A STUDY OF THE INFLUENCE OF BUOYANCY ON TURBULENT FLOW IN A VERTICAL PLANE PASSAGE

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ABSTRACT

Results are presented from an experimental study of buoyancy-influenced, turbulent flow of air through a vertical plane passage with one wall uniformly heated and the opposite one adiabatic. Detailed measurements of velocity and turbulence were made, using Laser Doppler Anemometry, for a range of conditions over which the influence of buoyancy on the flow was systematically varied by changing the heating rate and the mass flow rate. Profiles of fluid temperature were obtained using a fixed rake of thermocouples. Detailed measurements of wall temperature were made which enabled local values of heat transfer coefficient on the heated surface to be determined.

INTRODUCTION

Turbulent mixed convection in vertical passages is a mode of heat transfer which can be encountered in a variety of sensitive engineering applications. A good example is the cooling of nuclear reactors, where the influence of buoyancy on heat transfer can be a matter of considerable importance.

Much attention has been concentrated by researchers on the problem of heat transfer to air flowing through long, uniformly heated, vertical circular tubes [see, for example, Steiner (1971), Carr et al. (1973), Easby (1978), Jackson and Hall (1979), Polyakov and Shindin (1988), Jackson et al. (1989), Vilemas et al. (1992) and Li and Jackson (1998)]. As indicated below, such studies have yielded surprising results.

In the case of buoyancy-aided flow, the fluid is accelerated near the heated surface with onset of buoyancy influence and, consequently, its convective capability is improved. In spite of this, however, the effectiveness of heat transfer is reduced. This apparent anomaly can be explained by the fact that the shear stress in the layer of buoyant fluid near the heated surface is reduced, turbulence production is impaired and the diffusion of heat by turbulence becomes less effective. Beyond a certain threshold of buoyancy influence the shear stress is affected to such an extent that, having been reduced to zero in the near-wall region, it becomes sufficiently negative further out for significant turbulence production to take place there. The effectiveness of heat transfer then begins to improve with further increase of buoyancy influence.

In the case of buoyancy-opposed flow, the fluid near the heated surface is retarded with the onset of buoyancy influence with the result that its convective capability is reduced. However, the effectiveness of heat transfer is improved. This can be explained in terms of increased shear stress in the region near the heated surface, increased turbulence production and, therefore, more effective diffusion of heat by turbulence.

Although these explanations of observed heat transfer behavior in buoyancy-influenced pipe flow are generally accepted, not much is available in the way of detailed measurements of velocity and turbulence to support them. This study of turbulent flow and heat transfer in a vertical plane passage with one surface heated and the opposite one adiabatic has yielded measurements which provide direct evidence of mechanisms involved.

EXPERIMENTAL INVESTIGATION

The test section used in this investigation (see Figure 1) was a vertical passage of rectangular cross section 612 mm by 80 mm (aspect ratio 7.65:1) and height 4.0 m. One wall was heated by means of twenty separate plate-type heaters which had an instrumented insulation pack of high thermal resistance behind them to minimize heat losses to the surroundings and enable such losses to be reliably accounted for. The opposite wall and the two side walls were unheated and thermally insulated on the outside so as to achieve an approximately adiabatic thermal boundary condition. The walls were made of rigid stainless steel sheet 3 mm thick and were arranged so that they could each expand freely as their temperatures changed whilst remaining plane. The inside surfaces of the passage had a polished mirror-like finish with thermal emissivity of 0.12

The test section and flow circuit were arranged so that ambient air could be drawn into the test section either at the bottom as shown in Figure 1, to give upward (buoyancy-aided) flow, or at the top to give downward (buoyancy-opposed) flow. A standard orifice plate flow-metering

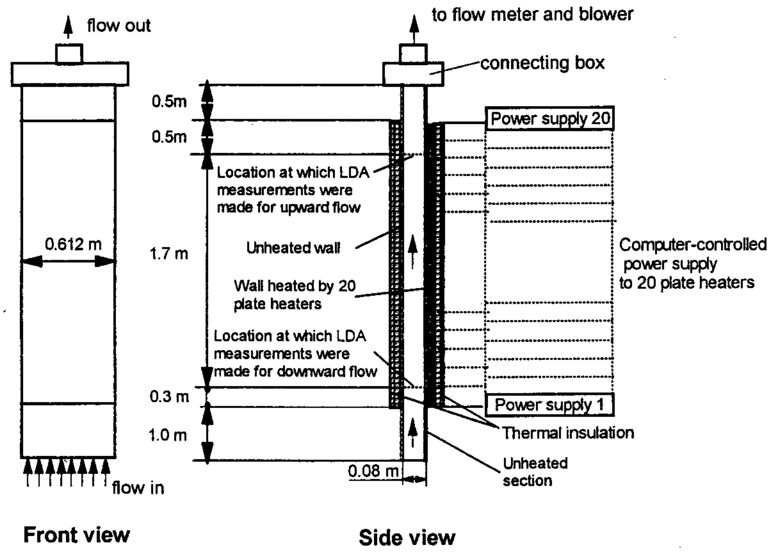

Figure 1 Test section (upward flow arrangement)

section was installed downstream of the test section to enable the flow rate of air to be accurately measured. Some honeycomb material was installed within the test section at inlet to straighten the flow.

The power supplied to each of the heaters on the test section wall could be controlled automatically by means of a multi-channel, computer-based system which enabled prescribed axial distributions of temperature to be achieved on that wall. Alternatively, prescribed distributions of heat input could be applied. In the study reported here, the power supply system was used in this mode with uniform heat input.

Over 140 chromel-alumel thermocouples were welded to the outside of the stainless steel walls of the test section to enable their temperature distributions to be measured in detail. The signals from these thermocouples were supplied to a 208 channel Intercole scanning system controlled by a Pentium PC. Software was developed which combined the monitoring, data logging, power control, measurement and processing activities into one single package. Knowing the wall temperature distributions and the surface emissivity, the radiative heat transfer between the test section walls could be calculated. Local values of the convective heat flux from the heated wall could be determined knowing the measured power input to each of the heaters, taking account of both thermal radiation and heat losses to the surroundings. Hence, local values of heat transfer coefficient could be found. The unheated walls were very well insulated on the outside and so most of the heat which they received by thermal radiation was transferred by convection to the air flowing over them within the test section.

Windows were installed on one of the side walls of the test section to enable velocity and turbulence quantities to be measured in the mid plane of the flow using Laser Doppler Anemometry. The two-component LDA system consisted of a 4 Watt argon-ion laser generator, a transmitter, a fibre optic probe, two photo-multipliers, two burst spectrum analysers and a further computer-based data acquisition system.

A comprehensive programme of experiments was completed using this equipment. This yielded detailed information concerning local heat transfer coefficients on the heated surface and profiles of velocity, turbulence and fluid temperature. A range of conditions was covered, over which the influence of buoyancy on the flow varied from being negligibly small to very strong. This was achieved by changing the power input to the heaters and the mass flow rate of air. Measurements of velocity and turbulence were also made without any heating applied (isothermal flow). The range of Reynolds number Re covered was from 44000 down to 7000 and Grashof number, based on wall heat flux Gr*, was varied from 3.0×10^8 to 9.0×0^9. The characteristic dimension used in Re and Gr* was twice the spacing between the heated and unheated walls of the test section. A buoyancy parameter $Bo^*[=Gr^*/(Re^{3.425}Pr^{0.8})]$, based on ideas developed by Jackson and Hall (1969, 1979) and updated by Jackson et al. (1989), was used to characterise the magnitude of buoyancy influence on the turbulent flow and heat transfer. The range of Bo* covered was from 10^{-7} to 10^{-4}.

RESULTS AND DISCUSSION

We begin by considering the heat transfer results. Firstly, the following correlation equation for developing, variable property forced convection was established using heat transfer data from those of our experiments performed under conditions where influences of buoyancy were negligible (ascertained by comparing profiles of velocity and turbulence quantities obtained with and without heating to check that they were identical).

$$Nu_f = C\times0.0228Re^{0.79}Pr^{0.4}\left(\frac{T_w}{T_b}\right)^{-0.34} \qquad (1)$$

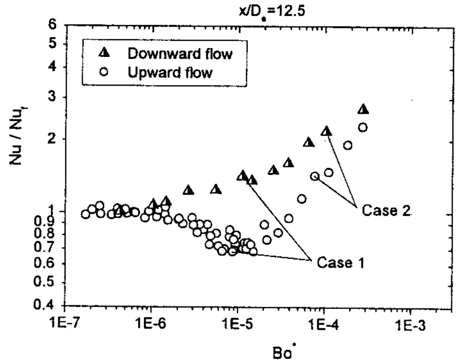

Figure 2 Buoyancy-influenced heat transfer

Table 1: Bo* and Nu/Nuf for selected cases

	Flow Direction	Bo*	Nu/Nu_f
Case 1	Upward	9.72E-06	0.68
	Downward	1.08E-05	1.41
Case 2	Upward	8.06E-05	1.42
	Downward	1.03E-04	2.18

C is a function of x/De and Re which describes the combined effect of simultaneous flow and thermal development along the test section and is given by

$$C = 1.0 + \left[0.69 + \frac{5520}{\mathrm{Re}}\left(\frac{x}{D_e}\right)^{-0.7}\right]\left(\frac{x}{D_e}\right)^{-0.29}\exp\left(-0.07\frac{x}{D_e}\right) \tag{2}$$

Next, the influence of buoyancy on heat transfer was examined by presenting data for upward and downward flow at the axial location x/De=12.5 (where the profiles of velocity, turbulence quantities were measured) in terms of Nusselt number ratio Nu/Nu_f and buoyancy parameter (see Figure 2). As can be seen from the figure, the impairment of heat transfer followed by recovery and enhancement of heat transfer found with upward flow in heated circular tubes and the systematic enhancement of heat transfer found with downward flow both occurred in the present experiments with a plane passage heated on one surface only. However, the onset of significant effects of buoyancy occurred when Bo* reached about 10^{-6} as compared with the value of about 5×10^{-7} for a circular tube and the maximum impairment of heat transfer with upward flow occurred when Bo^* was about 10^{-5} rather than about 10^{-6}. On the basis of the picture of buoyancy-influenced heat transfer provided by Figure 2, two particular cases have been chosen from present study for detailed examination. Table 1 shows the values of Bo* and Nu/Nu_f for upward and downward flow for each of these cases.

As can be seen from Figure 2 and Table 1, case 1 exhibits considerable impairment of heat transfer with upward flow and considerable enhancement of heat transfer with downward flow. Figures 3(a) to 3(d) show the profiles of velocity and turbulence quantities for unheated (isothermal) flow and the corresponding profiles for upward and downward flow with heating. In those figures the heated surface is where the normalised transverse coordinate y/b has the value unity. The unheated surface is where y/b is zero.

The distortion of the velocity profiles due to buoyancy aiding or opposing the flow can be clearly seen on Figure 3(a). The modification of shear stress within the flow due to buoyancy is clearly apparent from Figure 3(b), which shows the profiles of normalised turbulent shear stress. For upward flow the shear stress is very small near the heated surface and becomes negative, but still small in magnitude, over a considerable region further out. In contrast, for downward flow the shear stress is increased over the same region compared with that for unheated flow.

Effects of buoyancy on turbulence intensity are clearly evident on Figures 3(c) and 3(d), particularly in the case of the transverse component (Figure 3(d)). This is greatly reduced on the heated side with upward flow and significantly increased with downward flow. Thus, effects of buoyancy on turbulence consistent with impairment of turbulent heat transfer with upward flow and enhancement with downward flow are evident.

The unheated wall receives heat by thermal radiation from the heated one and this is mainly removed by the air flowing over it within the test section. That this convection process is also buoyancy-influenced is evident from the fact that both shear stress and turbulence intensity are significantly reduced near the the unheated wall with upward flow. The local value of Bo* (calculated using the incident radiant heat flux at that axial location) is about 1.5×10^{-6}. Thus, on the basis of the behaviour seen on Figure 2, we might expect that there would be some effects of buoyancy on the flow over the unheated wall.

Case 2 exhibits even stronger effects of buoyancy on heat transfer which cause the enhancement of heat transfer for both upward and downward flow (again, see Figure 2 and Table 1). Figures 4(a) to 4(d) show the profiles of velocity and turbulence quantities for this case. The distortion of the velocity profiles due to buoyancy aiding and opposing the flow (Figure 4(a)) is even stronger than for Case 1, as also is the modification of the shear stress within the flow (Figure 4(b)). Near the heated wall, apart from the region very close to it, negative shear stresses of considerable magnitude are present when the flow is aided by buoyancy and greatly increased positive shear stresses are present when the flow is opposed by buoyancy. The consequences of these influences of buoyancy on turbulence intensity are clearly apparent on Figures 4(c) and 4(d), where strong increases can be seen for both upward and downward flow. Thus, effects of buoyancy on turbulence on the heated side consistent with

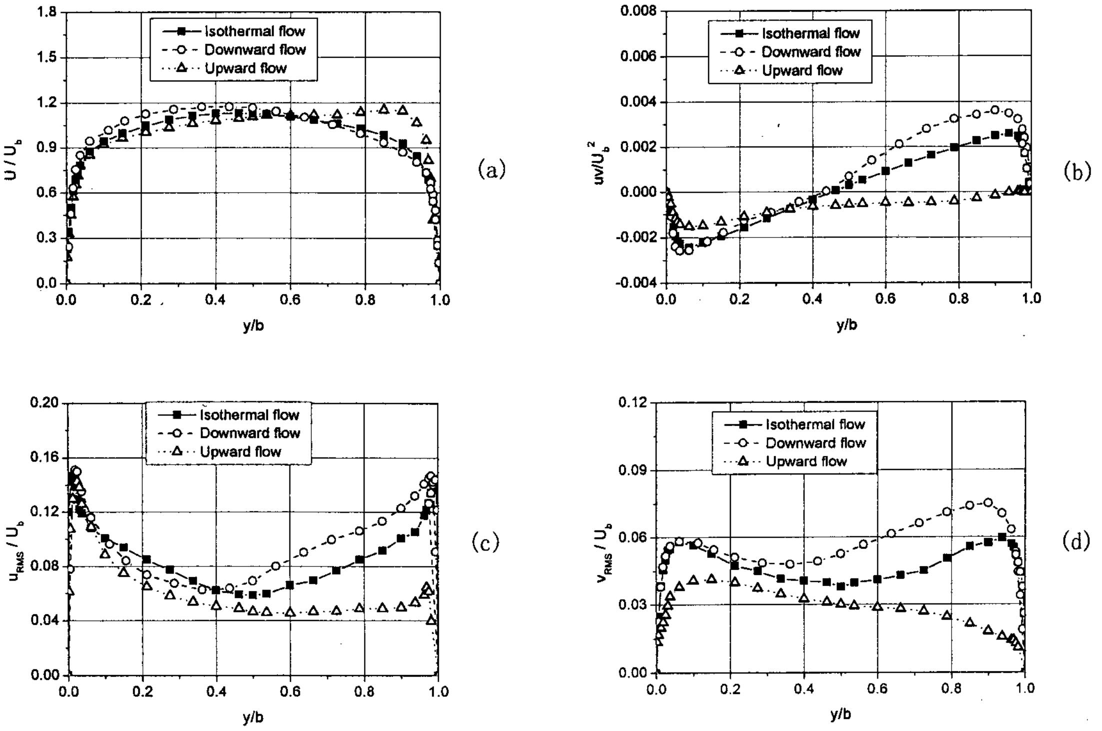

Figure 3 Profiles of velocity and turbulence quantities for case 1

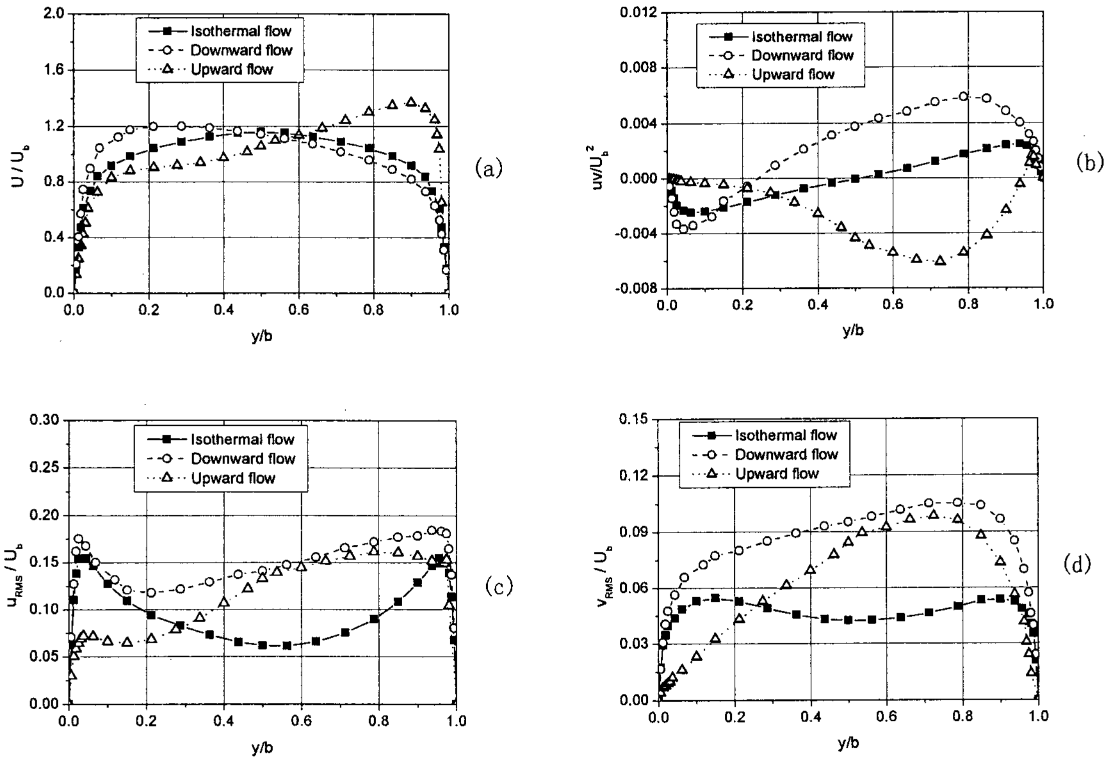

Figure 4 Profiles of velocity and turbulence quantities for case 2

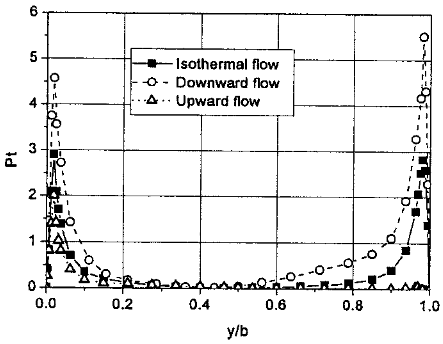

Figure 5 Turbulence production for case 1

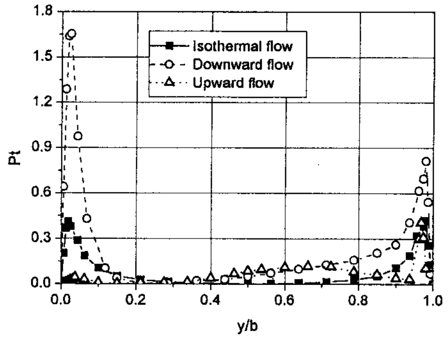

Figure 6 Turbulence production for case 2

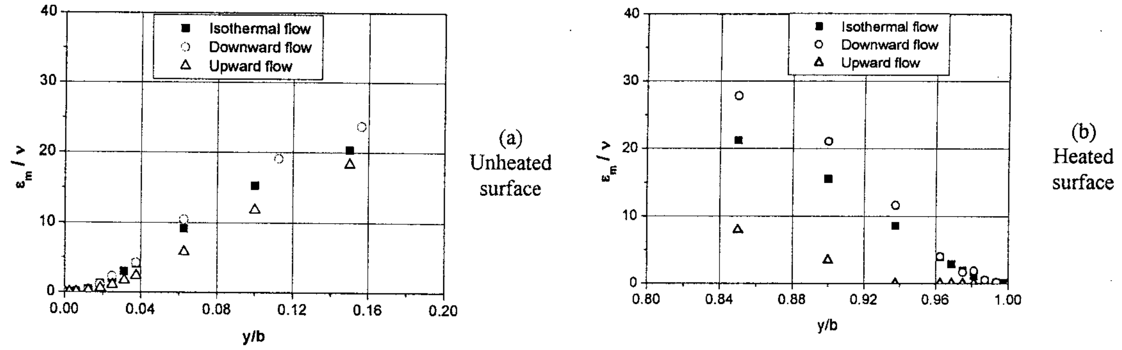

Figure 7 Normalized turbulent diffusivity near unheated and heated surfaces for case 1

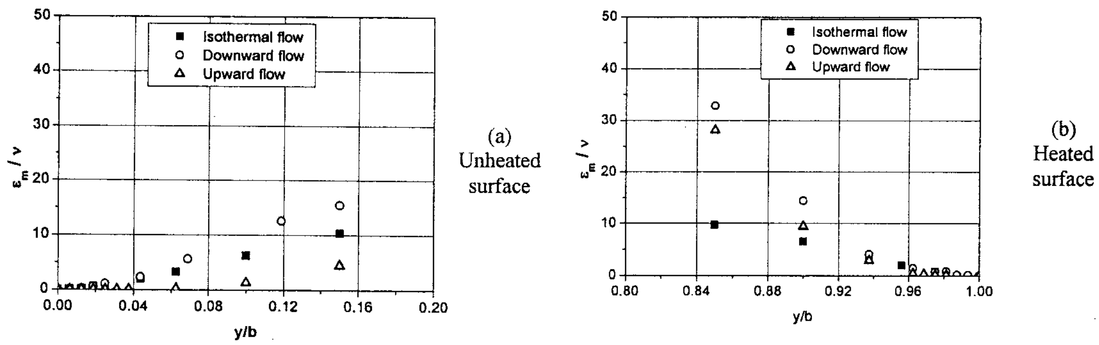

Figure 8 Normalized turbulent diffusivity near unheated and heated surfaces for case 2

enhancement of turbulent heat transfer with both upward and downward flow are clearly evident.

Near the unheated wall, where the incident thermal radiation is removed by convection, there is again clear evidence of buoyancy-influenced flow (the local values of Bo* on that surface are, respectively, 10^{-5} and 7×10^{-6}). As can be seen, there is a region near the unheated wall where the shear stress is greatly reduced with upward flow and significantly increased with downward flow. Very much reduced values of turbulence intensity are seen near the unheated wall with upward flow and increased values are seen with downward flow.

That the effects of buoyancy on turbulence seen on the profiles of turbulent shear stress and turbulence intensity shown in Figures 3 and 4 are due to the modification of the turbulence production can be seen by inspection of Figures 5 and 6, respectively. These two figures show profiles of turbulence production (the product of turbulent shear stress and velocity gradient) which is given the symbol P_t here. Figure 5 presents the results for case 1, where it can be seen that with upward flow the production of turbulence in the boundary layer on the heated wall is completely inhibited and with downward flow it is enhanced, not only near the surface but also well away from it. In the boundary layer on the unheated wall there is also evidence of reduced turbulence production with upward flow and increased turbulence production with downward flow. Figure 6 shows the corresponding results for case 2, where it can be seen that with upward flow turbulence is produced not only in the shear layer near the heated wall but also out in the core flow well beyond the location where the velocity reaches its peak value. In the same region the turbulence production with downward flow is seen to be significantly increased.

Near the unheated wall turbulence production is almost completely inhibited with upward flow but is strongly increased with downward flow. The very much reduced turbulence in the boundary layer on the unheated side with upward flow and the increased turbulence with downward flow is probably the reason why the effectiveness of heat transfer from the heated wall is so much less with buoyancy aiding the flow than it is with buoyancy opposing the flow.

The effects of buoyancy on the build up of the normalised turbulent diffusivity of momentum ε_m/ν (or ratio of turbulent viscosity to molecular viscosity μ_t/μ) near the heated and unheated walls can be seen for cases 1 and 2, respectively, in Figures 7 and 8.

The results for case 1 (Figure 7) show that with upward flow there is a strong reduction in turbulent diffusivity near the heated surface which corresponds to a big increase in viscous sub-layer thickness. With downward flow there is some indication of an increase in diffusivity and therefore a decrease in sub-layer thickness, but not a big one. Near the unheated surface the trends are similar but much smaller. The corresponding results for case 2 (Figure 8) show that near the heated wall there is an increase of turbulent diffusivity with both upward and downward flow, whereas, near the unheated wall the diffusivity is greatly reduced with upward flow (indicating that the viscous sub-layer there is much thicker) and is slightly increased with downward flow.

CONCLUSIONS

The results presented here show that reduced or increased turbulence production as a result of distortion of the mean flow field is the dominant mechanism by which the effectiveness of heat transfer in vertical heated passages is modified as a result of the influence of buoyancy. The modification of turbulence production leads to impaired or enhanced turbulent diffusion of heat.

NOMENCLATURE

b	distance between the unheated and heated walls
Bo*	buoyancy parameter, $Gr^*/Re^{3.425}Pr^{0.8}$
c_p	specific heat at constant pressure
C	flow and thermal development function
D_e	equivalent diameter, 2b
Gr*	Grashof number based on wall heat flux, $g\beta q D_e^4/(\nu^2 k)$
h	heat transfer coefficient, $q/(T_w-T_b)$
k	thermal conductivity
Nu	Nusselt number, hD_e/k
Pr	Prandtl number, $\mu c_p/k$
P_t	Turbulence production, $-\rho\overline{uv}\partial U/\partial y$
Re	Reynolds number, U_bD_e/ν
q	wall heat flux
T_w	wall temperature (absolute)
T_b	bulk fluid temperature (absolute)
u	axial component of turbulent velocity fluctuation
U	axial component of time mean local velocity
U_b	bulk fluid velocity
v	transverse component of turbulent velocity fluctuation
x	axial coordinate measured from start of heating
y	transverse coordinate from the unheated wall
β	thermal expansion coefficient
ε_m	turbulent diffusivity of momentum
μ	absolute viscosity
ν	kinematic viscosity, μ/ρ
ρ	density

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