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Film and transition boiling characteristics of subcooled liquid flowing through a horizontal flat duct

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Abstract—An experimental investigation was conducted to observe and analyze the flow boiling of a subcooled liquid flowing through a horizontal flat duct at high velocities. Analysis of the experimental data revealed several distinct characteristics: first, the region over which transition boiling occurred decreased in size as the liquid velocity and the amount of liquid subcooling increased; second, two fairly distinct regions were apparent within the film boiling regime, an auto model and non-auto model region. In addition, the previously developed theoretical analysis was modified and expanded to encompass the auto model film boiling region. This analysis provided an explanation for the two regions observed and established a foundation for further study of the phenomena surrounding this type of boiling.

INTRODUCTION

BOILING has long been recognized as one of the most efficient ways of cooling hot or heated surfaces and bubble incipience, development, and growth are of fundamental importance in many applications in the nuclear, chemical, and petrochemical industries. Although these phenomena have all been investigated for the case of low velocity flow or stationary pools, only a limited number of investigations have been performed for the case of high velocity, internal flows with substantial subcooling. These types of flow boiling problems arise in a wide variety of applications including: fusion reactors where the heat present in the primary containment vessel must be removed at extremely high temperatures and heat flux levels; electronic applications where the cooling of microelectronic devices may require removal of heat at flux levels exceeding 100 kW m^{-2}; chemical–petrochemical equipment applications where high heat flux exothermic reactions must be carefully controlled to maintain process stability; and metallurgical processes where rapid but strictly controlled cooling of very hot products exiting mills or furnaces are often needed.

Internal, high-velocity subcooled flow boiling inside tubes and channels is substantially different from that occurring in low-velocity subcooled boiling due to changes in the flow regimes and heat transfer mechanisms. Although this topic has received increased attention during the past several years, very little is known about the characteristics and mechanisms which govern the heat transfer characteristics. Clearly, flow boiling will vary significantly with increases in the liquid velocity and subcooling, but some new and significantly different characteristics may result. Recently, evidence has surfaced which indicates that the traditional pool boiling curve can be dramatically altered by using a highly subcooled liquid, flowing at high velocities. The influence of these high velocities and subcooling is of only limited significance in the nucleate boiling regime because the intense bubble action is relatively insensitive to motion and liquid temperature. In contrast, however, the heat transfer mechanisms in the transition and film boiling regimes are controlled primarily by the convective phenomena in the over-riding liquid layer, hence flow velocity and subcooling could have a much larger impact.

Using a study of quenched spheres traversing through subcooled water, Stevens and Witte [1] have provided some preliminary indications of the dramatic enhancement in the film and transition regimes. In this investigation, a tenfold increase in the minimum heat flux was observed for sphere velocities of 1.52 m s^{-1}, as the water temperature was decreased from 77 to 24°C. At the same time, the corresponding critical heat flux (CHF) increased by only a factor of two. This would indicate that for sufficiently high subcooling and velocity levels the critical heat flux and minimum heat flux approach one another, essentially eliminating the unstable transition boiling region. The experiments conducted by Yilmaz and Westwater [2], Broussard and Westwater [3], Fukuyama and Hirata [4], and more recently by Sankaran and Witte [5, 6]

NOMENCLATURE

h_f	latent	T_s	saturation temperature
M	molecular weight	T_w	wall temperature
q_{max}	maximum film boiling heat flux	T_r	reduced temperature
q_{min}	minimum film boiling heat flux	T_{rs}	saturated reduced temperature
q''	heat flux	ΔT_{sub}	subcooling
q''_w	wall heat flux	u	liquid velocity.
R_m	universal gas constant		
T_c	critical temperature	Greek symbol	
T_l	liquid temperature	ρ_v	vapor density.

support this hypothesis. In addition, the experimental data of subcooled sodium with high velocity flow presented by Witte [7] and the investigation of Bradfield [8] also showed that there was no significant reduction in the heat transfer characteristics in what would seem to be the transition region of film boiling for high velocity subcooled liquid flow.

Peng and Wang [9] experimentally investigated the flow boiling of subcooled R11 flowing through a horizontal duct and obtained some preliminary results, however, only a limited number of tests were conducted. For the subcooled flow film boiling, the experiments, data, and theoretical analyses by Wang and coworkers [10–17] have shown that film boiling heat transfer is dominated by the hydrodynamic and thermodynamic characteristics of the liquid, and rarely by the wall temperature. This type of flow boiling is referred to as the 'auto model' region [18]. In a more recent investigation [19], a film boiling model was developed based on the kinetic theory of gases and the concept of a heat transfer limit was presented for use with high subcooling and high velocity film boiling. In this work, non-equiibrium film boiling which occurs beyond this limit was theoretically shown to be directly dependent upon the wall temperature.

Evidence resulting from these past investigations indicates that the liquid velocity and level of liquid subcooling can significantly alter the general shape and characteristics of the traditional flow boiling curve. All of these investigations have, however, focused on small local regions of the flow boiling curve or specific problems associated with a particular investigation. As a result, a fundamental investigation of the overall characteristics of the entire internal flow boiling curve was conducted to determine the effects of high liquid velocities and subcooling and so, to better understand the effects of these parameters on the flow boiling of liquid flowing in a horizontal duct.

EXPERIMENTAL TEST FACILITY

The experimental test facility utilized in this investigation is shown in Fig. 1, which consists of a shielded pump with a pressure head of 50 m of H_2O and maximum flow rate 10 $m^3\ h^{-1}$; a liquid tank with a volume 40 l; and a heat exchanger, flowmeter, and test section. This experimental test facility has been utilized in several previous investigations as described in refs. [12, 15]. The test section used in the current investigation consisted of a stainless steel duct with a rectangular cross section, 19.2 mm high, 11.1 mm wide, and 200 mm long. As shown in Fig. 2, the test section was installed horizontally and heated uniformly from the bottom using an external heater constructed from stainless steel sheet 0.5 mm thick. Power to the heater was supplied by a large current transformer and was controlled and adjusted by a heat flux controller specifically developed for this test facility [15]. The associated instrumentation allowed the input heat flux to be measured to within $\pm 0.5\%$. A more complete description of the power controller utilized in this investigation and the accuracy with which the power could be controlled and measured is contained in ref. [20].

The flow rate and velocity of the working fluid, R11, was measured and monitored using a turbo flowmeter, and provided liquid flow rate measurements with experimental uncertainty of ± 0.05 m s^{-1}. The temperature throughout the flow loop was monitored and measured by a series of chromel–alumel thermocouples installed at different points including the inlet, exit, and wall of test section.

The primary objective of this investigation was to evaluate and determine the effect of liquid subcooling and velocity on the characteristics of internal flow boiling curve. Of particular interest, was the effect of these parameters on the transition region from nucleate boiling to film boiling. For this region, flow boiling curves were obtained for different flow velocities and levels of liquid subcooling while carefully controlling the wall temperatures and input power.

EXPERIMENTAL RESULTS

Figure 3 illustrates the general shape and characteristics of the flow boiling curves obtained in this investigation for several different flow velocities and levels of liquid subcooling. As illustrated, in the nucleate boiling regime, variations in the liquid velocity and/or level of liquid subcooling result in virtually no distinct measurable difference in the general

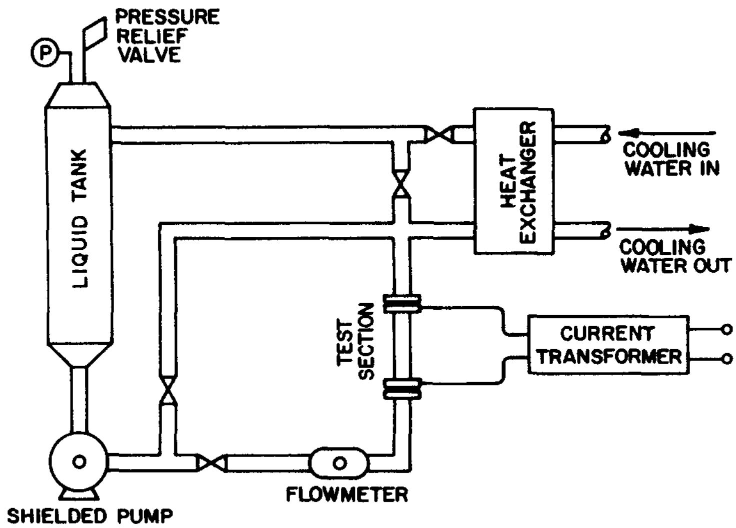

FIG. 1. Experimental test facility.

shape or characteristics. As shown, however, the location and magnitude of the critical heat flux (CHF) varies significantly for different conditions, increasing as both the liquid velocity and level of liquid subcooling increase. Also as shown, increasing the liquid velocity and level of liquid subcooling reduces the scope of the transition region, i.e. the regions BC, B′C′ and B″C″ shown in Fig. 3, until it eventually disappears, resulting in a smooth transition from nucleate boiling to film boiling with virtually no decrease in the wall heat flux. The experimental results of Fukuyama and Hirata [4] and Sankaran and Witte [6] shown in Figs. 4 and 5, respectively, demonstrate a similar trend but because of the limited amount of data in the region immediately beyond the critical heat flux it is difficult to determine precisely what is occurring.

The data we obtained in the current investigation (Fig. 3) indicate clearly that the film boiling regime can be subdivided into two regions. The first, the auto model region where the heat transfer is dominated by the hydrodynamic and thermodynamic parameters of the liquid, is essentially independent of the wall temperature, i.e. the regions CD, C′D′ and C″D″ in Fig. 3. In this region, increases in the liquid velocity and level of liquid subcooling, not only enhances the heat transfer but also widens the range of wall temperatures over which it occurs. In the non-auto model region shown as regions DE, D′E′ and D″E″ in Fig. 3, the heat transfer is clearly dependent upon the wall

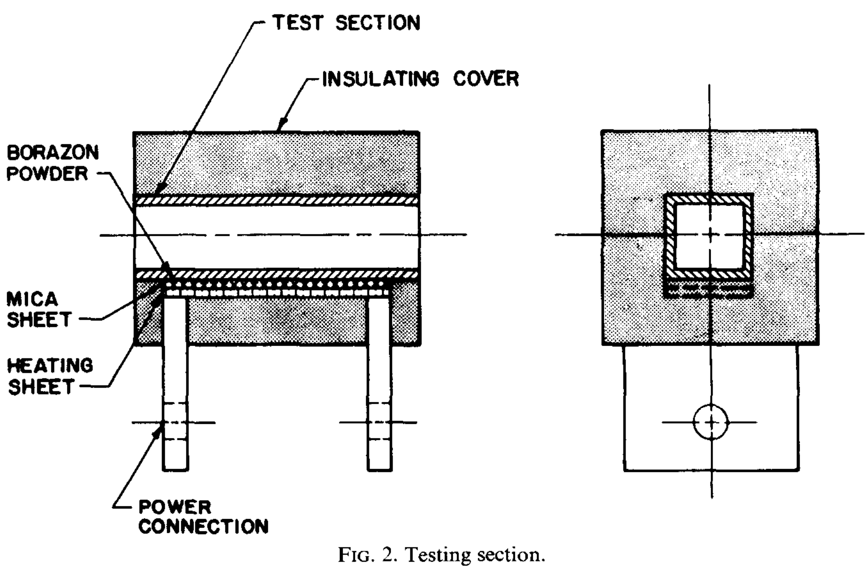

FIG. 2. Testing section.

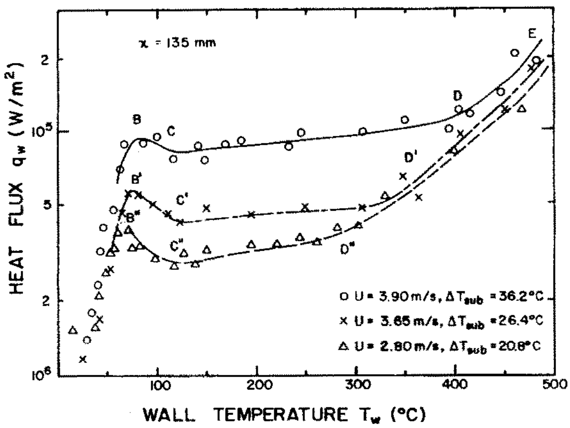

FIG. 3. Experimental results and comparison.

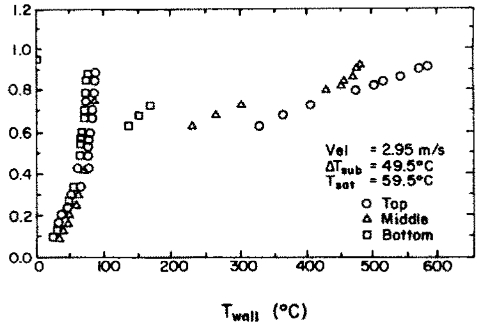

FIG. 5. Experimental results for external flow [6].

temperature and more closely resembles the behavior of the typical film boiling region. In this region, heat transfer is still enhanced by increases in the liquid velocity and level of liquid subcooling, but to a much smaller degree. Although not as distinct, the experimental data of Sankaran and Witte [6] shown in Fig. 5, indicate a similar change in slope at the division of the two film boiling regions.

Comparisons of the experimental data taken at different locations along the flow direction are illustrated in Figs. 6(a) and (b), for flow velocities of 3.65 and 3.90 m s^{-1}, respectively. As shown, the general shape of the flow boiling curves and precise values are similar and appear to be independent of the axial position. This may, however, be due to the small distance between the two test locations. It is believed that for a much longer test section, the characteristics and boiling curves occurring upstream would be somewhat different from those downstream, since some pressure drop and heating of the working fluid would occur as the fluid flows along the plate, decreasing the effective level of liquid subcooling. As mentioned previously, the level of liquid subcooling can significantly alter the critical heat flux value and transition and film boiling behavior.

Using the experimental results obtained in this investigation, a generalized subcooled flow boiling curve can be plotted as shown in Fig. 7. This generalized flow boiling curve exhibits several distinct characteristics; a nucleate boiling regime (AB), a critical heat flux (B), a transition boiling regime (BC), and two film boiling regions—the auto model region (region CD) and the non-auto model region (region DE). The principal differences between this curve and the traditional boiling curve are (i) the size of the transition boiling regime is reduced as the liquid velocity and level of liquid subcooling increase, (ii) the film boiling region expands as the liquid velocity and level of liquid subcooling increase, and (iii) two distinct regions exist in the flow film boiling regime. Although this explanation is supported by the experimental data obtained in the current investigation and also by the experimental data previously obtained by Fukuyama and Hirata [4] and Sankaran and Witte [6], additional experimental data and observations are necessary to further substantiate the shape and behavior of this generalized curve.

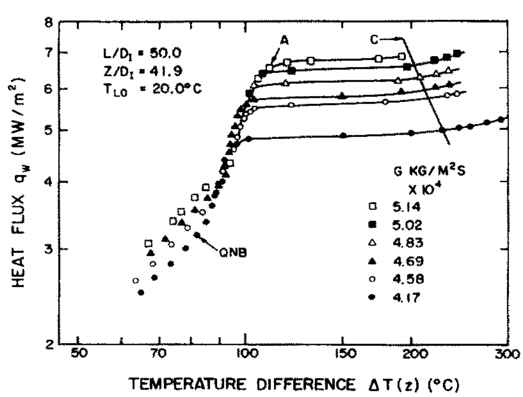

FIG. 4. Effect of mass flux on boiling curves [4].

DISCUSSION AND ANALYSIS OF RESULTS

When the liquid velocity and level of liquid subcooling become large enough, the experimental results presented in Fig. 3, indicate that the film boiling heat transfer rate in the auto model region approaches the critical heat flux. Peng and Wang [19] recently developed an analytical model using the kinetic theory of gases to predict the heat transfer limit for this case, i.e. the auto model region. The basic elements of this model are shown in Fig. 8 and can be summarized as follows.

(1) The flow can be divided into three regions; the liquid, interfacial and vapor regions.
(2) Because of the high liquid velocity and subcooling, the vapor film layer is so strongly suppressed that its thickness remains almost constant along the flow direction.
(3) The liquid velocity and level of liquid subcooling are high enough that the evaporation and condensation are completely controlled by molecular kinetic energy and independent of

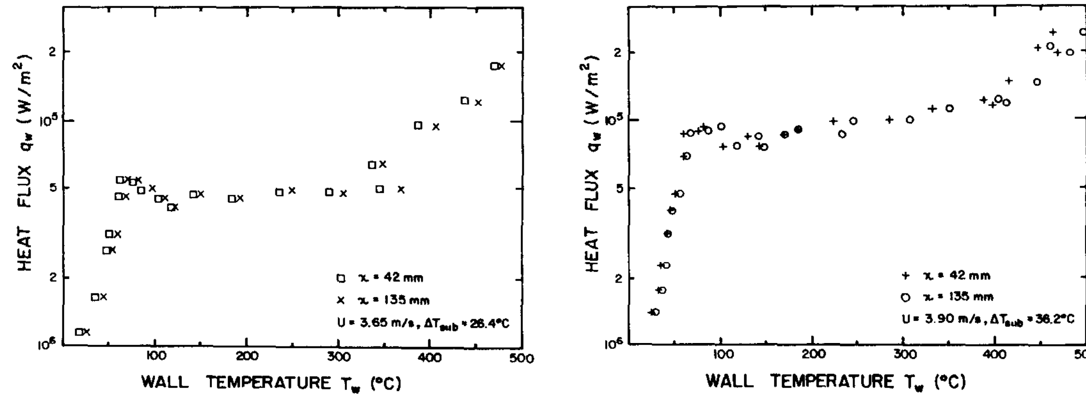

FIG. 6. Comparison of data taken at different locations.

the liquid velocity and level of liquid subcooling in the interfacial region.

(4) The temperature in the interfacial region is approximately equal to the saturation temperature.

Based on these fundamental considerations, the maximum heat transfer level for film boiling was found to be [19]

$$q_{\max} = 0.1\rho_v h_f\left(\frac{R_m}{M}T_c\right)^{1/2}(T_{rs})^{1/2} \quad (1)$$

where T_c is the critical temperature, T_s the saturation temperature, and T_{rs} the reduced saturation temperature and is equal to T_s/T_c.

From equation (1), it is clear that if the applied heat flux is higher than $q_{\max}$, the reduced temperature, T_{rs} must increase. As the critical temperature, T_c is a constant for a given fluid, then the saturation temperature, T_s, must increase, and since the saturation temperature, T_s, is fixed for a given pressure, the interfacial region will be at a temperature higher than the saturation temperature. When this occurs, the wall temperature will increase, increasing the heat flux from the wall to the interfacial region (i.e. across the vapor film). The result is that the film boiling in the interfacial region at the saturation temperature is in thermodynamic equilibrium and is therefore independent of the wall temperature. The film boiling occurring in the interfacial region where the temperature is higher than the saturation temperature is not in the thermodynamic equilibrium and is therefore dependent on the wall temperature. These two kinds of film boiling correspond to the experimental results presented in Fig. 3, i.e. the auto model region (CD) and the non-auto model region (DE).

In actuality, the film boiling heat transfer in the auto model region depends on the liquid velocity and subcooling and is somewhat less than the values predicted by equation (1). The results shown in Fig. 3 provide experimental evidence to support this. This implies that these two parameters suppress the molecular exchange of the liquid and vapor and therefore the heat transfer in the interfacial region. If equation (1) is used to predict the heat transfer in the auto model film boiling regions, some modifications should be introduced to account for these effects, i.e. equation (1) should be revised as

$$q_{\max} = 0.1\rho_v h_f\left(\frac{R_m}{M}T_c\right)^{1/2} T_{rs}^{1/2} f(u, \Delta T_{sub}) \quad (2)$$

where $f(u, \Delta T_{sub})$ is a modifying function included to account for the effect of liquid velocity and subcooling. Clearly this modifying function must be less than or equal to unity, i.e. $f(u, \Delta T_{sub}) \leqslant 1$. When either the liquid flow velocity or the level of liquid subcooling approach zero, i.e. $u \to 0$, $\Delta T_{sub} \to 0$, the condition approaches saturated pool boiling and $q_{\max}$ will be

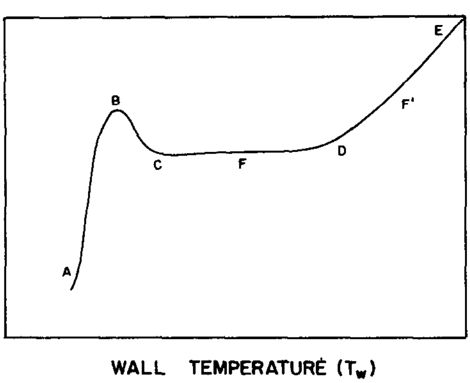

FIG. 7. Idealized flow boiling curve.

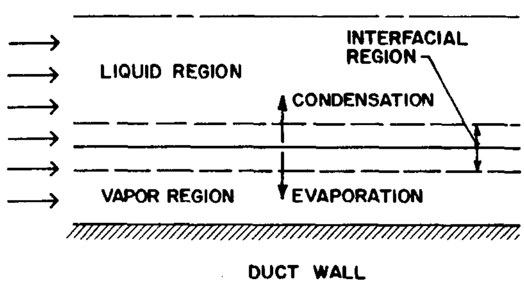

FIG. 8. Analytical model for film boiling.

equal to the minimum film boiling heat flux, resulting in the disappearance of the auto model film boiling region.

If the modifying function, $f(u, \Delta T_{sub})$ were known, the film boiling heat transfer in the auto model regime could be predicted. At the present time, insufficient experimental data are available and this function cannot yet be determined or estimated. It is apparent, however, that the modifying function is one which monotonically increases with u and ΔT_{sub}, and eventually approaches unity. In the non-auto model region, the film boiling heat transfer could also be calculated by using equation (1). In this region the interfacial temperature is, however, dependent upon the wall temperature and is higher than the saturation temperature. As a result, this technique could only be utilized when the interfacial temperature was known as a function of the wall temperature.

CONCLUSIONS

An experimental investigation was conducted to determine the characteristics of subcooled liquid flow boiling in a horizontal flat duct. Several flow boiling curves, extending from the nucleate regime through transition and into the film boiling regime were obtained. The experimental observations and results indicated that the transition region decreases in scope as the liquid velocity and level of liquid subcooling increase, eventually disappearing at the critical heat flux. The film boiling regime was divided into two distinct regions, an auto model region and a non-auto model region. In the auto model film boiling region, the heat transfer was found to be independent of the wall temperature and was governed by the thermodynamic and hydrodynamic characteristics of the flow. The auto model region of film boiling was found to decrease in scope as the liquid velocity and level of liquid subcooling decreased and finally disappeared as the heat flux approached the minimum film boiling heat flux.

A previously developed theoretical analysis was modified and expanded qualitatively to encompass the auto model film boiling region. This analysis provided an explanation of the causes and results of the two distinct regions observed in the experimental investigation and has established a foundation for further study of the phenomena surrounding this type of boiling.

As noted above, the work presented here is largely qualitative and requires further experimental and analytical work to clearly distinguish between the two types of flow film boiling. In particular, additional quantitative analyses are needed to determine the precise behavior in transition and film boiling regimes, and the effect due to the liquid velocity and the level of liquid subcooling.

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CARACTERISTIQUES D'EBULLITION EN FILM ET DE TRANSITION DES LIQUIDES SOUS-REFROIDIS S'ECOULANT A TRAVERS UN CANAL PLAT HORIZONTAL

Résumé—Une étude expérimentale est conduite pour observer et analyser l'ébullition d'un liquide sous-refroidi en écoulement à grande vitesse dans un canal horizontal plat. L'analyse des données expérimentales révèle plusieurs caractéristiques distinctes : d'abord la région sur laquelle l'ébullition de transition diminue de taille quand la vitesse du liquide et le sous-refroidissement du liquide augmentent ; de plus, deux régions bien distinctes sont apparentes dans le régime d'ébullition en film, une région d'auto-modèle et une autre de non auto-modèle. En outre, l'analyse théorique antérieurement développée est modifiée et étendue pour tenir compte de la région auto-modèle de l'ébullition en film. Cette analyse donne une explication des deux régions observées et elle fournit une base à d'autres études sur les phénomènes connexes à ce type d'ébullition.

DAS CHARAKTERISTISCHE VERHALTEN DES FILMSIEDENS UND DES ÜBERGANGSSIEDENS BEI UNTERKÜHLTER STRÖMUNG IN EINEM WAAGERECHTEN FLACHKANAL

Zusammenfassung—In einer experimentellen Untersuchung wurde das Strömungssieden einer unterkühlten Flüssigkeit in einem waagerechten Flachkanal bei hoher Geschwindigkeit beobachtet und analysiert. Die Auswertung ergab verschiedene ausgeprägte charakteristische Verhaltensweisen : (1) Die Ausdehnung des Gebiets mit Übergangssieden nimmt mit wachsender Flüssigkeitsgeschwindigkeit und mit wachsender Unterkühlung ab ; (2) im Gebiet des Filmsiedens lassen sich zwei Regionen unterscheiden : ein selbsterregtes Gebiet und ein nicht-selbsterregtes Gebiet. Außerdem wurde die früher entwickelte Theorie modifiziert und erweitert, um das selbsterregte Filmsieden zu berücksichtigen. Diese theoretische Analyse liefert eine Erklärung für die beobachteten zwei Gebiete und dient als Grundlage für weitere Untersuchungen dieser Siedephänomene.

ХАРАКТЕРИСТИКИ ПЛЕНОЧНОГО И ПЕРЕХОДНОГО КИПЕНИЯ ПРИ ТЕЧЕНИИ НЕДОГРЕТОЙ ЖИДКОСТИ В ГОРИЗОНТАЛЬНОМ ПЛОСКОМ КАНАЛЕ

Аннотация—Экспериментально исследовалось кипение при высокоскоростном течении недогретой жидкости в горизонтальном плоском канале. Анализ экспериментальных данных обнаружил некоторые особенности: во-первых, область переходного кипения уменьшалась в размере с ростом скорости жидкости и величины недогрева и, во-вторых, в режиме пленочного кипения отчетливо выделялись две области—автомодельная и неавтомодельная. Кроме того, ранее проведенный теоретический анализ был модифицирован и обобщен на случай учета автомодельной области пленочного кипения. Этот анализ дал объяснение обеим наблюдаемым областям и послужил основой для последующего исследования явлений, встречающихся при указанном виде кипения.