Experimental Investigation of Post-Dryout Heat Transfer in Annuli with Flow Obstacles

Ionut Anghel, Henryk Anglart, Stellan Hedberg
Royal Institute of Technology-KTH, AlbaNova Universitetsscentrum, Stockholm, SE-10691
iganghel@kth.se, henryk@kth.se, stellan@energy.kth.se

ABSTRACT

An experimental study on post-dryout heat transfer was conducted in the High-pressure Water Test (HWAT) loop at the Royal Institute of Technology in Stockholm, Sweden. The objective of the experiments was to investigate the influence of flow obstacles on the post-dryout heat transfer. The investigated operational conditions include mass flux equal to 500 kg/(m²s), inlet subcooling 10 and 40 K and system pressure 5 and 7 MPa. The experiments were performed in annuli in which the central rod was supported with five pin spacers. Two additional types of flow obstacles were placed in the exit part of the test section: a cylinder supported on the central rod only and a typical BWR grid obstacle cell. The measurements indicate that flow obstacles improve heat transfer in the boiling channel. On the one hand the dryout power is higher when additional obstacles are present. On the other hand the wall temperature in post-dryout heat transfer regime is reduced due to increased turbulence and drop deposition. The present data can be used for validation of computational models of post-dryout heat transfer in channels with flow obstacles.

1. INTRODUCTION

Post dryout heat transfer regime occurs during force flow evaporation process when liquid film becomes depleted at the heated wall surface. During post dryout heat transfer regime, the heat is transferred mainly to the vapour. Consequently, the heat transfer coefficient is much lower with results of a dramatically increase of the wall surface temperature. The immediate consequence of very high superheated wall could be the failure of the clad in case of nuclear fuel. Such regime can occur in case of an abnormal operation of Boiling Water Reactor. For instance, during refill phase in case of a small loss of coolant accident (LOCA) the fuel elements experience the post-dryout heat transfer situation, [9], [10]. In this case a proper model to calculate the wall temperature in order to avoid clad deterioration is required. Due to these facts a considerable amount of both experimental and analytical research has been performed. Still, the influence of the spacers/obstacles on heat transfers at both pre-critical heat flux (CHF) and post-CHF is still not completely elucidated.

Several researchers demonstrated that the temperature on the surfaces of various test sections is severely affected by the existence of an obstacle/spacer. However, only few experiments have been conducted in BWR typical operating conditions. Tuzla et al. carried out post CHF experiments in a 3x3 bundle, [3]. Using for the first time a special design of a hot patch, they obtained stabilized post-CHF conditions in the rod bundle geometry. Recently, Anglart and Persson have shown - using a typical BWR spacer - that at post-dryout heat transfer
conditions in a heated annulus (10x22.1x3650) mm, the dryout patches are effectively quenched downstream of spacers, [1]. As a continuation of this research, a new set of experiments with a significant improvement of the accuracy of temperature measurements were carried out by Anghel et al., [2]. The present experiments performed for low flow rate and high pressure conditions are relevant for LOCA conditions and can be used for validation of computational models of post-dryout heat transfer in channels with flow obstacles.

2. EXPERIMENTAL FACILITY

2.1 The loop

The loop used for the post-CHF experiments was designed to operate at pressures up to 25 MPa. All parts in contact with water (except the test section) are made of stainless steel. The loop construction allows for test sections up to 7 m in length. In Figure 1 a simplified flow diagram of the loop is presented. In the present experiments an annulus with a length of 3.65 m made of Inconel 600 is used.

The main components of the loop are: feed water pump, circulation pump, flow measurement system, regulating valve, pre-heater, test section, condenser and blow off valve. A secondary circuit with coolant water at 293.15 K is used to cool the circulation pump.

The loop is operating as follows. The circulation water first has to pass through the flow measurement system. From here the working fluid continues to the 155 kW pre-heater, which is needed to adjust the inlet temperature. Later on, the water at subcooled condition enters into the test section. After the test section, the water is passing through the condenser where the heat is evacuated and the two-phase mixture flow is changing to the saturated single phase liquid flow.

The water circulation in the loop is provided by the circulation pump, which has a pressure head of 100 meter water, a big part of this being used in the duct system between the pump and the test section to secure a stable operation of the loop.

![Figure 1: The High-pressure Water Test (HWAT) loop.](image)

Proceedings of the International Conference Nuclear Energy for New Europe, Portorož, Slovenia, Sept. 6-9, 2010
2.2 Test section

The test section consists of an annulus assembled from two concentric tubes. In this paper the inner tube will be referred to as rod while the outer tube will be referred to as tube. Both, the rod and the tube are manufactured from Inconel 600. This material was chosen because of the small rate of change of the resistivity with the temperature, [6]. The design pressure and temperature for the test section are 18.3 MPa and 973 K, respectively.

Two copper rings, 0.1 m long each, were soldered on both rod and tube. In the present paper the distance between the copper rings is referred to as the heated length. The electrical power was supplied via two copper electrodes connected to the copper rings. In order to keep heat losses at an insignificant level, 90 mm thick glass fiber insulation was mounted around the test section. Nevertheless, for calculation of the heat flux all the heat losses were taken into account.

The experiments conducted in case of a test section with pin-spacers are considered reference cases. After the reference cases were carried out, the test section is dismantled and two cylindrical obstacles with an inner diameter of 18.1 mm and 0.35 mm thickness made of stainless steel are silver soldered on the inner rod. A second series of the experiments are performed in the same thermal hydraulic conditions. Once the second series of experiments were performed, the test section was dismantled one more time and the cylindrical obstacles are replaced with two grid obstacles.

The flow area occupied by the flow obstacles is: 10.13% in case of pin-spacers, 7.3% in case of cylindrical obstacle and 10.07% in case of grid obstacle.
Figure 2: The flow obstacles used in the experiment: (a) pin-spacers, (b) pin-spacers and cylindrical obstacles, (c) pin-spacers and grid obstacles
2.3 Temperature measurements

The temperature of the annulus walls were recorded with 80 thermocouples of K-type, 40 located axially inside of the rod and 40 located outside of the tube. The thermocouples set inside of the rod were arranged in a bundle. One layer of the glass fibre tape and one layer of the mica tape were used to keep the bundle tightened and to insulate and protect the thermocouple heads from the electrically conducting hot surface of the wall. The thermocouples were pressed against the wall surface by small springs located in the opposite location. Axial locations of the thermocouples are presented in Figure 3. To calibrate the readings of the assembled thermocouples, three experiments were conducted in case of adiabatic, single phase flow at 298, 383 and 483 K. The temperature deviations are presented in Figure 4.

2.4 Experimental method

The standard methods to perform measurements of post-CHF heat transfer include the following steps:

1. for a set of chosen parameters such as inlet subcooling, mass flux and pressure, the power of the heater is set slightly below the level that corresponds to the first occurrence of dryout in the test section,
2. increase the power step-wise (keeping the rest of the parameters constant) and record the temperature distribution once the steady-state condition is achieved.
The procedure is repeated for the same inlet conditions, in case of all three different kinds of flow obstacles.

2.4 Uncertainties

During heat balance operation, the electrical power was compared with the enthalpy increase over the test section and the total power uncertainty was estimated as ±0.5 %.

In addition, the measurements of mass flux and temperature have the following uncertainties:

- Uncertainty in temperature measurements: 1.5 K for a wall temperature up to 473 K; 2.5 K for a wall temperature up to 973 K, [7].
- Uncertainty in mass flux: ±0.8 %, [8].

Performing the uncertainty propagation, it has been established that the uncertainty of the measured heat transfer coefficient in the post-dryout region is ±3.5 %.

3. EXPERIMENTAL RESULTS

3.1 General trends

It is known that post-dryout heat transfer regime can be reached after three different transitions in the evaporation process: critical heat flux, dryout of the liquid film, entrainment of the liquid film. The present work investigates only the dryout of the liquid film. In literature this type of regime is identified as “dispersed film flow boiling regime” or mist flow. In the post dryout heat transfer regime the surface of the wall is not necessarily always dry. The entrained liquid droplets can impinge on the wall surface and cool locally the wall surface before being evaporated or “pushed” back into the vapour phase, [11]. In the vertical channels like in BWR case, the liquid film is thinner on the top of the channels. Consequently, the dryout will occur first at the sub-channels exit and progress upward creating so-called dryout patch along the channel.

The present study shows that the influence of flow obstacles on post-dryout heat transfer is quite significant. Their primary effect is to disturb the flow field of the vapour phase which in turn causes the increase of deposition of liquid drops. The effect however depends on the obstacle shape and its axial location. In this study the net effect of obstacles was investigated by comparing the data obtained in a reference test section (with pins only) and a test section with introduced flow obstacles. The results of runs with three different geometries (with pins only, with pins and cylindrical obstacle and with pins and grid obstacles) are presented in Figures 5 through 10. Since there were no thermocouples placed azimuthally inside of the rod, no comments can be made regarding symmetry of the drypatch development.

3.2 Influence of cylindrical obstacle

Figures 5 and 6 show the experimental results obtained in the reference test section (only pin-spacers) and in the test section with the cylindrical obstacle, respectively. The operating conditions are as follows: mass flux G=500 kg/(m²s) , pressure P=5 MPa and inlet subcooling...
10 K. Initial dry patch appears in both cases at the exit of the test section. The effect of cylindrical obstacle can be deduced at the onset of dryout. In case of pin spacers, when heat flux is equal to 511 kW/m², the post-dryout heat transfer regime is fully reached while in case of cylindrical flow obstacles when heat flux is equal to 519 kW/m² the pre-dryout heat transfer regime is still dominating. When the heat flux increased to 529 kW/m² and 524 kW/m² respectively, a second dryout patch was developed upstream of the last pin spacer location. The effect of the pin spacer is clearly visible: the dry patches are quenched just downstream of its location and the surface superheat is reduced to the values observed in convective heat transfer regime.

Figures 7 and 8 show the experimental results obtained in the same test section and operational conditions but at 7 MPa pressure. The same effects as discussed before can be observed. It can be seen that when the rod heat flux exceeds 537.7 kW/m², the third dryout patch is initiated just upstream of the first cylindrical obstacle. The temperature of the wall surface is reduced just downstream of the cylindrical obstacle, but this effect disappears after approximately 80 mm. Instead, the effect of the last pin-spacers is very pronounced. For a short distance the liquid film is re-created after the pin-spacer and the local wall surface temperature corresponds to the pre-dryout heat transfer regime. The pin-spacer seems to be more effective in enhancing the heat transfer than the cylindrical obstacle. This may be caused by the fact that the flow blockage area of pin spacers is higher than that of cylindrical obstacles and thus local turbulence is increased.

When heat flux on the rod is increased from 537.7 to 571.9 kW/m².s, the wall temperature downstream of cylindrical obstacles drops by approximately 20-30 K. Taking into account the heat flux change, this temperature drop corresponds to an improvement of the heat transfer coefficient by approximately 20% when increasing the heat flux. This behaviour can be explained by an increase of the vapour velocity when the mixture quality increases. With increased velocity more turbulence is generated by the obstacles and thus more effective cooling is achieved.
Figure 9 shows the measured wall superheat in test sections operated at the same conditions (mass flux 500 kg/m².s and inlet subcooling 10 K) but different pressures equal to 5 and 7 MPa. As expected, the post-dryout conditions first appear in the case with pressure 7 MPa due to lower latent heat and thus higher quality.

### 3.2 Influence of grid obstacle

Figures 10 through 12 show the results obtained in a test section with grid obstacles in comparison with the reference case with pins only and with the test section with the cylindrical obstacle. As seen in Fig. 10, the dryout patch first appears at the exit from the test section when heat flux on the rod exceeds 504.8 kW/m². Only when the heat flux exceeds 517.7 kW/m² the dry patch moves upstream of the last grid obstacle. It should be noted that in the investigated range of conditions, the wall temperature monotonically increases with increasing heat flux.

The effect of various flow obstacles can be evaluated at the conditions corresponding to the onset of dryout, as shown in Fig. 11. In case of pin spacers, when heat flux is equal to 494.6 kW/m², the post-dryout heat transfer regime is fully reached, even the second dryout patch being developed while in case of cylindrical flow obstacles when heat flux is equal to 496 kW/m² the post dryout heat transfer regime is still in transition. For the grid obstacle, when heat flux is equal with 504 kW/m², the onset of dryout is observed.

A peculiar behaviour was noticed in some cases shown in Figs. 10 and 12 in which a dryout patch appeared just downstream of the last pin spacer. Usually this type of behaviour is not expected due to improved cooling conditions prevailing downstream of obstacles. It is believed that in the observed cases the liquid film was thinned due to pins and at high enough heat fluxes this lead to evaporation of the film and to a creation of a drypatch.
4. SUMMARY AND CONCLUSIONS

This paper describes new measurements of post-dryout heat transfer in an annular test sections with various flow obstacles. One of the goals of the experiments has been to provide detailed wall temperature distributions under post-dryout heat transfer conditions. The objective was accomplished by installation of 80 thermocouples along the test section. The

Figure: 9 Measured superheat of rod wall surface for various heat fluxes. Mass flux $G=500 \text{ kg/m}^2\text{s}$, inlet subcooling $\Delta T=10 \text{ K}$, pressure $P=5$–7 MPa (pin-spacers and cylindrical obstacle)

Figure: 10 Measured superheat of rod wall surface for various heat fluxes. Mass flux $G=500 \text{ kg/m}^2\text{s}$, inlet subcooling $\Delta T=10 \text{ K}$, pressure $P=7$ MPa (pin-spacers and grid obstacle)

Figure: 11 Measured superheat of rod wall surface for various heat fluxes. Mass flux $G=500 \text{ kg/m}^2\text{s}$, inlet subcooling $\Delta T=10 \text{ K}$, pressure $P=7 \text{ MPa}$ (pin-spacers, cylindrical obstacle and grid obstacle)

Figure: 12 Measured superheat of rod wall surface for various heat fluxes. Mass flux $G=500 \text{ kg/m}^2\text{s}$, inlet subcooling $\Delta T=10 \text{ K}$, pressure $P=7 \text{ MPa}$ (pin-spacers, cylindrical obstacle and grid obstacle)
achieved measurement accuracy makes the present data a valuable reference for validation of computational models that predict the post-dryout heat transfer.

It has been observed that flow obstacles have an essential influence on the post-dryout heat transfer. From all three different kinds of flow obstacles, the pin-spacers – which have the highest blockage ratio from all investigated flow obstacles - are the most effective, even in the case of very high heat flux being able to influence the recovery of the liquid film downstream of their locations.

ACKNOWLEDGMENTS

The financial support provided by Swedish Center for Nuclear Technology (SKC) is gratefully acknowledged.

REFERENCES


[6] Inconel 600 detailed technical report
   http://www.haraldpihl.se/engelsk/index.html


