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EXPERIMENTAL EVIDENCE SUPPORTING TWO-MECHANISM CRITICAL HEAT FLUX

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Abstract—Critical heat flux (CHF) experiments were performed in a high pressure, forced convection, boiling water facility employing flowing sodium as the heating medium. Water pressure ranged from 7.0 to 15.3 MPa, and the water mass flux ranged from 0.72 to 3.2 Mg/m^2s. Measurements were made of temperature fluctuations in the test section tube wall, adjacent to the transition boiling region downstream of CHF, with two thermocouples diametrically opposed at the same axial position. The temperature recordings indicated an abrupt change in hydrodynamic flow structure occurring at the same critical heat flux values where previously obtained CHF data exhibited abrupt changes in trend from heat flux dependent to heat flux independent. These results strongly support the two CHF mechanisms hypothesis and the associated CHF data trend representation for empirical curve fits to CHF data.

INTRODUCTION

THE TERM "critical heat flux" (CHF) applied to flow boiling denotes the abrupt change from good heat transfer to poor heat transfer. The former is often referred to as nucleate boiling and the latter film boiling by analogy to pool boiling phenomena. The term critical heat flux is often used synonymously with departure from nucleate boiling (DNB), dryout, burnout, and boiling crisis. For the purpose of this presentation, the general phenomenon of abrupt and dramatic change in heat transfer will be termed CHF. Departure from nucleate boiling (DNB) and dryout (or liquid film dryout) will denote CHF caused by specific mechanisms. The occurrence of two CHF mechanisms is the subject of this study.

The phenomenon of CHF in a forced convective boiling system is often the most important or limiting condition to a particular system thermal design. In some systems, CHF leads to intolerable rise in metal temperatures culminating in failure, thus the term burnout. In other systems where CHF is allowable, accurate prediction of its occurrence is often crucial to the thermal performance. As a result of the importance of CHF to a wide variety of applications, significant research has been performed in this area. Many investigators have developed empirical or semi-empirical equations which represent one or more sets of the available data. (These equations are often termed data correlation equations, but they will be referred to simply as empirical equations in this article to avoid confusion with the statistical cross-correlation function which is mentioned frequently henceforth.) This empirical equation form of data representation is invaluable in computer computation and system design. In developing these equations (of which there are many, and significant differences exist in the CHF predictions among them), investigators had to choose a mathematical form for the representation. This choice was generally guided by the data trends supplemented by mechanistic theory. However, given the average spread encountered in two-phase flow heat transfer data, the trends of the CHF data were not always clear, and multiple forms of empirical equations could represent the data equally well. Theoretical considerations do not conclusively establish the best of these forms either. As a result, there has existed, for some period of time, controversy as to the best form to use when representing CHF data by empirical equation, i.e. the form most representative of the physical phenomenon.

A considerable number of empirical equations are found in the literature which represent a significant amount of CHF data obtained at relatively high heat fluxes in test sections of relatively short lengths. Some of the more widely used of these are discussed in [1]. These equations generally represent the quality at CHF as a linear (or near linear) function of heat flux for fixed flow rate and pressure. The resulting trend is represented by section A–B of the curve of Fig. 1.

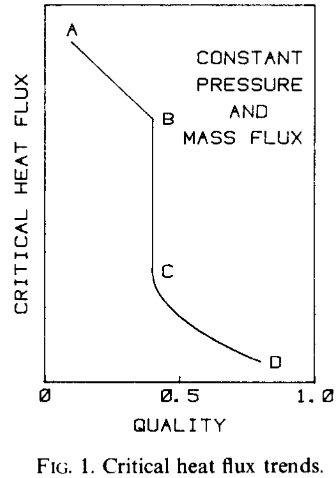

FIG. 1. Critical heat flux trends.

Soviet investigators appear to be the first to have obtained and interpreted CHF data that exhibited both a heat flux dependent trend as section A–B of Fig. 1 and a heat flux independent trend as section B–C of Fig. 1. (The heat flux dependent region, A–B, was termed CHF of the first kind, and region B–C is a portion of region B–C–D which was termed CHF of the second kind.) The Soviet work was reviewed in some detail in [2]. A large amount of these data given in [3] was obtained in long test sections allowing relatively low heat fluxes to be achieved. The entire plot of heat flux vs quality at CHF was postulated to have the form A–B–C–D of Fig. 1. A basic question then arose with respect to section B–C. That question is whether or not there is indeed a heat flux independent region. If not, the plot in Fig. 1 should be considerably smoother with a negative slope throughout.

In a recent article [4], Kitto presented a fine review of data and theories which both support and refute the existence of a heat flux independent region, section B–C of Fig. 1. The theories supporting the existence are based on the hypothesis that there are different CHF mechanisms in the heat flux dependent region (section A–B of Fig. 1) and in the heat flux independent region (section B–C of Fig. 1). The fact that a significant amount of data exhibit a sharp distinction in trend at point B in Fig. 1 supports this hypothesis. Kitto's article [4] summarizes the CHF mechanisms that have been postulated. However, most of the supporting data are not basic to the phenomena, i.e. the support comes from the form (two trends) of the data plotted as in Fig. 1. There is one exception as noted by Kitto [4] where an attempt was made to obtain experimental evidence of the two CHF mechanisms aside from the form of data plotted on the coordinates of Fig. 1. This exception was the salt experiments of [5] which indicated a difference in the droplet deposition rate on the heating surface between the heat flux dependent and heat flux independent regimes. This indication supported the microfilm hypothesis of Doroschuk [5] as to the CHF mechanism in the heat flux independent region. Hewitt [6] argued that these results could have been caused by other phenomena because of the way in which parameters were selected for the tests. Thus, the controversy regarding the heat flux independent region remained.

The results of the present investigation support the existence of two different CHF mechanisms in the heat flux dependent and independent regions of Fig. 1. From the experiments performed, information was obtained related to the two-phase flow structure in each of the two CHF regions, and like the salt experiments [5] these results add more fundamental support to the two CHF mechanisms concept than the bulk of the existing experimental data. The results show that a significant difference exists in the flow structure between the heat flux dependent and heat flux independent CHF regions as shown in Fig. 1. In addition, the results show that the transition from one structure to the other occurs rather abruptly (at point B in Fig. 1) and at a point predictable from the CHF data and empirical equations of [7].

EXPERIMENTS

Forced convection boiling experiments were performed in a high pressure water system. Water flowed vertically upward inside a steel tube heated by sodium flowing counter current in a surrounding annulus. Details of the test facility and test section are given in [7] and [8]. A brief summary with emphasis on features important to the present study follows.

Experiments were performed in the Argonne National Laboratory Steam Generator Test Facility (SGTF) which is nominally a 1 MW facility employing sodium to boil water. The test section is shown schematically in Fig. 2. The relatively long heated length of 13.1 m is typical of sodium heated steam generators for nuclear reactor applications. The geometry influence on the data and other test parameters is discussed in subsequent sections.

Two types of thermocouples (T.C.) were used on the test section shown in Fig. 2. The most important for this study were the internal thermocouples which were stainless steel sheathed with grounded junctions. These thermocouples were fed into the test section through the sodium annulus and brazed into the tube wall from the sodium side. The junctions, which were positioned nominally midway through the tube wall, were accurately located relative to the tube inside diameter. Two of these internal thermocouples are of particular importance. They were located at the same

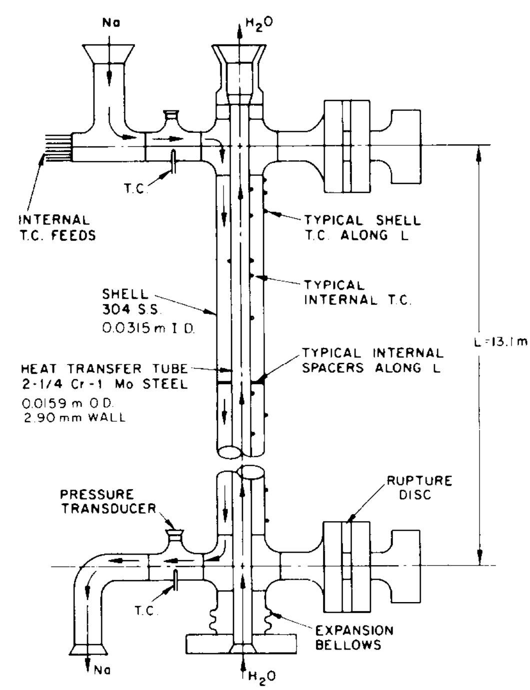

FIG. 2. Test section.

axial position, 9.1 m downstream of the water inlet to the test section, and 180° apart in the azimuthal direction.

Steady state tests were performed at water mass fluxes in the range of 0.7–3.2 Mg/m^2s and water pressures of 7.0–15.3 MPa. In each test, the sodium inlet temperature, sodium flowrate, and water inlet temperature were varied until CHF occurred slightly upstream of the two internal thermocouples located at the 9.1 m axial position. This procedure resulted in the two internal thermocouples being located adjacent to the transition boiling zone. The characteristic of the transition boiling zone of importance to this study is the temperature fluctuations induced in the tube wall and measured by the two internal thermocouples. These fluctuations are discussed in some detail in [8], but for the purposes of this study, it is sufficient to indicate that the test section parameters were adjusted such that the maximum amplitude temperature fluctuations in the tube wall, adjacent to the transition boiling zone, were measured by the two internal thermocouples.

Several experiments were performed with the water mass flux and pressure maintained at fixed values. The remaining test section parameters were used to obtain a large range of heat fluxes at the CHF position in these experiments. Then the entire procedure was repeated at 11 different combinations of water mass flux and pressure. In each experiment, the resulting raw data were recordings of tube wall temperatures as a function of time from each of the two internal thermocouples as well as other information from which the parameters at CHF were determined as described in [7]. The point of interest is the relation between these two wall temperature recordings over the entire range of the experiments.

RESULTS

As mentioned previously, extensive CHF data were reported in [7]. These data exhibited both the heat flux dependent and heat flux independent regions shown as sections A–B and B–C of Fig. 1, respectively. One subset of the data is shown in Fig. 3 as circular symbols on the same coordinates as Fig. 1 for fixed parameters of water mass flux (G) and pressure (P) as given in Fig. 3. Five experiments of the type discussed in the previous section were performed at the same values of water mass flux and pressure. By controlling the heat input, critical heat flux varied from 0.5–1.0 MW/m^2. In each of the five experiments, the statistical cross correlation function was determined from the recordings of the two internal thermocouples. The maximum values of the five normalized cross-correlation functions (the cross correlation coefficients) are plotted in Fig. 3 as a function of the critical heat flux. The cross correlation coefficient exhibits two extremes over the data range. It exhibits both low values, indicative of poor correlation between the thermocouple signals, and high values corresponding to good correlation. Since the thermal fluctuations in the tube wall are incited by the two-phase flow, the extreme differences of high and low coefficients may be attributed to significant differences in flow structure within the tube. This information alone is significant in supporting the two CHF mechanisms hypothesis where the two mechanisms are related to flow structure change. Furthermore, inspection of Fig. 3 reveals additional important results; the cross-correlation coefficient changes abruptly from low to high magnitude, and this abrupt change occurs at a critical heat flux of 0.5 MW/m^2 which marks the point of change from heat flux dependent to heat flux independent CHF region based on the CHF data (circular symbols).

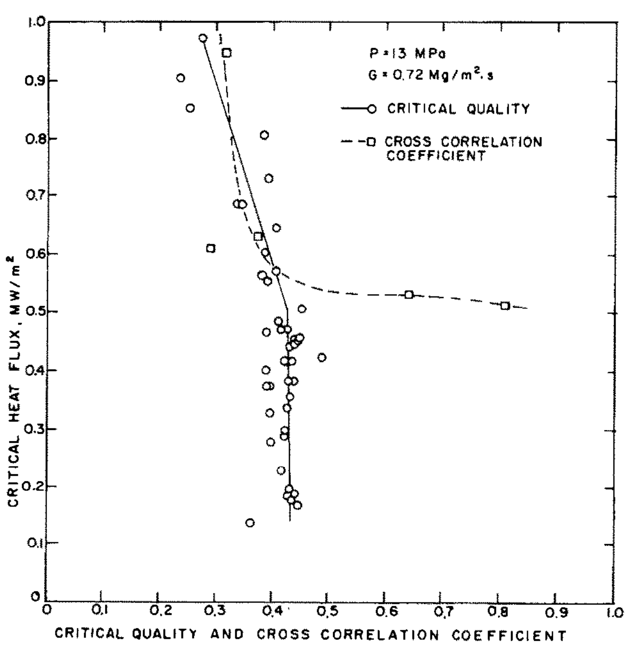

FIG. 3. CHF data and cross-correlation comparison.

Thus, the CHF data and the cross-correlation coefficient both exhibit abrupt changes in character at the same value of heat flux. This result further supports the existence of two CHF mechanisms resulting from change in flow structure.

A sample of the recordings from the two internal thermocouples for an experiment in which the correlation between them was very good (signified by a cross-correlation coefficient of 0.96) is shown in Fig. 4. It is seen that, while the two signals are not identical, the low frequency having the largest amplitude is very similar in both temperature recordings. In contrast, two signals are shown in Fig. 5 where the correlation is poor, and the cross-correlation coefficient is equal to 0.3. The two recordings are seen to be quite dissimilar.

As mentioned previously, multiple experiments were performed at each of 11 combinations of water mass flux and pressure. The effect of mass flux on the cross-correlation coefficient is shown in Fig. 6, and the effect of pressure in Fig. 7. Although some of the data are sparse, it is clear that the magnitude of the cross-correlation coefficient changes rather abruptly over a small range of critical heat flux. The solid lines shown in Figs. 6 and 7 were the results of a curve-fitting routine. A general equation was determined which predicted all the data from the experiments in this study. (This procedure compensated for the effects of sparse groups of data.) Then, for each set of experiments at fixed water mass flux and pressure, the critical heat flux was determined from this general equation at which the cross-correlation coefficient was 0.8. The value of 0.8 was chosen to represent the transition from poor to good correlation between the two thermocouple signals. The result was a table of 11 critical heat fluxes representing transition from poor to good correlation. A second table of transition heat fluxes was determined from the CHF data of [7]. The heat fluxes at point B of Fig. 1 were determined from those data at the same 11 combinations of water mass flux and pressure used in the experiments from which the cross-correlation coefficients were derived. The two tables are compared in Table 1.

As an example of the comparisons shown in Table 1, consider the data given in Fig. 3 which represent one of the 11 combinations of water mass flux and pressure employed in this study. The heat flux at the change from heat flux dependent to heat flux independent CHF occurs at 0.5 MW/m^2 as determined from the CHF data of [7] (the circular symbols in Fig. 3). The heat flux at a cross-correlation coefficient of 0.8 is also seen to be 0.5 MW/m^2 in Fig. 3. These two heat fluxes are listed in line 1 of Table 1. (The heat flux at a cross-correlation coefficient of 0.8 was actually determined from the general equation fit to the data rather than from inspection of Fig. 3. This equation is plotted in both Figs. 6 and 7 at the parameters of Fig. 3.) The results of the transition heat fluxes determined from both the CHF data of [7] and from the cross-correlation calculations are given in Table 1 for all 11 combinations of water mass flux and pressure employed in this study. The agreement between pairs of heat fluxes is considered to be very good.

DISCUSSION

The previously observed heat flux independent and heat flux dependent trends of CHF data represented insufficient information from which to draw conclusions concerning the *cause* of the trends. The addition of the cross-correlation results provided evidence upon which such conclusions may be based.

The change in cross-correlation coefficient, which represents an alteration in the nature of the tube wall

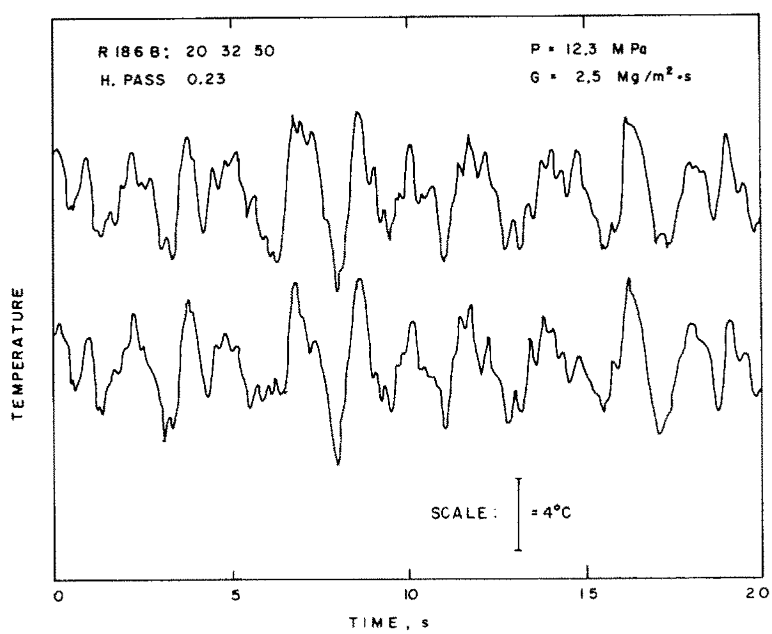

FIG. 4. Measured temperature: cross-correlation coefficient = 0.96.

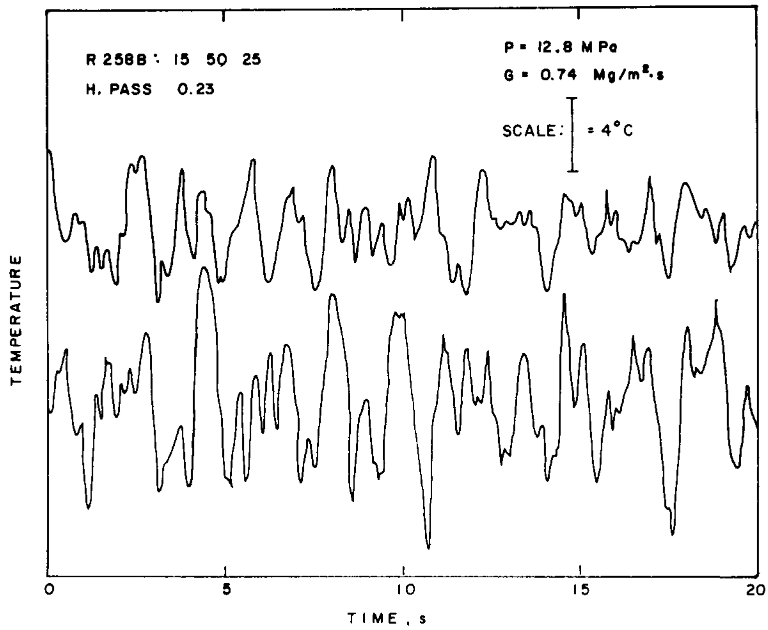

FIG. 5. Measured temperature: cross-correlation coefficient = 0.3.

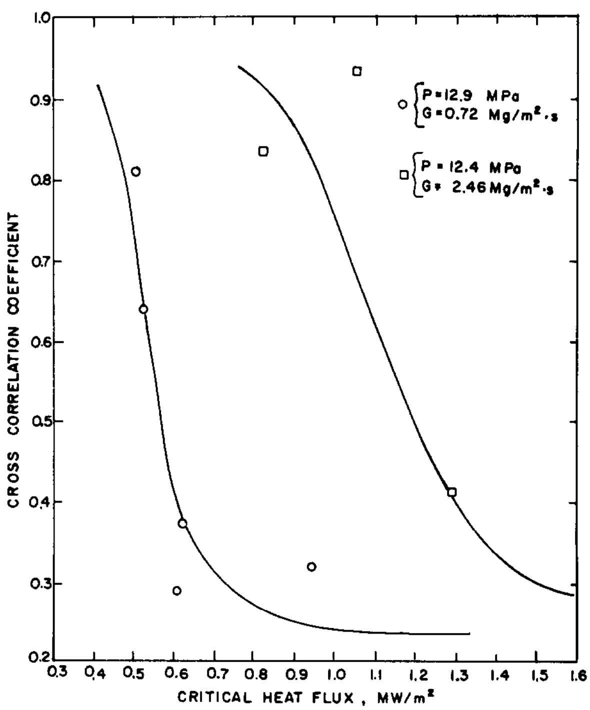

FIG. 6. Mass flux effect on cross-correlation.

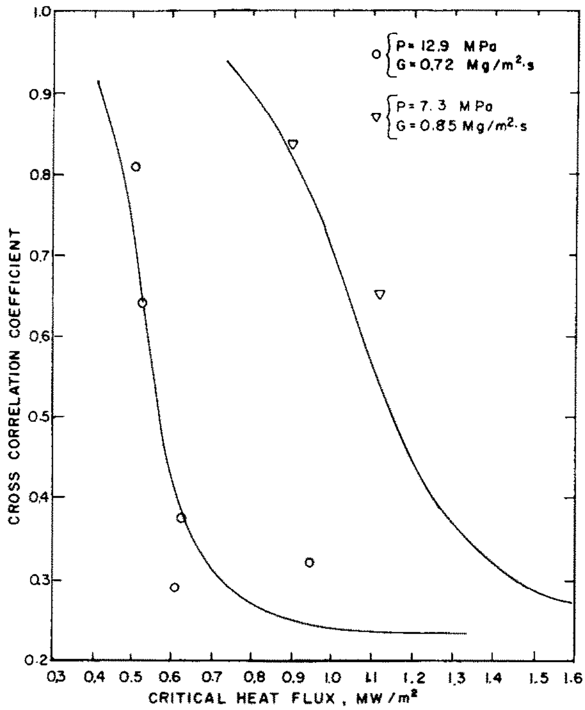

FIG. 7. Pressure effect on cross-correlation.

Table 1. Comparison of transition heat fluxes

P (MPa)	G (Mg/s/m^2)	Transition heat flux (MW/m^2) From CHF data	From cross-correlation
12.9	0.72	0.5	0.5
12.4	2.46	0.7	0.9
7.3	0.85	0.9	0.9
15.3	0.80	0.4	0.4
7.3	1.44	1.0	0.9
12.9	1.56	0.6	0.6
15.3	1.21	<0.2	0.2
7.0	2.44	1.0	1.0
15.3	2.46	≈0.6	0.6
7.3	3.10	<1.1	0.7
12.9	3.20	0.8	0.8

thermal fluctuations, signifies a change in the forcing function for the fluctuations. That forcing function is the structure of the two-phase flow in the transition boiling region. Thus, the change in CHF data trend from heat flux independent to heat flux dependent appears to occur when the hydrodynamic character of the transition boiling region makes an abrupt change. This condition of different hydrodynamic structure is a requirement of the postulate that two CHF mechanisms exist in the heat flux dependent and independent CHF regions, respectively. Although little information is added concerning the nature of these mechanisms, be they DNB or liquid film dryout, the results indicate that the hydrodynamic structure of the flow is different in the two CHF regions and that the change in structure occurs abruptly and at the critical heat flux marking the change in regions as observed from the previously reported CHF data (which also show an abrupt change between regions). These abrupt changes in two independent types of data occurring at the same values of critical heat flux provide strong substantiation of the existence of two CHF mechanisms which are well represented by heat flux dependent and independent regions.

Similar experiments to those reported in this article were reported in [9]. High pressure water was boiled in a sodium heated forced convective system, and tube wall temperatures in the transition boiling region were recorded. At one axial location, 4 thermocouples were located on the tube wall spaced 90° apart in the azimuthal direction. It was reported that in some experiments the temperature recordings appeared to be independent of each other, and in other experiments the recordings were clearly "synchronous." In these experiments the water entering the test section was either subcooled or two-phase. (In the present study, only subcooled inlet conditions were employed.) It was noted that the synchronous results were generally found when the inlet was two-phase, and the independent results were found when the water was subcooled at the test section inlet. Some agreement between these results and the present study may be postulated in the following manner. Tests performed with a two-phase inlet generally lead to lower heat fluxes at the CHF location than tests performed with subcooled water inlets. (The CHF axial location was fixed at the thermocouple location.) Thus, the synchronous (good correlation) results of [9] were likely to be associated with lower heat fluxes at CHF than the independent (poor correlation) results. This trend is consistent with the results of the present study in which higher heat fluxes were associated with heat flux dependent CHF and low cross-correlation coefficients. Lower heat fluxes lead to heat flux independent CHF and high cross-correlation coefficients.

CONCLUSION

Considerable CHF data exhibit two distinct trends. Observation of these data reveal that the form of the trends is heat flux dependent and heat flux independent. It has been postulated that these trends result from two different CHF mechanisms which are caused by a change in flow structure. Thus, establishment of the existence of two flow structures is essential to this hypothesis and to the concept of heat flux dependent and independent CHF. The results of this investigation supply strong evidence toward that establishment. The effects of two flow structures were observed. The change from one to the other occurred abruptly and at conditions consistent with the change in trends of the CHF data. Further, the changes in observed flow structure effects were very substantial. It is difficult to conceive of a single CHF mechanism persisting through such changes. Thus, through observed effects of two flow structures, strong support is provided for the two-mechanism CHF hypothesis. However, the form of the CHF data of heat flux dependent and independent regions resulting from the two CHF mechanisms, is still derived from the form of the CHF data itself.

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EVIDENCE EXPERIMENTALE EN FAVEUR DE DEUX MECANISMES DU FLUX CRITIQUE THERMIQUE

Résumé—Des expériences de flux critiques thermiques (CHF) sont conduites pour de l'eau bouillant à forte pression, en convection forcée, le fluide chauffant étant du sodium. La pression varie de 7 à 15,3 MPa, et le flux massique d'eau est compris entre 0,72 et 3,2 mg/m^2 s. Des fluctuations de température sont mesurées à la paroi du tube d'essai, dans la région d'ébullition de transition en aval du CHF, avec deux thermocouples diamétralement opposés pour la même position axiale. Les enregistrements de température indiquent un brusque changement de structure d'écoulement apparaissant aux mêmes valeurs du flux critique que dans des essais antérieurs, là où avait été remarqué des changements brusques dans le passage de la dépendance à l'indépendance du flux thermique. Ces résultats sont fortement en faveur de deux mécanismes du CHF et les données du CHF s'accordent bien avec une courbe empirique associée aux observations.

EXPERIMENTELLE UNTERMAUERUNG DES ZWEI-MECHANISMEN-MODELLS FÜR DIE KRITISCHE WÄRMESTROMDICHTE

Zusammenfassung—In einer mit flüssigem Natrium beheizten Hochdruck-Versuchseinrichtung zur Verdampfung von Wasser bei erzwungener Konvektion wurde die kritische Wärmestromdichte (CHF) untersucht. Druck und Massenstromdichte des Wassers waren 7,0 bis 15,3 MPa bzw. 0,72 bis 3,2 Mg/m^2 s. Im Grenzgebiet des Übergamgssiedens stromab des CHF wurden mit zwei in der gleichen axialen Position diametral angeordneten Thermoelementen die Temperatur-Fluktuationen in der Meßstreckenwand gemessen. Die Temperaturaufzeichnungen wiesen auf einen plötzlichen Wechsel in der hydrodynamischen Strömungsstruktur hin, der bei den gleichen Werten der kritischen Wärmestromdichte auftrat, bei denen vorher gewonnene CHF-Werte plötzliche Tendenzwechsel von wärmestromdichten-abhängigem zu wärmestromdichten-unabhängigem Verhalten zeigten. Diese Ergebnisse untermauern die Zwei-Mechanismen-CHF-Hypothese und die damit verbundene Darstellungstendenz für die empirische Kurven-Anpassung an CHF-Daten.

ЭКСПЕРИМЕНТАЛЬНОЕ ПОДТВЕРЖДЕНИЕ ИДЕИ ДВУХ МЕХАНИЗМОВ КРИТИЧЕСКОГО ТЕПЛОВОГО ПОТОКА

Аннотация — Критические тепловые потоки измерялись на установке с водой (расход от 0,72 до 3,2 Мг $м^{-2}$ $с^{-1}$), кипящей при высоком давлении (7–15,3 МПа) и вынужденной конвекции. Нагревающей средой служил жидкий натрий. Парой термопар, расположенных противоположно в одном и том же сечении, измерялись флуктуации температуры стенок трубы опытного участка, примыкающего к области переходного кипения, расположенной вниз по течению от области критического теплового потока. Измеренные значения температуры свидетельствуют о мгновенном изменении гидродинамической структуры течения при тех же значениях критического теплового потока, при которых ранее отмечались мгновенные изменения в переходе картины течения от зависимой к независимой от плотности теплового потока. Эти результаты служат хорошим подтверждением гипотезы о двух механизмах критического теплового потока, а соответствующее представление тенденции данных по критическому тепловому потоку для эмпирической кривой совпадает с данными по критическому тепловому потоку.