \rho_g)\dfrac{\varepsilon^3}{a}} \right]^{1/2} . \qquad (3)$$

Marshall and Dhir [10] defined the parameter *a*, surface area packing per unit volume of the column, as

$$a = \frac{6(1-\varepsilon)}{D_p} \;. \qquad (4)$$

For a bed with top flooding, several correlations were developed on this basis. The correlations presented by Wallis [11], Marshall & Dhir [10] work quite well for a high flow rate:

$$j_g^{*1/2} + j_l^{*1/2} = 0.775 \qquad \text{Wallis} \quad (5)$$

$$j_g^{*1/2} + j_f^{*1/2} = 0.875 \qquad \text{Marshal \& Dhir} \quad (6)$$

To the low flow region, a correlation developed by Schrock et al. [2] can be applied:

$$j_g^{*0.38} + 0.95\, j_f^{*0.38} = 1.075\,. \qquad (7)$$

The dimensionless superficial velocities j_k^* were calculated and plotted for the POMECO experimental data (Fig. 6).

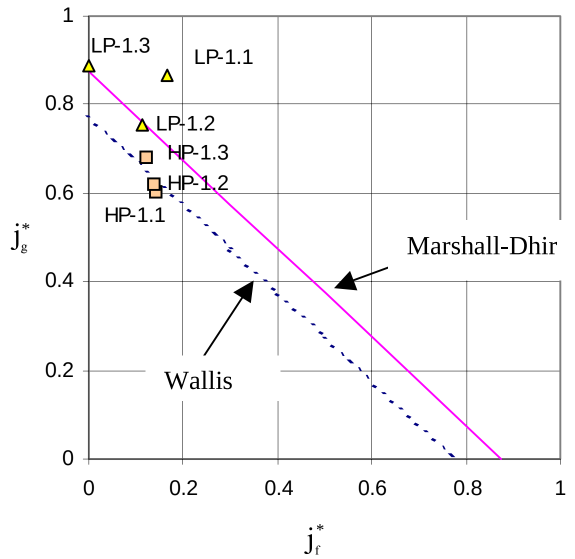

Fig. 6. Comparison of the experimental data with flooding correlations

As is seen from Fig. 6, the Marshall and Dhir correlation provides a good estimation for the flooding for the experiments LP-1.2 and LP-1.3. Both flooding limit and dimensionless superficial velocities for this case agree well with the experimental data. During both experiments, LP-1.2 and LP-1.3, additional gas flow through the test section was present.

For the case with no additional gas flow (experiment LP-1.1), the experimental data do not fit the correlation predictions, i.e. either gas or liquid phase superficial velocities were higher during the experiment, compared to the correlations. The better agreement for this case (LP-1.3) is obtained using the Schrock et al. correlation for the flooding limit prediction. In this case we obtain the constant C~1.1 (see the right hand side of equation (7)), instead of the correlation C = 1.075 predicted by Schrock et al..

On the other hand, the experimental data obtained during the experiments with a high porosity (e = 0.38) particle beds (experimental series HP-1, 2 and 3) provide lower values of the constant C, compared to the previous experimental case with the porosity of e = 0.26. Gas and liquid superficial velocities for the experimental series HP (HP here corresponds to a high porosity debris bed) agree best with the Wallis correlation (Eq. 5) estimation (Fig. 6).

5. CONCLUSIONS

Two sets of experiments at the POMECO facility were carried out. Flow of air was supplied through the test section in order to simulate an LWR severe accident scenario with MCCI, with gas generation from concrete structures. The concrete ablation rate and the associated gas generation rates were estimated equal to the ablation velocity at the later stages of the MCCI transient (about 5 cm/h of concrete ablation).

Two debris bed configurations were investigated: of porosities 0.26 (mean particle size 0.7 mm) and 0.38 (mean particle size 1.0 mm). During the experiments it was determined that:

• the addition of the air at the bottom of the porous bed significantly increases the quenching time for the low porosity small mean particle size beds;

• flooding limitation might be reached for the low porosity beds at high air flow rates, i.e. the penetration of the coolant into the particle bed may be impossible;

• for higher porosity bed composition (ε = 0.38; mean particle size 1 mm) the addition of the gas from the bottom does cause an increase in the bed quenching time, but the CCFL is not reached for this bed configuration, even at high gas flow rates.

A comparison of the experimental results with the empirical flooding correlations, developed by Wallis [11], Marshall & Dhir [10] and Schrock et al. [2] shows a good agreement for the flooding limitation prediction for the low porosity bed compositions (ε = 0.26), for the experimental with additional air supply through the test section. Experiment LP-1.1, carried out with no additional air supply, resulted in higher liquid / gas superficial velocities compared to the Wallis and Marshall & Dhir correlation. For this case, the closest agreement was obtained with Schrock et al., correlation predictions, although the experimental superficial velocities were still higher compared to the correlation predictions.

For the high porosity debris bed compositions (ε = 0.38), the experimental liquid/gas superficial velocities were lower than predicted by the Marshall-Dhir correlation. The close agreement with Wallis correlation was obtained for these test series (experiments HP-1.1, 2 and 3).

Larger number of experimental data, carried out over a wider spectrum of superficial gas/liquid velocities, as well as large variation of porous bed compositions (porosities and mean particle sizes) has to be obtained from the POMECO facility, in order to fully assess the CCFL correlations and to investigate the CCFL phenomenon in particulate debris beds.

NOMENCLATURE

BWR	Boiling Water Reactor
CCFL	Counter-Current Flow Limitation
CRGT	Control Rod Guide Tube
EdF	Electricitê de France
HP	High Porosity
LWR	Light Water Reactor
MCCI	Molten Corium – Concrete Interaction
POMECO	Porous Media Coolability, test facility
LP	Low Porosity
PWR	Pressurized Water Reactor
UCLA	University of California, Los Angeles

Received 20 February 2006

References

1. Sehgal B. R. et al. Investigation on Melt-Structure-Water-Interactions (MSWI) During Severe Accidents, SKI Report 99:42. Stockholm, 1999.
2. Schrock V. E., Wang C.-H., Revankar S., Wei L. H., Lee S. Y., Squarer D. Flooding in particulate beds and its role in dryout heat flux // Proceedings of 6th Information Exchange Meeting on Debris Coolability, UCLA, Ca, 1984.
3. Hu K., Theofanous T. G. Scale effects and structure of dryout zone in debris bed coolability experiments // Proceedings of 6th Information Exchange Meeting on Debris Coolability, UCLA, Ca, 1984.
4. Reed A. W., Boldt K. R., Gorham-Bergeron E. D., Lipinski R. J., Schmidt T. R. DCC-1/DCC-2 Degraded Core Coolability Analysis, Report NUGER/CR-4390, SAND85-1967. Washington, D. C., October 1985.
5. Barleon L., Thomauske K., Werle H. Extended dryout and rewetting of small-particle core debris // 6th International meeting on Debris Coolability. Los Angeles, Ca, November 7–9, 1984.
6. Tung V. X., Dhir V. K., Squarer D. Quenching by top flooding of a heat generating particulate bed with gas injection at the bottom // Proceedings of 6th Information Exchange Meeting on Debris Coolability, EPRI Report NP-4455. Palo Alto, Ca, March 1986.
7. Decossin E. Numerical Investigations on Particulate Debris Bed Coolability: Critical Analysis of the SILFIDE Experimental Project // Proceedings of NURETH-9 Conference. San Francisco, Ca, October 3–9, 1999.
8. Konovalikhin M. J., Sehgal B. R. Investigation of volumetrically heated debris bed quenching // Proceedings of ICONE-9 Conference. Nice, France, April 8-12, 1999.
9. Dell F. R., Pratt H. R. C. Flooding Rates for Packed Columns // Inst. Chem. Eng. 1951. Vol. 29. P. 89.
10. Marshall J. S., Dhir V. K., On the counter-current flow limitations in porous media // International Meeting on LWR Severe Accident Evaluation. Cambridge, Ma, August 28 – September 1, 1983.
11. Wallis G. One-dimensional Two-phase Flow. McGraw-Hill Boo Co, New York, 1969.

Audrius Jasiulevičius, Bal Raj Sehgal

EKSPERIMENTINIS PORĖTO DALELIŲ SLUOKSNIO AUŠINIMO TYRIMAS VEIKIANT PRIEŠPRIEŠINIAM NESIKONDENSUOJANČIŲ DUJŲ SRAUTUI

Santrauka

Straipsnyje pateikti tyrimai atlikti Stokholmo karališkojo technologijos instituto Branduolinės saugos skyriuje. Eksperimentams buvo panaudotas POMECO (Borous Medium Coolability) eksperimentinis stendas. Čia buvo ištirta tolygiai (vienodai) įkaitinto skirtingo porėtumo dalelių (smėlio) sluoksnio aušinimas pučiant iš apačios orą. Šiais eksperimentais buvo pratęsiami ankstesni tyrimai, atlikti tame pačiame eksperimentiniame stende, kurie buvo taikomi sunkiai AE avarijai, kai iš reaktoriaus korpuso išsiveržia išsilydęs kuras, tirti. Jis susidurdamas su įvairiomis betono konstrukcijomis generuoja nesikondensuojančias dujas, kurios veržiasi per porėtą susidariusių dalelių sluoksnį. Eksperimentų metu modeliuojamas sluoksnis įkaitinamas iki 500°C ir po to jis aušinamas iš viršaus užliejant vandeniu. Porėtajam dalelių sluoksniui aušinti iš apačios pučiamas įvairaus intensyvumo oro srautas.

Tyrimo rezultatai rodo, kad mažo porėtumo dalelių sluoksnio ($\varepsilon = 0{,}26$) užliejimo vandeniu riba pasiekiama mažais oro srautais ir mažesniais už nesikondensuojančių dujų srautus. Didelio porėtumo ($\varepsilon = 0{,}38$) sluoksniui reikia labai didelių oro srautų. Eksperimentų duomenų analizė ir palyginimas parodo, kad Marshall-Dhir ir Wallis gautos aušinimo laiko ir porėto sluoksnio užliejimo vandeniu koreliacijos gerai atspindi eksperimentų duomenis.

Raktažodžiai: sunki avarija, porėto dalelių sluoksnio aušinimas, CCFL – priešpriešinio dujų srauto ribojimas, eksperimentas, LWR – lengvojo vandens reaktorius

Àóäðþñ ßñþëåâè÷þñ, Áàë Ðàé Ñåãàë

ÝÊÑÏÅÐÈÌÅÍÒÀËÜÍÎÅ ÈÑÑËÅÄÎÂÀÍÈÅ ÎÕËÀÆÄÅÍÈß ÏÎÐÈÑÒÎÃÎ ÑËÎß ×ÀÑÒÈÖ Â ÓÑËÎÂÈßÕ ÄÅÉÑÒÂÈß ÏÐÎÒÈÂÎÏÎËÎÆÍÎÃÎ ÏÎÒÎÊÀ ÍÅÊÎÍÄÅÍÑÈÐÓÞÙÈÕÑß ÃÀÇÎÂ

Ðåçþìå

Èññëåäîâàíèÿ ïðîâîäèëèñü â Îòäåëå ÿäåðíîé áåçîïàñíîñòè Ñòîêãîëüìñêîãî êîðîëåâñêîãî òåõíîëîãè÷åñêîãî èíñòèòóòà. Íà ýêñïåðèìåíòàëüíîì ñòåíäå POMECO (Porous Medium Coolability) èññëåäîâàëñÿ ðàâíîìåðíî íàãðåòûé ñëîé, îáðàçîâàííûé èç ÷àñòèö (ïåñêà) ðàçëè÷íîé ïîðèñòîñòè, ïðîäóâàåìûé ñíèçó âîçäóõîì. Äàííûå ýêñïåðèìåíòàëüíûå èññëåäîâàíèÿ ÿâëÿþòñÿ ïðîäîëæåíèåì ïðîâåäåííûõ ðàíåå èññëåäîâàíèé íà òîì æå ñòåíäå, èñïîëüçîâàííîì äëÿ èçó÷åíèÿ òÿæåëîé àâàðèè íà ÀÝÑ â ñëó÷àå èçâåðæåíèÿ ðàñïëàâëåííîãî ÿäåðíîãî òîïëèâà çà êîðïóñ ðåàêòîðà. Ïðè ñîïðèêîñíîâåíèè åãî ñ áåòîííûìè îãðàæäàþùèìè êîíñòðóêöèÿìè ãåíåðèðóþòñÿ íåêîíäåíñèðóþùèåñÿ ãàçû, ïðîðûâàþùèåñÿ ÷åðåç ïîðèñòûé ñëîé ÷àñòèö. Â ýêñïåðèìåíòå äàííûé ñëîé íàãðåâàëñÿ äî 500°C, à â ïîñëåäñòâèè äëÿ îõëàæäåíèÿ ñâåðõó çàëèâàëñÿ âîäîé. Äëÿ îõëàæäåíèÿ ýòîãî ïîðèñòîãî ñëîÿ îí ñíèçó ïðîäóâàëñÿ ïîòîêîì âîçäóõà ðàçëè÷íîé èíòåíñèâíîñòè.

Ðåçóëüòàòû èññëåäîâàíèÿ ïîêàçûâàþò, ÷òî â ñëó÷àå ìàëîé ïîðèñòîñòè ñëîÿ ($\varepsilon = 0{,}26$) ïðåäåë çàòîïëåíèÿ âîäîé äîñòèãàåòñÿ ïðè ìàëûõ ïîòîêàõ âîçäóõà è ìåíüøèõ ïîòîêàõ íåêîíäåíñèðóþùèõñÿ ãàçîâ. Â ñëó÷àå áîëüøîé ïîðèñòîñòè ($\varepsilon = 0{,}38$) äëÿ ïðîäóâêè ñëîÿ íåîáõîäèìû î÷åíü èíòåíñèâíûå ïîòîêè âîçäóõà. Àíàëèç ýêñïåðèìåíòàëüíûõ è òåîðåòè÷åñêèõ äàííûõ ïîêàçûâàåò, ÷òî êîððåëÿöèÿ âðåìåíè îõëàæäåíèÿ è çàòîïëåíèÿ ïîðèñòîãî ñëîÿ âîäîé õîðîøî îáîáùàåòñÿ ìåòîäîì Marshall-Dhir è Wallis.

Ключевые слова: тяжелая авария, охлаждение пористого слоя частиц, CCFL – пределы противоположного потока газов, эксперимент, LWR – реактор легкой воды