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FREE CONVECTION HEAT TRANSFER TO CARBON DIOXIDE NEAR THE CRITICAL POINT*

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Abstract—Free convection from a wire to CO_2 near its critical point was investigated experimentally. Three general types of flow patterns were observed: (1) the usual free convection flow, (2) a highly turbulent flow in which fluid aggregates similar to bubbles were seen to appear and disappear at the wire, and (3) an oscillating flow in which the usual free convection flow alternated with the "bubble-like" pattern. Strong changes in the slope of the curve of heat-transfer rate vs. wall temperature were observed when the flow pattern changed from the usual pattern to the oscillating type of flow. In experiments in which the wire was replaced by a vertical strip, no unusual flow patterns were noted. It was concluded that a "bubble-like" flow condition can occur in heat transfer to a fluid near the critical point. Such a flow, however, is dependent not only on the variation in fluid properties but also on the geometry of the heating surface.

INTRODUCTION

IN THE last decade more and more attention has been paid to the problem of heat transfer to fluids in the supercritical region near the critical point. The designation "critical point" refers here to the thermodynamic state specified by a pressure and temperature above which the substance can exist in only one phase and below which it can exist in two phases. The term supercritical refers to the one phase region. In the following this term will be used more specifically to denote that portion of the one phase region which is close to the critical point. The reason for the increasing interest in this problem has been the fact that in several modern applications heat is being transferred to fluids which are in the supercritical region. For example, the boilers of some modern high pressure power plants operate in this region and in several present day rocket engines heat is transferred to propellants (frequently cryogenic fluids) which are in the one phase region near the critical point. Furthermore, heat-transfer experiments to fluids in this region have shown that the heat-transfer coefficient is extremely dependent on the temperature and the temperature gradient and, in addition, flow oscillations and "singing noises" have been reported in some cases. These phenomena seemed to require more thorough understanding and this need has given rise to a number of analytical and experimental investigations.

SOME PREVIOUS INVESTIGATIONS

One of the earliest investigations pertinent to the proposed program is that by Dickinson and Welch [1]. These authors determined the heat-transfer coefficient for supercritical water flowing in circular tubes. The data showed that in the vicinity of the critical point the heat transfer coefficient would increase significantly, sometimes as much as 100 per cent. Similar results were obtained by Chalfant [2]. Stimulated by results of this nature Goldmann [3] developed an analytical approach for explaining the experimental results. He found it possible to obtain rather satisfactory agreement for some heat-transfer conditions, but noticed definite differences for other conditions. In the later case the flow was generally accompanied by "whistling" or "singing" noises. Goldmann hypothesized that a special and unusual

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"bubble-like" flow might exist in this region and might explain the deviation from theory as well as the "whistling" noises. In this bubble-like flow clusters of low density fluid were imagined to grow and collapse and to bring about additional agitation favorable to heat transfer. Some indications of such bubble-like flow were observed in an early exploratory experiment in this laboratory [4] and similar flow patterns were reported more recently by Graham *et al.* [5].

Important additional experimental work in heat transfer to the critical point was performed both in free convection and forced convection. Among the publications concerning free convection are those by Fritsch and Grosh [6], Eckert and Simon [7], Schmidt [8], and Bonilla and Sigel [9]. Experiments on forced convection include those by Wood and Smith [10], and Koppel [11]. Other analytical approaches were proposed by Deissler [12], Hsu and Smith [13], and Hess and Kunz [14].

The various analytical and experimental results and their interpretations have given rise to extensive discussion among the research workers in the field. In particular Goldmann's hypothesis as to the occurrence of bubble-like flow has formed a subject on which divergent views have been offered. On the basis of experiments in free convection from a small vertical plate, Fritsch and Grosh have concluded that no unusual flow patterns occur under these conditions. Their own experiments were conducted at very low rates of heat transfer, but they have pointed to the work of Holt [15] which also included relatively high heat-transfer rates to extend their conclusions to a large range of heat-transfer rates. Domin [16] as well as Swenson, Kakarala and Carver [17] have conducted experiments in forced convection. By a judicious choice of the temperature at which the fluid properties are to be evaluated, they were able to correlate their results by equations of the type applicable to ordinary forced convection. This led them to conclude that no unusual flow pattern such as a bubble-like flow is likely to exist. On the other hand there are the observations of Chalfant in which two modes of heat transfer seemed to have occurred, one of them associated with a whistling noise. Whistling noises were also noted by Hines and Wolf [18]. In addition very abrupt changes in heat-transfer coefficients have been observed and although these values have been successfully correlated in some instances, some investigators do not feel that this fact excludes conclusively the existence of unusual flow patterns. Their doubts are based on the fact that the fluid properties vary greatly between the wall and the bulk of the fluid, and by selecting the properties to correspond to one or the other state the correlation can be made to fit a wide range of data.

DESIGN OF EXPERIMENT

In view of the results as presented in the foregoing section, it was felt that definite doubts remained as to the existence of any unusual flow patterns in the heat transfer to supercritical fluids. The resolution of this question seemed important, not only for academic interest but also for practical reasons. If indeed any bubble-like activity should occur under certain conditions, this could have a significant effect on the heat transfer as well as on the friction drop and could in addition lead to pressure oscillations and mechanical vibrations. Information on the possible occurrence of such effects is believed to be a prerequisite for the successful design of heat-transfer equipment.

This then led to the selection of a suitable experimental approach for examining the flow pattern associated with various heat-transfer conditions in the region of the critical point. It seemed appropriate to limit the scope of the present experiments to free convection. The test equipment for this case was expected to be simpler and more flexible than that required for forced convection and still it was believed that it would be feasible to detect some of the special phenomena that might occur in the heat transfer to a fluid near the critical point. In order to obtain a good understanding of these phenomena it was decided to design the apparatus so as to allow for direct visual observation of the flow pattern. This method of investigation, although qualitative in nature, is a most effective one in a case like the present where the flow patterns are likely to be very complicated and where there is no clear *a priori* concept of their shape.

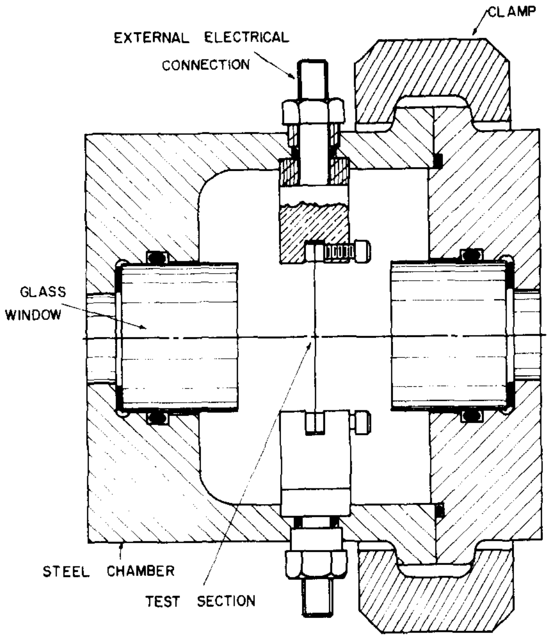

FIG. 1. Section through test chamber. Diameter of glass window 2·0 in; diameter of viewing port 1·2 in.

TEST INSTALLATION

The test apparatus consists of a pressure chamber (Fig. 1) with a cylindrical volume 4·5 inches in diameter and 3·0 inches in length. At each end of the cavity glass windows with a viewing area of 1·2 inches diameter are provided. The chamber is designed for a pressure of 1500 psi. The pressure in the chamber is controlled by means of a hydraulic accumulator operated on nitrogen gas. The heated wires or ribbons are held in clamps and stretched across the center of the cylindrical chamber. The entire chamber is located on an optical bench so as to allow shadowgraph illumination. The flow patterns can be projected on a screen for observation or recorded photographically. The temperature of the heating element is determined by measuring its change in electrical resistance which is accomplished by making the element itself part of a Wheatstone bridge circuit. The heat-transfer rate is determined from the electrical dissipation in the element and the temperature of the bulk fluid is measured by a thermocouple located 0·25 in below the element.

All wire and ribbon elements were selected for uniform smooth surface conditions. They were then degreased in a potassium hydroxide solution, rinsed in distilled water, annealed in a vacuum furnace, and finally cleaned in an ultrasonic alcohol bath. This procedure was found to be necessary in order to obtain reproducible results.

The test fluid was selected to be carbon dioxide

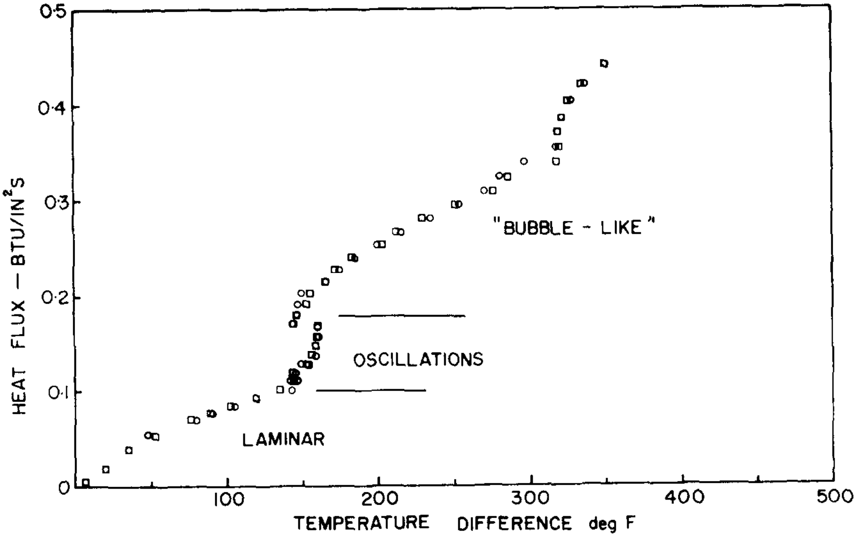

FIG. 2. Free convection from a horizontal wire (0·010 in dia., nichrome) to supercritical CO_2 (bulk pressure 1300 psia, bulk temperature 49°F). Data on the graph are from two separate tests.

as the critical state of this fluid corresponds to a temperature and pressure ($T_c = 87{\cdot}8\,^{\circ}\mathrm{F}$, $p_c = 1071$ psia) which can be obtained conveniently in the laboratory. In addition, the properties of carbon dioxide in the vicinity of the critical point are relatively well known. Furthermore, carbon dioxide has a fairly stable molecular structure and is not likely to decompose under the conditions of the present tests.

EXPERIMENTAL RESULTS

(a) *Horizontal wire*

The major portion of the experiments were conducted with a 0·010 inch diameter Nichrome

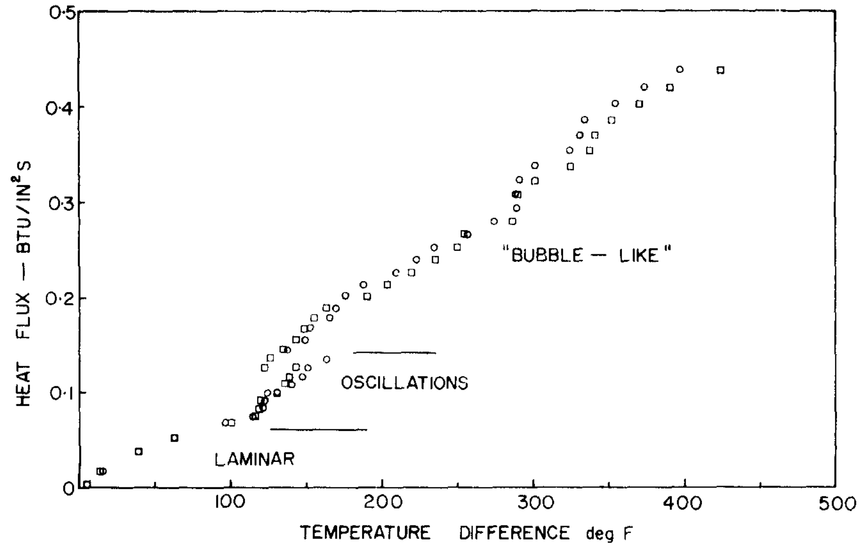

FIG. 3. Free convection from a horizontal wire (0·010 in dia., nichrome) to supercritical CO_2 (bulk pressure 1200 psia, bulk temperature 77°F). Data on graph are from two separate tests.

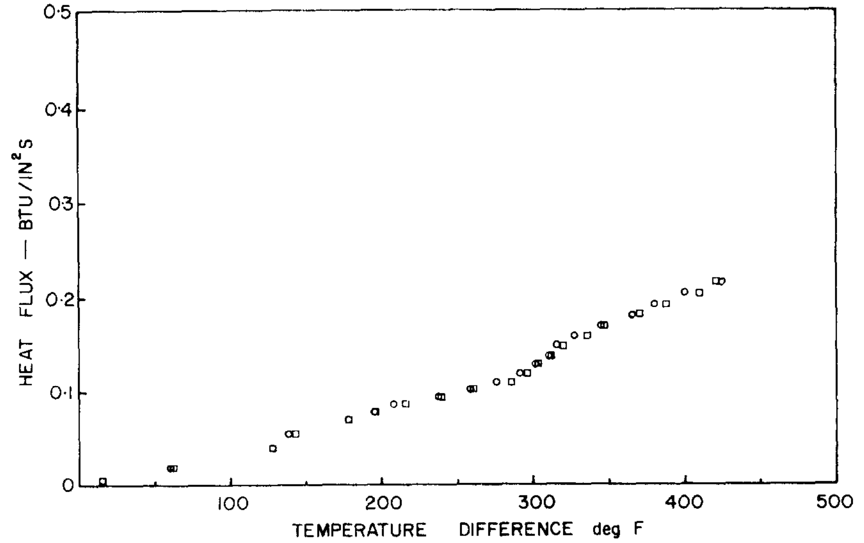

FIG. 4. Free convection from a horizontal wire (0·010 in dia., nichrome) to supercritical CO_2 (bulk pressure 1100 psia, bulk temperature 107°F). Data on graph are from two separate tests.

wire mounted in a horizontal position. Typical quantitative results of these experiments are presented as plots of heat flux versus the temperature difference between the wire and the bulk carbon dioxide (see Figs. 2–4). Shadowgraph images of typical flow patterns accompanying the heat transfer are shown as Figs. 5–9.

In the range of bulk state conditions used in this investigation (49–137°F, 1100–1500 psia), the results of experiments conducted in supercritical carbon dioxide were found to be similar whenever the bulk temperature of the carbon dioxide is below the level at which strong property changes occur. As shown in the quantitative results and photographs taken at wire surface temperatures up to a maximum of about 200°F, laminar flow is present at the wire and for some distance above the wire (see Fig. 5). In this laminar flow region, the slope of the heat flux versus temperature difference curve decreases with increasing heat flux. It should be noted that the maximum temperature differences observed coincident with laminar flow correspond to wire surface temperatures which are approximately 100 degF above the critical temperature. Maximum heat fluxes occurring with laminar flow depend upon the bulk state conditions, and range from 0·060 to 0·120 Btu/in^2 s.

At slightly higher heat fluxes and corresponding temperature differences, laminar flow is replaced by an unusual flow condition in which the flow oscillates with an irregular periodicity between two distinct flow patterns. The average frequency of this fluctuation varies between 20–250 c/min, depending on the bulk state conditions and the average heat flux through the wire surface. As shown in Fig. 6, one of these two flow patterns appears to be the same as the laminar flow pattern occurring at lower heat fluxes. The other of these two flow patterns, shown in Fig. 7, appears to be identical to a bubble-like flow pattern observed at higher heat fluxes. Variation of the wire temperature accompanies the oscillating flow patterns, as indicated by the instruments used to measure the wire temperature. For this oscillating flow condition, data corresponding to the average wire temperature have been recorded and the quantitative results show a rapid increase in the heat flux for very small variations in the temperature difference. This oscillating flow is observed for heat flux values ranging from 0·040 to 0·080 Btu/in^2 s above the maximum heat fluxes where laminar flow occurs alone. The frequency of the oscillation is, incidentally, influenced by the wire size and decreases with increasing diameter.

With an additional increase in the heat flux, the oscillating flow condition is replaced by a single flow pattern (see Figs. 8 and 9), visually identified by characteristic bubble-like forms along the underside of the wire and by a turbulent flow rising above the wire. This latter flow obscures further observation of flow conditions at the top of the wire. Although less distinct than the bubbles of nucleate boiling at subcritical pressures, the pockets of low-density fluid along the underside of the wire appear to fluctuate in size and position. High-speed motion pictures (approximately 2500 frames per min) taken of this unsteady flow condition show that the lack of distinct interfaces at the edges of these bubble-like forms makes it difficult to identify single "bubbles" and to study their behavior with time. The dimensions of these bubble-like forms are two to three times larger than those of the nucleate bubbles observed at subcritical pressures.

The changes in flow types are generally associated with changes in the slope in the curve of heat transfer vs. temperature difference. For several test conditions a sharp improvement in the heat-transfer coefficient accompanied the onset of the oscillating or bubble-like flow (see e.g. Fig. 2). For large temperature difference the slope would again gradually decrease.

Several experiments have also been carried out at bulk temperatures above the transposed critical temperature; i.e. above the temperature at which strong property changes occur (see Fig. 4). In each of these cases, laminar flow exists only at heat fluxes below 0·040 Btu/in^2 s and the relationship between heat flux and temperature difference for laminar flow is approximately linear. These heat-transfer conditions correspond more nearly to free convection of heat to a gas, with fluid property changes between the wall and bulk state conditions which are much less pronounced than those changes occurring in the previously discussed experiments at lower bulk temperatures. The results from the present experiment in which all temperatures were above the transposed critical temperature, differ somewhat from the previous one mainly as to the magnitude of the quantitative data: the heat-transfer rates associated with any particular temperature difference are only about half those recorded for the denser bulk state conditions. In addition, the oscillating flow does not appear. The laminar flow region is limited to a smaller range of heat flux and, above this range, it is replaced by flow conditions which may still be described as bubble-like, but the forms on the wire are less distinct than the bubble-like shapes discussed previously. These bubble-like forms develop gradually after transition to turbulent flow has already occurred in the boundary-layer flow on the wire, and they are not accompanied by an immediate increase in the heat-transfer rate. Although there was much less evidence of bubble-like motion, occasional short steep segments occur in the heat-transfer curves. These small discontinuities were sometimes accompanied by audible sounds, which may correspond to the "whistling" noted by previous investigators.

(b) *Flat strip*

To further investigate the effects of geometry on the free convection flow patterns and heat transfer in the supercritical region, a Chromax strip with a width of 0·125 inch and a thickness of 0·001 inch was prepared and installed in the test section. Tests were conducted at 1200 psia and 77·0°F, with the strip mounted in two different horizontal positions. In one test, the strip was placed with its broad side horizontal; in the other two tests, the strip was placed with its broad side vertical, thus forming a short 0·125 inch high wall.

As might be expected, the visual patterns in both of these strip orientations do not give a clear picture of the actual flow conditions at the surface of the strip. In the horizontal configuration considerable unsteady motion occurs on the top side of the strip and, except at high heat fluxes, steady flow occurs on the underside of the strip. At high heat fluxes, the flow appears to be similar to that observed on the underside of the round wire at supercritical pressures when the bulk temperature exceeds the critical temperature. With the strip mounted in the vertical position, the shadowgraph images show only that, in the wake above the strip, the distance between the point at which the flow becomes turbulent and the top of the strip diminishes as the heat flux is increased until the flow in the entire visible wake appears to be turbulent. No bubble-like forms were observed for any of the experimental conditions, even though the experiments included conditions under which the horizontal wire exhibited this phenomenon.

The quantitative results of experiments conducted with both positions of the strip are almost identical, with the horizontal-position experimental results showing a slightly lower temperature difference at any given heat flux. The experimental results for both configurations indicate a steady increase in the temperature difference between the surface temperature of the strip and the bulk fluid temperature with increasing heat-flux rates without any sharp changes in the slope of the heat-transfer curve.

The quantitative heat-transfer results obtained with laminar flow conditions occurring on the strips up to temperature differences of 150 degF are similar to the results obtained with the horizontal wire. However, laminar flow on the strips persists to much higher temperature differences and, after a temperature difference of 150 degF, the relationship between heat flux and temperature difference is nearly linear. Typical quantitative results of these tests are shown in Fig. 10.

DISCUSSION OF EXPERIMENTAL RESULTS

(a) *Laminar flow region*

The experimental results from this investigation indicate that, whenever laminar flow exists, the plot of heat flux vs. temperature difference shows negative curvature. The experimental heat-transfer curve exhibits this negative curvature for both the wire and the strip in either of its two positions.

Similar experimental results were obtained by Fritsch and Grosh [6] in experiments conducted on laminar free convection of heat from a 0·50 inch vertical wall to supercritical water. Fritsch and Grosh used a numerical integration

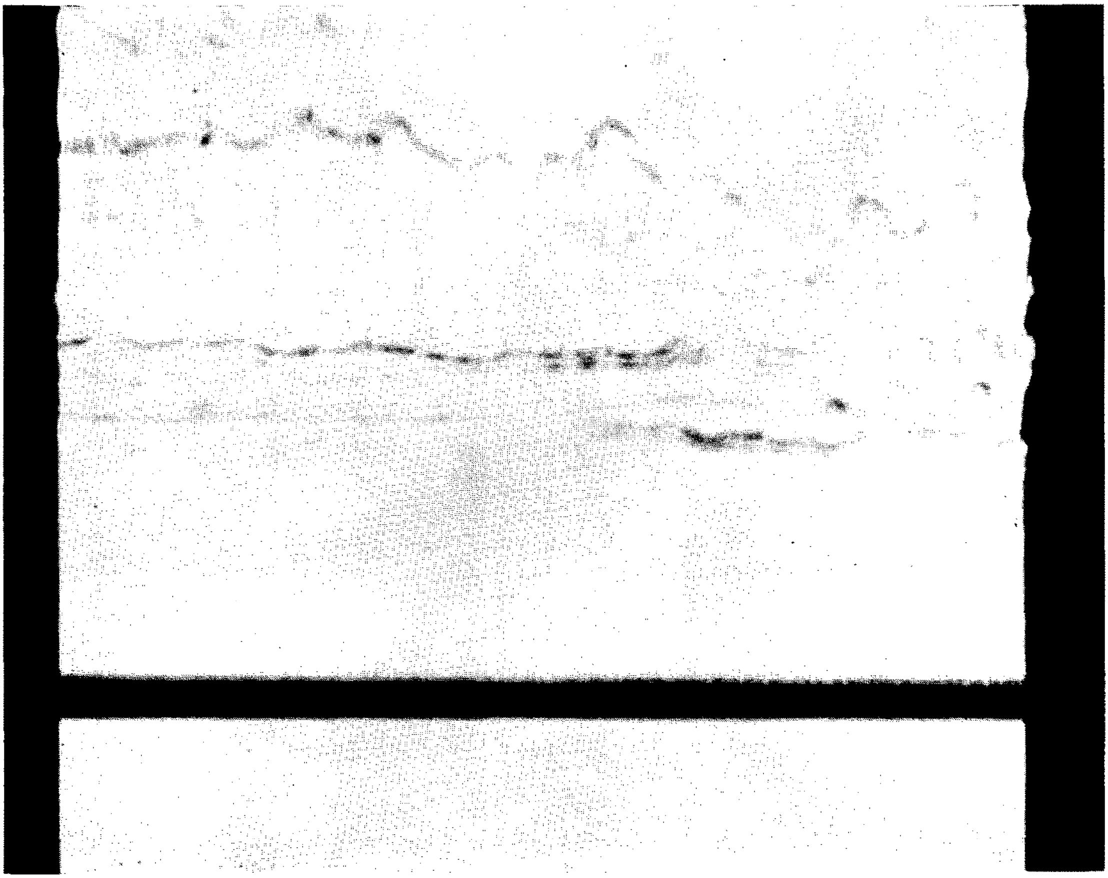

FIG. 5. Laminar flow up to some distance above the wire. Heat-transfer rate 0·10 Btu/in^2 s, pressure 1300 psia, bulk temperature 49°F, temperature difference 49 degF.

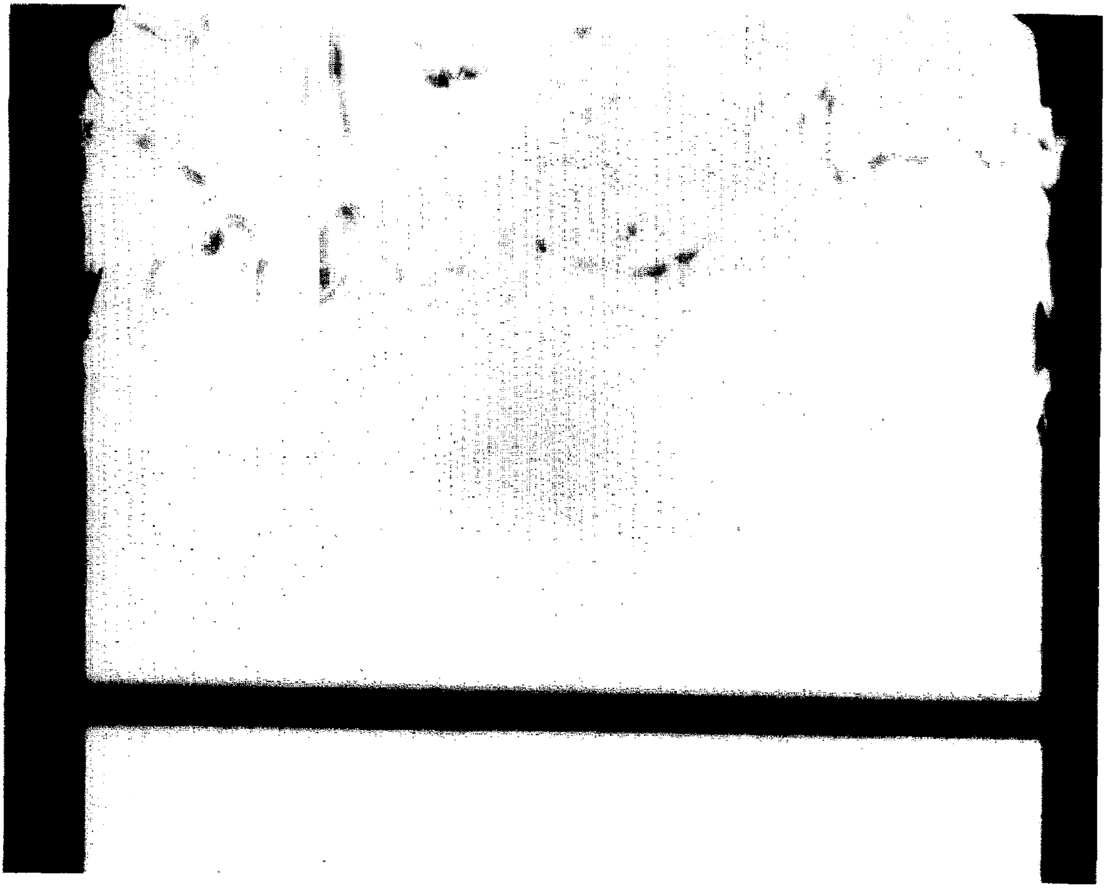

FIG. 6. Laminar flow pattern occurring during part of the cycle of the oscillating flow. Heat-transfer rate 0·15 Btu/in^2 s, bulk pressure 1300 psia, bulk temperature 49°F, temperature difference 159 degF.

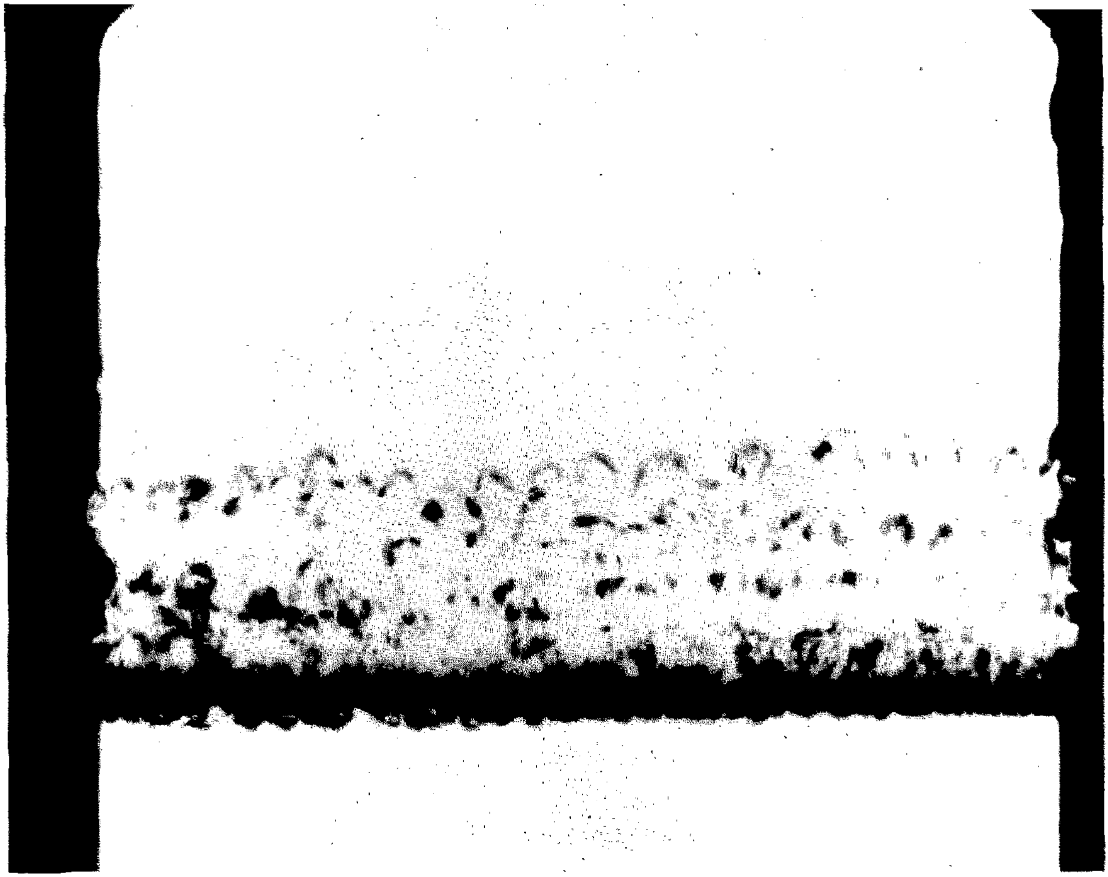

FIG. 7. Bubble-like flow pattern occurring during part of the cycle of the oscillating flow. Conditions same as for Fig. 6.

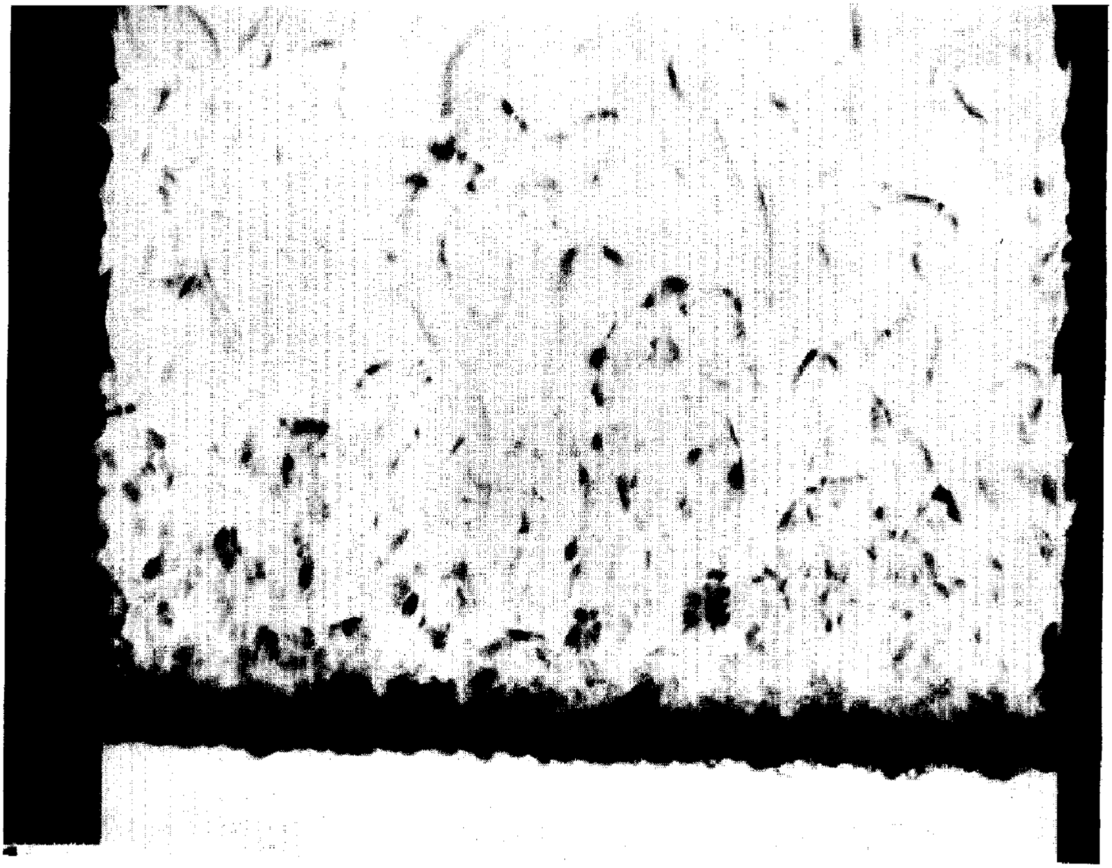

FIG. 8. Bubble-like flow. Heat-transfer rate 0·30 Btu/in^2 s, bulk pressure 1300 psia, bulk temperature 49°F, temperature difference 260 degF.

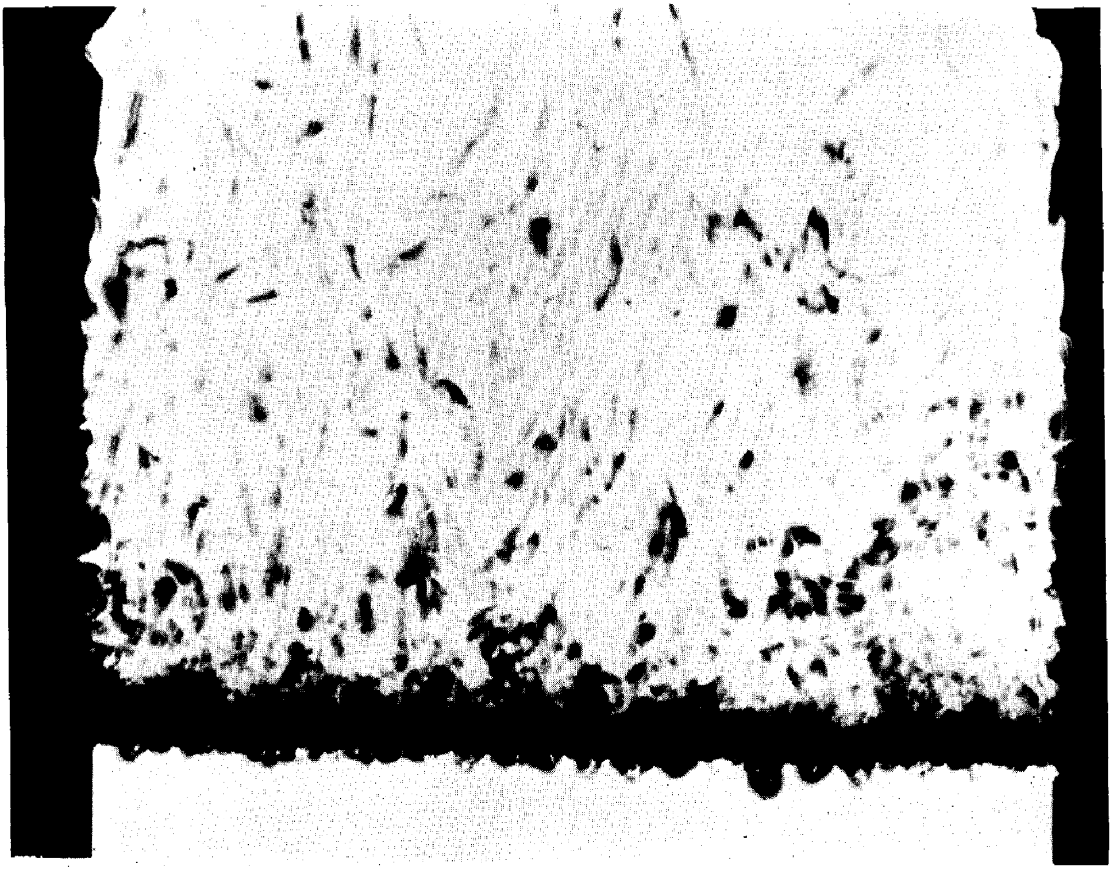

FIG. 9. Bubble-like flow. Heat-transfer rate 0·40 Btu/in^2 s, bulk pressure 1300 psia, bulk temperature 49°F, temperature difference 325 degF.

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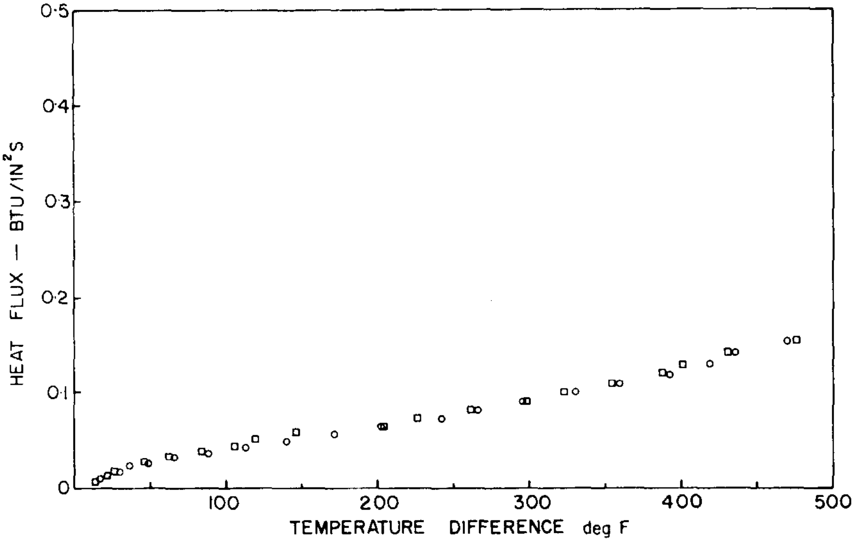

FIG. 10. Free convection from a short vertical wall (0·25 in high nichrome ribbon) to supercritical CO_2 (bulk pressure 1200 psia, bulk temperature 77°F). Data on graph from two separate tests

technique to solve the steady free convection boundary-layer equations for these flow conditions. Their solution, which takes into account density and specific heat variation in relation to temperature and employs a reference temperature in order to evaluate viscosity and thermal conductivity, yields analytical results which agree closely with their experimental results.

Therefore, in laminar flow it appears that free convection heat transfer can be adequately explained in terms of the usual boundary-layer equations for steady flow in a gravitational field. The difficulty in analytically predicting heat-transfer results for free convection laminar flow in a supercritical fluid then depends entirely on complications encountered in solving these differential equations for temperature-dependent fluid properties. The possibility remains, however, that stability limits of the laminar flow are affected by the fluid property variations and that these limits may differ, therefore, from the usual ones.

(b) *Bubble-like flow region*

The results in the bubble-like region may be roughly grouped into two sets. For the first the bulk temperature of the fluid is below the critical temperature and the wall temperature is sufficiently high so that the range in which most of the property changes occur is included between the two temperatures. The temperature differential may then be said to "span" the range in which the largest changes occur. The second set of results involves those in which the bulk temperature as well as the wall temperature are above the critical temperature. In both cases bubble-like flow patterns have been observed on the undersides of horizontal wires of three different diameters. These flow patterns appear to be the same as those patterns observed by Griffith and Sabersky [4] which occur on a horizontal wire heated in supercritical Freon 114A as well as more recently by Graham *et al.* [19].

When the temperature differential "spans" the region of strongest property changes, however, bubble-like flow is preceded by an oscillating flow condition in each of the tests with horizontal wires. In these cases also, bubble-like flow is accompanied by a significant improvement in heat transfer compared with that occurring with laminar flow. Plots made of several tests show that the first portion of the heat-transfer curve for the bubble-like flow is sometimes very steep (see Fig. 2) and resembles a nucleate boiling curve. The remainder of the heat-flux curve for this flow condition exhibits less slope and indicates that a nearly linear relationship exists between heat-flux rate and temperature difference. This latter curve resembles curves plotted from data on film boiling at subcritical pressures, although the flow patterns in the bubble-like case are dissimilar to those observed in the film boiling region. When, on the other hand, all temperatures are above the region of strong property changes, the bubble-like flow patterns are not preceded by the oscillating flow condition and the effects of the bubble-like flow on the heat-transfer process are not as pronounced.

Again it should be emphasized that bubble-like flow was observed in the experiments with the horizontal wire but that no bubble-like flow was observed in experiments using the Chromax strip. The experiments with the strip also did not show any sharp changes in the slope of the heat transfer curve.

(c) *Nature and occurrence of bubble-like flow*

One may conclude that the occurrence of the bubble-like flow patterns depends upon the fluid property changes, the heat-flux rate, the geometry of the heat-transfer surface, and the orientation of the surface in the gravitational field. Once the bubble-like flow is established, its effect upon heat transfer seems to depend on the magnitude of the changes in the fluid property values between those properties at the heat-transfer surface and those at the bulk state conditions of the fluid.

Having described the principal observations, one may next wish to speculate on the origin of the bubble-like flow. In this regard it appears that the unusual bubble-like flow condition results from a hydrodynamic instability. This instability would be one occurring in the laminar flow field under the combined effects of gravity and large property changes, which in turn are due to the temperature gradients of the heat transfer. The occurrence of bubble-like forms might be expected to result in an agitation of the fluid next to the wire surface, such as is caused in subcritical boiling by the growth and collapse of nucleate bubbles. The heat-transfer rates which accompany the bubble-like flow cannot be explained by the usual boundary-layer equations, and one may conclude that sufficient agitation is caused by the bubble-like flow to account for the improvement in heat transfer.

It should be pointed out that the bubble-like flow observed in this investigation, with its particular dependence on geometry and gravity, does not appear to be as general a phenomenon as nucleate boiling. The latter depends primarily on the state condition of the fluid and occurs with any geometry and flow and with or without gravity. The same statement applies to a comparison of bubble-like flow with the usual type of turbulent flow. For this reason, if bubble-like flow of some kind does occur in the heat transfer to a supercritical fluid for one certain set of conditions (either in free- or forced-convection) it should not necessarily be expected to occur in all cases. This dependence of bubble-like flow on geometry and gravity might explain the differences between the experimental results obtained by various investigators. This dependence may also explain why these results and their interpretations have been susceptible to differing opinions on whether or not heat transfer to supercritical fluids could be adequately explained without postulating unusual flow patterns.

(d) *Comparison to nucleate boiling*

The experimental results of this investigation indicate that there are both similarities and significant differences between heat transfer with bubble-like flow in supercritical fluids and heat transfer with nucleate boiling in liquids at subcritical pressures. For example, the results show that the boundaries of the pockets observed in the bubble-like flow are less distinct than those of nucleate bubbles, which exhibit a sharp physical division between the vapor and liquid phases. On the other hand, the distinguishability of the bubble-like forms indicates that there are steep density gradients associated with the boundaries of the low-density regions.

Among the more basic differences is the fact that the temperature distribution in the immediate vicinity of a nucleate boiling bubble must differ from the temperature distribution in the vicinity of any bubble-like form in a supercritical fluid. The lack of surface tension leads to the absence of superheating of the surrounding fluid. As a consequence the growth of the low density regions and the heat-transfer conditions existing in the supercritical bubble-like flow should be fundamentally different from those associated with nucleate boiling. High-speed motion pictures of the bubble-like flow tend to confirm such a view and there appears to be less agitation of the fluid near the heat-transfer surface with the bubble-like flow than with nucleate boiling. "Agitation" is here assumed to be related to bubble motion and, when these motion pictures are projected at normal speeds, the frequencies and velocities of the bubble-like flow appear to be lower than those expected for nucleate bubbles. This lesser agitation is believed to explain why the bubble-like flow observed at supercritical pressures is generally less effective as a heat-transfer process than nucleate boiling at subcritical pressures.

There are, however, also further definite similarities to nucleate boiling. In addition to a visual similarity, the first part of the bubble-like flow also behaves like nucleate boiling in another respect: both exhibit a considerable increase in the heat-transfer rate compared with laminar flow at the same temperature difference; in some cases the beginning portion of the heat-transfer curve for bubble-like flow is very steep. However, whereas in free convection nucleate boiling this increase would be expected to start at a surface temperature within a few degrees of the saturation temperature, the surface temperature associated with the onset of bubble-like flow is approximately 100 degF above the critical temperature.

(e) *Oscillating flow conditions*

One unusual result of this investigation is the observation of distinct oscillations between two different flow patterns. These oscillations occur in a definite range of heat-flux values for free convection from a horizontal wire in a supercritical fluid under conditions of strong property changes. Through visual observation of shadowgraph images, high-speed motion pictures, and photographs of this phenomenon, it can be seen that the flow oscillated between steady laminar flow and unsteady bubble-like flow. This oscillation is accompanied by corresponding variations in the test section temperature.

Temperature data recorded for this flow condition indicate the average wire temperature for the oscillating flow cycle. It appears that, at a particular condition in the laminar region, the increase of heat flux and surface temperature results in an instability of the steady flow which subsequently develops into the bubble-like flow. Presumably at this point the heat-transfer mechanism of bubble-like flow is so much more effective than that of laminar flow that the test section temperature quickly drops to a level at which the bubble-like density pockets collapse and the flow again becomes laminar until the temperature increases to the level where the oscillating flow cycle repeats itself.

An interesting observation regarding oscillating flow is the implied absence of a single flow condition capable of steadily transferring heat from the wire over a finite range of heat-flux rates. Presumably this absence is the result of a laminar flow instability developing directly into the bubble-like flow which, in turn, requires a higher heat flux to be maintained continuously. The required heat-flux value apparently is not obtained until the heat flux is near the higher levels of heat flux associated with oscillating flow.

CONCLUSIONS

On the basis of the experimental results, and the interpretations made in the course of this investigation, the following conclusions may be made: (1) A bubble-like flow condition, unlike the flow expected in a fluid with constant property values, does occur with free convection heat transfer to a supercritical fluid. (2) This flow condition is believed to be the result of a hydrodynamic instability in the preceding laminar flow structure. (3) The occurrence of the bubble-like flow depends on the changes in fluid properties and on the shape as well as the orientation of the heating surface. (4) The bubble-like flow condition can have a strong effect on the heat-transfer process when large changes in the property values are present. (For more detailed information on the test equipment as well as on the experimental results the reader is referred to reference [20].)

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Résumé—La convection naturelle à partir d'un fil dans du CO_2 près du point critique a été étudiée expérimentalement. Trois types généraux de configurations d'écoulement ont été observées: (1) l'écoulement habituel de la convection naturelle, (2) un écoulement très turbulent dans lequel on voit des aggrégats de fluide semblables à des bulles apparaître et disparaître sur le fil, et (3) un écoulement oscillatoire dans lequel l'écoulement habituel de convection naturelle alterne avec la configuration de "bulles". Des changements importants de la pente de la courbe du flux de chaleur en fonction de la température pariétale ont été observés lorsque la configuration de l'écoulement est passée de la configuration habituelle au type oscillatoire d'écoulement. Dans les expériences dans lesquelles le fil a été remplacé par un ruban vertical, aucune configuration inhabituelle d'écoulement n'a été remarquée. On a conclu qu'un écoulement sous forme de "bulles" peut se produire dans le transport de chaleur à un fluide près du point critique. Un tel écoulement, cependant, dépend non seulement de la variation des propriétés du fluide, mais également de la géométrie de la surface chauffante.

Zusammenfassung—Die freie Konvention von einem Draht in CO_2 nahe dem kritischen Punkt wurde experimentell untersucht. Dabei wurden drei allgemeine Arten von Strömungsformen beobachtet: (1) die gewöhnliche freie Konvektionsströmung, (2) eine stark turbulente Strömung in der blasenähnliche Flüssigkeitsballen am Draht erscheinen und verschwinden und (3) eine oszillierende Strömung in der gewöhnliche freie Konvektion mit blasenähnlicher Strömung abwechselt. Starke Änderungen im Kurvenverlauf des Wärmeübergangs in Abhängigkeit von der Wandtemperatur zeigten sich beim

Übergang der Strömung von der gewöhnlichen zur oszillierenden Art. In Versuchen in welchen der Draht von einem senkrechten Streifen ersetzt wurde, konnten keine ungewöhnlichen Strömungsmuster bemerkt werden. Es wird gefolgert, dass "blasenähnliche" Strömungsbedingungen beim Wärmeübergang an eine Füssigkeit nahe dem kritischen Punkt auftreten können. Eine derartige Strömungsform hängt jedoch nicht allein von der Änderung der Stoffwerte ab sondern auch von der Geometrie der Heizfläche.

Аннотация—Экспериментально исследовался теплообмен между проволокой и CO_2 вблизи критической точки при свободной конвекции. Наблюдались три общих типа картин течения: (1) Обычное свободно конвективное течение; (2) сильно турбулентное течение, при котором было видно, как агрегаты жидкости, подобные пузырькам, появлялись и исчезали на проволоке и (3) осциллирующее течение, при котором картина обычного свободно-конвективного течения изменялась подобно «пузырьковому» течению. Сильные изменения в наклоне кривой зависимости скорости теплообмена от температуры стенки наблюдасиь при изменении картины течения от обычной до осциллирующей. В тех экспериментах, в которых проволока была заменена вертикальной полоской, не наблюдалось необычных картин течения. Был сделан вывод, что течение, подобное «пузырьковому», может иметь место при переносе тепла к жидкости вблизи критической точки. Однако, такое течение зависит не только от изменения характеристик жидкости, но также от геометрии поверхонсти нагрева.