BRAD STATHAM NOVEL DESIGN OF A CRITICAL HEAT FLUX EXPERIMENTAL FACILITY

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This paper discusses the design of a critical heat flux (CHF) experimental water flow loop being constructed at McMaster University. A brief review of existing water-based CHF data in open literature is presented. The loop's physical specifications—mass flux, heat flux, sub-cooling, and pressure—are determined so that some identified gaps in current CHF data can be eliminated by performing experiments. The design of the loop structure, data acquisition system, calibration requirements, instrumentation and uncertainties, standard operating procedures and some measurement uncertainties are also presented.

Introduction

Critical Heat Flux (CHF) is a significant parameter for the operation of thermal systems such as nuclear reactors. At heat fluxes beyond CHF the heated surface temperature will increase significantly due to poor heat transfer properties. For highly subcooled flows the increase is often enough to damage or destroy the heating element. In high-quality flows the temperature rise is usually smaller due to a less abrupt transition between heat transfer modes. These types of CHF are sometimes referred to as departure from nucleate boiling (DNB) and dryout (DO) respectively. The type of CHF and the temperature excursion that may occur as CHF is approached depends on the variations in two-phase flow regimes and many other parameters throughout a given system.

In nuclear reactors, post-CHF operation should always be avoided. Recent regulatory changes in Canada mandate that operation at or above CHF is prohibited for new designs (CNSC 2006). The ability to avoid CHF is a critical part of the licensing of new reactor designs in Canada and therefore the ability to predict it is equally critical for reactor designers.

CHF is often visually represented as the peak of a pool boiling curve with temperature on the abscissa and heat flux on the ordinate axis at the point where the heat transfer regime changes from nucleate boiling to transition boiling (Collier and Thome 1996). In a heat-flux controlled system the curve does not have a 'peak' but transitions directly from nucleate boiling to film boiling with an accompanying large increase in temperature, such that the 'curve' becomes flat (Hewitt and Hall-Taylor 1970). CHF in convective boiling is considerably more complex than this simple representation, but it provides a good mental picture to be used for reference.

Over the last 60 years thousands of CHF data points have been experimentally measured for a very wide range of flow conditions, power profiles, and geometries (Hall and Mudawar 2000; Olekhnovitch *et al* 2008). Several databases of CHF data for water in uniformly heated tubes currently exist that include tens of thousands of data points.

Despite these heroic efforts, no agreement has yet been reached on what parameters may best determine CHF. Usually CHF is presented as a function of pressure, hydraulic diameter, mass flux, and inlet enthalpy or local quality (Collier and Thome 1996). Heated length, while sometimes listed as a secondary parameter, has also been found to play an important role, even over several hundred pipe diameters (Lee *et al* 2000). Hundreds of correlations and empirical models using a variety of input variables have been developed with varying degrees of success over specific ranges of conditions.

In the absence of a universal model of CHF, Groeneveld *et al* (2006) have developed a CHF look-up table (CHF-LUT) based on experimental data for water flowing in uniformly heated tubes. The CHF-LUT is becoming a *de facto* reference for CHF prediction as it has become more robust and widely accepted (Groeneveld *et al* 1986, 1995, 2006; Olekhnovitch *et al* 2000; IAEA 2001). Many researchers are beginning to address the problem of predicting CHF for practical problems—such as that of a fuel channel in a CANDU reactor or a fuel assembly in the core of a PWR or BWR—using a reference that is based on data obtained using much simpler geometry (Fortini and Veloso 2002; Pioro *et al* 2000).

Any CHF prediction method can

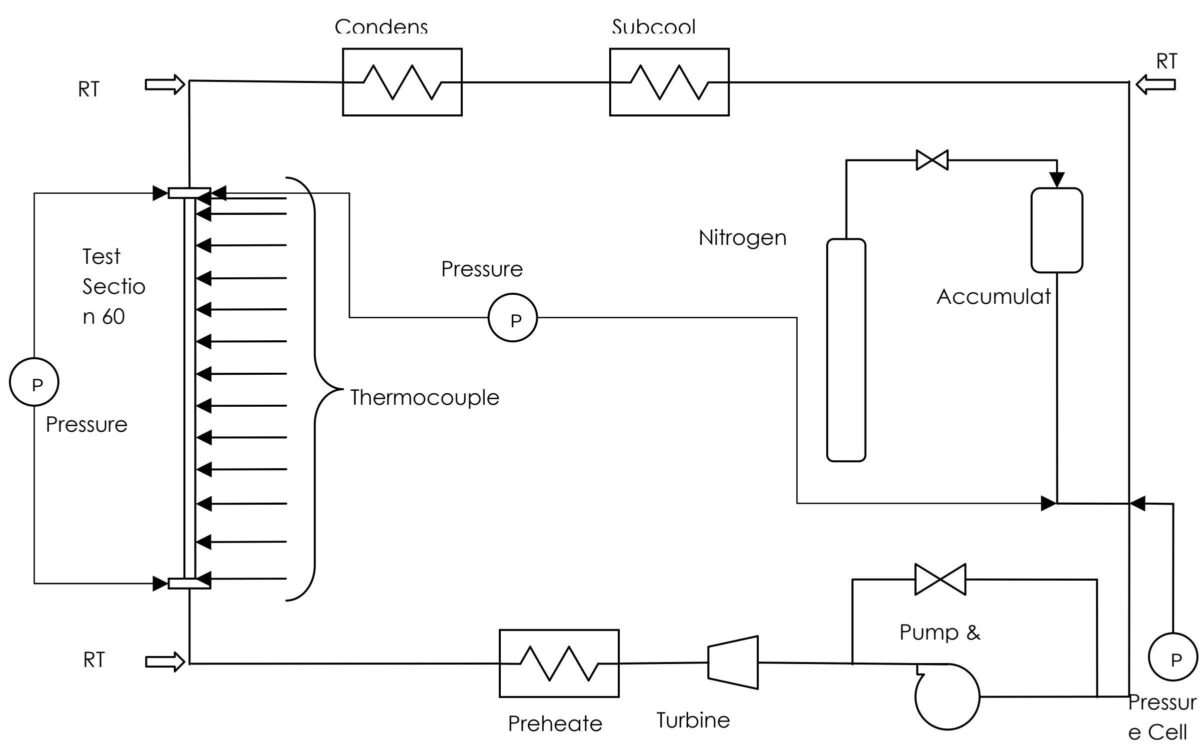

Figure 1: Flow sheet for the planned facility at McMaster. RTD, flowmeter, and pressure measurements are transmitted using 4-20 mA signals to a 40-bit DAC. Thermocouple signals are fed directly to the DAC.

only be as accurate as the experimental data used to derive it. It is for this reason that an experimental CHF research program is being developed at McMaster University. Procurement has begun for a facility designed to perform critical heat flux experiments.

Design Considerations

The authors of the CHF-LUT have indicated, by shading in regions of the CHF-LUT itself, many regions where extrapolation was necessary to obtain values of CHF for the specified pressure, mass flux, and flow quality. By looking at the data available in the open literature Olekhnovitch *et al* (1999) identified a need for additional CHF data over a wide range of flow parameters for pressures less than 60 bar and performed a series of experiments to begin addressing the identified gaps. Experiments at McMaster will supplement existing CHF data as needed.

In their review of available CHF data, Hall and Mudawar (2000) identified some inconsistencies in the rigour with which the experimental methods used to gather CHF data were reported. These included:

- Indicating the position where temperature and pressure measurements are made in relation to the test section
- Ensuring the accuracy of temperature and pressure measurement instruments to calculate saturated fluid properties
- Publishing test section pressure drop data
- Frequency of fluid deaearation
- Flow development length upstream of the test section

Cheng *et al* (1997) also identified the following additional sources of uncertainty for their CHF experiments: time-dependent fluctuation of measurements, size of final test section power increase, contact resistance of power connectors, environmental heat losses, test section wall conduction, and data acquisition system.

Therefore, the two most significant considerations when designing the experimental apparatus were: the accuracy of measurement instruments and experimental rigour, and ensuring that the capabilities of the loop fall within the ranges that have been identified where there is a need for more data.

Specifications

A flow diagram for the proposed facility is shown in Figure 1. A Miller SR-1000 B1 welder capable of providing 1000A at 40V (40 kW) will be used to power the preheater. At full power, the preheater would therefore be capable of raising water from 'room temperature' (nominally 20^{o}C) to saturation at 100 bar for flow rates up to 30 kg s^{-1}. This flow rate is much higher than will be possible using ½" tubing. Therefore, inlet subcoolings up to 650, 800, and 1300 kJ kg^{-1} at pressures of 10, 20, and 100 bar respectively will be possible. This assumes that the operating fluid will be reduced to 'room temperature' (approximately 20°C) by the subcooler and subsequently raised to the desired desired inlet enthalpy by the preheater at the indicated pressures.

The Omega Engineering FTB-9511 turbine flow meter is capable of measuring volumetric flow rates from 400-8000 cc/min. For an 8mm interior diameter tube containing saturated water at 20 bar, this represents a mass flux range from approximately 120 to 2250 kg m^{-2} s^{-1}. Flow rates may initially be limited by the available pump head which has yet to be determined. Additional pumps may easily be added or replaced to increase the loop's mass flux capabilities if needed.

A 1 m test section constructed using a 0.250 in OD Inconel 600 tube with 0.028 in walls is estimated to have a resistance of 0.0838 Ω. Inconel 600 is desirable as a test section material because its resistivity is nearly invariant with respect to temperature in the range of 35-500°C.

A 90 kW low ripple SCR power supply capable of supplying 1125A has been ordered. Assuming that lead cables and power busses have a negligible resistance the test section power will be limited by the available output of the power supply—it will not be current limited. Using the test section described above heat fluxes of approximately 5000 kW m^{-2} will be possible. The power supply capabilities are the strongest limits on the range of parameters over which the loop may be useful when it is commissioned.

½" by 0.028 in Swagelok SS316 tubing is being used for the majority of the loop's components. All of the loop's components have been chosen so that they are capable of operating, or are capable of being easily replaced by components capable of operating, at pressures of up to at least 100 bar.

The axial wall temperature profile and CHF detection will be measured using type K thermocouples. Near the test section exit, the thermocouples will be placed closely together axially for improved resolution. Robustness of CHF detection will be ensured by placing thermocouples in 4 radial positions at the test section exit. CHF will be assumed to have occurred after a nominal wall temperature rise of at least 3°C is maintained, since initial experiments will be limited to the annular film dryout type of CHF which may most often be characterized as 'stable' (Groeneveld 1986).

A highly accurate data acquisition system will be used to bus all measurement data into a control computer. Sufficient capacity will be available to significantly increase the possible number of instruments that can be used at once. This will allow the loop's instrumentation to be supplemented as needed.

Further Capabilities

The range of conditions over which the loop will be capable of reaching CHF will initially be limited by the power supply, pump head, and the need to maintain the test section in working order. The power supply is modular in design and can be easily expanded in 15kW increments. Pump capability may also be expanded by adding more pumps or replacing the existing pump.

Furthermore, the loop may be used to perform a multitude of other experiments despite the fact that it will be commissioned as a CHF test facility. With appropriate test sections and instrumentation the loop may be used to perform two-phase flow experiments including: two-phase convective heat transfer, annular film flow, entrainment and deposition in annular flow, two-phase pressure drop, etc. (Hewitt and Hall-Taylor 1970). The experimental possibilities will be limited mostly by the size of the tubing used for the main loop components, the length of the test section leg of the loop, and the accuracy of the instrumentation which is discussed below.

Instrumentation Uncertainties

Temperature Measurements

Fluid temperature measurements will be made using IEC 60751 Class 'A' RTDs that have a minimum uncertainty of ±0.65°C at 250°C. The RTD output will be converted to a 4-20 mA signal using a transmitter with an uncertainty of 0.1°C, a DAC error of 0.05% of the span, and a drift of less than ±0.1% span over 12 months. Calibration accuracy is ±0.05%. Neglecting the data acquisition system's uncertainty and assuming yearly calibration and a 100°C calibrated span, the measurement uncertainty is less than ±0.7°C.

The fluid temperature will be measured at the loop's 'corners' that may be up to 1m from the test section inlet and outlet depending on the length of the test section. Therefore, adequate insulation must be provided to ensure that environmental heat losses in the pipe sections leading into and out of the test section are negligible.

The type K thermocouples that will be used to measure the test section wall temperature are accurate to within ±1.1°C. Additional uncertainties will arise due to transmission losses and the data acquisition system's cold junctions, conversion inaccuracy, drift, and calibration. Internal wall temperatures will be calculated using the 1-dimensional conduction equation in radial co-ordinates using the transformation of variables described in Novog *et al* (2007).

Pressure Measurement

Gauge and differential pressure measurements will be made using Rosemount 3051C SMART pressure transmitters with reference accuracies of up to ±0.065% of the calibrated span, and overall calibrated uncertainty of less than ±0.15% of span.

Flow Measurement

Volumetric flow rate will be measured using a turbine flow meter with a calibrated inaccuracy of as little as ±0.5% of the reading. The frequency output of the turbine meter will be converted to a 4-20mA signal using a transmitter with a linearity of ±0.3% full scale. A calibration curve, supplied with the flow meter itself, will be needed to convert the 4-20mA signal into a flow rate using the control computer.

Test Section Power Measurement

The power applied to the test section will be measured directly. This will be achieved by multiplying the square of the current flowing through the test section by the test section resistance. Current measurement will be performed using a shunt resistor that has not yet been procured.

Standard Operating Procedures

Calibration

All of the facility's instruments will be calibrated at least monthly while experiments are being performed in order to minimize the contribution of drift to measurement inaccuracy. Instrument spans will be adjusted and calibrated to reflect the expected ranges of fluid and flow properties for each set of experiments at a specific pressure. Calibration dates and instrument spans for each instrument will be logged in a log book kept in the laboratory, and stored in a spreadsheet file on the lab computer. Current instrument measurement spans and the latest calibration date will be posted in two places in the lab that will be highly visible to the loop operators.

The water used as the working fluid in the loop will be deaerated as frequently as prudently possible. No experiments will be performed unless the water has been deaerated within the previous six months. Deaeration records will be kept with the calibration data in their own section in the logbook and spreadsheet.

Safe Operation

For safety, calibration data will be programmed into the power supply and data acquisition system control software to warn operators if the flow characteristics or properties are outside the current calibrated spans of any of the instruments.

Before performing any experiments or operating the loop, users must review the most recent calibration and deaeration data to ensure they meet the guidelines set out above. The loop must be checked to ensure that it is full of fluid, using a bleed valve located on the accumulator. The accumulator's mass must also be measured using the scale it hangs from to determine whether or not it contains water. If either of these tests fail, the loop must be replenished with deaerated water.

Once calibration records and the fluid inventory have been checked, the user must ensure that there are no leaks from any fittings and that all of the loop's components and fittings are secured. Electrical connections must be visually checked before any power supplies are activated i.e. the pump, preheater, or test section power supplies. The user should also check the electrical resistance of the various electrically isolated sections of the loop to ensure that there are no 'short circuits'. The guard panels surrounding the loop should then be closed.

After determining that the loop is structurally and electrically sound, the loop must be operated using the following procedure. Operators must wear appropriate personal protective equipment and obey all other posted safety precautions in addition to those listed above and below:

1. Ensure that the bypass valve (see Figure 1) is fully open and activate the pump. Allow the flow rate to reach steady-state, then adjust the bypass valve incrementally, allowing flow to reach equilibrium with each step, until the desired flow rate is achieved.
2. Begin to pressurize the loop by gradually opening the regulator on the nitrogen tank in small steps. After each pressure step, adjust the bypass valve as needed to

maintain the desired flow rate. Continue this process, allowing the flow and pressure measurements to stabilize after each adjustment, until the desired operating pressure is reached. The operator and assistant must ensure that all instruments are on-scale at all times.

3. Open the control valves to allow full water flow to the secondary side of the tube-and-shell condenser and subcooler. Adjust pressure and flow if necessary.
4. If all instruments remain on-scale, activate the preheater at its lowest power. Increase the preheater power in steps until the desired inlet temperature is achieved, while observing the pump inlet temperature. After each step, adjust the pressure and flow as necessary.
5. Finally, activate the test section power supply and increase test section power in steps, adjusting pressure, flow, and preheating after each step to maintain the desired operating conditions and allowing the loop to reach steady-state after each adjustment. Care must be taken to ensure that the pump inlet temperature remains below the pump's operating limit.
6. Continue to increase test section power and adjust flow parameters until within 15% of the predicted CHF value. Increase power in very small steps. As mentioned above, the uncertainty in the CHF value is partially determined by the size of the last power step taken before CHF is reached.
7. Once CHF has been reached, record all measured parameters for 20s at a frequency of at least 20Hz using the data acquisition system and control computer if the test section temperature is within a safe limit (i.e. at least 100^{o}C below any potential metallographic phase changes from the phase that existed before CHF was reached). If the wall temperature is unsafe, reduce test section power immediately.
8. Reduce test section power well below the CHF value, making sure that flow parameters are on-scale and safe. Shutdown of the loop should follow the reverse order of the operating procedures. Care should be taken to ensure that there is no two-

phase flow in the loop after test section power is removed and that the fluid temperature is below saturation at atmospheric pressure before depressurization can begin.

Safe and accurate experiments will be ensured if the procedures described above are always followed.

Conclusion

CHF is a phenomenon of critical importance for the design and safety analysis of nuclear reactors. Many methods of predicting CHF are available that may be improved or further verified by additional experimental data.

An experimental thermalhydraulics facility has been designed to perform experiments to gather accurate CHF data at McMaster University. Its configuration at the time of initial commissioning will enable it to be benchmarked against existing CHF data for mass fluxes in the range of 1000 - 2000 kg m^{-2} s^{-1}, pressures from 10-20 bar, inlet subcoolings from 0 to at least 650 kJ/kg, and heat fluxes up to 5000 kW m^{-2} using a 90kW power supply. The design allows for its capabilities to be expanded over time, and test sections can be implemented to perform a wide variety of two-phase flow experiments.

Instrument uncertainties and calibration procedures have been discussed. A robust standard operating procedure was outlined to ensure operator safety and accurate experimental data.

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