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The effects of transient conditions on the onset of intermittent dryout during blowdown

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HIGHLIGHTS

- This papers presents the results of an experimental investigation of transient critical heat flux in high quality and intermediate pressure water.
- In existing literature conclusions vary from those showing no effect of transient conditions to results which show 30–40% improvement in CHF.
- Along with new CHF data points in the liquid film dominated flow regime, the authors provide a methodology for producing bias free estimates of CHF based on existing correlations.
- With these bias free CHF estimates, comparisons are made between transient and steady-state CHF at comparable local conditions.
- The work concludes that based on consistently collected and analyzed data that quasi-steady CHF experiments adequately predict transient CHF using the same local thermalhydraulic conditions.

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ABSTRACT

For a given set of conditions in a boiling system the point of liquid film dryout or departure from nucleate boiling corresponds to the change from convective or nucleate boiling to transition or film boiling. This change is associated with a rapid deterioration of the heat transfer coefficient and the heat flux at this transition is denoted the critical heat flux (CHF). Computer models used to predict station transients and CHF rely heavily on empirical correlations to predict the CHF. Liquid film CHF data are usually obtained using a quasi-steady method wherein the heat flux is incremented in small steps with each step being allowed to reach a new equilibrium until an abnormal temperature increase is detected on the experimental surfaces. In applying a correlation derived from steady-state experiments to transient analyses these codes implicitly assume that dryout will occur for the same local conditions during transients as during steady state conditions. There is some disagreement in literature as to the validity of this hypothesis. This paper provides new steady-state and transient experimental data for CHF in water at intermediate pressures and demonstrates that for high-quality CHF that indeed CHF occurs at comparable local conditions during transients and steady-sate.

1. Introduction

For a given set of conditions in a boiling system the point of liquid film dryout or departure from nucleate boiling corresponds to the change from convective or nucleate boiling to transition or film boiling. This change is associated with a rapid deterioration of the heat transfer coefficient and the heat flux at this transition is denoted the critical heat flux (CHF).

In a heat flux controlled system like a nuclear power reactor the heat transfer deterioration will cause a concomitant surface temperature increase unless the thermal power generated in the fuel is decreased. Operation at these elevated temperatures can cause undesirable material degradation and may contribute to fuel sheath failures. Preventing the system from exceeding the CHF is frequently cited as an important safety criteria for nuclear power plants. The Canadian Nuclear Safety Commission (CNSC) provides a regulatory guide that uses the prevention of the onset of intermittent dryout (OID, Groeneveld, 1986)as a sufficient but not necessary criterion for demonstrating fuel integrity during postulated design basis accidents (Canadian Nuclear Safety Commission, 2006).

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

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on transient computer codes that predict the thermalhydraulic conditions and compare the cladding surface heat flux to the predicted CHF at each point in time. Computer models, in TRACE, RELAP5, or CATHENA for example, are used to predict the response of the reactor system to postulated failures and then to assess the acceptability of the results (Bajorek et al., 2008; United States Nuclear Regulatory Commission and others, 2002; Hanna, 1998).

These computer models rely heavily on correlations of empirical data to close the system of mass, momentum and energy conservation equations and to predict the CHF. Liquid film dryout data are usually obtained using a quasi-steady method wherein the heat flux is incremented in small steps with each step being allowed to reach a new equilibrium until an abnormal temperature increase is detected on the experimental surfaces. In applying a correlation derived from steady-state experiments to transient analyses these codes implicitly assume that dryout will occur for the same local conditions during transients as during steady state conditions.

Lyons and Swinnerton (1983a,b) suggest that the quasi-steady method is effective for predicting the dryout position during pressure transients while the works of Celata et al. (1991, 1992, 1988) and Moxon and Edwards (1967) suggest that a delay in the onset of dryout, relative to that predicted using the quasi-steady method, may occur for pressure and flow transients respectively.

The time of the onset of dryout during a reactor transient is of interest because of its relevance to reactor design and safety system performance. Choosing appropriate reactor SCRAM settings is just one example of where this analysis is useful. Establishing the uncertainty in the quasi-steady CHF prediction methods is important because these uncertainties affect operational constraints—*i. e.* SCRAM set-points, shutdown system performance requirements, *etc.*—and reactor power. The computer codes utilizing such quasi-steady empirical information are often tested against large scale integral tests as part of the validation process. Such validation often establishes the integrated code uncertainty, but it does not illuminate the extent to which CHF phenomena are adequately captured.

Few dedicated CHF datasets exist for transient conditions. The evaluation of quasi-steady prediction methods is also made more complicated due to the prediction biases that can occur for a given test facility. In a given test facility there may be an inherent bias in predicting even the steady-state data using a given CHF prediction methodology (*e.g.*, a Look-up Table). The bias in the steady-state predictions will alter the subsequent transient predictions, and hence obscure the impact of the transient itself on CHF.To thoroughly examine the differences between steady state and transient results it is necessary to:

- Collect steady state data in a facility under the relevant conditions using the appropriate fluids,
- Correlate this data or use the data within an existing correlation such that the predictions from the method can reproduce the steady-state data without bias,
- Collect new transient experimental data in the same facility and
- Compare the measured CHF under transient conditions to the bias-free prediction method.

This paper provides new steady-state and transient experimental data for CHF in water at intermediate pressures and outlines a method to provide bias free estimates of CHF. New transient CHF data are presented and analysed using the bias-corrected method so that the effect of the transient on CHF can be isolated. New steady-state CHF data in the limiting quality regime (LQR)—see, *e.g.* Groeneveld, 2011 for more information on the LQR—is presented for which this method was derived.

1.1. Background

Experimental CHF data has accumulated for many decades and covers a wide range of pressures, steam qualities, coolant mass fluxes, fluids and geometries. Many correlations (Hall and Issam, 1999; Shim and Park, 2004; Fortini and Marcelo, 2002) have been derived from various subsets of the available data with correspondingly varied ranges of validity.

Several correlations, like those of Biasi et al. (1967) or Katto and Ohno (1984), apply to a relatively large range of conditions. Groeneveld *et al*'s CHF look-up table (LUT) incorporates more than 20,000 unique data points normalized to equivalent conditions for water in 8 mm tubes (Groeneveld et al., 2007). The LUT uses smoothing functions to ensure consistent parametric trends and uses the Katto and Ohno correlation to fill regions where data is sparse or discontinuous. The experimental data used to derive these prediction methods are almost universally from steady or near-steady state experiments. The LUT method has been widely implemented in system thermalhydraulic codes for safety analysis.

Past investigations of transient CHF fall into one of three categories: i) transient data is analysed against an existing correlation or correlations without reference to a consistent baseline, ii) steady data from the experimental apparatus used to conduct transient experiments is used to establish the bias in the correlation(s) being tested in some way, *e.g.* the ratio of the predicted to the observed steady state CHF, but this information is not applied to the analysis of transient experiments, or, iii) steady state data is used to create a new correlation or modify an existing one such that facility specific predictions can be made and compared against transient data directly. These approaches have varying degrees of rigour but only the last approach permits a satisfactory quantitative conclusion about bias in the quasi-steady method's prediction of the *time* at which the CHF is exceeded. Establishing the transient effect on CHF is a priority, since all downstream efforts to correct (or not correct) quasi-steady CHF prediction are affected by these conclusions.

Chang *et al* proposed a transient-effects correction for the Biasi *et al* correlation that seemed to improve the correlation's performance for the flow and power transient data of Moxon and Edwards (Chang et al., 1989; Moxon and Edwards, 1967). However, they did not establish the original correlation's baseline performance against the available steady state experimental data prior to assessing the performance of their transient CHF correction method. Hence it is unclear if the correction results solely from a steady state bias or if it includes some transient effect.

Lee and Lin analysed flow transient dryout data using a homogeneous equilibrium model (HEM) code Lee and Lin, 1993. For their transient data the critical heat flux ratio—the ratio of the observed to the predicted CHF—was consistent with the CHF ratio observed in their steady state data for similar conditions. Lyons and Swinnerton also performed a similar analysis of their own pressure-transient CHF data (Lyons and Swinnerton, 1983a,b). They used the predicted 'dryout length' or dryout position to compare the bias in their steady and transient data relative to several dryout prediction methods including Whalley's liquid film flow model (Whalley et al., 1984). Their results did not show a significant change in dryout length as a function of time between the quasi-steady prediction method and the experimental data and, moreover, the predictions of the liquid-film flow model were not significantly different when the transient terms were removed.

Celata *et al* tuned an existing R-12 correlation so that more than 95% of their approximately 1000 steady-state data points were predicted within ±10% and subsequently used the modified correlation to predict the transient data (Celata et al., 1986). Their earlier analyses for flow, pressure and power transients