BOILING CRISIS EXPERIMENTS UNDER OSCILLATING FLOW CONDITIONS AS FOUND IN THE IN- VESSEL RETENTION (IVR) PASSIVE HEAT REMOVAL SYSTEM

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ABSTRACT

Based on studies investigating the flow pattern occurring in the flow path of the ex-vessel cooling of the In- Vessel Retention (IVR) passive heat removal system, which has been integrated in several advanced water cooled reactors of generation III+, this experimental study was designed to investigate the cooling limit of the reactor pressure vessel governed by boiling crisis. The experiments are performed at 1200 mbar pressure using a stainless steel heater mounted on one of the channel walls of the COSMOS-L test facility. The effects of flow oscillation amplitude and period, mass flux, flow channel orientation and inlet sub-cooling on the critical heat flux (CHF) are investigated. For a better understanding of the boiling crisis phenomenon flow features were investigated in detail, using high-speed vitalometries.

INTRODUCTION

Aiming to prevent vessel melt and entry of the core melt in the containment building in case of a core melt accident the In- Vessel Retention (IVR) through External Reactor Vessel Cooling (ERVC) was developed as a passive safety concept for the advanced safety reactors of the generation III+ (AP1000, CAP1400 e. t. c). As cooling of the vessel is achieved through nucleate boiling, the occurrence of boiling crisis is the limiting factor for the passive systems performance, when the boiling regime switches to film boiling and the structure temperatures start rapidly rising until meltdown.

Former studies [1,2] generally confirm a decrease of the CHF under flow fluctuations. One of the latest and for the IVR ERVC- case more relevant investigation, conducted by V. K. Dhir [3] using a test section with a 2x2 cm² cross sectional area and a 0.406 mm thick and 28.0 cm long Hastelloy B-2 ribbon heater mounted on one side of the rectangular flow channel, additionally investigated the effect of the gravity vector. It showed an enchantment of the critical heat flux by flow oscillations, as the liquid approached saturating temperature with the heater facing down (0°). Furthermore, this tendency would reach a maximum after which the relative critical heat flux q^* would decrease. Up to this day, this phenomenon also as the phenomenon of boiling crisis stayed still unresolved. The fluid of investigation was PF- 5060.

The current study aims further investigating the boiling crisis phenomenon at IVR ERVC- relevant parameter range including inclination angle, sub cooling, mean mass flux, period and amplitude of sinusoidal flow oscillations at a prototypical IVR pressure of 0.12 MPA [4,5]. The focus in this paper will be on the optical observations of the boiling crisis.

EXPERIMENTAL SETUP AND COSMOS-L FACILITY

COSMOS-L WATER-STEAM LOOP

Boiling crisis experiments are performed in the COSMOS-L falcility, which is a closed deionized water-steam loop for forced convection flow boiling experiments. In Figure 1. A simplified flow chart shows the loops components. The systems pressure is beeing set by filling or leaving out pressurized air from the pressurizer. The inlet sub cooling in the experiments is beeing set by the preheater. The mass flux in the experiments is controlled by a gear pump and a control valve located directly after the preheater, that is also used to stabilize the two-phase flow inside the test section. Furthermore, additional two control valves located in the bypass to the test section and directly before the test section induce flow oscillations by synchronously opening and closing. The COSMOS-L flow channel is of rectangular geometry with a coss-section of 43×43 mm².

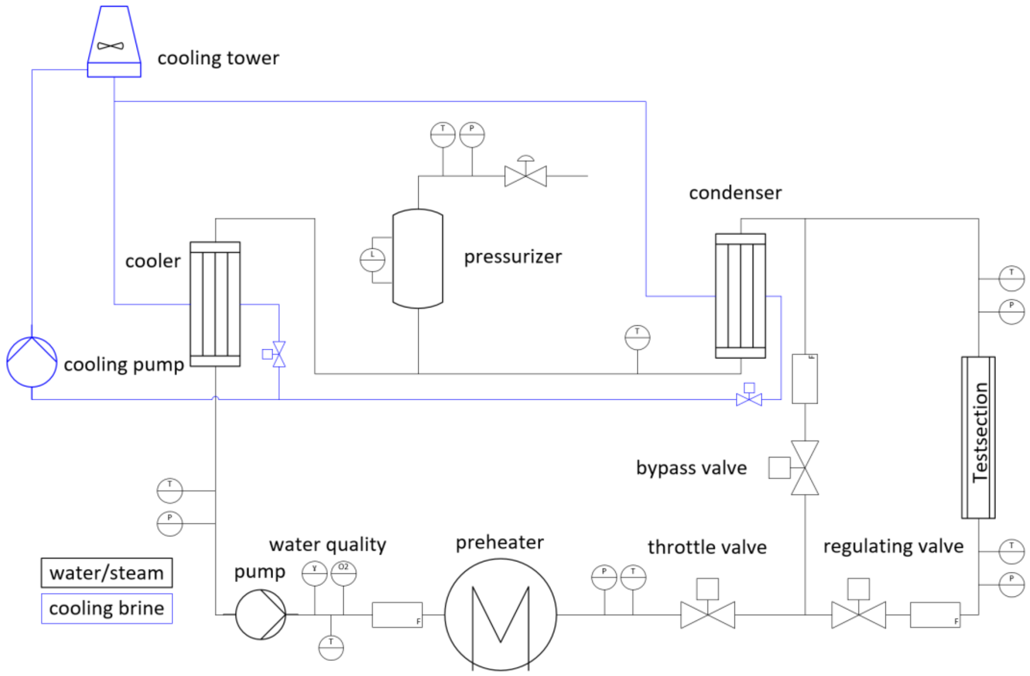

Figure 1: Simplified COSMOS-L flow chart

TEST SECTION

In order to simulate the external RPV structure heated by core melt a 1 mm thick, 20 mm wide and 357 mm long stainless steel sheet heater was mounted in the COSMOS-L flow channel. As the heater power is supplied by an AC voltage through direct electrical heating using copper connectors, which are brazed at the two ends of the sheet heater in a distance of 300 mm, the effective heated length results to 300 mm. Whith the insulation structure surrounding the heater build in the COSMOS-L flow channel, the resulting cross section of the experimental channel is 20×21mm². The flow channel with the test section has the option to be inclined in order to investigate the boiling crisis at the lower and the zylindric part of the RPV. In this study the BC under the inclination angles of 90°, 45° is investigated.

MEASUREMENT SYSTEM

Besides numerous sensors over the water-steam loop recording system parameters in order to ensure safe operating conditions, two thermocouples are placed at the inlet and outlet of the test section as well as two pressure transducers recording experimental parameters. Furthermore, eleven thermocouples are buildt in the test section, detecting the immediate temperature rise during departure from nucleate boiling (DNB), measuring the heater backside temperature. In case a temperature rise, indicating the DNB, is detected, an immidiate shutdown of the heating curent is induced in order to avoid damage of the sheet heater. With two wires applied on the back of the heater, the voltage over the heater is measured. In pair with the current being measured by a current transformer, the heating power is obtained. At last the flow rate is recorded at three points, after the pump in the main- and bypass with a Coriolis flow meter. A data acquisition system records experimental parameters with a rate of 100 Hz.

The optical measurement system represents a pair of high-speed cameras, recording the phenomenon at 1500 fps from the top and the side view. The equipment is being triggered to save by the same signal, that shuts down the heater power in the case of BC, so every frame can be corresponded to a measurement signal.

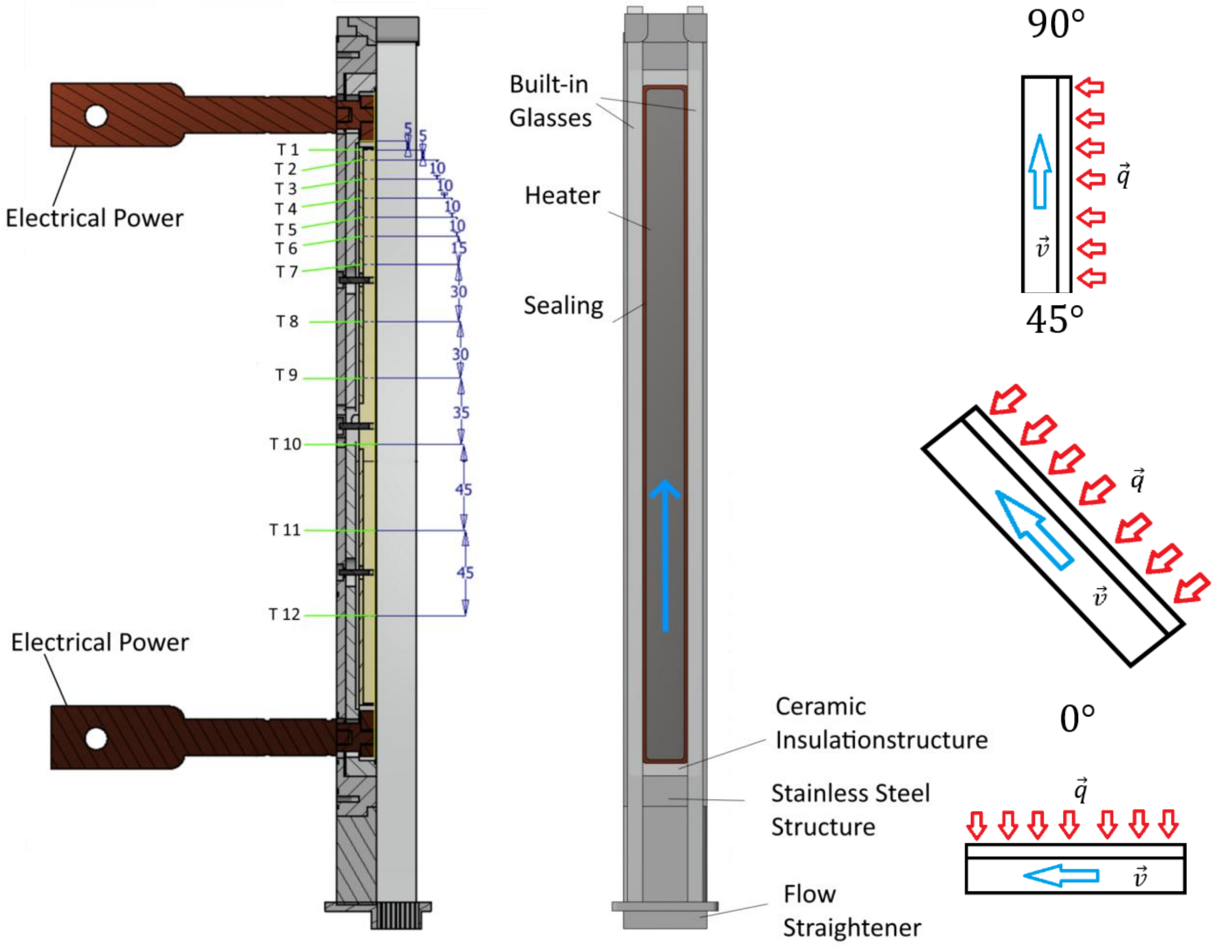

Figure 2: Test section with thermocouple placement and schematic of orientation

MEASURED SIGNALS UNCERTAINTY

The heating power in the experiments is measured by an AV wattmeter (0-80 kW). The input signals are the voltage and the current intensity. The voltage signal is tapped by two cables at the backside of the heater. A current transformer reduces the current intensity from high values (0-1650 A) to a low ampere range of 0-5A which is transmitted to the wattmeter. The specified accuracy of the current transformer and the wattmeter is 0.2 % and 0.3 % respectively giving the resulting accuracy of 0.5 % for the measured power signal. The pressure is being measured by a type Silicon-on-Sapphire (SOS) pressure transducer with an uncertainty of 0.4% including linearity and hysteresis, stated in the calibration certificate. The used type K thermocouples were calibrated with a device where the thermocouples are placed in a copper cylinder heated from both ends besides a reference sensor. In order to consider the influence of all parts of the measurement chain (thermocouple, compensating cable, amplifier etc.) the configuration from the thermocouple tip to the acquired signal was the same for the calibration and the measurements in the experiments. The reference temperature in the device is being stabilized by the control system in a range of ±0.03 K The accuracy of the reference sensor is

±0.02. With the maximum deviation of the approximation curve being ±0.1 K the measurement uncertainty of the whole thermocouple measurement system in the experiments results in ±0.15 K. The measurement uncertainty of the Coriolis flow meter is stated to be ±0.15%.

RESULTS

OPTICAL EVIDENCE OF THE BOILING CRISIS

In most of the recorded experiments the appearance of a vapour spot at the position with the temperature excursion Figure 4 could be observed e. g in Figure 3. Although, due to the large vapour slug and high steam fraction in the channel at the moment BC occures, the formation of the vapour spot on the heater surface can not be seen, the vapour spot on the heater can be seen after the vapour slug slides further. It sticks to the wall and does almost not change its form. With the corresponding side view it appears as the thickness should be very small, as it is barely visible. In its appearance it reminds one of a solder over a metals surface, once the surface energy in the Young Equation [6] is high enough. Thus, it can be theorized that the mechanism leading to BC, might be similar to the mechanism behing a solder wetting a mettalic surface Figere 5. With $\boldsymbol{\theta}$ being the contact angle, $\boldsymbol{\sigma_1}$ the interfacial tension solid-gas(in case of the solder melt)or solid-fluid(in case of nucleate boling), $\boldsymbol{\sigma_2}$ the interfacial tesion solid-solder melt(in case of the solder melt) or solid-gas (in case of nucleate boiling) and $\boldsymbol{\sigma_3}$ the surface tension. According to this model, boiling crisis occurres when $\sigma_1 > \sigma_2 + \sigma_3 cos\theta$.

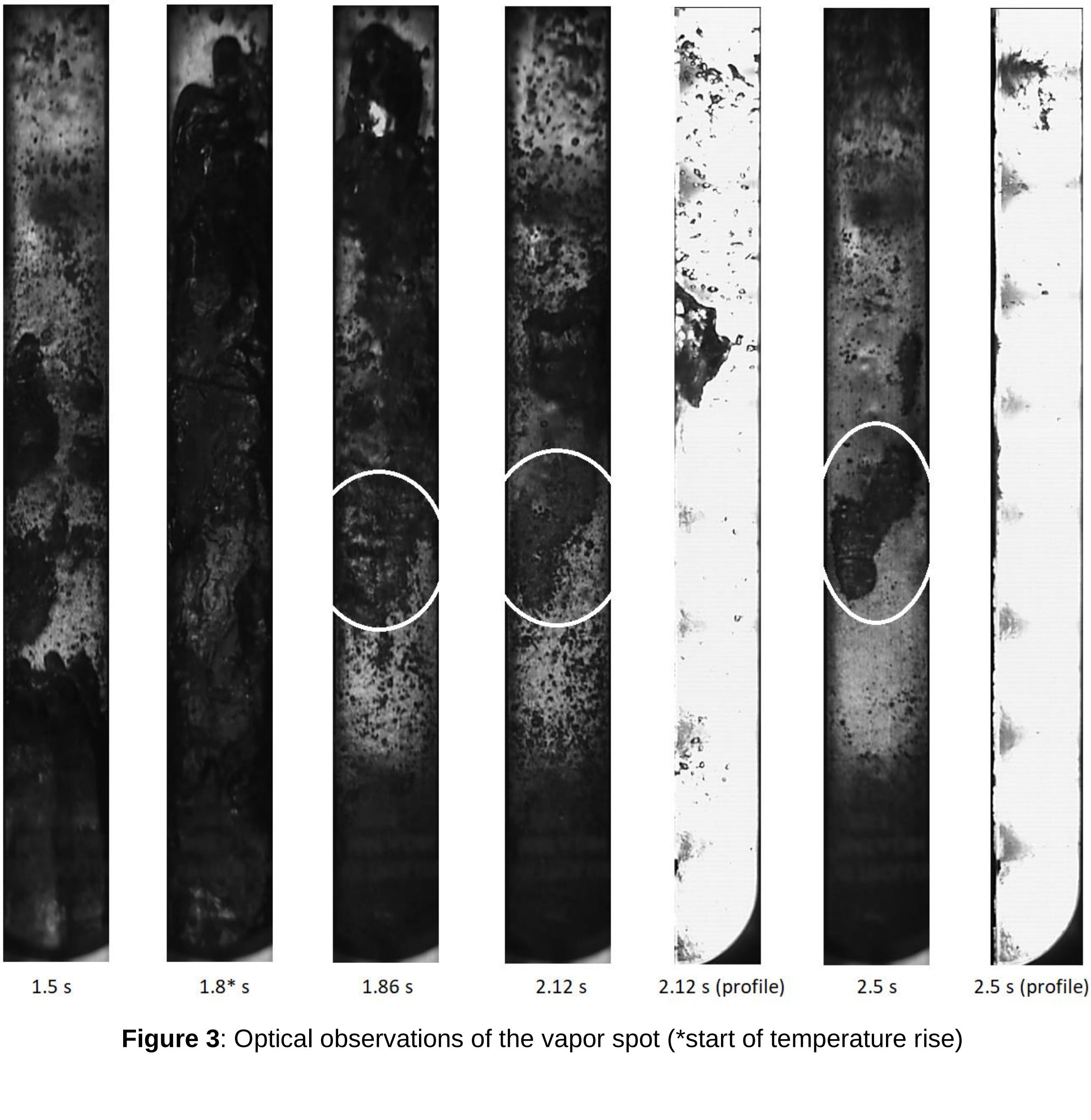

Figure 3: Optical observations of the vapor spot (*start of temperature rise)

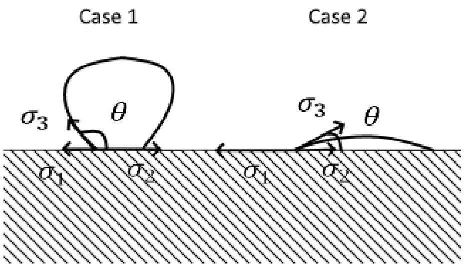

Figure 5: Illustration of Young model

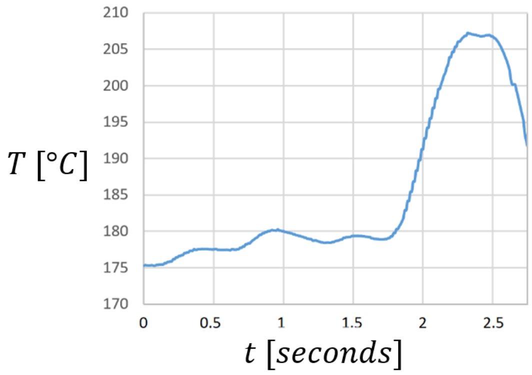

Figure 4: Temperature excursion at the vapor spots position

CRITICAL HEAT FLUX AT STEADY STATE CONDITIONS

To quintify the effect of flow fluctuation on the critical heat flux, a reference measument series at steady state was needed. The results agree with previously listed invetigations. A higher mass flux and inlet subcooling would result in a higher critical heat flux. Furthermore, with the inclination angle getting smaller, the critical heat flux is reduced. This can be explained with the byoncy force pushing the steam bubbles against the heater, resulting in a higher overheating and in lower condensation rates with the bulk flow.

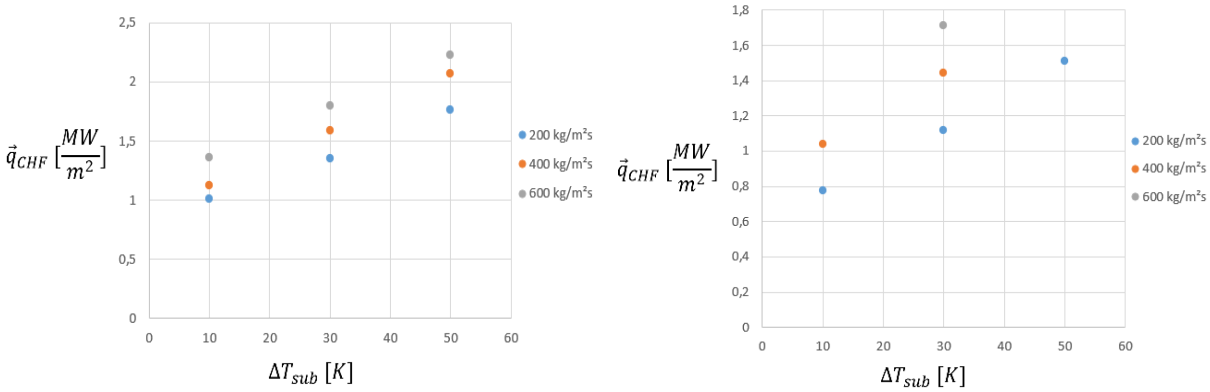

Figure 6: Critical heat flux in dependence of inlet sub cooling (left figure 90°, right figure 45°)

CRITICAL HEAT FLUX AT OSCILLATING FLOW CONDITIONS

Additionaly to the parameters in the steady flow experiments, the oscillating flow experiments involve the variation of oscillation amlitude $\frac{\Delta G}{G}$ and oscillation period τ. The effect of the oscillations on the critical heat flux is expressed by setting the critical heat flux at flow oscillations in relation to the steady flow critical heat flux:

$$q^* = \frac{\vec{q}_{\text{CHF, Oscillations}}}{\vec{q}_{\text{CHF, No Oscillations}}}$$

Confirming the results of previously listed studies an increased amplitude of oscillations and period results in a reduced critical heat flux, althoug in some of the runs the difference, being in the range of measurement uncertainty, is neglieble small. In one of the runs thogh, at 45° inclination angle the critical heat flux is even 3% higher, not being anymore in the uncertainty range. Even more surprising is, that the run with the same oscillation amplirude but lower period resulted in the expected reduced critical heat flux, thus breaking the expected trend. A reason for this behaveiour, might be the occurrence of high-frequency $f = 1.3$ pressure and flow fluctuations as a result of the condensation induced water hammer phenomenon, that appeared in the experimental runs at inclined surface with higher inlet sub cooling. As the pressure would exceed 5 bar the saturation temperature and the density would increase, thus preventing the boiling crisis from occuring. Furthermore, the pressure fluctuations might have an effect on the surface tension balance in Figure 5, influencing the wettabillity of the heater surface.

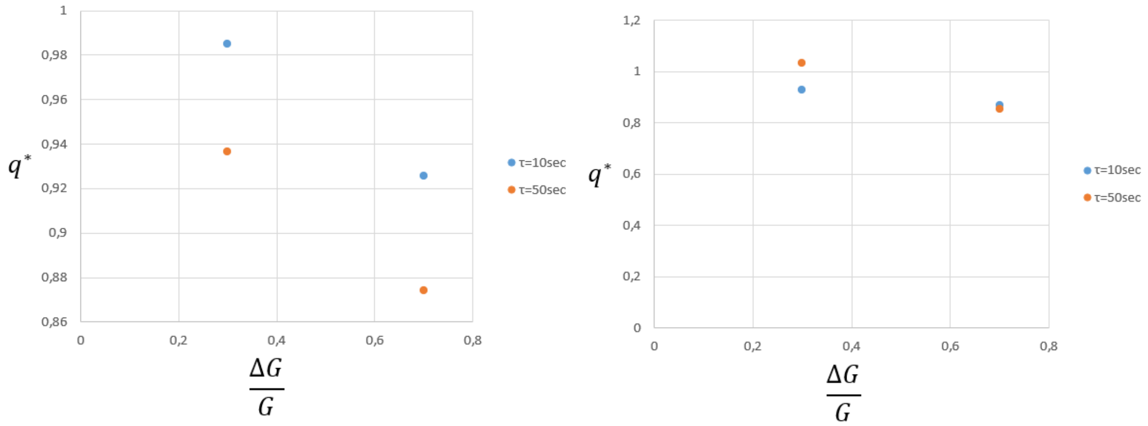

Figure 7: q^* in dependence of $\frac{\Delta G}{G}$, $G = 400 kg/m^2 s$, $\Delta T_{sub} = 30\ K$ (left figure 90°, right figure 45°)

CONCLUSION

The optical observations in pair with recorded data might be an indicator of the appliability of the assumptions and theories stated in the present work, althogh not sufficient as a prove of them. To determine the rightness of the proposed explanations of the phenomenon, more information regarding properties such as surface tension, interfacial tensions, wall superheat at every point of the heater, pressure distribution all over the channel, vaporization and condensation rates are nessesary.

Regarding the effect of the condensation induced water hammer phenomenon, futher investigations of the effect of low frequecy oscillations and the facilitys water head over the test section on the high frequency pressure and flow oscillations is needed, in order to determine if low frequency flow oscillations can improve the critical heat flux at inclined surfaces.

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