CRITICAL HEAT FLUX EXPERIMENT IN INTERNALLY HEATED VERTICAL ANNULUS AT LOW FLOW AND LOW PRESSURE CONDITIONS

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ABSTRACT

An original experimental mockup is built for studying the phenomenon of burnout at low flow and low pressure conditions in order to fill up the gaps in the results of some former publications. The test section is an internally heated annulus using solid stainless steel heater of 6 mm diameter and 454 mm heated length. The outer glass tube has an inner diameter of 16.3 mm. The experiments were carried out with water coolant in the pressure range of 110-200 kPa, the mass flux was varied in the range of 50-110 kg/(m^{2}s) and the inlet subcooling enthalpy was kept around 12.5 kJ/kg. It was found that the correlation of Doerffer et al. [6] approaches our results with an RMS error of 23.8%.

KEYWORDS
Critical heat flux, experiment, vertical annulus, internally heated, low pressure

1. INTRODUCTION

The phenomenon of CHF (Critical Heat Flux) has been studied for a number of decades and it is still an intensively researched field today because of its complexity. The sudden drop of heat transfer coefficient between the coolant and the heated wall may lead to the destruction of the heater's surface so the exact prediction of critical heat flux is an inevitable goal especially in the nuclear industry where the fissile products and the coolant are separated by the fuel cladding, which confines the hazardous fissile products from the environment. Numerous researches have been carried out for CHF prediction in

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annuli. Most of them focuses on the high pressure and high flow region, but recently significant work has been done to the low flow low pressure region, too. The meaning of correlation in this area is finding an appropriate function, which describes the measured data the best. There are hundreds of empirical or semi empirical correlations proposed by different authors for critical heat flux estimation. One part of the correlations is a set of specific correlations covering a narrow experimental range and the validity of these correlations is limited. Other group of the correlations consists of general correlations [6,14], which can be used for example in two-phase flow codes. The uncertainty of these correlations depends on the physical parameters and they could be higher in the low pressure low flow region, where fewer measurement points are available.

Groeneveld et al. [10] concluded that despite the large number of CHF studies performed in directly heated tubes during the past 50 years, significant gaps remain in the data and they suggest additional CHF experiments to fill up these gaps.

El-Genk et al. [7] mention that although many CHF correlations are available for multirod bundles, annuli and tubes, those correlations had been developed mainly for high flowrate and high pressure data. Consequently, using those correlations for low pressure low flow conditions could be inappropriate.

Ahmad and Groeneveld [1] conducted CHF measurements with freon and water for uniformly heated annuli. They have come to the conclusion that accurate modeling of CHF in annuli can be achieved if the physical size of the model is identical to the prototype.

Chun et al. [3] carried out CHF experiments in an internally heated vertical annulus under low flow conditions at a pressure range of 0.57 to 15.01 MPa. It was found that the correlation of Doerffer [6] using the 1995 look-up table [11] and the Bowring [2] correlation gives good prediction, however, both overestimate slightly the CHF for pressures below 10 MPa. The authors concluded that the premature CHF due to the unstable flow, which is frequently observed in low flow conditions, did not occur.

Chun et al. [5] performed measurements in vertical annulus with chopped cosine axial heating and they found that the predictions of Doerffer et al. [6] and the Bowring [2] correlations had suffered considerably large errors, compared to the prediction for uniform heat flux distribution.

In the early study of Fiori and Bergles [8] the authors used electrically heated pipe with hollow core. They did not install burnout protection system in some of their individual CHF experiments so their test sections ended in failure because of the melting of the heaters. They observed a localized hot patch which expanded rapidly (1-2 s) over the entire circumference and melted the metal. They also carried out CHF measurements to investigate the effect of wall thickness. It was found that critical heat flux (q_{cr}) was increased to 58 percent when the wall thickness was increased from 0.012 to 0.078 in.

Schoesse et al. [20] conducted CHF measurements in a vertical annulus composed of an inner heated rod and an outer tube made of glass at low flow low pressure conditions (0.128 MPa, 20-280 kg/(m^{2}s)). The inner rod was made of stainless steel with a heated length 1000 mm and with an outer diameter of 10 mm. The outer tube was a Pyrex glass tube with 22 mm inner diameter. They observed flow reversal and upward flow of the water film for mass flux of 80 to 140 kg/m^{2}s. It was found that for low mass flux, CHF is induced by the phenomena of flooding and chugging at the top of the heater. For the high mass flux and high inlet subcooling CHF is induced by the pulsated annular flow or churn flow at the top of the heater. For the high mass flux and low inlet subcooling CHF is caused by the churn-annular or bubble-annular flow transition at the middle and lower part of the heater. One of their finding was that the location of CHF occurrence could be related to the location of the most unstable flow pattern depending on the inlet conditions. The authors developed a CHF correlation which they found to be congruent with other researcher's data within acceptable error margin.

Wu et al. [21] conducted CHF measurements in bilaterally heated narrow annuli in a pressure range from 0.6 MPa to 4.2 MPa and mass flux from 60 to 130 kg/(m^{2}s). The test section in their measurements was thermally insulated. It was found that in case of internal heating the CHF has a maximum value in the function of pressure at about 23 bar. They also gave empirical correlations for predicting CHF using the local condition concept.

Haas et al. [12] carried out CHF measurements with a vertical internally heated annuli with Zircaloy-4 inner tube with wall thickness of 0.65 mm and with outer glass tube at low pressure conditions. The length of the heated rod was 326 mm. In one of their set of measurements the geometry was selected to be similar with that of Rogers [19] in order to provide comparable conditions. It was found that the CHF data measured by Rogers agreed very well with the author's CHF data. They found that the CHF values were almost constant for pressures between 120 and 200 kPa and their measurements showed an increasing tendency for pressures between 200 and 300 kPa for constant mass flux and inlet conditions. They also concluded that the CHF location varied in the upper half of the heated section for smaller annular geometry with L/D_{he}=39.3 (heated length / heated equivalent diameter) and the CHF at larger annulus with L/D_{he}=13.2 appeared always at the top end. They found that the experimental values agreed the best with the calculated values of a rod-centered approach of Doerffer et al. [6] using an empirical vapor quality term for CHF in annuli. However, this correlation showed inconsistent behavior for higher vapor qualities and higher mass fluxes.

Haas in his PhD. dissertation [13] reported the expanding and rewetting of a dry patch on the porous media close to the CHF conditions as it had been described by Fiori and Bergles [8]. The visual observation was done by a fast digital video camera.

Park et al. [18] carried out CHF measurements for water in internally heated vertical concentric annuli at near atmospheric pressure. They used two-phase flow visualization technique. Both upward and downward flow was investigated with three test sections of relatively large gap sizes. They prepared their test section of Pyrex tube in order to make the visual observation possible. 0.6 m long 19 mm outer diameter heater tube was used with a wall thickness of 1 mm. They observed that the trends were consistent with the previous understanding except that the CHF for downward flow was considerably lower (up to 40 %) than that for the upward flow. The critical quality was found much lower than that for round tubes at the same inlet conditions due to the effect of the unheated outer wall. They conclude that the correlation of Doerffer et al. [6] shows reasonable prediction over the widest parameter ranges, but there are no reliable correlations for very low pressure conditions ($P < 1000$ kPa) indicating a strong need for new correlations with enhanced prediction capability.

According to this literature review, there is a strong need for carrying out measurements in the low flow and low pressure region in order to strengthen their completeness by filling up the missing gaps. The structure of this paper is as follows: in chapter 2. the experimental mockup and the measurement conditions are described. Experimental results are summarized in Chapter 3. The result of the comparison of the measurements with the correlation of Doerffer et al. [6] is shown in Chapter 4. Chapter 5. concludes the paper.

2. EXPERIMENT

2.1. Test facility

The schematic view of the loop is presented in Figure 1. It is composed of a test section, a condenser, a pressurizer, a high pressure argon tank, a low pressure argon tank, a pump, throttle valves and a preheater. The loop is filled with demineralized water which is degassed during the heat-up period. The pump is a HALM made 230 V~/100 W rotary type. The preheater is a standard 230 V~/1.6 kW heater. The condenser is a ZILMET type metal-plated heat exchanger with 15 kW cooling capacity at nominal conditions. The condenser was cooled by tap water. The data acquisition system is based on ADAM modules. The pressure was measured by SITRANS Z SIEMENS pressure transducers. The test section inlet and outlet temperatures were measured by PT100 resistance thermometers. For all other temperature measurements K type sensors made by ourselves were used. McMillan 102 Flo-Sen 8T impeller type flow meter was used for the mass flow measurement. The pressurizer is equipped with a safety valve opening at 5 bar.

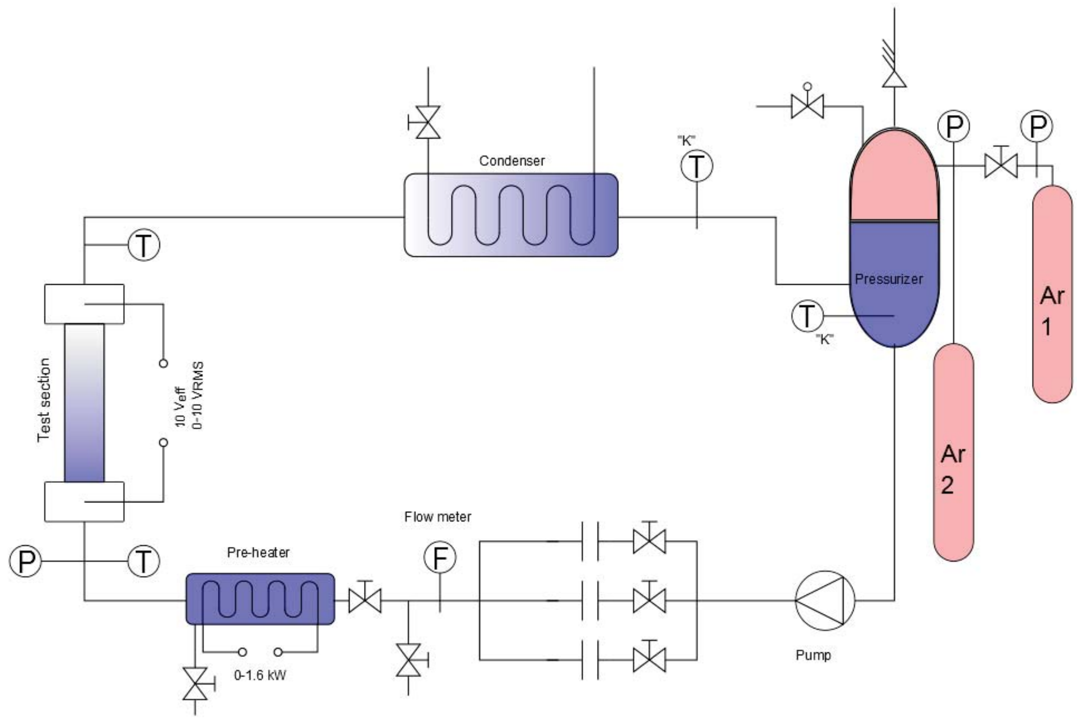

Figure 1. Schematic diagram of the test loop.

2.2. Test section

The test section is an internally heated annulus. The layout of the upper head of the test section is presented in Figure 2. The electrical heater is a stainless steel solid rod with an active length of 454 mm and 6 mm diameter. Both ends of the stainless steel heater have a diameter of 16 mm, which are terminated by copper electrodes of the same diameter. The stainless steel rod and the copper electrodes are screwed and welded. The outer glass tube has an inner diameter of 16.3 mm and outer diameter of 20 mm. The heater is connected to the external copper electrodes and powered by an AC chopper type power supply (0 - 10 VRMS/800 A max).

Observation of wall temperature of the heater is an important task. The thermocouples are generally used for shutting down the electrical power when CHF is detected because the sudden temperature peak caused by CHF could lead to the destruction of the heater. Several technical implementations are possible for mounting the thermocouples to the heater, but they should be as close to the wall as it is possible in order to measure the correct wall temperature value.

Significant part of the CHF experiments for vertical annuli were carried out by using an electrically heated tube with hollow core in order to lead the thermocouple wires inside of the heater [18, 21, 9, 15, 16, 7, 12] or installing the electrical heater inside the hollow core [4, 17]. In some other experiments [20] the thermocouple sheaths were laid in excavated grooves on the heater. The grooves were welded to smooth out the surface but the heater was hollow.

In the present study a solid stainless steel rod has been used for the heater. Three thermocouples were mounted from the outside to the surface with a clamping ring. The sheath diameter of the K-type thermometers is 0.5 mm for the two in the lower elevations and 0.25 mm for the upper position. The thermocouple sheaths are led to the head of the test section inside the annulus. This concept has the drawback that the flow is perturbed by the thermocouple wires and by the clamps that fix the end of the thermocouple to the surface, but it has the advantage that the rod is not so sensitive to the burnout because it has larger thermal inertia.

To test the facility, preliminary measurements have been performed without mounting the thermocouples. At the first switch-on at reaching the CHF red glowing was observed on the surface spreading rapidly, but less fast than observed by Fiori and Bergles [8]. The heating was on for 5-8 s after the onset of CHF, when the electrical power supply was manually disconnected. Due to the thermal load, oxidation was found on the previously glowing surface. About 80-100 mm of the heater was affected, fortunately the geometry has not changed. It is worth mentioning that at the second CHF the glowing started at a non-oxidized part of the heater just right under the oxidized location. This repeated again in the third CHF test, where the glowing occurred already at about the middle of the test section, but in this case the reason of the dryout was a sudden pressure decrease of the system close to the CHF point. It may imply that the oxidized surface has less probability for the CHF at the same conditions but the investigation of this phenomenon was out of the scope of the present paper. All the measurements presented here were carried out with the pre-oxidized heater using three thermocouples mounted from outside. The positions of the thermocouples are 3 mm, 54 mm and 182 mm from the reference point where the diameter of the heater is starting to increase at the top of the heater (Figure 3.).

The estimated uncertainties of the measurements are the following:
Mass flow rate: 3 % on the scale of 20 g/s.
Pressure: 0.25 % on the scale of 6 bar.
Temperature measured with K-type thermocouples: ±2.5°C for full scale of 300°C.
Temperature measured by Pt100 thermometers: ± 0.8°C for the scale of 100°C.
Electric power measurement: ± 5% for the scale of 6 kW.

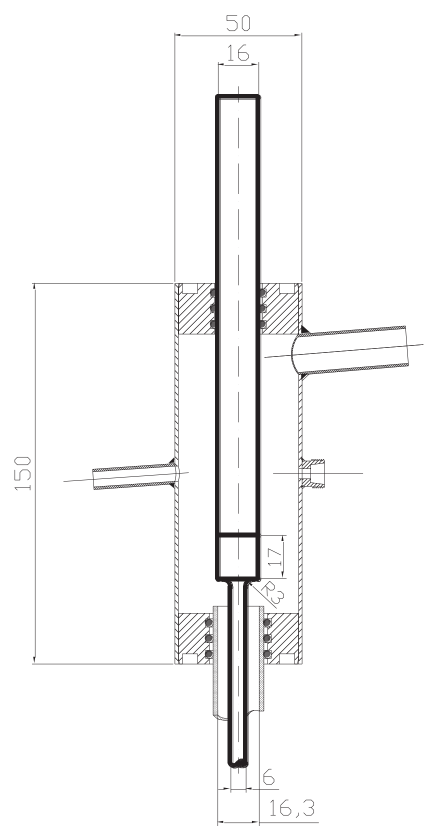

Figure 2. Technical drawing of the upper part of the test section.

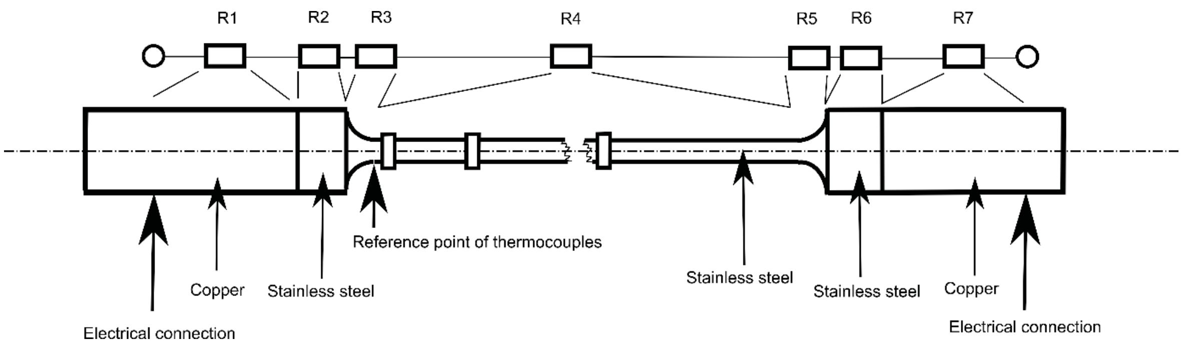

Figure 3. Electrical representation of the heater.

The upper part of figure 3. shows the electrical representation of the heated rod. The heat generation along the rod depends on the local electrical resistance and the actual current in the rod. The R1 and the R7 resistances represent the copper parts of the heater, which are connected to the stainless steel rod. Results of calculation of power distribution along the rod (Table I.) show that 97.56% of the total heating power is generated in resistance R4. In CHF calculations the heat flux was worked out using the total measured power and the surface of the heater symbolized by R4. In these calculations the temperature dependence of stainless steel and copper resistances were also neglected. The heat loss on the outer surface of the glass wall as well as the heat loss caused by the heat conduction of copper electrodes were not taken into account.

Table I. Calculation of relative power along the rod based on Figure 3.

	Diameter	Length	Cross section	Specific resistance	Resistance	Relative power
	mm	mm	mm^2	Ohm*m	Ohm	%
R1	16	124.68	201.0619298	1.68E-08	1.04E-04	0.09
R2	16	17.32	201.0619298	7.00E-07	6.03E-04	0.52
R3	8	5	50.26548246	7.00E-07	6.96E-04	0.60
R4	6	454	28.27433388	7.00E-07	1.12E-01	97.56
R5	8	5	50.26548246	7.00E-07	6.96E-04	0.60
R6	16	17.32	201.0619298	7.00E-07	6.03E-04	0.52
R7	16	124.68	201.0619298	1.68E-08	1.04E-04	0.09

2.3. Experimental process

The experimental process started with long (usually more than two hours) heat-up period, in which the water coolant is degassed and the whole mockup is heated up. In this phase the high mass flow rate was kept by the pump in order to reach the steady state in the pressurizer sooner. The heating-up process was done by the preheater. The desired mass flow rate at the beginning of the measurement was set by the three manual valves and a constant increase of electrical power was given to the rod with a rate of 100 W/minute, until CHF was detected. The detection of CHF in this study is based on the measurement of the surface temperature of the electrically heated rod at three axial positions. When the temperature of the heater in any of the three measurement points is detected to be higher than 170 ^{o}C, the power shuts down automatically. Typical temperature excursion and the corresponding power profile can be seen in Figure 4. indicating the CHF phenomenon. It can be seen that the temperature is above 300 ^{o}C.

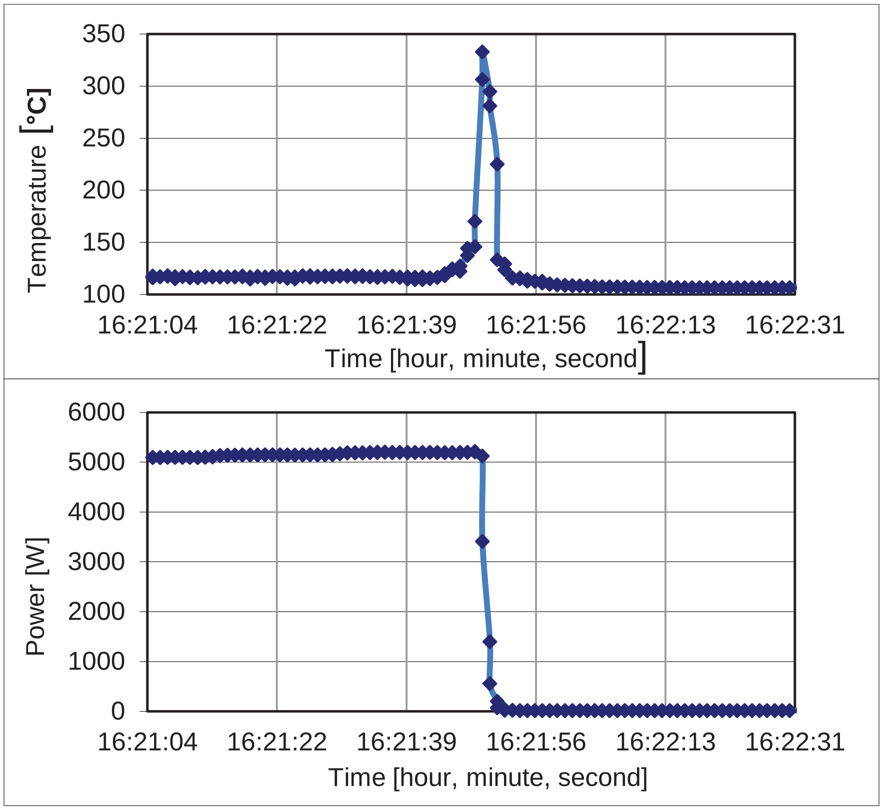

Figure 4. Typical result of CHF detection. A.) (top) Time evolution of surface temperature measured by the upper thermocouple. B.) (bottom) The corresponding power of the heater.

2.4. Range of experiments

54 CHF data points were measured in the experiments for this study. The mass flux varies from 50 to 110 kg/(m^{2}s), the pressure varies from 1.1 bar to 2.25 bar. The inlet subcooling was kept 3 ±0,3 ^{o}C below the saturation temperature, which corresponds to the subcooled enthalpy of 12.5 kJ/kg.

3. RESULTS

3.1. Axial position of critical heat flux

It was found that the CHF occurred usually on the top of the heater. Using three thermocouples proved to be sufficient for CHF detection and for the prevention of the heater from the burnout. Among the 54 measured CHF data points, only one was detected by the second thermocouple and no CHF has been observed at the thermocouple in the lower position. The CHF data point measured with the thermocouple at the middle position was observed at 62.8 kg/(m^{2}s) mass flux which was relatively low in the measurement set. This observation is similar to that of Haas et al. [12]. They reported that at L/D_{he} =13,2 the CHF appeared always at the top of the hater for mass fluxes larger than 250 kg/(m^{2}s). In our experiment the L/D_{he} = 12.12, which is close to the value of Haas et al. [12]. It has to be mentioned that at higher L/D_{he} (39.3) value the CHF appeared mainly at the upper part of the test section but not always at the top in the measurement of Haas et al. [12]. It was observed that the CHF position could vary in the axial position on the heated surface even for the same parameter set. This phenomenon was also observed by Schoesse at al [20]. It was reported that the location of CHF occurrence could be related to the location of the most unstable flow pattern depending on the inlet conditions.

3.2. The effect of the mass flux and pressure on the CHF

The CHF measurement results are summarized in Figure 5. The critical heat flux values exhibit increasing tendency as the mass flux is increased in the 50 to 110 kg/(m^{2}s) region. This tendency is true for all the pressure ranges from 1.1 bar to 2.25 bar. It can be seen that the CHF values also increase with the pressure at constant mass flux, which is in agreement with other observations [3, 21].

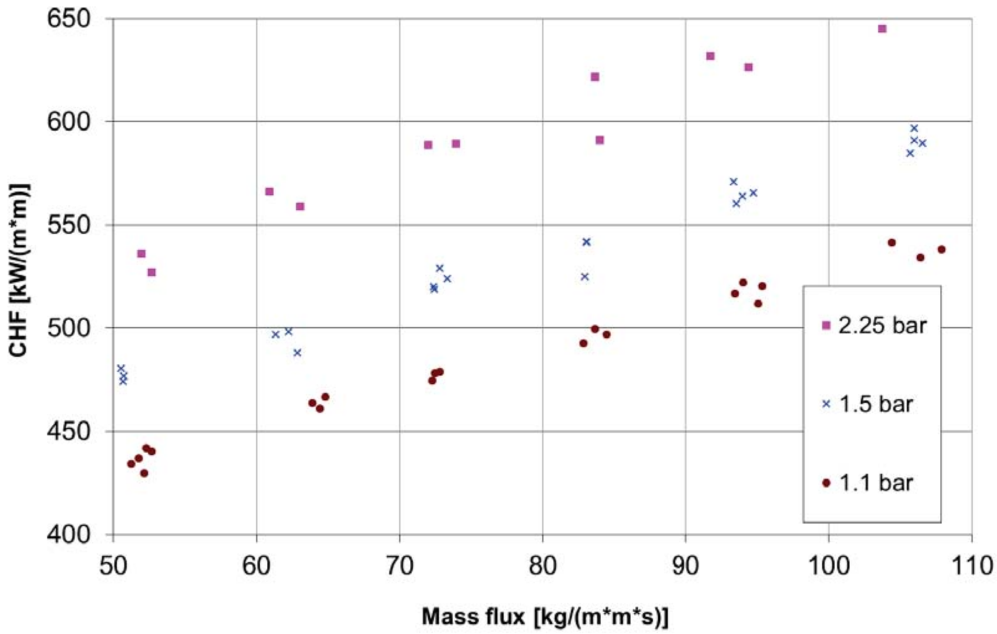

Figure 5. Measured critical heat flux values in the function of mass flux.

The critical quality (the quality at the critical heat flux) can be calculated by the steady state heat balance equation according to the following expression:

$$X_c = \frac{4 D_i L_h q_c}{(D_o^2 - D_i^2) G h_{fg}} - \frac{\Delta h_i}{h_{fg}} \tag{1}$$

In Figure 6. the calculated critical qualities are shown in the function of the mass flux. It can be stated that the critical quality is decreasing with the increasing mass flux and it increases with the increasing pressure, which supports the observations in the literature data [18].

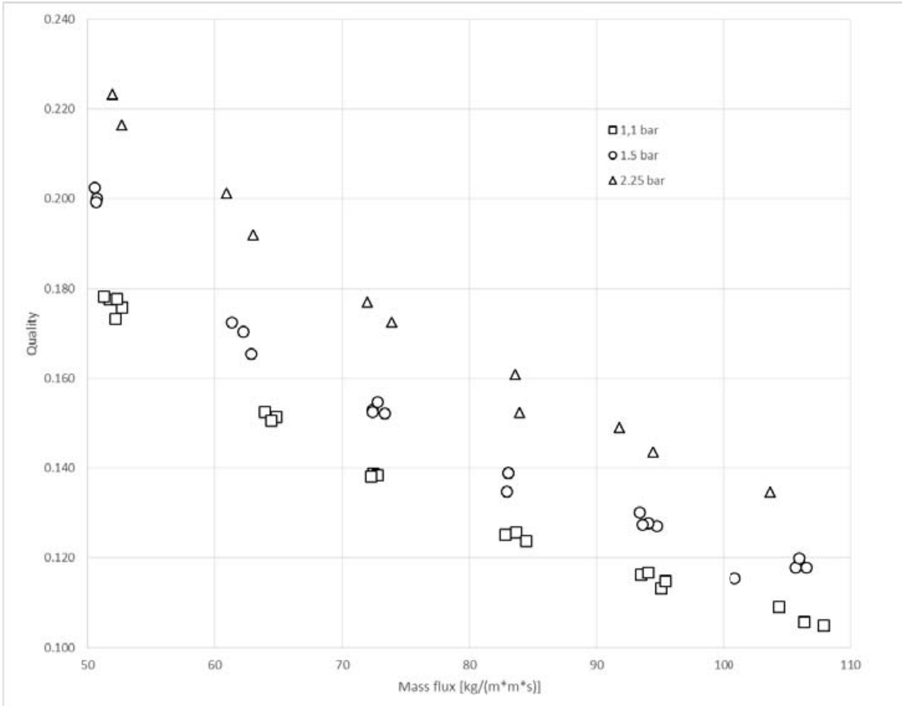

Figure 6. The calculated critical qualities (from heat balance) in the function of mass flux.

4. COMPARISON OF CFH DATA WITH [6]

The predicted CHF values given by the correlation of Doerffer et al. [6] are compared with the present measurement data. The 3 k correlation of Doerffer et al. [6] for internally heated vertical annuli uses the 1995 look-up table of Groeneveld et al. [11]. First the critical heat flux has to be determined for 8 mm diameter pipe and then three multiplication factors have to be taken into account according to the quality, gap and pressure effect. The relative error $\frac{q_{c,pred}-q_{c,exp}}{q_{c,exp}}$ is depicted in Figure 7, which shows mass flux dependence. It can be seen that the correlation of Doerffer et al. [6] using the 2006 CHF look-up table of Groeneveld et al [10] gives worse statistics comparing to that when the 1995 CHF look-up table is used. It can be explained by the fact that the correlation of Doerffer et al. [6] has not been adapted to the new 2006 look-up table of Groeneveld et al. [10]. Table II. contains the average error, standard deviation and the RMS values. It can be seen that use of the correlation of Doerffer et al. [6] with the 1995 look-up table gives better statistical properties for all the average deviation, standard deviation (S.D.) and the root mean square (RMS) values.

Table II. Statistical properties of the correlation of Doerffer et al. [6] compared to the present measured data.

	Avg.	S.D.	RMS
Doerffer (using look-up table 2006)	0.114	0.278	0.300
Doerffer (using look-up table 1995)	0.103	0.215	0.238

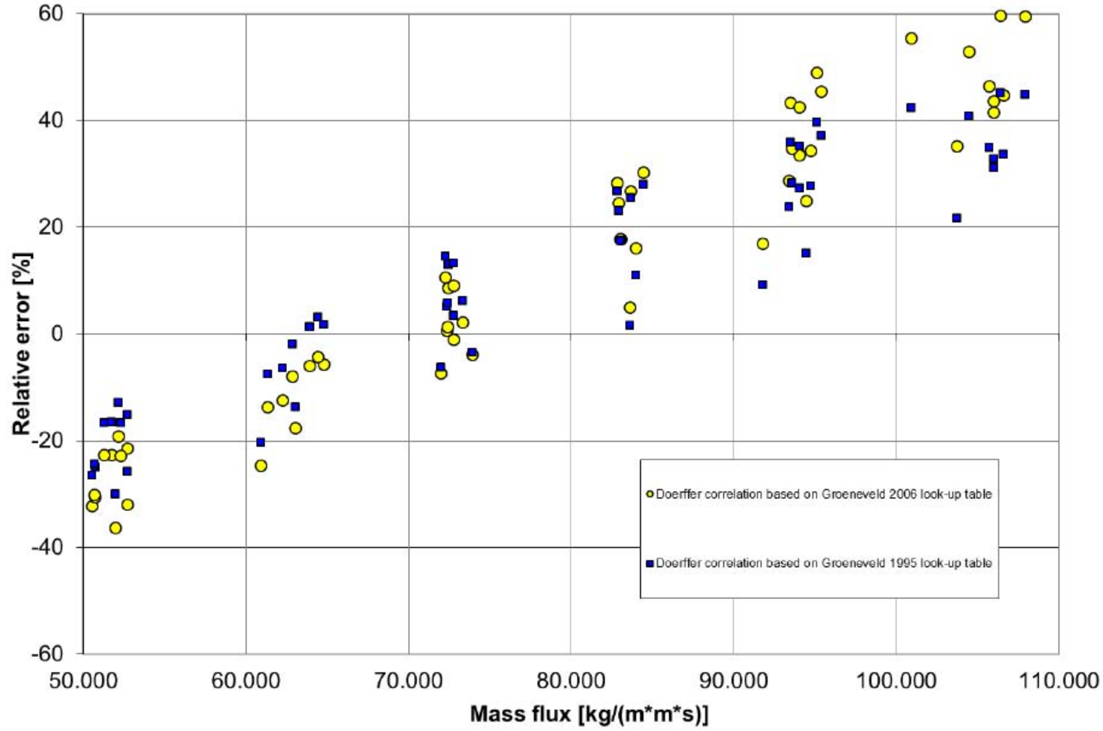

Figure 7. Relative error of the correlation of Doerffer et al. [6] compared to the current measurements.

Future work

The present results are planned to be compared with other measurement data and correlations. The authors would like to extend their measurements to higher mass flux and pressure ranges.

5. CONCLUSION

Critical heat flux measurements were carried out in vertical annulus with internal heating at low flow and low pressure conditions. The electrical heater is a solid rod which differs from the measurement technique usually used in CHF measurements for annuli. The measurement data were compared with the correlation of Doerffer et al. [6]. It was found that the average error is 0.103, the standard deviation is 0.215 and the RMS value is 0.238.

ACKNOLEDGEMENT

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