Experimental Studies of Buoyancy-influenced Convective Heat Transfer in Heated Vertical Tubes at Pressures Just Above and Just Below the Thermodynamic Critical Value

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In this paper some previously unpublished results are presented from a detailed experimental study of heat transfer to carbon dioxide in a vertical heated tube at pressures just above and just below the critical value. They exhibit some striking features which are associated with influences of buoyancy on turbulence and the turbulent diffusion of heat combined with very strong variation of fluid properties which could have important implications for applications where at supercritical and near-critical pressure is used to remove heat from the core of the reactor. The test section used in the study was a long, thin-walled stainless steel tube of internal diameter 19mm. An unheated flow development length was followed by one which was uniformly heated by direct electrical resistive means using alternating current. The heated section of the tube was instrumented with many thermocouples welded to its outer surface. Experiments were performed with both upward and down flow at both supercritical and subcritical pressures. A range of reduced pressure P/Pc from 1.12 to 0.88 was covered (the critical pressure Pc for CO2 is 73.8 bar and its critical temperature Tc is 31°C). Many of the experiments were performed at pressures very near to the critical value (reduced pressures in the range 1.027 to 0.982). At a series of particular values of flow rate and pressure the power applied to heat the test section was systematically varied in steps causing a variety of wall temperature distributions to be achieved. Examples of such distributions are presented in the paper and considered in the context of the SPWR application.

KEYWORDS: Supercritical and subcritical pressures, buoyancy influences, turbulent heat transfer, vertical passages, impairment of turbulent convection, SPWR

I. Introduction

Recently, there has been a renewed interest in heat transfer to fluids at pressures above the thermodynamic critical value, see Jackson1-3, driven by the need to develop innovative nuclear reactors which can compete in terms of cost, safety and reliability with other types of power generation plant. The Supercritical Pressure Water-cooled Reactor (SPWR), is thought to have the potential to improve the economics of nuclear power generation by taking advantage of three particular benefits associated with using water at supercritical pressure as a coolant, namely, improved advantage of three particular benefits associated with using water at supercritical pressure. The Supercritical Pressure Water-cooled Reactor (SPWR), is thought to have the potential to improve the economics of nuclear power generation by taking advantage of three particular benefits associated with using water at supercritical pressure as a coolant, namely, improved steam cycle efficiency, compact size and reduced complication, see Oka and Koshizuka3.

Results from heat transfer experiments using fluids at supercritical pressure in vertical passages sometimes exhibit striking features, particularly in the case of upward flow. This is not surprising in view of the strong dependence of the physical properties of such fluids on temperature and pressure, see Figure 1. There are particularly rapid variations of properties with increase of temperature along an isobar in the vicinity of the so-called pseudocritical temperature (the value at which the specific heat achieves its peak value). The fluid changes from being a liquid-like substance on a molecular scale to being a gaseous one without any discontinuity without the complication of any change of phase. As pressure is increased the pseudocritical temperature increases, the peak value of specific heat falls and the variation of the other properties with temperature becomes less severe. This pattern of behaviour is followed by most fluids. However, the similarity between different fluids is not strict; the manner in which the properties vary cannot simply be characterised in terms of normalised pressure P/Pc and normalised temperature T/Tc.

The diffusion of heat (by both molecular and turbulent action) can be strongly modified by the variations with temperature of thermal conductivity, density and specific heat within the fluid. Furthermore, density variations can cause the turbulence in the flow to be affected through the influence of buoyancy and also thermal expansion and, this affects the heat transfer by turbulent diffusion. With the fluid bulk temperature just below the pseudo-critical temperature such influences develop readily when the heat flux reaches a level which causes the temperature of the heated surface to exceed the pseudo-critical value. Density variations sufficient to generate strong buoyancy-induced motion superimposed on the forced flow field are then present. Heat transfer to fluids at pressures just above the critical value has attracted the interest of many researchers, see for example the review papers of Petukhov4, Hall5, Hendricks et al6, Hall, Jackson and Watson7, Jackson and Hall8, Hall and Jackson9 and Jackson et al10. The earliest studies of heat transfer to supercritical pressure fluids flowing through tubes were performed using water. They were done to assist with the development of once-through steam generators for conventional, fossil fuelled power stations operating at pressures above the critical value. Severe localized impairment of heat transfer was found with upward flow in vertical tubes when the wall temperature exceeded the critical
Figure 1  Variations of the properties of a supercritical pressure fluid with temperature and pressure
value, see Shitsman\textsuperscript{11} and Ackerman\textsuperscript{12}. This phenomenon was initially attributed to the presence of low conductivity, vapour-like fluid adjacent to the tube surface and likened to film-boiling. It was even given the name ‘pseudo-boiling’. However, anomalous distributions of wall temperature were also found in some experiments at lower flow rates with low power input where the tube temperature did not exceed the pseudo-critical temperature, see for example Vikrhev et al\textsuperscript{13} and Alferov et al\textsuperscript{14}. Under such conditions, the fluid was in a liquid-like state even in the wall layer region. That the anomalous behaviour was due to buoyancy became apparent later when results from experiments with ascending flow were compared with others for descending flow under otherwise identical conditions and found to be very different, see for example Shitsman\textsuperscript{15} and Hall and Jackson\textsuperscript{16}. In the present paper some hitherto unpublished results from such experiments, which were performed using carbon dioxide as the working fluid at pressures just above and just below the critical value, will be presented.

Although a considerable body of valuable experimental data exists on heat transfer to fluids at supercritical pressure and can be used to enable progress to be made with the thermal design of advanced reactors cooled by water at supercritical pressure, much of it is not directly applicable because the earlier research was aimed at the development of steam generators for conventional plant. In that application the need was for heat transfer data for water flowing in tubes of relatively large diameter, typically 20 mm, at pressures well above the critical value (about 240 bar). The conditions in the SPWR application are very different and there is a need not only for data covering normal operating conditions, where the flow rates will be suitable high and the pressure well above the critical value, but also fault conditions which include operation at reduced flow rate and near-critical and subcritical pressures. Very little work has been done which is applicable for operation at such pressures, a notable exception being that of Herkenrath et al\textsuperscript{17}. Therefore, the results presented here, which cover near critical and subcritical pressures are of particular relevance to fault studies for SPWR.

II. Experimental apparatus

This basic study of buoyancy-influenced heat transfer to carbon dioxide at pressures near the critical value was carried out using the arrangement shown in Figure 2. The experimental facility was designed to operate at pressures just above and just below the critical value of 73.8 bar and to accommodate vertical tube test sections of various diameters. The one used initially (see Figure 3) had an internal diameter of 19 mm. It was made from cold finished, seamless stainless steel tube of wall thickness 1.625 mm. As can be seen from Figure 3, an unheated entry length of 64 diameters was followed by a length of 129 diameters which was uniformly heated by direct electrical resistance means. The heated section was instrumented with over 160 chromel alumel thermocouples which were resistance welded to the outer surface of the tube at axial locations approximately one tube diameter apart, in some cases in sets of three around the circumference.

The inlet and outlet fluid temperatures were measured by two sets of thermocouples, which were placed inside the fluid stream at those locations so as to enable reliable average bulk fluid temperatures to be determined there. The fluid temperature rise through the test section was also measured directly by means of a thermopile comprising eight thermocouple junctions at inlet and outlet respectively connected in a differential arrangement. A mixing box containing several perforated copper discs was provided at the test section outlet to ensure that thorough thermal mixing of the fluid occurred there before its temperature was measured. All the thermocouples were connected through a scanner/switch unit to an ice ‘cold junction’ and the electrical signals were measured using a digital voltmeter having a resolution of 2.5 microvolts (equivalent to a temperature difference of about 0.06°C).

Before entering the test section the carbon dioxide passed through an electrical pre-heater unit and after leaving the test section it passed to a shell and tube cooler, the function of which was to remove all the heat supplied in the pre-heater and the test section. The fluid then entered a flow metering section before being returned by a canned centrifugal hydraulic circulating pump to the pre-heater at temperatures well below the pseudo-critical value (about 32°C at an operating pressure of 75.8 bar). The mass flow rate was found using a sharp-edged orifice plate flowmeter arrangement. The pressure difference between the tappings was measured using a mercury in glass manometer and thermocouples situated within a pocket in the flow downstream of the orifice plate were used to measure the fluid temperature. The arrangement conformed to the British Standards 1042 recommendations. The test section was designed so that it could be readily turned upside down with a minimal amount of modification to the pipework. In this way, heat transfer could be studied with either upward or downward flow.

The experimental results presented in this paper are in the form of a series of graphs of wall temperature versus distance along the heated section. Also shown are the inlet and outlet bulk temperatures and the bulk temperature variation along the tube calculated from an energy balance. A range of values of inlet fluid temperature, mass flow rate, heat input and pressure were covered in the experiments. In some cases the wall and bulk temperature spanned the pseudo-critical value, so that gaseous-like fluid was present within the thermal layer adjacent to the heated surface. In other cases the wall temperature did not exceed it and so the fluid was liquid-like even near the heated surface.

III. Experimental results and discussion

Figures 4 and 5 show the effects on wall temperature for upward and downward flow of varying the heat flux and mass flow rate with the CO\textsubscript{2} at a pressure just above the critical value (P=75.8 bar, P/P\textsubscript{c}∼1.03). The Reynolds number range was from about 2x10\textsuperscript{3} to 2x10\textsuperscript{4}. Very strong effects of buoyancy on heat transfer are evident in some of these results.

In the case of upward flow, striking axial non-uniformities of wall temperature developed when the pseudo-critical value was exceeded, especially at the higher
Figure 2  Line diagram of the experimental facility flow circuit without test section

Figure 3  Test section, stainless steel type 321; bore 19.05 mm; wall thickness 1.625 mm
Figure 4 Effects of varying wall heat flux and mass flow rate on wall temperature for upward and downward flow at a pressure just above the critical value ($P/P_c \sim 1.03$ with $Re$ in the range $2 \times 10^5$ to $10^6$)
Figure 5  Effects of varying wall heat flux and mass flow rate on wall temperature for upward and downward flow at a pressure just above the critical value (P/P_c ∼ 1.03 with Re in the range 6x10^4 to 2x10^5)
Figure 6 Effect on wall temperature of reducing the pressure just above the critical value (with $P/P_c$ in the range 1.120 to 1.095 and $Re \sim 2 \times 10^5$)
Figure 7 Effect on wall temperature of increasing the heat flux at a pressure just below the critical value \( P/P_c \sim 0.990 \) with upward flow at \( \text{Re} \sim 2 \times 10^5 \)
Figure 8  Effect on wall temperature of increasing heat flux further at a pressure just below the critical value ($P/P_c \sim 0.990$ with upward flow at $Re \sim 2 \times 10^5$)
Figure 9 Effect on wall temperature of increasing the heat flux at a further pressure just below the critical value (P/P_c ~0.985 with upward flow at Re~2×10^5)
**Figure 10** Effect on wall temperature of increasing the wall heat flux at a further pressure just below the critical value ($P/P_c \sim 0.982$ with upward flow at $Re=2 \times 10^5$)
Figure 11  Effects on wall temperature of varying (a) pressure, (b) heat flux and (c) inlet fluid temperature at subcritical pressures well below the critical value ($P/P_c \sim 0.955$ to 0.917 with upward and downward flow at $Re \sim 5 \times 10^4$)
values of flow rate covered. Under such conditions there was also considerable circumferential non-uniformity of wall temperature at some axial locations (the vertical lines shown on the wall temperature distributions provide an indication of the extent of this circumferential variation).

Figure 6 shows the effect on wall temperature distribution of varying the pressure (in the range of normalized pressure P/Pc from about 1.120 to 1.0095) for experiments where the heat flux was in each case high enough to cause severe axial non-uniformity of wall temperature. As can be seen, the form of the distribution does change as the pressure is varied.

Figures 7 to 10 show the effects of heat flux on wall temperature for pressures just below the critical value (P/Pc in the range 0.990 to 0.982) with upward flow at a Reynolds number of about 2x10^5. Three modes of heat transfer can be identified, namely, forced convection heat transfer to liquid carbon dioxide, at low values of heat flux, subcooled nucleate boiling, which occurred with increase of heat flux, and film boiling following a gradual departure from nucleate boiling. The striking non-uniformities of wall temperature found with upward flow at slightly supercritical pressures are present again in the film boiling region downstream of the location where departure from nucleate boiling occurred. It is clear that, in this range of pressures just below the critical value, the heat transfer behaviour under conditions of film boiling is very similar to that at pressures just above the critical value. A point worth noting is that under such conditions the effectiveness of heat transfer is lower at pressures just below the critical value than at pressure just above it.

Finally, in Figures 11(a), (b) and (c), results are presented from experiments performed with upward and downward at lower values of pressure in the high subcritical range (70.5 bar down to 67.7 bar, P/Pc from 0.955 to 0.917). The Reynolds number is about 5x10^5. Under these conditions the transition which takes place from nucleate to film boiling is quite different from that at higher values of pressure near to the critical value. Instead of being gradual, it is accompanied by an almost step increase of wall temperature. As can be seen, the behaviour is similar for upward and downward flow but in the latter case the step increase of temperature is delayed and is reduced considerably in magnitude. Thus, the film boiling process is modified by buoyancy in such a way that the effectiveness of heat transfer in the post transition region is significantly better for downward flow than for upward flow.

IV. Consideration of the results in relation to SPWR

The results presented here clearly could have important implications in connection with the use of water at supercritical pressure to remove heat from sensitive plant such as a nuclear reactor and it is appropriate to consider them in relation to SPWR application.

The diameter of the test section used in this study was considerably larger than the equivalent diameter of a sub-channel in the core of such a reactor (19 mm as compared with about 3 to 4 mm). Experiments with two test sections of smaller diameter, 8 mm and 5 mm, were also performed later. The results from those experiments will be reported separately (space limitations prevent them from being included here).

In the case of the experiments using the 8 mm diameter test section, buoyancy-induced localized impairment of heat transfer of the kind found with the 19 mm diameter tube occurred at a lower Reynolds number of about 4x10^3. With the 5 mm diameter test section the corresponding value was about 3x10^3. Thus for a passage of equivalent diameter 3 to 4 mm it would appear that with CO_2 as the working fluid similar effects might be found at a Reynolds number of about 2x10^3.

In Reference 16 Hall and Jackson offered an explanation of the phenomenon of impairment of heat transfer in heated tubes due to buoyancy in terms of the partial laminarisation of a flow due to reduction of shear stress across the buoyant layer of fluid adjacent to the heated wall, reduced turbulence production and impaired turbulent diffusion of heat. Such ideas led them to a criterion for the onset of buoyancy-induced impairment of heat transfer in terms of a dimensionless parameter formed by combing Grashof number and Reynolds number in the form Gr/Re^2 to characterize the strength of the buoyancy influence. The Grashof number was defined in term of the difference between the density of the density of the core fluid and the density of the buoyant wall layer fluid. Using this buoyancy parameter it is possible from the information reported here concerning the onset of severe localized impairment of heat transfer to estimate the Reynolds numbers at which similar effects might be expected with tubes of reduced diameter. This approach gives values which are broadly consistent with those found in the case of the two test sections of smaller diameter.

When the same approach is applied to the results of the experiments with supercritical pressure water of Shitsman and Ackerman it leads to an estimate of the Reynolds number for occurrence of severe localized impairment of heat transfer in water for a passage of equivalent diameter typical of an SPWR sub channel of about 2x10^5. Thus if during operation of SPWR at reduced flow rate the Reynolds number based on sub-channel equivalent diameter fell to such a value then severe localized impairment of heat transfer due to the influence of buoyancy might be encountered regions where the bulk temperature was slightly below the pseudocritical value and the heat flux was sufficient to raise the fuel pin temperature significantly above the pseudocritical value. Clearly the implications of such an occurrence need to be considered very carefully.

V. Conclusions

The experimental results presented here highlight the fact that heat transfer to fluids at pressures just above and just below the critical pressure can be strongly affected by buoyancy, with the result that for upward flow severe localized impairment of heat transfer is experienced even under conditions where the Reynolds number is relatively high (2x10^7 in the case of the present results).

The effect is particularly pronounced when the heat flux is high enough to cause the wall temperature to exceed the pseudo-critical value. Then the fluid in the near-wall region
has a much lower density than that in the core region and very considerable changes of all the fluid properties occur in the thermal layer where the temperature passes through the pseudo-critical value. Under such conditions the mean flow, turbulence and thermal fields are modified in such a way that the effectiveness of heat transfer is strongly affected.

It would appear that the worst condition in terms of heat transfer is encountered at pressures just below the critical pressure where the mode of heat transfer is film boiling. At such pressures the heat transfer behaviour exhibits very similar characteristics to that at slightly supercritical pressure.

With further reduction of pressure a stage is reached where departure from nucleate boiling is accompanied by an almost step increase of wall temperature and subcooled film boiling ensues. Under such conditions influences of buoyancy are still present and lead to quite different behaviour for upward and downward flow. In the latter case, transition to film boiling is delayed and gives rise to a significantly reduced step change in surface temperature.

The implications in advanced reactors of the phenomena encountered in the present study could be important, especially for operation under fault conditions at reduced flow rate and at pressures just above or just below the critical value. It will certainly be necessary to avoid conditions where such phenomena might be present in SPWR. In order to do this a sound understanding of the fundamental thermal physics of buoyancy-influenced heat transfer to fluids at near-critical pressure will be needed.

**Nomenclature**

- \( \epsilon_p \) specific heat \( \text{kJ/kg K} \)
- \( d \) tube diameter (m)
- \( G_r \) Grashof number (based on density difference) \( = g(\rho_b - \rho_0) \beta T \rho V^2 \)
- \( k \) thermal conductivity (W/mK)
- \( P \) pressure (bar)
- \( T \) temperature (°C)
- \( \text{Re} \) Reynolds number \( = \rho \mu d / \mu_v \)
- \( \nu \) velocity (m/s)

**Greek**

- \( \mu \) viscosity (kg/ms)
- \( \nu \) kinematic viscosity (m²/s)
- \( \rho \) density (kg/m³)

**Subscripts**

- \( b \) bulk
- \( c \) critical value
- \( pc \) pseudocritical value
- \( w \) wall

**References**