Int. J. Heat Mass Transfer. Vol. 10, pp. 1499–1508. Pergamon Press Ltd. 1967. Printed in Great Britain

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

ROLF H. SABERSKY† and EDWARD G. HAUPTMANN‡

(*Received* 6 *September* 1966 *and in revised form* 14 *March* 1967)

Abstract—Experimental results are presented for forced convective heat transfer from a flat plate in carbon dioxide near the thermodynamic critical point. State conditions were varied throughout the critical region, but most tests were conducted in the single phase (supercritical) state. One of the principal objectives was direct visual observation of the heated flow field, and high speed movie films were taken using a color Schlieren apparatus. A few exploratory hot wire measurements of velocity fluctuations near the plate were also made.

Although the experimentally determined heat-transfer coefficient became large whenever the plate temperature approached the pseudocritical, no significant change in the gross nature of the flow field could be observed. In particular no "bubble-like" phenomena could be detected such as has been observed in free convection with other heater geometries. The high heat-transfer coefficients were accordingly ascribed to the large values of thermodynamic and transport properties occurring near the critical point as well as to more minor modifications of the turbulent motion.

INTRODUCTION

NEAR the critical state, very large changes in thermodynamic and transport properties of a fluid can occur with only slight changes in fluid temperature and pressure. Accurate prediction of heat-transfer characteristics of such fluids thus becomes a complicated if not impossible procedure.

The critical point itself may be defined as the pressure and temperature at which no distinction between the liquid and vapor phase of the fluid can be made. In what follows, the term "supercritical" is used to denote the region in which the fluid pressure is just slightly above the critical value. Another concept to which reference will be made is the *pseudocritical temperature.* This quantity is defined as the temperature at which the thermodynamic and transport properties have their maximum rate of change with temperature at constant pressure. Its significance is that below the pseudocritical temperature, the fluid has liquid-like properties while above, it more closely resembles a vapor.

Because of the need for information on heat-transfer coefficients in such applications as liquid fuel regenerative rocket engines, high pressure steam generators, and internally cooled gas turbine blades, many experiments have been conducted over the past few years to secure the required data. In some of these investigations, unusual behavior of the experimental equipment and erratic heat-transfer results were observed [1–5]. Other experimenters noted large pressure and flow oscillations [6–9], as well as intense noise generation in the experimental apparatus [10–12]. Several theoretical investigations attempted to incorporate the large property variations occurring in supercritical fluids into the usual equations governing shear stress and heat transfer, and thereby predict heat-transfer results. When the bulk states considered were sufficiently far removed from the critical, or when heat-transfer rates were low, reasonably good agreement could be obtained [13–17]. However, many experimental results

* This paper is based on work carried out under NSF Grant 14071, sponsored by the National Science Foundation.

† Professor, California Institute of Technology.
‡ Assistant Professor, University of British Columbia.

for fluids near the critical state show wide discrepancies from the predicted performance. These discrepancies, in addition to the unusual behavior of experimental apparatus, have led some observers to suggest that the basic mechanism of heat transfer to supercritical fluids might be different than that to a single phase fluid far removed from the critical point.

In one hypothesis [18] of this kind it is postulated that the fluid adjacent to a very hot surface could have overall properties much like a vapor, while the relatively cool freestream fluid would be more like a liquid, and that the ensuing motion resemble nucleate boiling. Support for such a concept may be derived from a recent experimental study of free convective heat transfer from a horizontal cylinder in supercritical CO_2 [19]. The results of these experiments showed that under certain conditions of heat flux and bulk properties, the basic nature of the heated flow field could abruptly change to an unusual "bubble-like" flow with an attendant sharp increase in heat-transfer rate.

The purpose of the present investigation was the study of forced convection heat transfer to supercritical fluids, the primary objective being to determine if unusual transfer conditions also existed in this case. It was felt that direct visual observation of the heated surface, in a manner similar to reference [19], would be of assistance in identifying such a mechanism. These visual observations, along with limited measurements of heat transfer, would admittedly have little value for the quantitative prediction of supercritical heat-transfer rates. However, it was hoped they would aid in the selection of realistic models of the heat-transfer mechanism to be used in future theoretical studies. To aid in the interpretation of the visual observations, a hot wire probe was inserted in the flow near the heated surface and records were made of the fluctuations in wire current.

A detailed description of this investigation, in addition to a review of other pertinent studies in supercritical fluids may be found in [20].

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows a schematic diagram of the forced circulation loop used in this investigation. The heated flat plate is located at mid-height in a glass-walled rectangular channel 2-in high and 1-in wide, with the plane of the heated surface horizontal. The rectangular channel itself is located inside a 4-ft long horizontal cylindrical vessel 3 in. in diameter, having two glass viewing ports as shown in Fig. 2. The rectangular channel may be moved within the vessel so that the entire 1-ft length of heated plate surface is visible. The test fluid flows into the cylindrical vessel at a low speed (about 0·1 ft/s) and passes through a contracting transition section, entering the rectangular test channel and passing over the flat plate. An optical bench was located with its axis normal to the flow direction and parallel to the surface of the heated flat plate. The bench was used for a color Schlieren system, with a scheme of multiple point source and matching cutoffs specially adapted for sharp focusing effects, following ideas outlined in [21]. Flow fields were recorded with a Fastex 16 mm movie camera having a terminal speed of 8000 pictures per second.

The flat plate is made of $\frac{1}{8}$-in thick Pyrex glass with a thin electrically conducting film fired on to one surface. An electrical current was dissipated in the thin film and the heat transmitted to the fluid. A sharp-edge metal nose was fitted to the leading edge, and positioned so that no flow separation occurred on the heated side. Plate surface temperatures were measured with thermocouples located in 0·025-in diameter holes drilled through the plate and inserted flush with the heated surface. The thermocouples were cemented into position, the upper portion of the drilled hole being filled with cement and smoothed off so as to minimize disturbances to the flow field.

The hot wire probe was placed at a height of approximately 0·010 in above the heated surface, and about 7·50 in from the leading edge (opposite a surface thermocouple). The probe was

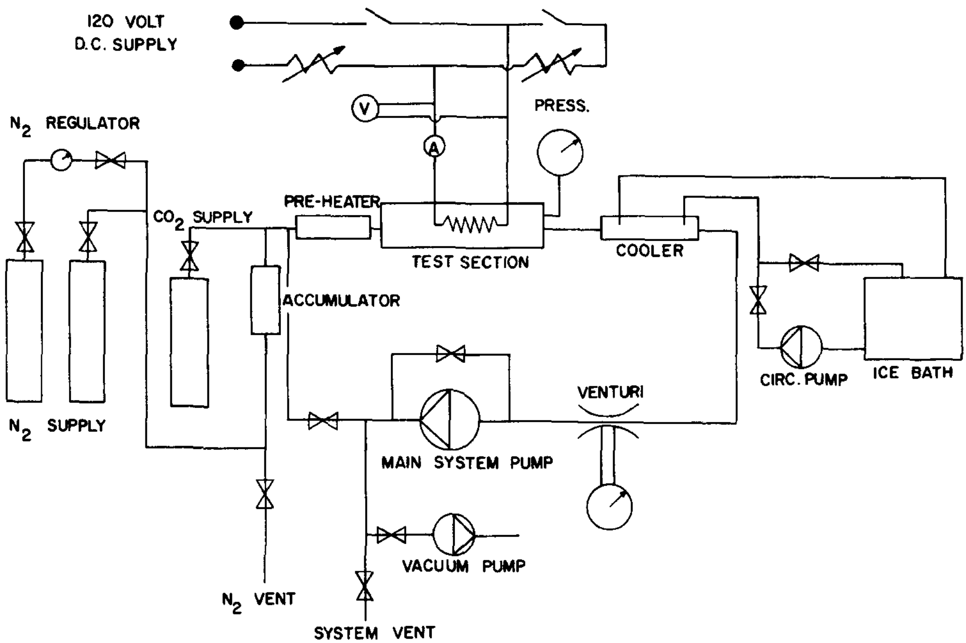

FIG. 1. Schematic diagram of forced convection apparatus.

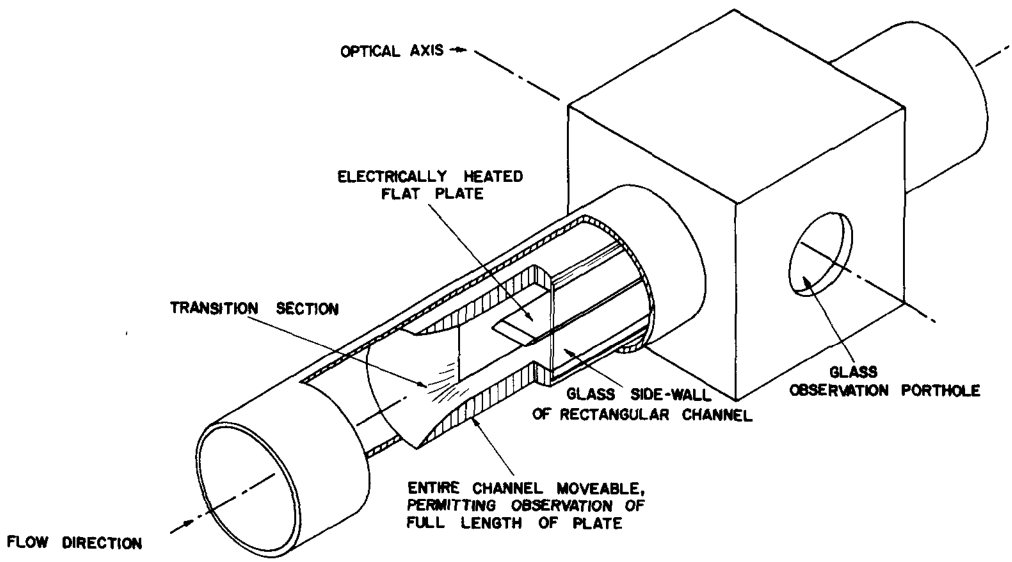

FIG. 2. Sectioned view of forced convection apparatus—test section.

connected to a Shapiro–Edwards constant temperature anemometer set and operated so that the probe current was affected principally by velocity fluctuations. Further details of the apparatus are given in [20].

A series of tests were conducted at fluid pressures of 1050, 1100 and 1200 psia (critical pressure of CO_2 1071 psia). The main portion of the tests conducted at these pressures were performed with the fluid temperature fixed at 75, 85, 95 and 105°F (critical temperature of CO_2, 87·8°F) while the surface temperature of the plate was varied uniformly from the freestream to as much as 500 degF above this value (at a maximum heat flux of 77000 Btu/h ft^{2}F). Each series of these tests were repeated at various freestream velocities, up to a maximum of of 1·5 ft/s.

A second, less extensive set of tests was conducted at the pressures cited above, but with fixed flow rates and heat flux while the freestream temperature was allowed to vary uniformly.

In order to gain some information about the effect of free convection on heat-transfer rates, a few experiments were conducted with the heated surface facing downwards. To place the test plate into this position, the entire cylindrical pressure vessel could be rotated 180° about its longitudinal axis. Thus the location of the flat plate in the channel and the approaching flow field was unchanged, and the results could be directly compared to those obtained with the plate in its normal position.

RESULTS

A. Heat-transfer measurements

The thermocouples employed for measuring surface temperatures were located in the fully turbulent downstream portion of the boundary layer. The trend of the heat-transfer results recorded from each of the thermocouples were quite similar (except for a length-scaling factor due to their different locations) and so only the results of a *single* thermocouple, 7·25 in downstream of the leading edge are presented here. On the basis of this length the Reynolds number is approximately 10^6 for a velocity of 1·5 ft/s.

Let us first consider the results from a series of tests at supercritical pressures but for bulk temperatures *below* the pseudocritical value. For each test the bulk temperature was maintained constant and the surface temperature was increased in steps. For these cases the heat-transfer coefficient was observed to increase with increasing surface temperature, reaching a maximum when the surface was very near the pseudocritical temperature. Further increases in surface temperature above the pseudocritical resulted in a decreasing heat-transfer coefficient. The actual magnitude of the peak heat-transfer coefficient was observed to depend on freestream pressure, temperature and velocity. Pressures nearest the critical exhibited the highest heat-transfer coefficients, while at any fixed pressure the heat-transfer coefficients increased as the freestream approached the pseudocritical temperature. A sample plot of experimental results is shown in Fig. 3 for freestream conditions of 1100 psia and 75°F. It may be worth noting incidentally that, although the heat-transfer coefficient exhibits a peak in Fig. 3, the corresponding actual heat-transfer rate increased smoothly with increasing surface temperature and in no instance were abrupt changes such as in [19] recorded.

For tests in which the freestream temperatures were above the pseudocritical, the heat-transfer coefficient decreased slightly with increasing surface temperature. This behavior may be seen for example in Fig. 4 which was taken at freestream conditions of 1100 psia and 105°F. It should be noted that the curve shows no peaks and in this respect it differs from the ones which were obtained for stream temperatures below the pseudocritical.

A few results were also obtained in another series in which the freestream temperature was varied and the flow rate and heat flux were maintained constant. The data are presented in Fig. 5, which shows that for temperatures below the pseudocritical (approximately 90°F at 1100

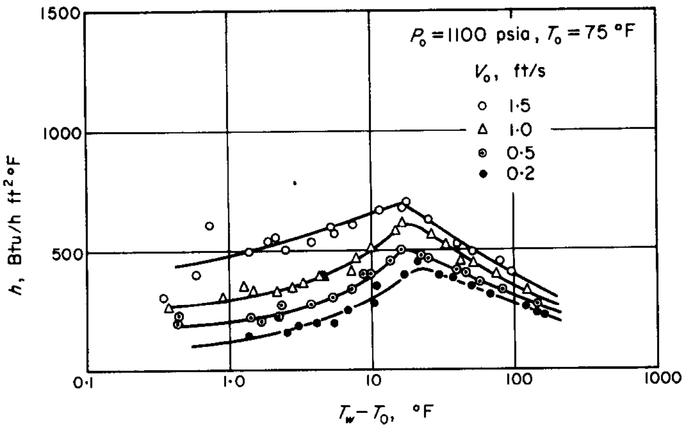

FIG. 3. Heat-transfer coefficient for a flat plate in supercritical CO_2 at 1100 psia and 75°F. (Pseudocritical temperature, 90°F.)

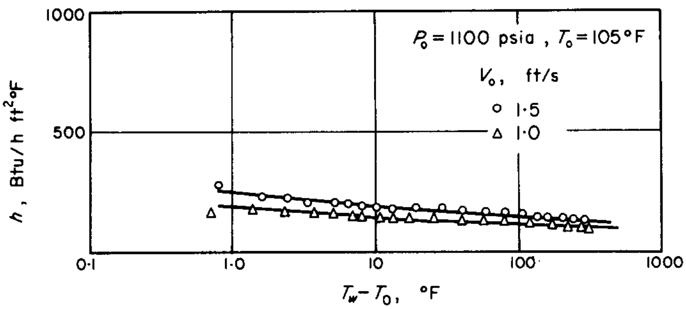

FIG. 4. Heat-transfer coefficient for a flat plate in supercritical CO_2 at 1100 psia and 105°F. (Pseudocritical temperature, 90°F.)

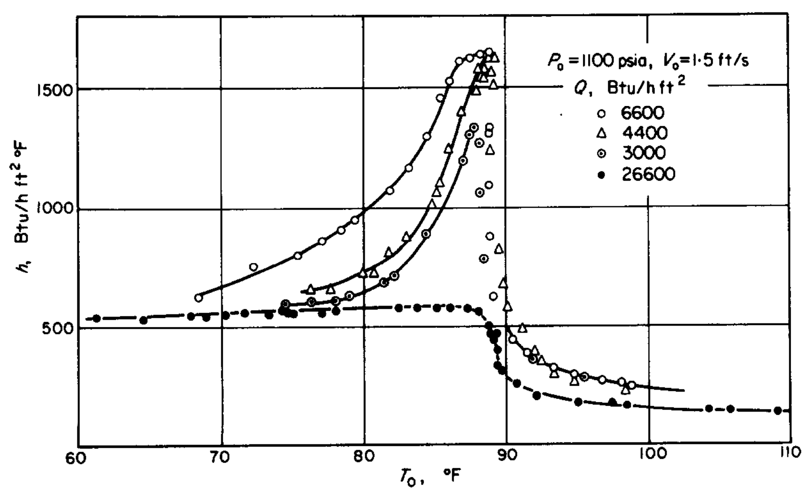

FIG. 5. Heat-transfer coefficient dependence on freestream temperature for a flat plate in supercritical CO_2 at 1100 psia. (Pseudocritical temperature, 90°F.)

psia) the heat-transfer coefficient was extremely dependent on heat-transfer rate (or equivalently on surface temperature). Large heat-transfer coefficients were measured when the freestream was slightly below the pseudocritical temperature, provided the heat rate was such so that the surface was just slightly above the pseudocritical temperature.

Although most of the tests were performed with the plate facing up, a few were also conducted with the heated side facing downward so as to obtain an indication of the influence of the gravitational field on the present data. When both freestream and surface temperatures were below the pseudocritical, the heat-transfer coefficient was not significantly altered by inverting the heated surface. With both freestream and surface temperatures above the pseudocritical, no influence of direction of body force could be detected. However, when the surface temperature was above and the freestream temperature was below the pseudocritical, the heat-transfer coefficient was appreciably reduced by inverting the plate. Nevertheless, the general shape of the curve was maintained, and the maximum occurred at about the same temperatures.

For purposes of comparison some experiments were performed at 1050 psia at which pressure the fluid is subcritical. The familiar regimes of nucleate, partial and complete film boiling were easily identified and Fig. 6 shows the heat-transfer coefficient as a function of the temperature difference. One may clearly see the characteristically sharp rise of the curve at the beginning of nucleate boiling. Peak nucleate heat flux was about 18500 Btu/h ft^2, and the temperature difference at the onset of stable film boiling about 63 degF for a freestream velocity of 1·5 ft/s.

B. Flow field observations

Single frames have been selected from a few of the high speed movies taken of the heated flow field and are shown in Figs. 7–10. In the color film record, the cold freestream fluid appears green, and subsequent warmer regions are yellow and red, respectively. The freestream fluid moves from left to right and the heated flat plate appears as the horizontal black band at the bottom of the photographs.

Figures 7–9 show the heated turbulent boundary layer at freestream conditions of 1100 psia and 75°F with a freestream velocity of 1·5 ft/s.

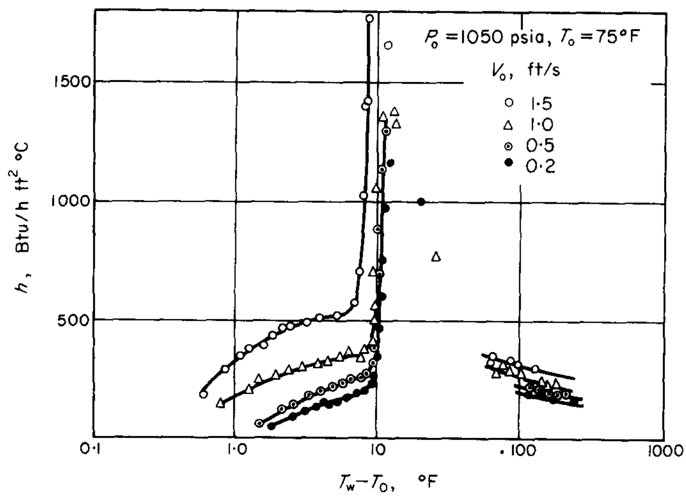

FIG. 6. Heat-transfer coefficient for a flat plate in subcritical CO_2 at 1050 psia and 75°F.

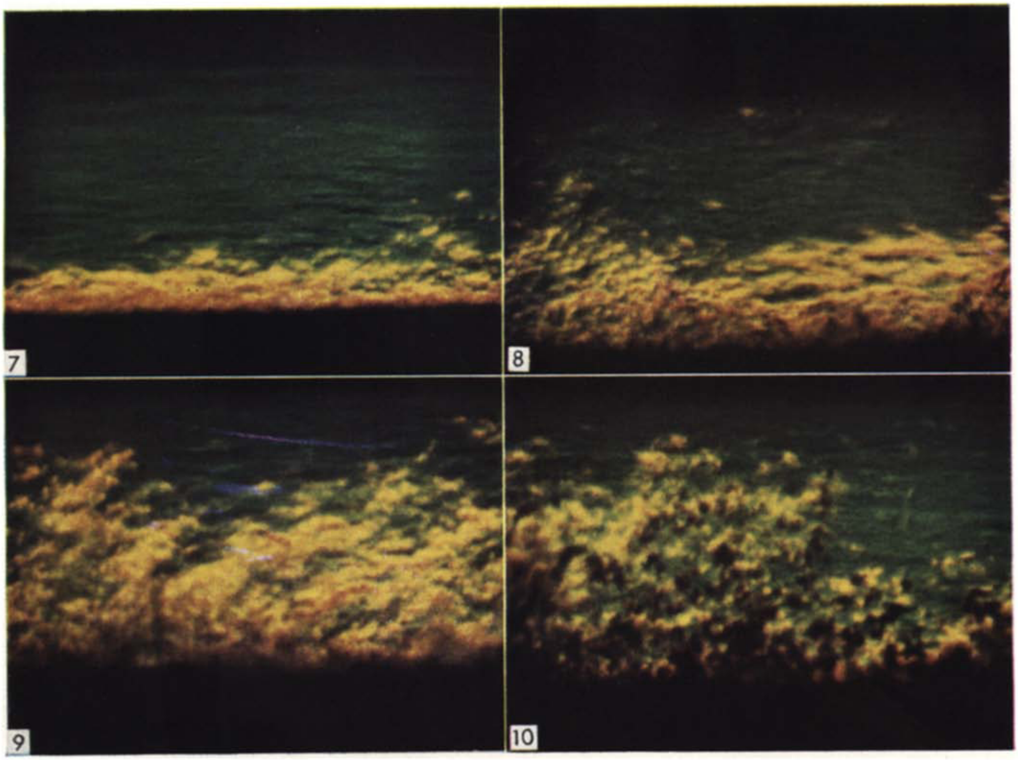

FIG. 7. Heated flow field over a flat plate in supercritical CO_2 at 1100 psia and 75°F. (7·5 m from leading edge, 5× enlarged, V_0 = 1·5 ft/s, $T_w - T_0$ = 8·9 deg F.)

FIG. 8. Heated flow field over a flat plate in supercritical CO_2 at 1100 psia and 75°F. (7·5 in from leading edge, 5× enlarged, V_0 = 1·5 ft/s, $T_w - T_0$ = 17·8 deg F.)

FIG. 9. Heated flow field over a flat plate in supercritical CO_2 at 1100 psia and 75°F. (7·5 in from leading edge, 5× enlarged, V_0 = 1·5 ft/s, $T_w - T_0$ = 60·6 deg F.)

FIG. 10. Heated flow field over a flat plate in subcritical CO_2 at 1050 psia and 75°F. (7·5 in from leading edge, 5× enlarged, V_0 = 1·5 ft/s, $T_w - T_0$ = 83·2 deg F.)

These figures form a sequence in which the surface temperature is increasing. At low heat-transfer rates the surface temperature is below the pseudocritical and the flow field appears to be substantially that of a constant property turbulent flow as shown in Fig. 7. A slight amount of fluid motion normal to the heated surface, probably caused by free convection, could be detected by viewing the movie films. Figure 8 shows the flow field occurring near the peak heat-transfer coefficient in Fig. 3. The surface temperature is about 2 degF above the pseudocritical and the ratio of freestream to surface fluid density is about 2·5. Although small dark areas indicating regions of rapid change in density were detected, the main portion of the flow did not exhibit any unusual effects and still appears similar to a normal turbulent forced flow field. At surface temperatures further above the pseudocritical the regions of differing density appear increased in size, and free convective motion becomes superimposed on the basic forced flow through a large portion of the boundary layer. Figure 9 shows the flow for a temperature difference of about 60 degF, and a ratio of freestream to surface density of about 4·5. As a comparison, Fig. 10 (the only photograph in the subcritical region) shows the heated flow field at 1050 psia and 75°F. The heat-transfer rate is such that stable film boiling occurs (a temperature difference of about 83 degF). The vapor film itself is not visible, but large vapor clusters which break away and rise into the freestream fluid appear as the large black spots.

The results of some of the measurements of the velocity fluctuations are shown in Fig. 11. The "turbulence level" plotted was arbitrarily taken as four times the RMS value of the fluctuating part of the probe current, in order to compare with usual measurements in homogeneous flows. The turbulence level at 1·5 ft/s freestream velocity and 1100 psia and 75°F remains relatively constant for surface temperatures below the pseudocritical. As the surface temperature increases beyond the pseudocritical, the turbulence level begins to increase slowly until at a temperature difference of 136 degF it is approximately three times the unheated plate level. No sharp or discontinuous increase was noted when the surface was at the pseudocritical temperature, where the heat-transfer coefficient reaches its peak. At this flow rate, the hot wire was situated approximately at the outer edge of the buffer or transition region of the boundary layer. By way of comparison, Fig. 12 shows that at the onset of nucleate boiling in a subcritical fluid a sharp and abrupt increase in turbulence level could be detected.

DISCUSSION

The heat-transfer results described in the previous section indicate that heat-transfer coefficients for fluids near the critical point

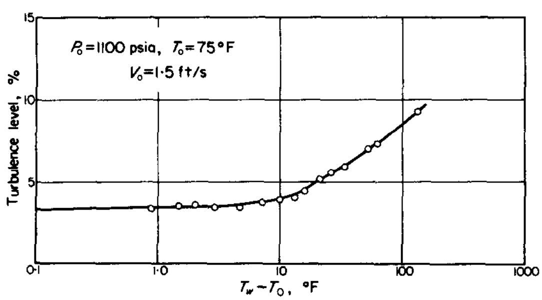

FIG. 11. Turbulence levels near a heated flat plate during forced convection heat transfer to supercritical CO_2 at 1100 psia and 75°F.

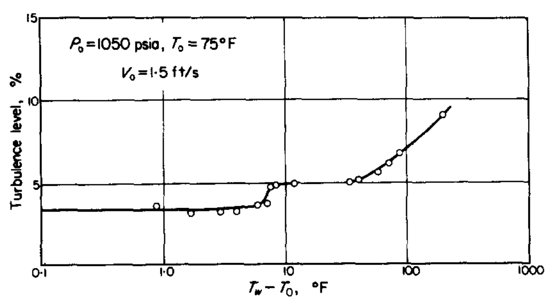

FIG. 12. Turbulence levels near a heated flat plate during forced convection heat transfer to subcritical CO_2 at 1050 psia and 75°F.

definitely depend on the freestream and surface temperatures, and particularly on the magnitude of these temperatures relative to the pseudocritical temperature. The information obtained is quite similar to that found in several previous forced convection studies. For example in a liquid-like freestream fluid, a peak heat-transfer coefficient was obtained when the surface temperature was near the pseudocritical. This type of peak was also found in [22]. With the heat-transfer rate fixed at a sufficiently low value, increases in freestream temperature produced a maximum in the heat-transfer coefficient at temperatures slightly below the pseudocritical as in [23]. However, at larger heat-transfer rates, the heat-transfer coefficient exhibited a sharp drop when the freestream temperature slightly exceeded the pseudocritical. The resulting low value after the drop may actually correspond to a minimum. Thus *both* maxima and minima in heat-transfer coefficient may occur depending on the heat-transfer rate and bulk fluid properties. This experimental indication may possibly serve to explain some of the apparently conflicting results regarding the occurrence of maxima and minima in the heat-transfer coefficient near the critical point. Comparing the photographs of the flow field occurring at the peak heat-transfer coefficients with those where the fluid acted essentially as a constant property fluid, it can be seen that although differences exist in the detailed nature of the flow, the *basic* flow pattern resembles normal turbulent forced convection for all the regions investigated in this study. In particular, no significant break-up of the normal forced convection pattern (such as occurs for example in nucleate boiling) could be observed when the heat-transfer coefficient reached its peak. The hot wire studies also showed the turbulence levels occurring at the peak heat-transfer coefficient were not grossly different from those occurring in normal turbulent flows. Nevertheless, some modification of the spectrum and intensity of the turbulent motion probably did occur. Effects of this type have been postulated by previous investigators, e.g. Hall, Jackson and Khan [24].

It should be stressed that although in the present experiments the basic heat-transfer mechanism was found to be similar to normal forced convection, this need not be the case for other heater geometries or possibly very different test conditions. In contrast to the present results, the experiments described in [19] show that under certain conditions a discontinuous change in heat-transfer rate may occur during natural convection from a heated wire, and that such a change is accompanied by a complete disruption of the flow pattern existing prior to the change.

CONCLUSIONS

The purpose of the present experiment was to study forced convection of CO_2 in the single phase region near the critical point. The flow was examined visually and by means of certain hot wire measurements. In the range of experimentation no gross flow disturbances could be detected which could be likened in any way to those observed in earlier free convection around a cylinder, or to the disturbance observed in nucleate boiling. The improvement in the heat-transfer coefficient which was observed is therefore ascribed to the actual values of the thermodynamic and transport properties throughout the fluid as well as to possible modifications of the turbulent fluctuations.

ACKNOWLEDGEMENTS

This paper is based on work carried out under NSF Grant 14071, sponsored by the National Science Foundation, and the authors gratefully acknowledge this support.

REFERENCES

1. E. Schmidt, E. Eckert and U. Grigull, Wärmetransport durch Flussigkeiten in der Nahe ihres kritischen Zustandes, *Jb. dt. LuftForsch.* **2**, 53 (1939).
2. L. E. Dean and L. M. Thompson, Study of heat transfer to liquid nitrogen, ASME No. 56-SA-4 (1956).
3. W. B. Powell, Heat transfer to fluids in the region of the critical temperature, *Jet Propul.* **27**, 776–783 (1957).
4. R. P. Bringer and J. M. Smith, Heat transfer in the critical region, *A.I.Ch.E. Jl* 3 (1), 49 (1957).
5. N. L. Dickinson and C. P. Welch, Heat transfer to supercritical water, *Trans. Am. Soc. Mech. Engrs* **80**, 746–752 (1958).

6. J. P. BOGGS and J. H. HOLMAN, Heat transfer to Freon-12 near the critical state in a natural circulation loop, *J. Heat Transfer* **82**, 221–226 (1960).
7. D. G. HARDEN and J. H. BOGGS, Transient flow characteristics of a natural circulation loop operated in the critical region in *Proc. Heat Transf. Fluid Mech. Inst.* pp. 38–45. Stanford University Press, Palo Alto, Calif. (1964).
8. R. S. THURSTON, Pressure oscillations induced by forced convective heat transfer to two-phase and supercritical hydrogen, Los Alamos Report, LAMS-3-7- (February 1964).
9. A. J. CORNELIUS and J. D. PARKER, Heat transfer instabilities near the thermodynamic critical point, in *Proc. Heat Transf. Fluid Mech. Inst.* pp. 317–329. Stanford University Press, Palo Alto, Calif. (1965).
10. A. I. CHALFANT, Heat transfer and fluid friction experiments for the supercritical water reactor, P.W.A.C.-109 (June 1954).
11. D. G. RANDALL, Some heat transfer and fluid friction experiments with supercritical water, Reactor Heat Transfer Conference (November 1956).
12. W. S. HINES and H. WOLF, Heat transfer vibrations with hydrocarbon fluids at supercritical pressures and temperatures, A.R.S. Propellants, Combustion and Liquid Rockets Conference (April 1961).
13. C. A. FRITSCH and R. J. GROSH, Free convective heat transfer to a supercritical fluid, *Proceedings of 1961 International Heat Transfer Conference*, Part V, 1010–1016 (August 1961).
14. J. R. LARSON and R. J. SCHOENHALS, Turbulent free convection in near critical water, *J. Heat Transfer* **88**, 407–414 (1966).
15. R. G. DEISSLER, Heat transfer and fluid friction for fully developed turbulent flow of air and supercritical water with variable fluid properties, *Trans. Am. Soc. Mech. Engrs* **76**, 73–85 (1954).
16. K. GOLDMANN, Heat transfer to supercritical water at 5000 psia flowing at high mass flow rates through round tubes, *Proceedings of 1961 International Heat Transfer Conference*, Part III, 561–568 (August 1961).
17. H. L. HESS and H. R. KUNZ, A study of forced convection heat transfer to supercritical hydrogen, *J. Heat Transfer* **87**, 41–48 (1965).
18. K. GOLDMANN, Special heat transfer phenomena for supercritical fluids NDS 2-31 (November 1956).
19. K. K. KNAPP and R. H. SABERSKY, Free convection heat transfer to carbon dioxide near the critical point, *Int. J. Heat Mass Transfer* **9**, 41–51 (1966).
20. E. G. HAUPTMANN, Ph.D. Thesis, California Institute of Technology, Pasadena, Calif, University Microfilms, Ann Arbor, Mich. No. 665372 (December 1965).
21. A. KANTROWITZ and R. L. TRIMPI, A sharp-focusing Schlieren system, *J. Aeronaut. Sci.* **17**, 331–314 (1950).
22. H. S. SWENSON, C. R. KAKARALA and J. R. CARVER, Heat transfer to supercritical water in smooth-bore tubes, *J. Heat Transfer* **87**, 477–489 (1965).
23. R. D. WOOD and J. M. SMITH, Heat transfer in the critical region—temperature and velocity profiles in turbulent flow, *A.I.Ch.E. Jl* **10** (2), 180 (1964).
24. W. B. HALL, J. D. JACKSON and S. A. KHAN, An investigation of forced convective heat transfer to supercritical pressure carbon dioxide, *Proceedings of 1966 International Heat Transfer Conference*, Part I, 257–266 (August 1966).

Résumé—On présente les résultats expérimentaux pour le transport de chaleur par convection forcée à partir d'une plaque dans le gaz carbonique près du point critique thermodynamique. On a fait varier les conditions d'état à travers la région critique, mais de nombreux essais ont été effectués dans l'état (supercritique) avec une seule phase. Un des principaux objectifs était l'observation visuelle directe du champ de l'écoulement chauffé, et des films à grande vitesse ont été pris à l'aide d'un appareillage strioseopique en couleur. Quelques explorations par fil chaud des fluctuations de vitesse près de la plaque ont été également effectuées.

Bien que le coefficient de transport de chaleur déterminé expérimentalement devenait élevé lorsque la température de la plaque approchait la température pseudocritique, aucun changement sensible dans la nature générale du champ d'écoulement pouvait être observé. En particulier, aucun phénomène du type avec "bulles", comme ce qui a été observé dans la convection naturelle avec d'autres géométries thermiques, ne pouvait être décelé. Les coefficients élevés de transport de chaleur étaient attribués par conséquent aux grandes valeurs des propriétés thermodynamiques et de transport au voisinage du point critique aussi bien qu'à des modifications plus secondaires du mouvement turbulent.

Zusammenfassung—Für den Wärmeübergang bei Zwangskonvektion an einer ebenen Platte in Kohlendioxyd nahe dem thermodynamisch kritischen Punkt werden Versuchsergebnisse mitgeteilt. Die Zustandsbedingungen wurden in kritischen Bereich variiert, die meisten Versuche sind aber im (überkritischen) Einphasengebiet durchgeführt. Eines der Hauptziele war die direkte visuelle Beobachtung des beheizten Strömungsfeldes; dazu wurden Hochgeschwindigkeitsfilme mit Hilfe einer Farbschlierenapparatur aufgenommen. Einige klärende Hitzdrahtmessungen der Geschwindigkeitsschwankungen nahe der Platte sind ebenfalls durchgeführt worden.

Obwohl die experimentell bestimmten Wärmeübergangskoeffizienten stets gross wurden bei Annäherung der Plattentemperatur an die pseudokritische, konnten keine bedeutsamen Veränderungen in der

Gesamterscheinung des Strömungsfeldes wahrgenommen werden. Insbesonders wurden keine "blasenähnlichen" Phänomene entdeckt, wie sie bei freier Konvektion in anderen Heizanordnungen beobachtet wurden. Die grossen Wärmeübergangskoeffizienten werden dementsprechend den grossen Werten der thermodynamischen- und der Transporteigenschaften zugeschrieben, wie sie nahe dem kritischen Punkt auftreten, sowie einigen kleineren Änderungen der turbulenten Bewegung.

Аннотация—Представлены результаты экспериментов по теплообмену при вынужденной конвекции на плоской пластине в двуокиси углерода вблизи термодинамической критической точки. Условия менялись во всей критической области, но большинство опытов проводились в однофазном (сверхкритическом) состоянии. Одной из главных целей исследования было прямое наблюдение в поле нагреваемого потока, для чего применялась высокоскоростная киносъемка с использованием цветной шлиренаппаратуры. Некоторые измерения пульсаций скорости вблизи пластины производились методом нагретой нити.

Хотя каждый раз, когда температура пластины приближалась к псевдокритической, экспериментально найденные коэффициенты теплообмена имели большую величину, значительных изменений в общем характере поля течения не наблюдалось. Большие коэффициенты теплообмена можно объяснить высокими значениями термодинамических величин, наблюдаемых вблизи критической точки, а также менее значительными изменениями в турбулентном движении.