MEASUREMENT OF TRANSIENT CRITICAL HEAT FLUX IN A HEATED TUBE AT INTERMEDIATE PRESSURES IN WATER

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Abstract

Predicting the CHF for the wide range of abnormal or accident conditions is an essential part of the design and analysis of nuclear power reactors. Most design basis accident predictions are based on transient computer codes that compare the cladding surface heat flux to the predicted CHF. The prediction of CHF is based on empirical data obtained under quasi-static conditions. In applying a steady-state experimental results to transient analyses these codes implicitly assume that dryout will occur for the same local conditions under transients. There is contradictory evidence in literature as to the differences observed in steady tests versus transient behaviour. This paper assess the prediction of transient critical heat flux using quasi-steady methods by performing new experiments with depresurization rates up to 1MPa/s and comparing prediction methods to the new data. Experiments were conducted at pressures of 2–6 MPa, mass fluxes from 1000–2500 kg m^{-2} s^{-1}, and inlet flow quality of -0.148 in a 1.321 m vertical, uniformly heated 4.6 mm inside diameter tube. The experimental results support the application of existing prediction methodologies to fast transients starting from either pre-existing PDO conditions or with small initial margins to dryout.

1. Introduction

The public safety risk associated with an operating nuclear reactor is largely based on the ability of the reactor system to keep the public from being exposed to fission products and other heavy elements. In order to minimise safety risks while maximising the benefits to the public most countries that take advantage of nuclear power generation have developed robust regulatory regimes that reactor operators must comply with in order to retain their operating licence. In Canada the Canadian Nuclear Safety Commission (CNSC) oversees compliance with the operating licences of nuclear power reactors and other nuclear installations in accordance with the Nuclear Safety and Control Act. Regulations have evolved along with the safety analysis techniques used to assess the consequences of postulated accidents. The current licensing environment, under CNSC RD-337, is based on quantitative estimates of the risk of specific radioactive releases and risk estimates for several classes of postulated anomalous behaviour. A large portion of the analysis required for reactor licensing is related to the prediction of consequences that result from the behaviour of the reactor during postulated accidents.

The tools and methodologies used to assess these conditions rely heavily on empirical information derived from experiments. These experiments and consequently the resulting empirical correlations are largely conducted with steady or near-steady state conditions. The application of these “quasi-steady” correlation to transient accident predictions requires careful consideration. In the case of critical heat flux, two major databases disagree on the impact of applying steady-state correlations to the prediction of transients. A delay in time to the onset of dryout at the test section exit relative to the time predicted based on steady-state data was observed in the R-12 experiments of Celata et al [1, 2]. Steady-state prediction methods were sufficient to predict the upstream progression of a pre-existing dryout front in the water experiments of Lyons and Swinnerton [3]. This paper examines the available database for the prediction of transient critical heat flux by performing new experiments with depressurization rates up to 1MPa/s and comparing prediction methods to the new data. Experiments were conducted at pressures of 2–6 MPa, mass fluxes from 1000–2500 kg m-2 s-1, and inlet flow quality of -0.148 in a 1.321 m vertical, uniformly heated 4.6 mm inside diameter tube.

2. Background

In nuclear reactors, a primary public safety priority is to keep fuel cool. Satisfying this criteria substantially reduces the risk of a release of radioactive material because it ensures the physical boundaries, including the fuel sheath, fuel channels (in a pressure tube reactor), and reactor vessel, remain intact. Therefore the limitations to fuel cooling are of great interest and importance to nuclear power plant designers, operators, safety analysts, and regulators. One of the primary limits to heat transfer and fuel cooling in a nuclear reactor during the progression of an accident is generically called the critical heat flux (CHF). The CHF is the rate of heat transfer per unit surface area where a significant deterioration in the convective heat transfer coefficient is observed. The prevention of CHF is specifically cited in CNSC regulatory guide G- 144 as a permissible acceptance criteria for the primary reactor trip mechanism. While discussions continue between the operators and regulators to transition acceptance criteria to more relevant fuel conditions such as sheath temperature, prediction of CHF will remain an important factor in the accuracy and confidence of such predictions.

A great deal of work that is available in the literature has been done to obtain experimental CHF data over a wide range of operating conditions, fluids and geometries. These experimental data have been analysed to identify and model the underlying physical phenomena and to correlate and compile the data so that it may be used to predict the CHF over a similarly wide range of relevant conditions. Several general features have been identified in the literature. CHF may nominally be parametrically represented as a function of pressure, mass flux, quality, and diameter. The correlation and prediction of CHF contains many layers of complexity: in a nuclear fuel bundle any or all of them may vary with axial, radial and azimuthal position in the channel. At a given position in a heated channel each of these terms ultimately depends on the upstream history of the flow. Therefore CHF may also be influenced by the heated length, boiling length, or annular flow length in the channel [4,5,6,7].

CHF correlations may fall into two broad categories: those based on the local conditions hypothesis and those that include upstream history effects. The local conditions hypothesis postulates that the CHF at any point in a channel is dependent only on the conditions at that point in the channel and independent of 'how' those conditions arose. History-based methods, such as the boiling length average approach, tend to include integral information over part or all of the channel. CHF may also be divided into two broad phenomenological categories: the departure from nucleate boiling (DNB) and liquid film dryout. DNB is associated with subcooled coolant conditions or saturated conditions where nucleate boiling is the dominant heat transfer mechanism. At the point where DNB occurs the heat transfer mechanism switches from nucleate boiling to transition or film boiling. The heat transfer deterioration associated with DNB is dramatic and may result in near-immediate failure of the heater under test. Dryout refers to the depletion of the liquid film that flows along the surface of the heater in annular flow. This CHF mechanism occurs under saturated conditions with relatively high steam quality. It is usually associated with a smaller discontinuous change in the heat transfer coefficient or even a gradual transition to post-dryout heat transfer behaviour. Groeneveld [8] called the gradual deterioration of the heat transfer coefficient the 'onset of intermittent dryout' or OID and fully-depleted heat transfer the 'onset of dry sheath' or ODS when liquid contact with the wall ceased altogether.

For CHF in heated tubes the look-up tables from Groeneveld et al are widely used [9,10,11]. The look-up table has the advantage of being comprehensive, accurate and easy to use. Correction factors are applied to the table to account for flow geometry in alternate orientations and differing geometries.

Most of the existing CHF data has been collected using steady-state experiments. These steady-state experiments form the basis of the understanding of underlying CHF phenomena used for modelling, correlation development and as the foundation for the CHF look-up tables. In nuclear safety analysis and other relevant applications of CHF prediction, however, the CHF will not be reached under steady state conditions. Instead it will occur under abnormal or accident conditions where the input power, channel pressure or mass flow rate change rapidly with time. Codes like RELAP5, TRACE, and CATHENA are based on one-dimensional finite volume methods to simultaneously solve the time-dependent mass, energy, and momentum transport equations for both liquid and vapour. These codes are used to predict the local conditions in the reactor during accidents. CHF is predicted by using these transient conditions as inputs to the steady-state based methods. The investigation of transient effects is not unique to dryout but is a common pursuit in all aspects of convective heat transfer.

The examination of the transient effects on CHF have been investigated in the past [12]. Two major pressure transient dryout experimental data sets were available prior to the present work. The conclusions of the authors of the two major existing datasets, however, seem to disagree: Whalley, Lyons and Swinnerton's [3, 13] results suggest that steady-state prediction methods are sufficient to predict the progression of a dryout front up a uniformly heated tube. Celata et al [1] show that transient effects are important in delaying the onset of dryout. Hochreiter examined the effect of transients relative to the uncertainty used in prediction of CHF and found the latter to be dominant [14]. Groeneveld examined the effect of transients and proposed a small correction factor [15]. Given that even for tube based experiments there is debate as to the effect of transients on CHF, a new experimental apparatus was designed and used to perform experiments to resolve these issues and is reported in this paper.

In order to analyze the transient data and methods it is first necessary to describe the two major methodologies for correlating CHF, the direct substitution and heat balance methods. When the local conditions in a channel—pressure, mass flux and quality—at the observed OID in a steady-state experiment are directly used as input to a CHF prediction method in order to assess the method's performance it is referred to as the direct substitution method (DSM). The HBM involves performing a heat balance on the test section of interest to evaluate the quality at a given location as a function of test section heat flux. The predicted dryout point is the intersection between the heat balance and the CHF quality curve for the prediction method.

The difference between the accuracy of the HBM and the DSM is illustrated in the performance evaluation of the 2006 CHF look-up table [11]. The LUT's RMS error when evaluating the data from which the table is derived in comparison with the compiled table is 39% for the DSM compared to 7% for the HBM. While the HBM methods appears most consistent, HBM methods are difficult to implement in fast transients where the heat balance to the fluid changes radically from time step to time step. The differences in these methods were discussed in depth during the round table discussion on reactor power margins that may be found in volume 163 of Nuclear Engineering and Design. In response to this discussion Hejzlar and Todreas [16] made a recommendation to use the HBM to compare the performance of different prediction methods against steady-state experimental data and each other but, when the DSM is to be used, to specify the steady-state DSM performance for each correlation used as well. These recommendations are followed in the present work.

3. Experimental Facilities

The experimental facility constructed for this investigation is shown below.

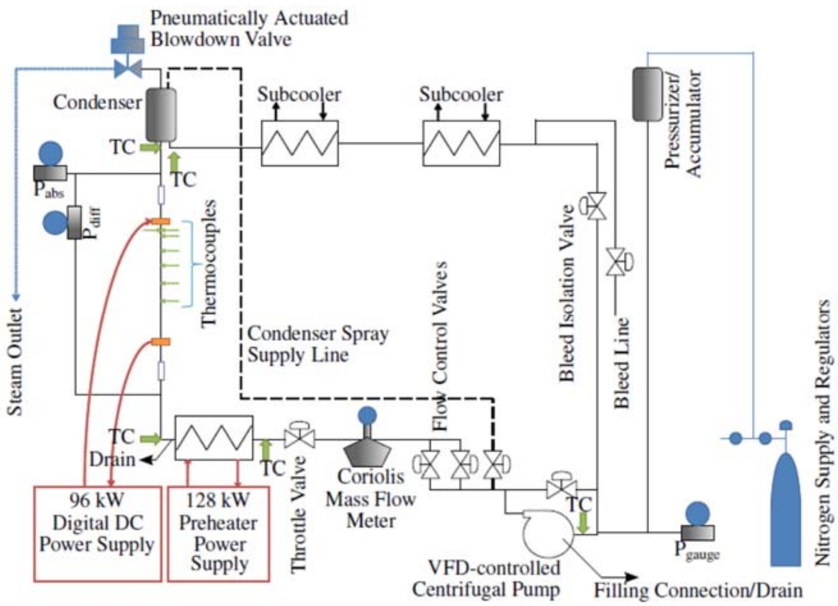

Figure 1: Schematic of McMaster High Pressure CHF Experimental Facility

A Klaus Union SLM NVHO 040-025-200-09E04 sealless magnetic drive centrifugal pump with a design operating point of 75 m head at 833 cm3 s-1 volumetric flow at 2-15MPa was used to supply the driving force for the fluid through the circuit. Flow control was via bypass lines, precision flow control valves and a programmable Variable Frequency Drive (VFD). A NIST traceable calibrated AW-Lake ACM1500 Coriolis mass flow meter was used to measure the flow to the test section. Pressure was recorded at the test section outlet condenser using a NIST traceable calibrated outlet pressure sensor (Rosemount 3051CA) with uncertainty better than 0.1 MPa. The two-phase flow was condensed using spray from the pump bypass line and the subsequent single phase flow passed through two subcoolers prior to returning to the pump. System pressure was controlled using a Nitrogen bladder accumulator (Hydac SB330-10A1/02S-210C 10 L). Blowdown transients were initiated using a High Pressure 10-11-AF4-MPO-NC electrically controlled pneumatically operated valve connected to the top of the condenser. Its opening time was estimated to be 90 ms using a high-speed video camera and the blowdown flow rate was controlled by inserting appropriately sized tubes at the exit of the blowdown valve.

A 128kW DC and a 96kW programmable DC power supplies (TopCon by Magnavolt) were used for the preheater and test section, respectively. The test section and preheater voltage were measured using 0–100 V WAP-DS-99A-3 Watanabe isolation transformers that converted the voltage into a 4–20 mA current signal. The supply current was converted into voltage signals using model #90000-1143 2000 A calibrated shunt resistors from Canadian Shunt Industries. Estimates of the heat flux uncertainty are less than 45kw/m2 and are consistent with the single-phase energy balance results of better than 1.5% over a wide range of conditions. All uncertainties include allowances for the National Instruments data acquisition system.

All temperature measurements were made using calibrated Omega type K thermocouples. The supplier stated accuracy of these probes is the greater of 1.1C or 0.4% for 0 to 1250C. Inlet and outlet temperature measurements were taken using specially designed mixing connectors to ensure well mixed conditions at the probe tips. Test section wall temperatures were measured using Omega KMQIN-010U-6 and KMQIN-010U-12 K-type 0.25 mm diameter Inconel 600 sheathed thermocouples. They were silver-soldered to the outside of the tube surface. Before performing experiments this technique was tested on two thermocouples. They were calibrated, soldered to a test piece of Inconel, and then cut out from the tubing surfaces where the thermocouples were attached. Once they were removed—along with small pieces of the tube—they were re-calibrated and found to be within specification. The test section and wall thermocouple locations are shown in below.

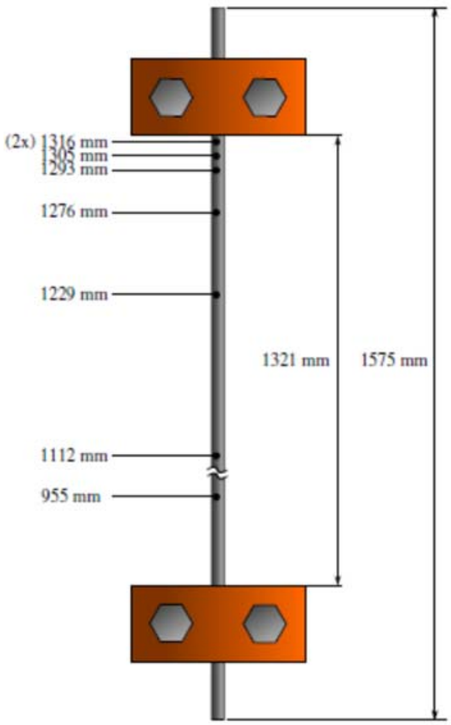

Figure 2: Experimental Test Section and Measurement Locations

The experimental methodology was as follows:

1) Test section power was increased in small steps keeping all other test parameters at the desired value with steady-state conditions achieved prior to the next power step.
2) The quasi-steady experiment was continued until CHF was reached in any of the thermocouples. OID was indicated either by an abnormally large increase in test section wall temperature as a function of power, or through an increase in the standard deviation of the thermocouple signals beyond those typical in steady-state experiments. The steady-state CHF conditions were then recorded.
3) Power was then decreased in small increments until CHF no longer occurred in the test section, and then power was further decreased another 2% to ensure no dryout existed anywhere in the channel.
4) Once steady conditions were achieved, a blowdown was initiated by opening the fast acting valve on the test section outlet. Data was collected at a rate faster than 1ms and the transient was allowed to proceed for 3 to 10s depending on the blowdown rate being considered. Such times are sufficient for CHF to be reached at multiple locations in the test section.
5) Once the blowdown was terminated by closing the fast acting valve, conditions were allowed to equilibrate and the next test condition was examined.

In order to examine the effect of pre-existing dryout in the channel, experiments were also conducted without step 3, so that some dryout existed in the channel prior to the blowdown.

By examining the time dependent variation in the wall temperature plots the time and local conditions at the point of CHF could be determined. A sample of the transient CHF data collected is shown below, where the wall temperature plots clearly show the propagation of CHF from the outlet towards the inlet. RELAP5 MOD 3.3 was used with the measured inlet and outlet boundary conditions to determine the local fluid conditions at the measurement locations, which were then used to generate CHF predictions for each thermocouple and compare these to the measured transient results. In all more than 120 steady-state and transient data were collected over a range of initial pressure, flows and blowdown rates.

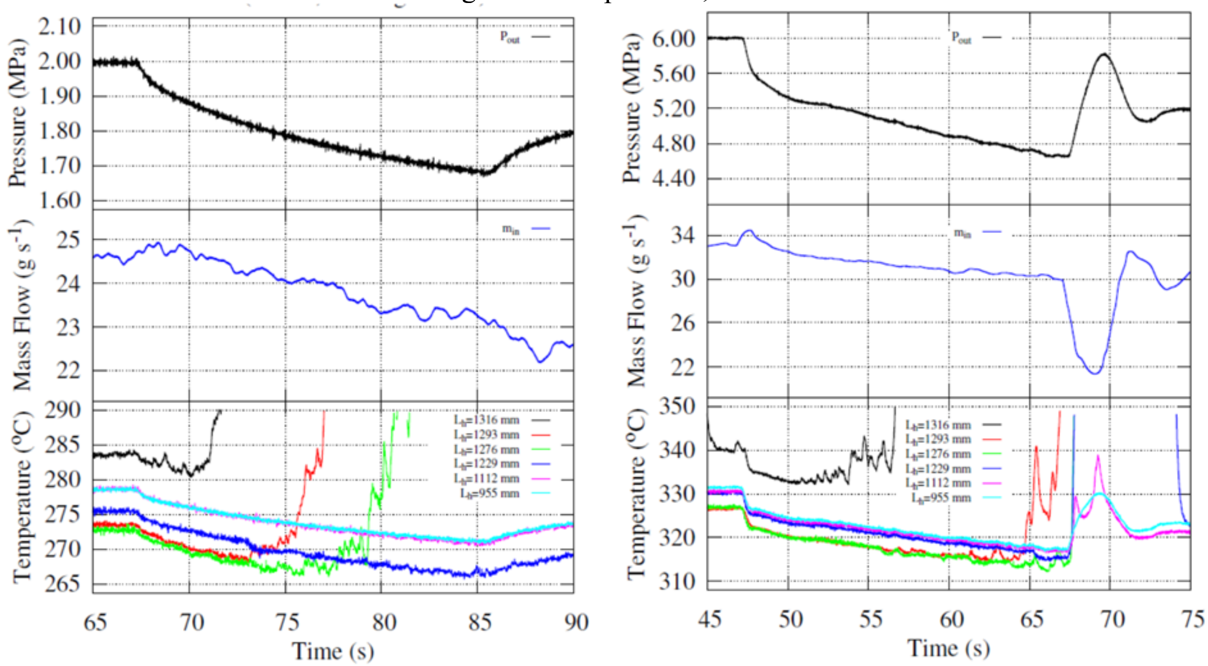

Figure 3 Transient Experimental Results Under a) Initial 2.0MPa and b) Initial 6.0 MPa Conditions. Time for the onset of CHF are shown in the lower figures as the steep increase in temperature trajectory.

4. CHF Results

The steady-state CHF data collected during the experiments outlined above were collected and tested against several CHF prediction methods using both the HBM and DSM methodologies. The unaltered DSM yielded poor results for steady-state predictions: the CHF look-up table and the Biasi et al correlation underpredicted the data by 46% and overpredicted the data by 15%, respectively. The HBM using the look-up table, Biasi et al correlation, and the Katto-Ohno correlation had overall mean prediction errors of -8.7%, 3.9% and 6.3% respectively. The rationale for the DSM performance is largely attributed to the sub-region of conditions examined here (near the limiting quality domain where CHF is extremely sensitive to quality, and as such small deviations in the local quality cause large changes in the predicted dryout). A discussion on the acceptability of such behaviour under transients is discussed below.

In order to isolate the effect of the transient on CHF from other biases, a rigorous analysis routine was established. For example there is some scatter and expected deviation in the CHF lookup table, even when compared to these new steady-state data, as shown in the figure below for the Look-up Table (LUT) and Katto –Ohno correlation. Therefore some method must be used to establish the time and value of CHF predictions which is bias free to the greatest extent practicable. Since CHF is a function of many input variables, a methodology was used to correct the heat flux and critical quality in order to generate bias free steady-state CHF predictions as outlined in Statham [17]. After the correction the Biasi correlation provided a mean error of near 0%. However, the LUT results are more complex. In general in this near limiting quality regime CHF is extremely sensitive to changes in local quality, and hence the assumptions within the LUT while providing good predictions of dryout times (since even small changes in quality during a blowdown drive down the predicted CHF by a large amount), the actual value of CHF under low pressure conditions was not captured well even in the corrected DSM results.

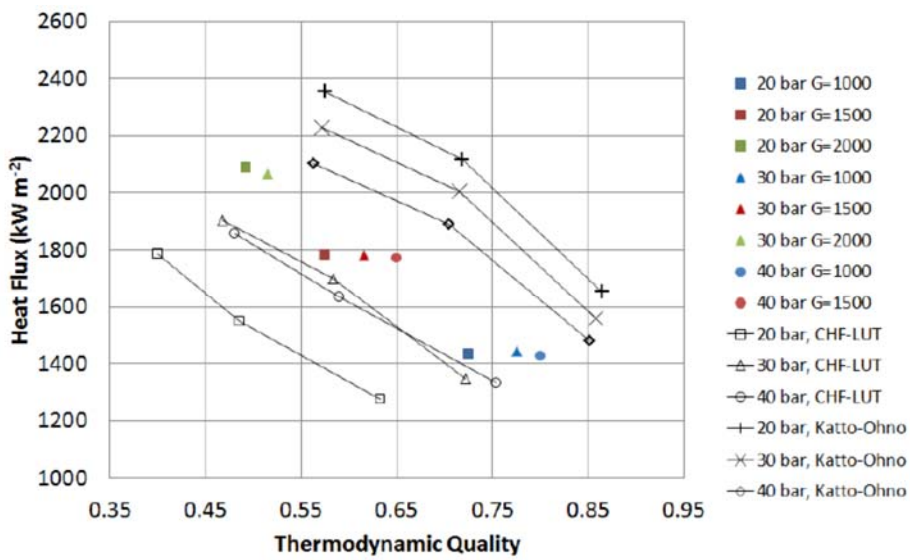

Figure 4 Measured Steady-State Critical Heat Flux Compared to the Look Up-Table (LUT) and Katto-Ohno Prediction Methods

The transient results are characterized by a rapid initial mass flow rate increase followed by a gradual decay as the transient progressed. The initial mass flux increase was caused by the initiation of the blowdown at the exit of the test section and the associated drop in the outlet side pressure. The mass flux decay is closely associated with the pressure: the flow rate decays more quickly during faster transients. Some data from the literature suggests that there is a delay in the onset of dryout during rapid mass flow transients. For example, Moxon and Edwards [18] reported a delay in the onset of dryout but their mass flow decayed to half its initial value in less than 1 s, indicating very large changes in hydraulic resistance. In the present work the flow was never observed to decrease to half of its original value even over the course of transients up to 30 s long. In our work, almost all liquid in the loop is in the recirculation line and is kept below 100C, thereby a large drop in pressure would not affect the loop pressure drop significantly.

Another typical property of these transients is the decrease in measured wall temperature with time before the onset of dryout. The heat transfer coefficient may change slightly as the pressure and mass flow decay and the quality consequently increases. These effects played only a minor role; the decrease in wall temperature was primarily caused by the change in saturation temperature as the pressure decreased. This decrease in wall temperature complicated the data analysis somewhat because thermal energy stored in the wall of the test section was released as the fluid temperature changes.

In the present work RELAP5 predicted an increase in convective heat flux of 1.6% due to thermal inertia in the test section wall for the fastest tested transient with a maximum depressurisation rate of approximately 1.0 MPa s^{-1}. The time evolution of the convective heat flux for this experiment is shown below. This figure shows the total heat flux, including the effect of stored energy, delivered to the fluid over time at the simulated test section volume nearest the end of the heated length. This increase in heat flux to the fluid is the same order of magnitude as the overall uncertainty in the measured test section heat flux based on electrical power alone.

For the data presented in this paper the power transient effect due to thermal energy storage was negligible. This is in contrast to what was observed in the pressure transient experiments of Celata et al where the thermal energy storage transient was the main reason dryout was observed. This effect was also discussed briefly by Whalley, Lyons and Swinterton but not modelled during their analysis of the predicted vs observed dryout time.

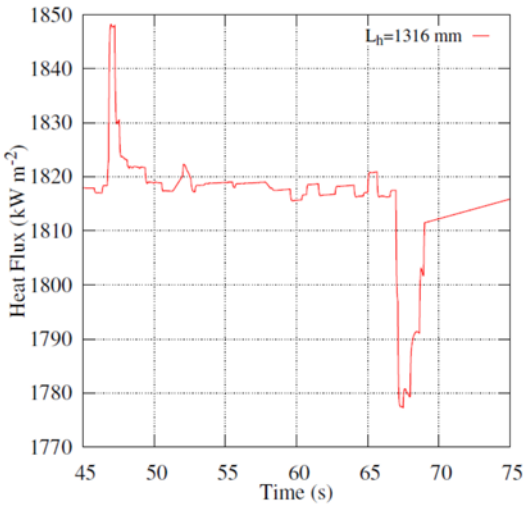

Figure 5 Total wall heat flux as a function of time as determined by RELAP5 including the electrical and wall thermal inertial contributions during a typical blowdown transient.

The experimental results shown in the following figures are for cases where in the initial condition prior to blowdown either had pre-existing post-dryout conditions at the downstream end (PDO cases) or where the initial conditions were 2% below the threshold to CHF (with margin to dryout – MTD conditions). The results are reported in terms of their ability to capture the dryout time (zero delay), under predict dryout time (meaning there is a positive delay between predictions and measurement) or over predict dryout time (meaning the measurements precede the predicted CHF). In some cases dryout was not predicted during the time frame of the transient so these data are excluded from the analysis).

From the results in Figure 6 it is clear the uncertainties in predicted dryout times are approximately normally distributed with a mean near zero using both the Biasi correlation and the LUT, indicating that the quasi-steady CHF prediction methods are sufficiently accurate to predict dryout under fast blowdown transients. The reasons behind the Celata predictions which show very significant delays are unclear, but may be related to the working fluid (in their case R-12). In particular Celata showed cases where the contribution from the stored energy in the wall was up to 50% of the applied heat flux whereas in our tests in water the fraction was on the order of 1% (see Figure 5). Given the differences in fluid properties, the relative thermal inertia of the wall compared to the diffusivity of the coolant is substantially different in water than Freons, which may have led to differing results in the Celata's work as compared to this study and the data from the UK.

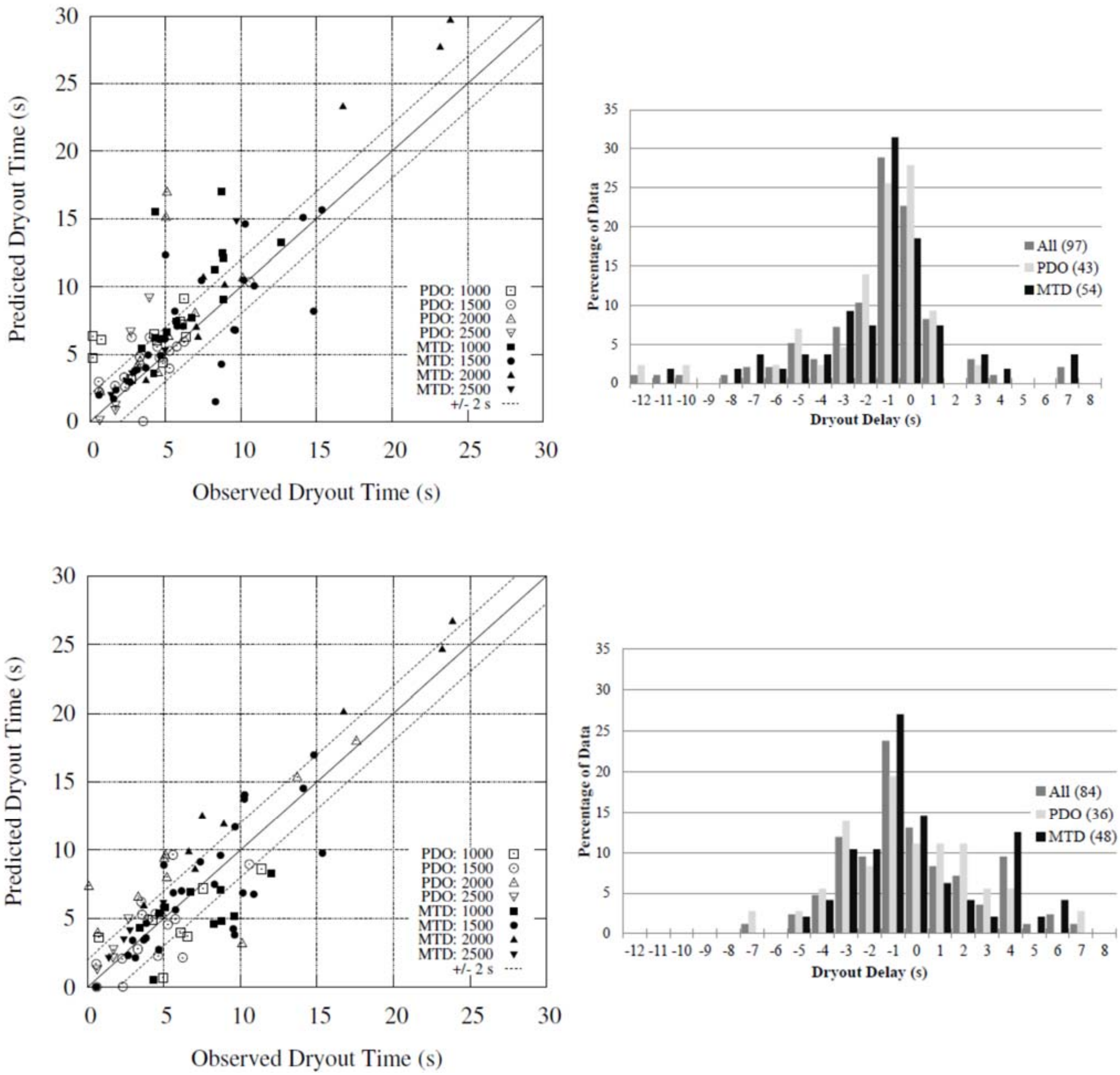

Figure 6 Predicted vs. observed CHF during fast blowdown transients for the LUT and Biasi correlations (left) and histogram of the delay time for each prediction method (right).

5. Conclusion

This work has demonstrated the validity of assumptions of applying quasi-steady state CHF to fast pressure transients and is consistent with data collected by Whalley, Lyons and Swinterton in the UK for both tests with initial PDO and tests with margin to dryout. While the UK study used on tests with pre-existing PDO, it appears that the conclusions are appropriate for data with small margin (1-2%) and PDO. These conclusions are also consistent with Reference 14 which showed the dominant effect on uncertainty were geometrical and local condition orientated, in particular during the transients, as compared to changes in local CH. It is unclear if data with larger initial dryout margins would behave similarly since data from Moxon and Edwards showed significant coupled flow transients which were not observed in this test.

In terms of the other CHF data base from Celata which showed large delays in transient dryout under blowdown cooling, the rationale for such behaviour seems largely attributable to the large magnitude wall storage heat relative to the applied electrical power. In order to examine the effect of wall storage to fluid properties additional data from the Celata would be required, or new tests using refrigerants under the same conditions as those discussed here would be needed.

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