

REVIEW OF SOME EXPERIMENTAL STUDIES OF TURBULENT MIXED CONVECTION COVERING A WIDE RANGE PRANDTL NUMBER

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Abstract

The early experimental studies of buoyancy-influenced turbulent convective heat transfer to fluids flowing upwards and downwards in long uniformly heated vertical tubes were mainly performed using water at atmospheric pressure as the working fluid. In addition, some experiments using air were reported and even some using mercury. At that time there was also quite a lot of interest in heat transfer to water at supercritical pressure and also carbon dioxide. More recently, experimental results have been obtained using liquid sodium. The Prandtl numbers in the studies referred to above cover a wide range of values, being well in excess of unity under some conditions in the case of the supercritical pressure fluids and atmospheric pressure water, just under unity in the case of air, much less than unity in the case of mercury and even lower in the case of liquid sodium. Over the years a good general understanding has gradually been achieved of the complex manner in which buoyancy affects heat transfer in conventional fluids such as water and air. Up to a point, the behaviour in the case of a liquid metal such as mercury can be reconciled with such arguments. However, this is certainly not so in the case of liquid sodium. In the present paper results from a number of experimental studies of buoyancy-influenced heat transfer in vertical tubes are reviewed. This is done with the aim of providing a picture of observed behaviour consistent with our understanding of the basic mechanisms of convective heat transfer, taking account of the complicated manner in which the mean motion, turbulence and the heat transfer are affected by buoyancy. The starting point is to view convective heat transfer in wall shear flows in terms of the local balance between diffusion of heat (turbulent and molecular) and advection of heat by the flowing fluid. Prandtl number affects the radial temperature profile and therefore the variation of density across the shear flow and, in turn, the extent of the buoyancy-influenced region across the shear layer. Buoyancy affects the mean motion, aiding it in the case of upward flow and opposing it in the case of downward flow. Thus, in the case of buoyancy-aided flow advection of heat is increased and for buoyancy-opposed flow it is reduced. Buoyancy also has the effect of modifying the distribution of shear stress across a wall shear flow which affects the production of turbulence, reducing it with onset of buoyancy influence for upward flow and impairing heat transfer by diffusion. This trend eventually changes with further increase of buoyancy influence. For downward flow, turbulence production and turbulent heat transfer are systematically enhanced with increase of buoyancy influence. In turbulent flow at sufficiently high Peclet number (turbulent flow of fluids with Prandtl numbers of about unity and above), the diffusion of heat by turbulence is of

dominant importance and so the effects of buoyancy on heat transfer are as just indicated. However in the case of fluids having Prandtl numbers very much less than unity (where the Peclet number is smaller), diffusion of heat by turbulence is of secondary importance and so, even if buoyancy has had a significant effect on the turbulence in the flow, its effect on heat transfer is no longer dominant. So, enhancement of heat transfer occurs with upward flow due to the increased advection and impairment occurs with downward flow. These simple physical ideas enable the seemingly anomalous heat transfer behavior in the case of fluids having very low Prandtl number to be reconciled with the completely different behavior of fluids with higher Prandtl number. The main objective of this paper is to illustrate these ideas with reference to a selection of experimental data and to discuss them. The data used to do this was mostly produced by the author, his colleagues and students. Some of investigations are not widely known about. So, this paper should be helpful to those who currently have a particular interest in the topic covered.

Keywords: Turbulent mixed convection, buoyancy-influenced heat transfer, water, air, mercury, liquid sodium

Introduction

The term ‘mixed convection’ is used to describe the mode of heat transfer in fluids where the flow field is modified significantly due to non-uniformity of gravitational body force stemming from the temperature dependence of fluid density. It is usually thought of in terms of the concept of fluid buoyancy. Another term commonly used to describe mixed convection is ‘combined free and forced convection’. Mixed convection is mode of heat transfer encountered in a variety of very different and important applications. It is a complicated topic where the observed trends are sometimes quite contrary to what might be intuitively expected.

Much of the research on mixed convection has been done using uniformly heated circular tubes and there are many direct practical applications of such work. However, it should be noted that, under buoyancy-influenced conditions, the thermal boundary condition in the experiment can be an important factor determining flow behaviour and heat transfer.

The effectiveness of heat transfer by forced convection, as characterised by the Nusselt number Nu , depends on Reynolds number, Re , and Prandtl number, Pr . In the case of heat transfer by free convection Nusselt number depends on Grashof number, Gr , and Prandtl number, Pr . Thus, for combined free and forced convection it is not surprising that Nu depends on Re , Gr and Pr .

1. The effects of buoyancy on turbulent flow in vertical pipes

In all the experiments which will be considered here the flow entering the heated pipe was turbulent. When heat transfer takes place to a fluid flowing upward and downward through a vertical pipe, the mean flow and turbulence fields can both be modified as a result of the influence of buoyancy. The observed heat transfer behaviour can be readily explained by considering the influences of buoyancy on the velocity profile, the distribution of shear stress across the flow and the production of turbulence.

In the case of upward flow, the force due to buoyancy acting on the warmer fluid of lower density near the pipe wall aids the motion. Consequently, there is a tendency for the velocity

there to increase. In the case of downward flow, buoyancy opposes the motion and thus there is a tendency for the velocity in the near-wall region to reduce. However, the influence of buoyancy has the additional effect of modifying the variation of shear stress across the flow. This can have a profound effect on the turbulence present in the flow.

2. Effect of buoyancy on heat transfer

Under conditions of upward flow in a heated vertical passage, the turbulent shear stress is reduced, turbulence production is reduced and heat transfer is less effective, even though the advection of heat is improved due to the increased fluid motion in the near-wall region. However, above a certain threshold of buoyancy influence, turbulence production is restored, heat transfer recovers and can even become enhanced.

In contrast, with downward flow in a heated vertical passage turbulence production and heat transfer are both systematically enhanced with increase of buoyancy influence. These interactions between forced flow and buoyancy-induced motion lead to some surprising effects which will be illustrated and explained here mainly by examination of results obtained in experiments carried out at the University of Manchester by the author and his co-workers in the course of their research.

3. Fluids at supercritical pressure

The interest at Manchester University in turbulent mixed convection heat transfer dates back to the nineteen sixties when some experiments with water at supercritical pressure flowing upward in a vertical heated tube were reported by a Russian researcher, Shitsman [1]. These exhibited the striking localized effects shown in Figure 1. The researcher was studying the problem of tube overheating in once-through steam generators for conventional thermal power plant systems operating at supercritical pressure. In his experiments, highly localised impairment of heat transfer developed with increase of heat loading.

Later, the results shown in Figure 2 were obtained in experiments at Manchester using carbon dioxide at supercritical pressure. As can be seen, distributions of wall temperature exhibiting sharp localised peaks were again found with upward flow but such behaviour did not occur with downward flow. The effectiveness of heat transfer with upward flow was very different to that found with downward flow under otherwise identical conditions.

It was clear that observed behaviour in these experiments was clearly attributable to the influence of gravity on the flow. The peaks first developed when the wall temperature exceeded the pseudo-critical value. The fluid in the near-wall region then had physical properties similar to those of a gas whereas the remainder of the fluid was liquid-like. Thus, the near-wall fluid then experienced a strong force due to buoyancy which aided its motion. This might have been expected to improve the effectiveness heat transfer. However, serious localised impairment of heat transfer occurred.

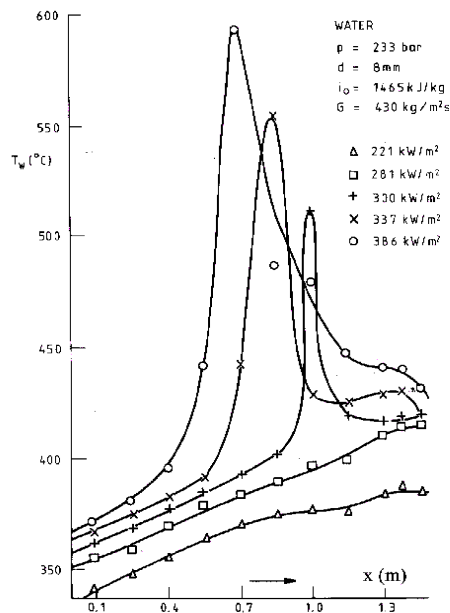


Figure 1 Localised impairment of heat transfer with water at supercritical pressure flowing upwards in a heated tube, Shitsman [1]

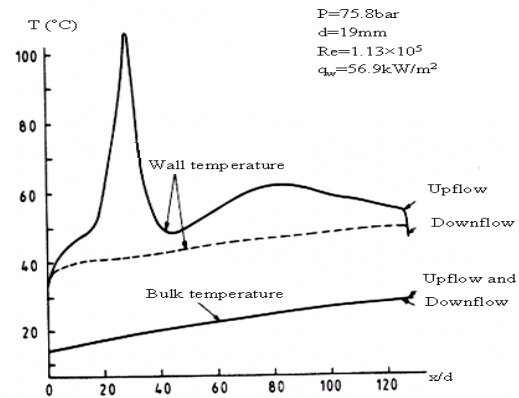


Figure 2 Influences of buoyancy on heat transfer to carbon dioxide at supercritical pressure for upward flow and downward flow, Evans Lutterodt [2] (see Hall and Jackson [3])

In further experiments, where the inlet fluid temperatures and heat fluxes were such that the wall temperatures did not exceed the pseudo-critical value (Figure 3), the results obtained still exhibited localized impairment of heat transfer in the case of upward flow. Although the fluid in the near-wall region was liquid-like its density was nevertheless lower than that of the fluid in the core flow region and clearly that there was still a significant influence of buoyancy.

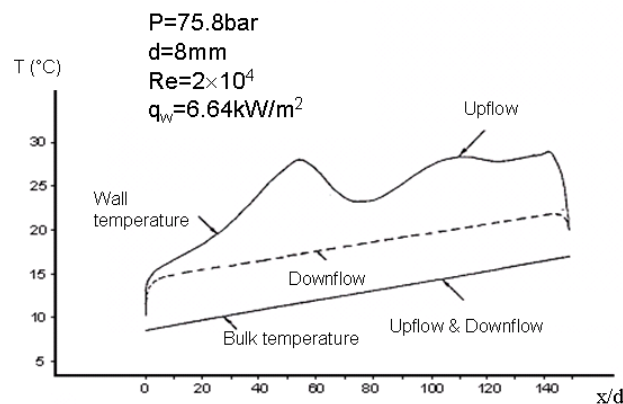


Figure 3 Heat transfer to liquid-like CO₂ at supercritical pressure with wall and bulk temperatures both below T_{pc} , Evans Lutterodt [2] (see Jackson and Hall [4])

Some experimental results for water at supercritical pressure where the wall temperatures were mostly, but not exclusively, below the pseudocritical value of pressure are presented on Figure 4.

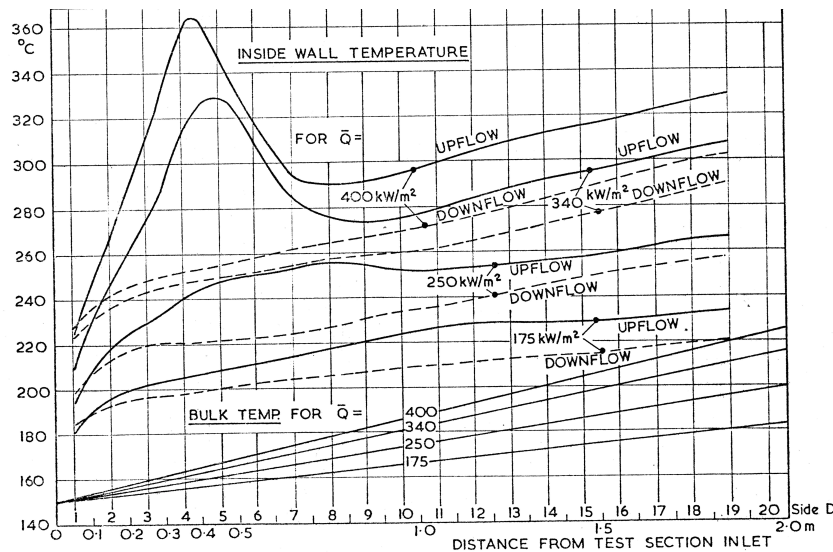


Figure 4 Mixed convection heat transfer to water at 250 bar for upward and downward flow; tube bore 22.5mm and mass velocity 380 kg/m²s, Watts [5] (see Watts and Chou [6])

From these experiments and also those for CO₂ presented on Figure 3 it is evident that impairment of heat transfer due to the influence of buoyancy might be encountered with ordinary fluids such as water or air under conditions of upward flow in heated tubes.

4. Turbulent mixed convection with conventional fluids

When, the localised impairment of turbulent heat transfer seen in experiments with fluids at supercritical pressure was identified as being due to buoyancy, the understanding of combined free and forced convection in conventional fluids was still rather limited. However, from about 1970 onwards there was a growing interest in turbulent mixed convection and, much further research was done on it. A number of comprehensive reviews of work on mixed convection in vertical passages with conventional fluids were published subsequently; see, for example, Jackson and Hall [4] and Jackson *et al* [7].

5. Observed effects of buoyancy on heat transfer in water and air

Impairment of the effectiveness of heat transfer occurs with upward flow of water and air at atmospheric pressure when the experimental conditions are adjusted so as to produce a significant influence of buoyancy by reducing the flow rate or by increasing the heat flux. The impairment of heat transfer builds up with increase of buoyancy influence until a stage is reached where the heat transfer coefficients fall to about 50% of that which might be expected at the same flow rate in the absence of buoyancy influence. Then, with further increase in the influence of buoyancy, recovery of heat transfer occurs until it even becomes enhanced in relation to that for forced convection. However, with downward flow a systematic improvement in effectiveness of heat transfer occurs with increase of buoyancy influence.

Contrasting behaviour with upward and downward flow was found in the investigation of Fewster [8], using water at atmospheric pressure in a heated vertical pipe of bore 100 mm, see Jackson et al [7] and Jackson and Fewster [9].

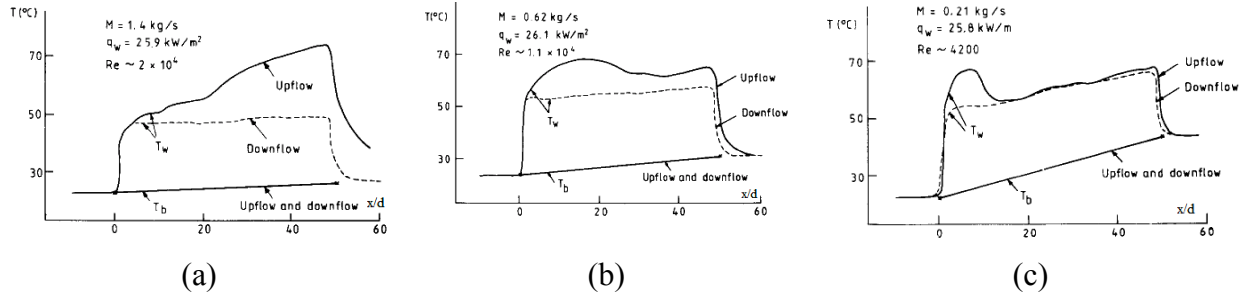


Figure 5 Turbulent mixed convection heat transfer with upward and downward flow of water at atmospheric pressure in a heated pipe of internal diameter 100 mm, Fewster [8].

A fuller picture of turbulent mixed convection with water flowing in a uniformly heated vertical pipe, was obtained later by Rouai [10] (see Jackson and Rouai [11]). Sample results from that study for a range of conditions with increasing buoyancy influence are presented in the form of axial distributions of Nusselt number for both upward and downward flow. The corresponding distributions of Nusselt number for forced convection determined using the well established empirical equation of Petukhov and Kirillov [12] are also shown. In Figure 6(a), development of impaired heat transfer with upward flow and enhancement of heat transfer with downward flow can both be seen. In the results shown on Figure 6(b), recovery of heat transfer effectiveness has occurred with upward flow and the enhancement of heat transfer with downward flow is increased. The influence of buoyancy is very strong in the results shown in Figure 6(c) and considerable enhancement of heat transfer is evident for both upward and downward flow. Furthermore, the results for upward and downward flow are surprisingly similar. Even though the Reynolds number is only 2500, values of Nusselt number of about 100 are achieved, which indicates that the flow is extremely turbulent.

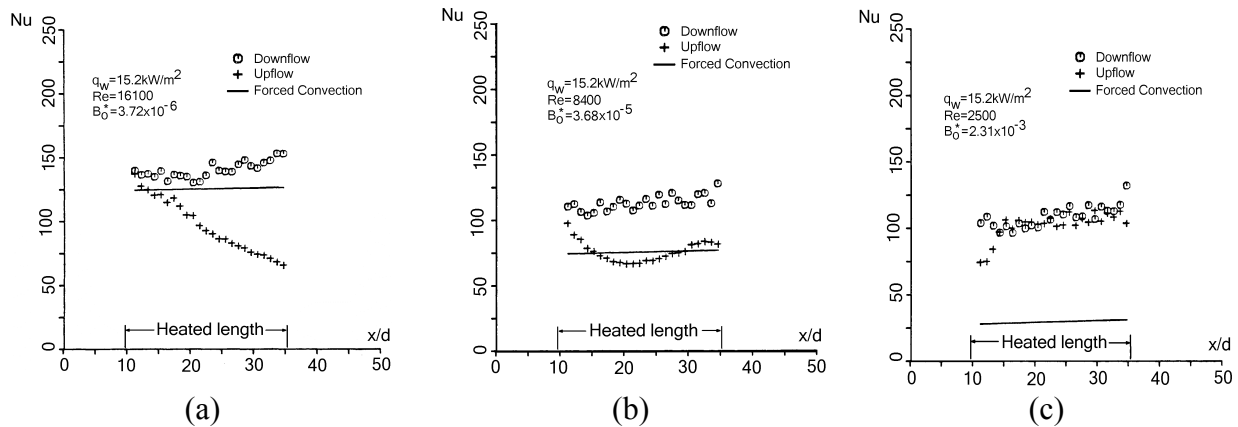


Figure 6 The experiments of Rouai [10]

In an experimental investigation carried out by Ejiogu [13] with upward flow of air in a relatively short heated pipe of diameter, 613 mm, impairment of heat transfer followed by

recovery was again found (see Byrne and Ejiogu [14]). In experiments with downward flow using a pipe of the same diameter, Axcell [15] found systematic enhancement of heat transfer due to buoyancy (see Axcell and Hall [16]). Later, Li [17] carried out a very detailed investigation of mixed convection heat transfer to air with upward and downward flow using a long heated tube (see Jackson and Li [18]). Samples of the results are shown on Figure 7. Distributions of Nusselt number for forced convection heat transfer with negligible influence of buoyancy calculated using the correlation equation of Petukhov, Kurganov and Gladuntsov [19] are also presented in each case.

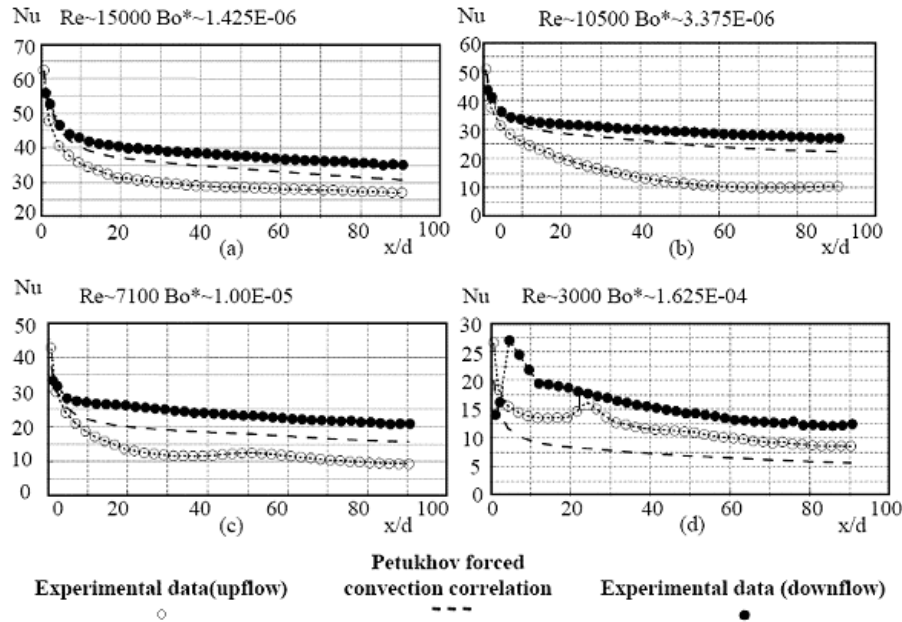


Figure 7 Turbulent mixed convection heat transfer to air at atmospheric pressure with upward and downward flow in a long uniformly heated tube, Li [17]

As can be seen, for upward flow impairment of heat transfer effectiveness in relation to that for forced convection occurred with onset of buoyancy-influence. This was followed with further increase of buoyancy influence by recovery and then enhancement of heat transfer. For downward flow, systematic enhancement of heat transfer in relation to that for forced convection occurred with increase of buoyancy influence.

6. Explanation of buoyancy-induced impairment and enhancement of heat transfer

In the case of upward flow in a heated pipe the buoyancy of the wall layer fluid in a heated flow helps to overcome the downward shear force exerted on it by the wall. Thus, a situation can be envisaged where the shear stress in the upward direction applied to the buoyant layer by the adjacent fluid further away from the wall is lower than it otherwise would be, compare curves (a) and (b) on Figure 8. Since, with a fluid such as air or water, the buoyant thermal layer is mainly within the viscous sub-layer and inner part of the buffer layer, this reduction of shear stress is experienced in the region where the turbulence production is concentrated. As a result, the production of turbulence is likely be diminished and the flow should take on some of the characteristics of a normal turbulent pipeflow not affected by buoyancy but at some lower value

of flow rate, and so reduced turbulence can be expected. If a condition were to be reached where the upward force due to buoyancy acting on the wall layer fluid was just sufficient to overcome the downward shear force exerted on it by the wall, the core fluid would not experience any shear stress. With further increase of buoyancy influence, the wall layer fluid should exert a force in the upward direction on the core fluid and the shear stress there becomes 'negative'. Then, the velocity profile in the core region will become inverted and if the shear stress becomes sufficiently negative, a stage will be reached where turbulence can be generated very readily in that region.

In the case of downward flow in a heated pipe the effect of buoyancy is in the opposite sense, so the shear stress in the wall layer region will be increased, compare curves (a) and (c) on Figure 8. Turbulence production will be enhanced and therefore, as the influence of buoyancy is increased the flow will progressively take on some of the characteristics of normal pipeflow, not affected by buoyancy, at higher and higher values flow rate.

The modification of mean flow and turbulence resulting from the influence of buoyancy affects both the advection and the diffusion of heat. With upward flow in a heated vertical pipe the effectiveness of heat transfer will tend to be improved as a result of the advection of heat being increased. However, it will be impaired as a result of reduced turbulent diffusion of heat and because the contribution of turbulent diffusion completely dominates that of molecular action in fluids such as air or water, the net effect of the onset of significant buoyancy influence in upward flow will be an impairment of the heat transfer process. As the strength of the buoyancy influence is increased, the effectiveness of heat transfer will eventually recover when turbulence production is restored as a result of the inversion of the velocity profile. In the case of downward flow in a heated pipe, the effectiveness of heat transfer will become systematically enhanced with increase of buoyancy influence as a result of the improved turbulent diffusion of heat, even though the flow in the near-wall region is retarded by the influence of buoyancy and the advection of heat is reduced.

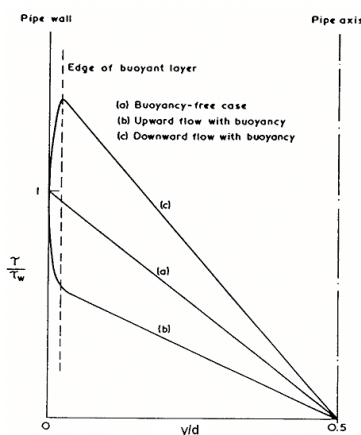


Figure 8 Influence of a buoyant wall layer on the radial distribution of shear stress

7. Turbulent mixed convection with liquid sodium

For a fluid such as liquid sodium which has a very low value of Prandtl number (typically 0.010-0.005) the effect of buoyancy on heat transfer in a vertical passage is quite different from that in the case of conventional fluids such as air or water. With liquid sodium it is found that mixed convection heat transfer is enhanced with buoyancy-aided flow and impaired with buoyancy-opposed flow, see Cotton, Jackson and Yu [20], Volchkov *et al* [21], Wendling *et al* [22] and Johnston [23], see Jackson, Johnston and Axcell [24]. This very different behaviour can be understood by considering the relative importance of the effects of molecular and turbulent diffusion of heat. For fluids such as air and water the latter effect is completely dominant but for a fluid such as liquid sodium, which has a very high thermal conductivity, this is not so, especially at relatively low values of Reynolds number in the turbulent range (low Peclet number). The thermal conductivity of liquid sodium is so high that diffusion by turbulent action is of greatly reduced relative importance. Thus, even though the turbulence in the flow might be strongly modified as a result of the influence of buoyancy distorting the velocity profile, the consequences of this in terms of diffusion of heat are relatively unimportant with sodium.

Thus, enhancement of heat transfer is found under buoyancy-aided conditions due to the increased advection of heat and impairment occurs under buoyancy-opposed conditions due to the reduced advection. The heat transfer trends exhibited are therefore similar to those found in laminar mixed convection in other fluids. Data obtained by Walton [25] in experiments with liquid sodium in a uniformly heated pipe of internal diameter 67 mm and heated length 2.4 m under conditions of turbulent mixed convection exhibit such trends are shown on Figure 9 (see Jackson *et al* [26]).

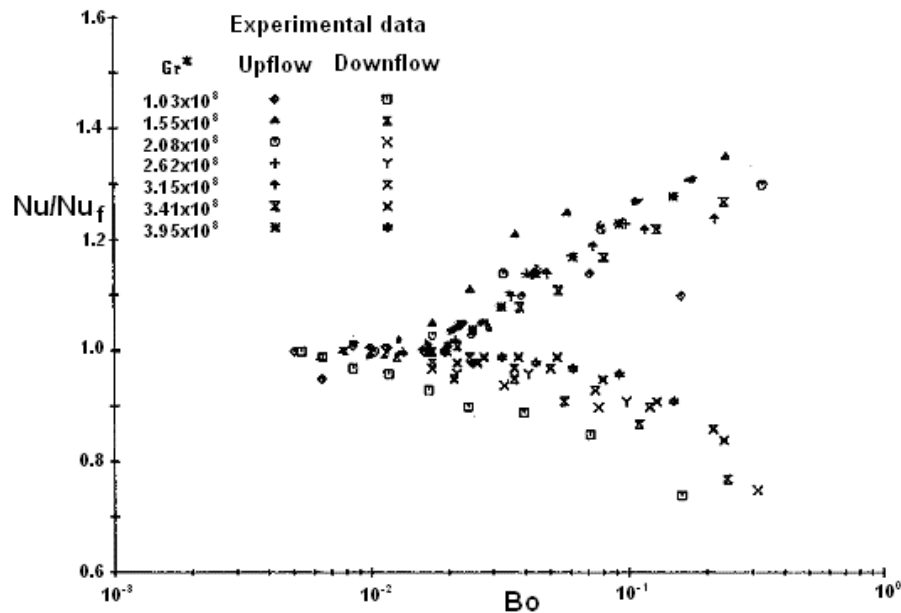


Figure 9 Turbulent mixed convection heat transfer to liquid sodium at relatively low Peclet number in a uniformly heated vertical pipe, Walton [25]

Conclusions

It can be seen that the effects of buoyancy on heat transfer in vertical tubes are very different in fluids at supercritical pressure, conventional fluids, liquid metals such as mercury and molten metals such as liquid sodium.

As can be seen from the results presented here for fluids at supercritical, the extent to which the fluid properties vary strongly with temperature can result in some very striking behaviour.

The physical properties of the fluids considered here are very different and the combination of fluid properties $\eta c_p / k$ (the dimensionless parameter Prandtl number) can be seen to be particularly important in characterizing such effects.

The influence of buoyancy on the basic mechanisms by which heat is transferred by convection in moving fluids, namely, advection (the transport of energy by a flowing fluid) and diffusion (the transport of energy by conduction and turbulent action), are of key importance.

The first of these mechanisms depends directly on whether buoyancy is aiding the motion (upward flow in a heated tube) or opposing it (downward flow in such a tube). The second one can be crucially dependent on the effect of buoyancy on the turbulence generation in the fluid but also depends on the relative importance of the diffusion of heat by turbulence and conduction. This, in turn, depends on the product of Prandtl number and Reynolds number (Peclet number).

These ideas have all been illustrated by the selection of experimental data presented here which has mostly come from a lengthy ongoing series of studies carried out over the years by the author, his students and his colleagues at the University of Manchester. The material used in this paper has been extracted from notes prepared by the author for an 'in house' training course on 'Mixed convection Heat Transfer - Review of the Fundamentals, State of the Art and Design Procedures' which is offered to Universities and research organisations.

Nomenclature

Bo^*	Buoyancy parameter for the uniform wall heat flux case, $Bo^* = Gr^* / Re^{3.425} Pr^{0.8}$
d	Pipe diameter (mm)
i	Enthalpy (kJ/kg)
c_p	Specific heat at constant pressure (J/kgK)
G	Mass velocity (kg/m^2s)
Gr^*	Grashof number for the uniform wall heat flux case, $Gr^* = g\beta q_w d^4 / (\lambda \nu^2)$
M	Mass flow rate (kg/s)
Nu	Nusselt number, $Nu = \alpha d / \lambda$
Nu_f	Nusselt number for forced convection, i.e. with negligible influence of buoyancy
p	Pressure (bar)
Pr	Prandtl number, $Pr = \eta c_p / \lambda$
q_w	Wall heat flux (kW/m^2)
Re	Reynolds number, $Re = Gd / \eta$
T	Temperature (K or °C)
T_b	Mixed mean (bulk) temperature (K or °C)
T_w	Wall temperature (K or °C)

T_{pc}	Pseudocritical temperature (K °r oC)
x	Axial coordinate from the start of heating (m)
y	Transverse coordinate, measured across the flow from the wall (m)

Greek letters

α	Heat transfer coefficient, (W/m ² K), $\alpha = q_w / (T_w - T_b)$
η	Dynamic viscosity (N/ms)
λ	Thermal conductivity (W/mK)
τ	Shear stress (N/m ²)
τ_w	Wall shear stress (N/m ²)

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