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An overview of measurements, data compilations and prediction methods for the critical heat flux in water-cooled tubes

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ABSTRACT

This paper describes the history and state of the art of measuring and predicting the Critical Heat Flux (CHF) in water-cooled tubes. Over the past 70 years, over 40,000 tube-CHF measurements have been obtained in over 160 separate studies. About 17 separate compilations of CHF datasets in water-cooled tubes have been produced, many overlapping each other. In addition, hundreds of tube-based CHF prediction methods can be found in the literature. The pertinent experimental details and concerns for these datasets and the proliferation of CHF prediction methods are discussed. A graphical presentation of the ranges of conditions covered by these CHF datasets is included.

1. Introduction

Before the advent of nuclear reactors, there was no urgent need for CHF measurements as most boiling processes where CHF was encountered were temperature-controlled (e.g., heat exchanger tubes in fossil-fuelled boilers). However, water-cooled nuclear reactors, which are limited in power by the CHF occurrence, are basically heat-flux-controlled systems. Hence, exceeding the CHF can have serious consequences, in particular for Pressurized Water Reactors (PWRs). For this reason, most of the countries with an interest in nuclear energy became active in CHF measurements by the mid 1900s, and have continued doing so up to the present. In the USA, McAdams et al. (1949), and Jens and Lottes (1951) were the first to report flow boiling CHF measurements.

Along with CHF measurements, which were originally limited to tube geometries, CHF prediction methods were also proposed starting in the late 1940s. The earliest tube-CHF prediction methods were primarily empirical. These crude empirical correlations lacked any physical basis, and had a limited range of application. Subsequently, a large number of phenomenological equations or physical models for CHF were developed; some of these models have been used in reactor safety analysis codes. Physical models and phenomenological equations, however, depend on the mechanisms controlling the CHF, which changes with flow regime. This necessitates the use of a combination of different models, equations or correlations for predicting the CHF for the wide range of conditions that can be encountered during reactor accident transients. Because of this, and because of the large proliferation of CHF equations and correlations (over 500 CHF correlations are currently available for uniformly-heated water-cooled tubes), a more universal CHF prediction methodology was required. Hence, look-up tables for predicting the CHF in water-cooled tubes were subsequently derived (Groeneveld et al., 1986, 1996, 2007a).

The CHF look-up table is basically a normalized CHF databank for water-cooled tubes. Compared to other available prediction methods, the look-up table approach has the following advantages: (i) greater accuracy, (ii) wider range of application, and (iii) correct asymptotic trend. Although look-up tables were initially developed for tubes, and have been successfully used in subchannel codes, the greatest potential for their application is in predicting the consequences of postulated loss-of-coolant accidents (LOCAs).

It should be emphasized that tube based CHF prediction methods discussed in this paper will generally be of limited usefulness in predicting the CHF in bundle geometries for conditions where bundle CHF data are available. However bundle CHF measurements at accident conditions are generally unavailable, in which case the analyst may employ reliable tube-based CHF prediction methods after correcting for effects such as speed of the transient, axial and radial flux distribution, geometry, spacers etc. Possible expressions to account for these effects have been proposed by Groeneveld et al. (2003), Tong and Weisman (1996) and Collier and Thome (1994).

Note that virtual all bundle CHF measurements were obtained on electrically-heated fuel-bundle simulators, and are subsequently

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extrapolated to in-reactor conditions. Few in-reactor CHF measurements were obtained in the 1960s and 1970s; they have been recently reviewed by Groeneveld (2017) who also presented some concerns related to extrapolating CHF measurements from out-reactor fuel simulators to in-reactor conditions.

Section 2 of this paper discusses the types of CHF experiments and CHF detection methods employed during the past 70 years, as well as various factors that could affect the uncertainty in the CHF measurements. Section 3 describes the experimental datasets and data compilations for CHF measurements in water-cooled tubes. Section 4 provides an overview and the evolution of CHF prediction methods in simple geometries. Section 5 presents graphically the database coverage of the present tube-CHF database and discusses the lack of data at certain flow conditions.

2. CHF measurements

2.1. CHF detection methods

CHF is typically characterized by a noticeable increase in surface temperature in response to a small change in heat flux. This change in temperature can be very drastic, as is the case for PWR-type conditions (referred to as “fast dryout”; see Groeneveld, 1986), or this change can be gradual as for Boiling Water Reactor (BWR) conditions (referred to as “slow dryout”). Over the past 70 years, CHF experimenters have used many different CHF detection methods; the four main methods are summarized below.

Visual The early CHF papers identified the CHF as the heat flux at which the test section “started to redden visually”. This method was used by some of the early researchers (e.g., Hood and Isakoff, 1962). Although this method could work well for fast dryouts or Departure from Nucleate Boiling (DNB) at subcooled CHF conditions, the slow dryouts, typical for BWR conditions, would only result in modest temperature excursions that did not result in a discoloration of the heated surface.

Physical Burnout At high flow rates and high subcoolings, the CHF is typically very high, making it difficult to quickly switch off the power at CHF to avoid test section failure. Several investigators reported that their CHF corresponded frequently to a physical burnout at CHF occurrence (e.g., Hood and Isakoff, 1962; Pabisz and Bergles, 1996).

Change in Test Section Resistance The test section material used in most CHF experiments is either Inconel or stainless steel. Inconel has a very low temperature coefficient of resistivity compared to stainless steel which has a much higher value. By using a stainless steel test section as one leg of a Wheatstone bridge, CHF can be detected when the change in test section resistance due to a significant temperature excursion results in an imbalance in the Wheatstone bridge, triggering a power supply trip. This method of CHF detection was reported by Dell et al. (1969), Matzner et al. (1965), Hewitt et al. (1965) and others.

Test Section Thermocouples The most common method for detecting CHF is using thermocouples attached to the downstream end of the heated length of the test section. This method is very effective for most types of CHF occurrences, with the possible exception of very fast temperature excursions where a method based on detecting a change in test section resistance may be more reliable. For very slow dryouts, the thermocouple method may not always be effective because of the absence of a noticeable dryout temperature excursion. Here a more reliable method is based on monitoring the change in the slope of heated wall temperature vs. heat flux or $\Delta T_w/\Delta q$ (Groeneveld, 1986).

Other CHF detection methods that have been explored include those based on acoustic, ultrasonic and infrared techniques; these novel methods however are not yet sufficiently mature and have not been employed in obtaining the more than 160 tube-CHF datasets used for deriving CHF prediction methods.

In some cases, the CHF was actually a “by-product” of a film-boiling experiment during which detailed wall temperature distributions were measured. For any given heat flux, the CHF quality was either assumed to be the quality where the first rise in surface temperature was detected, or defined as the average of the last pre-CHF quality and the (subsequent) first post-CHF quality. Examples of this type of CHF measurement are given by Era et al. (1966), Bennett et al. (1967) and Herkenrath and Mork-Morkenstein (1969).

2.2. Primary and secondary CHF parameters

CHF is primarily a function of flow conditions and test section geometry. Since the look-up table and the overwhelming majority of empirical tube-CHF correlations are based only on CHF measurements obtained in a tubes having a uniform axial flux distribution, the impact of non-circular geometries and axial flux distribution on CHF will not be discussed.

During CHF experiments, the CHF is a function of the following primary parameters: pressure (either at the start of the heated length or at the CHF location), inlet temperature, mass flow rate, diameter (D) and heated length (L). It has been shown by several experimenters (e.g., Lee and Obertelli, 1963; Lee, 1965) that the primary parameters heated length and inlet temperature can be replaced by thermodynamic quality at the CHF location, provided that the heated length is sufficiently long (e.g., $L/D > 50$) to remove any upstream history effects. Thus, for a given inside diameter, CHF becomes a function of the flow conditions at CHF, i.e., mass flux, pressure, and thermodynamic quality. These are the three parameters of the CHF look-up table.

The following secondary parameters could also affect the CHF in uniformly heated tubes:

- Test section orientation: Although most CHF tests have been performed for upward flow in vertical test sections, some investigators have investigated the CHF behavior in horizontal flow and downflow (e.g., Wong et al., 1990). Based on an extensive analysis of CHF in horizontal tubes, Wong has shown that the effect of test section orientation is not significant at high mass velocities where flow stratification is suppressed. The boundaries of flow stratification can be estimated from flow regime maps such as those proposed by Taitel and Dukler (1975).
- Test section material: Test section material in general has little effect on CHF during flow boiling. However, for low flows and conditions where CHF is due to DNB, highly conductive test section materials could dissipate hot spots under bubbles and thus increase the CHF (Berenson, 1962).
- Type of heating: The large majority of CHF experiments are performed on directly heated tubes (Joule heating), while the most typical application is indirect heating of a fuel sheath where the heat source is nuclear heat. Leung et al. (1982) compared experimentally the CHF for direct and indirect heating and observed no significant difference.
- Wall thickness: Several experimenters (e.g., Bergles, 1963; Bennett et al., 1965) investigated the wall thickness effect of CHF but found no discernible effect. Some effect could possibly be present for very thin walls that could limit the heat diffusion of hot spots during a DNB-type CHF .
- Surface roughness: Most test sections have a very smooth surface finish (similar to a fuel sheath) and the impact of the very small surface roughness is not found to be significant. Even for cases with a machined surface roughness, the impact of roughness on CHF is generally small as it is usually the vapor generation rate at the surface that determines the CHF occurrence. However when the surface roughness becomes larger than the film thickness (in annular film dryout), a reduction in CHF could occur due to premature film breakdown. In addition, a roughened surface provides preferential nucleation sites that could affect the CHF when DNB is the main mechanism of CHF occurrence (Bergles, 1976; Berenson, 1962).
- Inlet /outlet throttling: In the majority of the CHF experiments, the