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FORCED CONVECTIVE HEAT TRANSFER TO TURBULENT CO_2 IN THE SUPERCRITICAL REGION

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Abstract—Measurements were made of the wall temperatures of a 4·56 m long, $2·28 \times 10^{-2}$ m dia. tube with heat transfer to turbulent flow of CO_2 at supercritical pressure. In some experiments the change in state of the CO_2 between the inlet and the outlet of the tube, covered the full supercritical range between the liquid and the gaseous phases and in others the effect of varying the inlet state through the supercritical region, was investigated. Measurements were made with both vertically upward and downward flow through the tube to determine the effect of changing the direction of the flow relative to bouyancy forces. A comprehensive set of data was obtained for pressures from 7.44×10^6 to $10·32 \times 10^6$ N/m^2, heat fluxes from $0·8 \times 10^4$ to 35×10^4 W/m^2 and mass flows from 0·127 to 0·695 kg/s. Deviations of the local heat transfer from that for normal gaseous or liquid CO_2 ranged from factor of two deteriorations to order of magnitude improvements.

NOMENCLATURE

Nu, Nusselt number;
Pr, Prandtl number;
Re, Reynold number;
T_B, bulk temperature [°C];
T_W, wall temperature [°C];

1. INTRODUCTION

WHEN a fluid at supercritical pressure, in turbulent flow through a long tube, is heated from subcritical to supercritical temperature, it gradually changes phase from a liquid to a gaseous state. At positions in the tube far from this change, where the fluid is either entirely liquid or gaseous, the coefficient for heat transfer from the tube wall to the fluid (obtained from the usual single phase correlations) is approximately the same for both states. During the phase change near the critical temperature when all the physical properties vary widely, order of magnitude improvements and deteriorations in heat transfer occur with several fluids [1–4] and the concept of a constant transfer coefficient relating heat flux to temperature difference is no longer valid.

Possible explanations of these phenomena have been suggested, involving the effects of buoyancy due to density gradients [2], of radial differences in viscosity [1] and of rapid changes in density in the flow [5] on heat transfer by turbulent convection through the fluid. A thorough explanation, substantiated by experimental measurements, is however not yet possible for two reasons.

Firstly, the conditions under which appreciable deviations in heat transfer occur are not well defined by the limited and sometimes contradictory experimental data in the literature (see review [6]). Hence, the first objective of the present investigation of heat transfer to supercritical CO_2 was a systematic study of the dependence of the wall temperature distribution along a uniformly heated tube on the inlet temperature, the pressure, the wall heat flux, the mass flow and the vertically upward and downward directions of flow. The inlet temperature was varied from subcritical to supercritical values, so that with lower values the whole of the phase change occurred within the heated tube and with higher values the effect of differing inlet states within the region of phase change, could be examined. This latter effect was expected to be important because with changing heat-transfer characteristics during the phase change, variation in near critical inlet states may influence the characteristics throughout the completion of the phase change. The direction of flow was varied to investigate further the effect of changing this direction relative to buoyancy forces, following recent reports [1, 2] that deteriorated heat transfer occurs only with upward flow.

The second reason why supercritical heat transfer phenomena have not been fully explained is that most of the existing data are confined to wall temperatures with no measurements within the flow. The only exceptions are the measurements over a limited part of the near critical region, of mean velocity and temperature profiles through CO_2 flow in a tube by Wood and Smith [7] and the Schlieren pictures of CO_2 flow over a heated flat plate by Sabersky and Hauptmann [8]. The former show maxima in velocity at varying radial positions corresponding to the critical temperature and support the observation of the latter that there is a strong interaction between the heat transfer and the flow, which differs from that of fluids with nearly constant physical properties. It therefore seems that more extensive measurements of the flow and of the heat transfer through it are needed to obtain a better understanding of and to verify any hypotheses about the improvements and deteriorations in supercritical heat transfer. These data are to be obtained in the next stage of the present programme.

2. APPARATUS

The CO_2 was recirculated round a closed loop. The test section was a stainless steel tube of 4·56 m length, $2{\cdot}28 \times 10^{-2}$ m i.d. and $1{\cdot}27 \times 10^{-3}$ m wall thickness. It was electrically insulated from the rest of the loop and heated by alternating current. The 150 kW power supply was capable of producing uniform heat flux up to 50×10^4 W/m^2 over its surface. There was a 10 diameter long straight entrance immediately upstream of the heated section. The tube was mounted vertically with alternative pipe connections at each end, so that the CO_2 flow could be either upwards or downwards.

Some fifty thermocouples were clipped to the tube along its length and round its diameter to measure its outer surface temperatures. These thermocouples were read by an automatic data recording system. Their calibrations were checked in situ by passing wet steam through the tube under isothermal conditions. With electrical heating on the tube the temperature drop through the wall and hence its inner surface temperature was calculated from its thermal conductivity, on the assumption of uniform heat generation. There was locally some variation in temperature round its circumference, presumably due to variation in wall thickness. In analysis of the results, this variation was averaged. The error in inner wall temperature due to this and other possible inaccuracies varied from less than 0·5 degC at 30°C to 10 degC at 300°C. The bulk temperature of the CO_2 entering and leaving the test section were measured by thermocouples in mixing boxes to an accuracy of 0·5 degC.

Stresses due to pressure in the test section were such that it could be operated with wall temperatures up to 200°C at $10{\cdot}3 \times 10^6$ N/m^2 and up to 300°C at $8{\cdot}25 \times 10^6$ N/m^2. It was protected from excessive pressure by bursting discs and from excessive temperature by the thermocouples which were connected to an automatic power cut-out if the temperature exceeded a set value.

The rest of the loop consisted of a CO_2 cooler, a B.S. 1042 flow measuring orifice, a pump and a pre-heater before the test section. The cooler to remove heat from the CO_2 was a counter-current heat exchanger with surface extension on the CO_2 side. Atmospheric pressure water recirculated through the other side and was itself cooled in a conventional cooling tower. An automatic controller which varied the water flow rate, was used to maintain the temperature of the CO_2 leaving the heat exchanger constant at 15°C. At this temperature the physical properties of CO_2 are substantially independent of supercritical pressure and the standard orifice plate could be used to measure the flow rate to the usual accuracy of about 2 per cent. The pump used was capable of recirculating the CO_2 through the loop at flows from 0·1 to 0·7 kg/s. The pre-heater had a maximum power of 30 kW and was used to set the temperature of the CO_2 entering the test section at any desired value.

CO_2 was supplied to the loop from commercial cylinders in which the pressure was maintained well above the critical value by heating jackets around the cylinders. Manual adjustment of the pressure in the loop by bleeding CO_2 in or out, was found quite adequate to control it to an accuracy of $3{\cdot}5 \times 10^3$ N/m^2. The absolute pressure was recorded to this accuracy by an electromanometer, connected to the test section entry. During operation at any fixed mass flow and heat flux, CO_2 pressures and temperature round the loop generally remained stable to $3{\cdot}5 \times 10^3$ N/m^2 and 0·5 degC respectively and the wall temperatures were quite steady and reproducible within the experimental accuracy.

3. RESULTS

With this apparatus the independent variables, CO_2 pressure, inlet bulk temperature, heat flux and mass flow were varied through the following ranges:

Pressure	$7{\cdot}44 \times 10^6$–$10{\cdot}32 \times 10^6$ N/m^2
Inlet temperature	15–35°C
Heat flux	$0{\cdot}8 \times 10$–35×10^4 W/m^2
Mass flow	0·127–0·695 kg/s both vertically upward and downward.

These conditions caused the dependent variables, CO_2 bulk outlet temperature, wall temperature and Reynolds numbers to vary in the ranges:

Outlet temperature	18–70°C
Wall temperature	20–300°C
Reynolds number at entry	$0{\cdot}09$–$0{\cdot}57 \times 10^6$
Reynolds number at outlet	$0{\cdot}3$–$1{\cdot}65 \times 10^6$.

The critical point for CO_2 is given by:

Critical pressure $= 7{\cdot}38 \times 10^6$ N/m^2
Critical temperature $= 31$°C.

These conditions fully cover the near critical temperature range from about 30 to 40°C in which the physical properties vary rapidly. All properties used in this work are taken from the recommendations of the recent comprehensive survey by Vulkalovich [9].

For each test, a comparison was made between the rates of electrical energy input to the test section and of heating the CO_2, the latter being calculated from the flow rate and the enthalpy

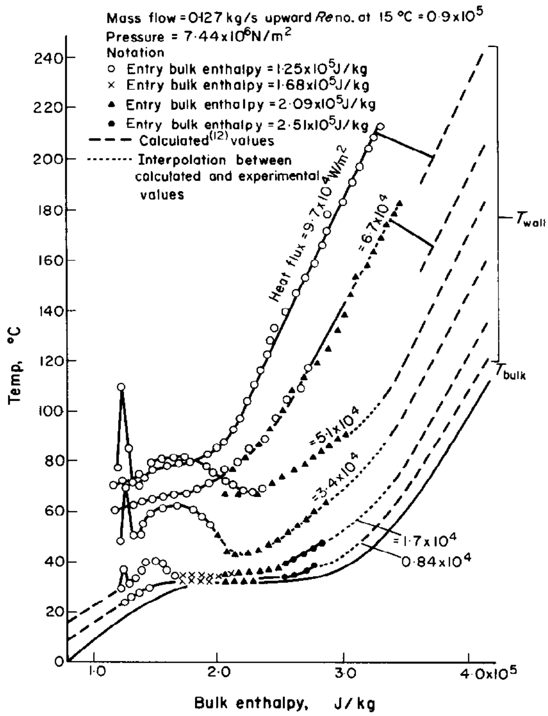

FIG. 1. Wall and bulk temperature vs. bulk enthalpy.

difference between the inlet and outlet bulk temperatures. A balance to an accuracy of better than 5 per cent was usually obtained when both these temperatures were far from the critical value. When either was close to the critical value, the accuracy deteriorated due to rapid variation in enthalpy with temperature.

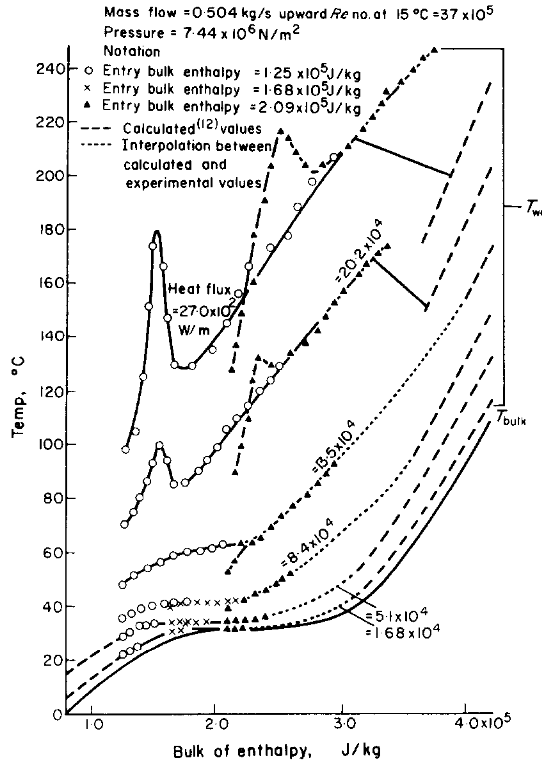

FIG. 2. Wall and bulk temperature vs. bulk enthalpy.

The variation in CO_2 bulk enthalpy along the test section was calculated from the uniform wall heat flux, the flow rate and the enthalpy at either inlet or outlet bulk temperature, choosing that which was further from the critical value. The local bulk temperature along the test section was then generally obtained from thermodynamic data [9].

It was not however possible to do this for tests with pressures above $8{\cdot}25 \times 10^6$ N/m^2 and temperatures below 40°C because there appear

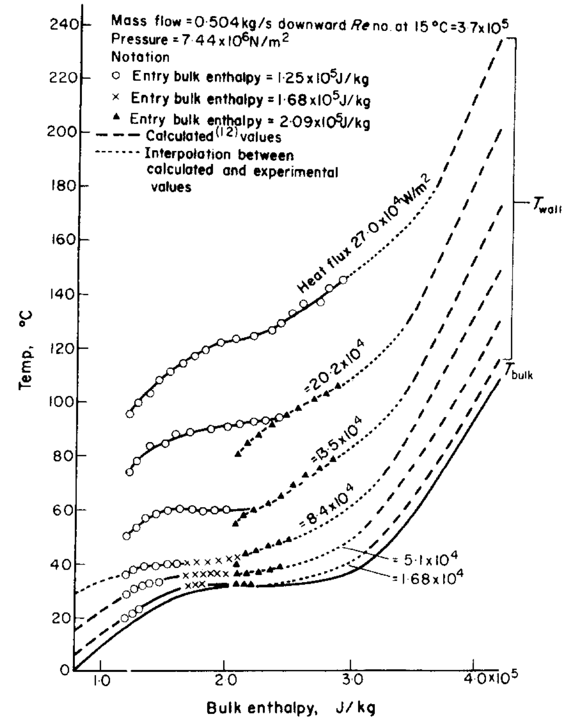

FIG. 3. Wall and bulk temperature vs. bulk enthalpy.

to be no data relating enthalpy to temperature under these conditions. A series of tests at pressures above $8{\cdot}25 \times 10^6$ N/m^2 was therefore made with the outlet temperature kept constant at 40°C while the heat flux and flow rate were varied. From these it was possible to relate the inlet temperature to difference in enthalpy from its known value [10] at 40°C. This new data was then used to obtain the local bulk temperature along the test section, under these conditions.

A representative selection of the data obtained is given in Figs. 1–6. The wall and bulk temperatures are plotted against bulk enthalpy for different heat flux in:

Fig. 1 for a mass flow of 0·127 kg/s upward at $7{\cdot}44 \times 10^6$ N/m^2
Fig. 2 for a mass flow of 0·504 kg/s upward at $7{\cdot}44 \times 10^6$ N/m^2
Fig. 3 for a mass flow of 0·504 kg/s downward at $7{\cdot}44 \times 10^6$ N/m^2

Fig. 4 for a mass flow of 0·504 kg/s upward at 10·32 × 10^6 N/m^2.

Other results are plotted as heat-transfer coefficient vs. bulk temperature in Fig. 5 for a mass flow of 0·695 kg/s upward at 7·44 × 10^6 N/m^2 and vs. bulk enthalpy in Fig. 6 for a mass flow of 0·127 kg/s both upward and downward at 7·56 × 10^6 N/m^2. Additional data at other conditions are available [10].

For tests at high heat flux, the total heat input was sufficient to heat the CO_2 from well subcritical inlet to well supercritical outlet temperatures and single sets of results extend over the whole of the near critical enthalpy change. At low heat flux however, only a small fraction of this enthalpy change was produced along the whole length of the test section. To obtain results over the whole of the critical region, it was then necessary to keep the heat flux, pressure and mass flow constant and repeat the wall temperature measurements with inlet temperature increased in appropriate steps by adjusting the pre-heater power. These varying inlet conditions are shown in Figs. 1–4 by different notation.

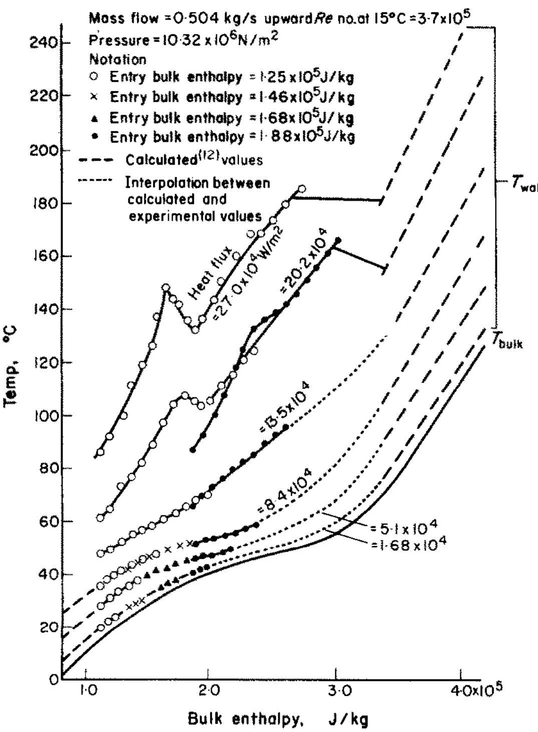

FIG. 4. Wall and bulk temperature vs. bulk enthalpy.

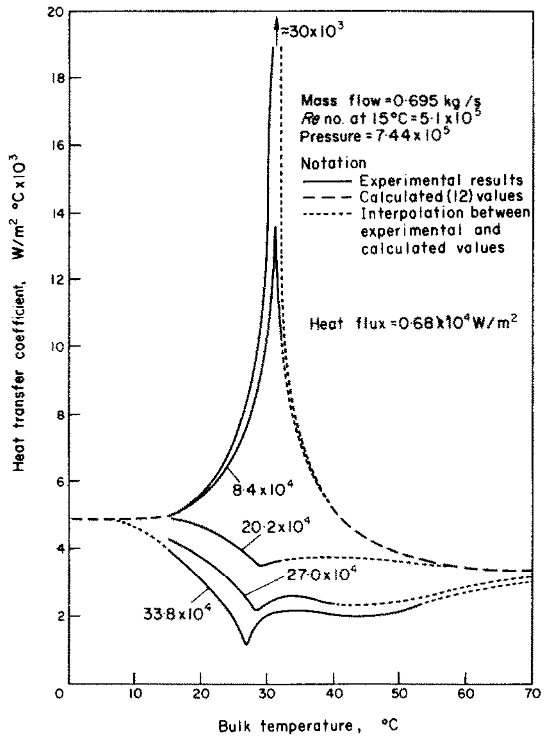

FIG. 5. Heat-transfer coefficient vs. bulk temperature.

To provide a comparison with the present results, the heat transfer coefficients and wall temperatures predicted by the Colburn [11] single phase heat transfer correlation

$$Nu = 0{\cdot}023\, Re^{0{\cdot}8}\, Pr^{0{\cdot}3}$$

for conditions when both the wall and bulk temperatures are either below or above the critical region, 30–40°C, are plotted as dashed lines on Figs. 1–5. When the ratio of the absolute values of these temperatures, T_W/T_B exceeds 1·1, as occurs with gaseous conditions with high heat flux, the Nusselt number in the above correlation is multiplied by $(T_W/T_B)^{-0{\cdot}27}$ to

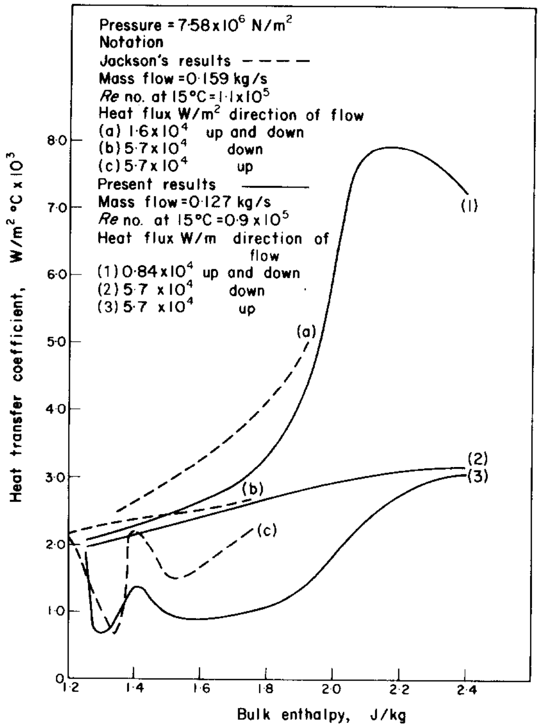

FIG. 6. Comparison of present results with Jackson's results [14].

allow for the small variation in physical properties as recommended by Pickering [12] from Jackson's work [13] with low pressure gaseous CO_2.

4. DISCUSSION

4.1 *Effects of heat flux and inlet enthalpy*

Typical effects of varying heat flux are shown in Fig. 2 for slightly supercritical pressure, $7{\cdot}44 \times 10^6$ N/m^2, a mass flow of 0·504 kg/s upwards giving a Reynolds number of $3{\cdot}7 \times 10^5$ at 15°C and bulk temperatures from 15 to 70°C. Outside the critical region, the above heat transfer correlation predicts wall temperatures in fair agreement with the experimental data for low heat flux. For high heat flux, its predictions are a little below the observed values for bulk temperatures up to 70°C but the discrepancy is decreasing with increase in bulk temperature.

Inside the critical region at low heat flux there is an order of magnitude improvement in heat transfer in terms of the wall to bulk temperature difference. For example, a flux of $1{\cdot}68 \times 10^4$ W/m^{2}s to the subcritical liquid and supercritical gas requires a temperature difference of about 5 degC, whereas only about 0·5 degC is required in the critical region. This improvement is not limited to a local region in the test section but was observed over its full 4·56 m length in tests at different entry conditions. It extends from about $1{\cdot}7 \times 10^5$ to $2{\cdot}7 \times 10^5$ J/kg bulk enthalpy.

As the heat flux was increased, two effects were observed. Firstly the above broad improvement disappears. For example at a bulk enthalpy of $2{\cdot}1 \times 10^5$ J/kg an 8 times increase in heat flux (from $1{\cdot}68 \times 10^4$ to $13{\cdot}5 \times 10^4$ W/m^2) increases the temperature difference by a factor of 60 (from 0·5 to 30 degC). At this increased flux and at higher values the temperature difference through most of the critical region is approximately the same as that either below or above the region.

The second effect of increased flux is that a local peak in wall temperature developed along a short length (0·3–0·6 m) of the tube and became progressively bigger with further increase in flux. For example, at a flux of $27{\cdot}0 \times 10^4$ W/m^2, this peak approximately doubles the local wall to bulk temperature difference. The conditions at which this peak occurs cannot be simply defined. It is certainly not associated with local bulk enthalpy alone as shown in Fig. 2 where the peak occurs at a bulk enthalpy of $1{\cdot}55 \times 10^3$ J/kg when the CO_2 temperature entering the tube is 18°C and at $2{\cdot}5 \times 10^5$ J/kg for an entry temperature of 32°C. In all the data obtained, the peak develops within a short distance (about 0·6–0·9 m) from the start of the heated part of the test section. It therefore appears to be an entry effect which occurs when CO_2 is heated from any inlet condition within the critical region, independently of the local bulk enthalpy. Down stream of these peaks, Fig. 2 shows that the wall temperature again becomes dependent on heat flux and local bulk enthalpy only.

Further data for a mass flow of 0·695 kg/s upward, showing effects very similar to those described above, are given in Fig. 5. Here the data is plotted as heat transfer coefficient vs. bulk temperature for various heat flux. Hence the improvements and deteriorations appear as maxima and minima respectively in the transfer coefficient.

4.2 *Effect of mass flow*

At all flows investigated from 0·22 up to 0·695 kg/s, the variation in wall temperature with heat flux was closely similar and as described in 4.1. At the lowest flow, 0·127 kg/s (Fig. 1), however, the wall temperature behaviour was rather different. The improvement in heat transfer at low heat flux was still present but at intermediate flux, $3{\cdot}4 \times 10^4$ and $5{\cdot}1 \times 10^4$ W/m^2, two peaks in wall temperature—the second being much broader than the first—were observed. These two peaks were quite reproducible but both disappeared with further increases in flux to $6{\cdot}7 \times 10^4$ and $9{\cdot}7 \times 10^4$ W/m^2—in contrast to the behaviour at higher flow rates where the single peak became more pronounced as the flux was increased.

4.3 *Effect of direction of flow*

The effect of changing the direction of flow from vertically upward to vertically downward is shown typically by comparing Figs. 2 and 3 for $7{\cdot}44 \times 10^6$ N/m^2 and 0·504 kg/s. At this and all other mass flows, the peaks in wall temperature were present for upward flow only and not for downward flow. The improvements in heat transfer at low heat fluxes however remained unchanged and independent of the direction of flow.

4.4 *Effect of pressure*

The effect of increased CO_2 pressure is shown in Fig. 4 for a pressure of $10{\cdot}32 \times 10^6$ N/m^2 and a mass flow of 0·504 kg/m^2 upward. At this pressure both the improvement in heat transfer at low heat flux and the peak in wall temperature are much diminished. From data obtained at other pressures it is concluded that the unusual heat-transfer effects at near critical temperature are greatest at slightly supercritical pressure and have become negligible at about one and half times the critical pressure. This behaviour confirms that these effects are caused by variation in physical properties with temperature because this variation is similarly related to pressure.

5. COMPARISON WITH OTHER DATA

The only published data for heat transfer to supercritical CO_2 at heat flux, pressure, mass flow rate and tube diameter comparable to the present values are those of Jackson [14]. He obtained wall temperature measurements over part of the critical region with heat flux up to $5{\cdot}7 \times 10^4$ W/m^2 at a mass flow rate of 0·159 kg/s both vertically upward and downward in a tube of $1{\cdot}9 \times 10^{-2}$ m dia. at $7{\cdot}56 \times 10^6$ N/m^2 pressure. These conditions with a Reynolds number of $1{\cdot}1 \times 10^5$ at 15°C are approximately the same as those for the lowest mass flow rate 0·127 kg/s at $7{\cdot}56 \times 10^6$ N/m^2 in the $2{\cdot}28 \times 10^{-2}$ m dia. tube of the present work, with a Reynolds number of $0{\cdot}9 \times 10^5$. Both sets of results are compared for both upward and downward flow in Fig. 6 where the heat-transfer coefficient is plotted against bulk enthalpy. The agreement can be seen to be satisfactory in that both data show substantial improvement of heat transfer with low flux independently of the direction of flow and two maxima in the transfer coefficient with slightly higher flux for up flow only. The occurrence of these maxima with intermediate heat flux and their disappearance at higher flux (Fig. 1) suggests that they may be caused by some unstable effect which can collapse and re-establish itself.

The work of Sabersky and Hauptmann [8] on heat transfer from a flat plate to a flow of supercritical CO_2, is also relevant in attempting to explain the present results. The heat transfer coefficients in Fig. 5, particularly those with high values for low heat flux, show a variation with bulk temperature very similar to that found by these workers (see Fig. 5 of [8]). With improved transfer, their observations, both visually and by hot wire anenometer, showed that the flow in the boundary layer was not much changed from that for constant property fluids and they ascribe the improvement mainly to the direct effect of the property variation on the transfer coefficient. With high heat flux giving much reduced coefficients, they observed a thickening of the boundary layer and increased turbulence near its outer edge. (Because they did not allow for the variation in hot wire sensitivity with CO_2 temperature, see Fig. 9.2 of [15], their estimate of the increase in turbulence may have been low). They attribute these changes to the large difference in density between the wall and bulk temperatures. The results here show improved heat transfer independently of the direction of flow and deterioration only when the flow is upward and there are large radial density gradients through the CO_2. This suggests that only the latter was caused by changes in flow due to buoyancy and therefore agrees with the above observations.

The present results can also be compared qualitatively with Shitsman's extensive investigation of heat transfer to supercritical water in vertical tubes [1]. This shows the same general behaviour of local deteriorations in heat transfer which occur over a wide range of bulk enthalpy when the flow is upward. Shitsman associates the deterioration with large differences in viscosity between the wall and bulk temperatures and in the results here such viscosity differences are always present when deterioration occurs. His hypothesis is however that these differences cause a laminarization of the boundary layer and this does not seem consistent with the above observation of increased turbulence in this layer with deteriorated transfer. An attempt was made to fit the present results to the supercritical correlation suggested by Shitsman but this only poorly correlated the deteriorated transfer and completely failed to correlate the improvements.

It does not therefore yet appear that the variations in supercritical heat transfer have explained experimentally but all the above results suggest that changes in both density and viscosity through the fluid and in the flow pattern are relevant. The theoretical analysis of Hall and Jackson [2] proposes a mechanism for the deterioration in transfer due to local suppression of turbulence in the boundary layer. This can be caused by reduction in the shear stress in upward flow by buoyancy forces acting on a thin layer of low density fluid near the wall. They suggest a criterion for its occurrence involving the changes in both density and viscosity through the flow, in qualitative agreement with the above conclusions. To verify this analysis quantitatively, measurements of these changes are required [2].

Such data are to be obtained from further work now in progress with the present apparatus. A fast response resistance thermometer is being used to measure mean and fluctuating temperatures through the boundary layer from which the changes in physical properties will be obtained. Measurements of turbulence, heat flux and shear stress through the core of the flow are also being made by a combination of this thermometer with hot wire anemometry [16]. It is hoped that these results will give more insight into the mechanisms of supercritical heat transfer.

6. CONCLUSIONS

From the present work it is concluded that:

1. At low heat flux, heat transfer throughout the critical region shows an order of magnitude improvement over that at well sub- or supercritical temperature, independently of the direction of flow.

2. At high heat flux, peaks in wall temperature result in a substantial local increase of the wall to bulk temperature difference at the beginning of heating in the critical region. They occur only when the flow is upward and when there are large radial changes in the density and viscosity,

suggesting that they are caused by the effects of buoyancy on turbulence in the flow.

3. For low flow rate, double peaks in wall temperature occur at intermediate heat flux and disappear with further increase in flux, showing that the buoyancy effect is unstable.

4. All these effects decrease with increasing supercritical pressure to become insignificant at about one and a half times the critical value, confirming that they are caused by the rapid near critical variation in physical properties.

5. New data for the enthalpy/temperature relationship for CO_2 from 15 to 40°C $10{\cdot}32 \times 10^6$ N/m^2 has been obtained.

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TRANSPORT DE CHALEUR PAR CONVECTION FORCÉE TURBULENTE DANS DU CO_2 DANS LA RÉGION SUPERCRITIQUE

Résumé—On a mesuré les températures pariétales d'un tube de 4,56 m de long et de 2,28 cm de diamètre avec transport de chaleur dans un écoulement turbulent de CO_2 à pression supercritique. Dans quelques expériences, le changement d'état du CO_2 entre l'entrée et la sortie du tube, couvrait toute la gamme supercritique entre les phases liquide et gazeuse et, dans d'autres, l'effet de la variation d'état à l'entrée, à travers la région supercritique, a été étudié. On a fait des mesures avec un écoulement vertical vers le haut ou vers le bas à travers le tube pour déterminer l'effet du changement de la direction de l'écoulement par rapport aux forces d'Archimède. Un ensemble complete de données a été obtenu pour des pressions de $7{,}00 \,.\, 10^6$ à $10{,}32 \,.\, 10^6$ Pascals, des flux de chaleur de $0{,}8 \,.\, 10^4$ W/m^2 et des flux de masse de 0,127 à 0,695 kg/s. Des variations du transport de chaleur local à partir de celui pour du CO^2 normal, liquide ou gazeux, d'une diminution par un facteur deux à des améliorations d'un ordre de grandeur.

WÄRMEÜBERGANG BEI ZWANGSKONVEKTION AN TURBULENTES CO_2 IM ÜBERKRITISCHEN BEREICH

Zusammenfassung—Es wurden die Wandtemperaturen eines 4,56 m langen Rohres mit einem Durchmesser von $2{,}28 \times 10^{-2}$ m bei Wärmeübergang an eine turbulente Strömung von CO_2 bei überkritischen Drücken gemessen. In einigen Versuchen überdeckte die Zustandsänderung von CO_2 zwischen Rohranfang und Rohrende den ganzen überkritischen Bereich zwischen der flüssigen und der gasförmigen Phase. In anderen Versuchen wurde die Auswirkung der Variation des Anfangszustandes im überkritischen Bereich untersucht. Es wurden Versuche gemacht mit vertikal nach oben und nach unten gerichteter Rohrströmung, um die Auswirkung eines Wechsels der Strömungsrichtung relativ zu den Auftriebskräften festzustellen. Ein umfassender Datensatz wurde erarbeitet für Drücke von $7,44 \times 10^6$ bis $10,32 \times 10^6$ N/m^2, Wärmesträme von $0,8 \times 10^4$ bis 35×10^4 W/m^2 und Massenströme von 0,127 bei 0,695 kg/s. Die Abweichungen des lokalen Wärmestromes gegenüber dem bei normalem gasförmigen oder flüssigen CO_2 reichten von Verringerungen um den Faktor zwei bis zu Verbesserungen um Grössenordnungen.

КОНВЕКТИВНЫЙ ТЕПЛООБМЕН ТУРБУЛЕНТНОГО ПОТОКА CO_2 В СВЕРХКРИТИЧЕСКОЙ ОБЛАСТИ

Аннотация—Измерялись температуры стенки трубы длиной 4,56 м, сечением $2,28 \times 10^{-2}$ ири теплообмене в турбулентном потоке CO_2 при сверхкритическом давлении. В некоторых экспериментах изучалось изменение состояния CO_2 на участке между входом и выходом из трубы во всей сверхкритической области между жидуой и газообразной фазой, а в других — влияние изменения состояния на входе в сверхкритической области. Измерения производились по вертикали вверх и вниз по потоку для определения влияния изменения направления течения на подъемные силы. Полуено достаточно много данных в интервале изменения параметров давления (7,44–10,32). 10^6 н/м², теплового потока $(0,8–35) \times 10^4$ вт/м², массового потока (0,127–0,695) кг/сек. Наблюдается снижение теплообмена по сравнению с теплообменом в обычном газообразном или жидком CO_2.