Int. J. Heat Mass Transfer. Vol. 21, pp. 911–921
0017-9310/78/0701-0911 $02.00/0

SPACE–TIME CORRELATION MEASUREMENTS IN A TURBULENT NATURAL CONVECTION BOUNDARY LAYER

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(*Received* 8 *June* 1977 *and in revised form* 2 *December* 1977)

Abstract—Spatial correlations normal to the wall and longitudinal space–time correlations of temperature fluctuations have been measured. The relative independence of the flow in the sublayer from that outside has been noted. In the transition region a strongly periodic phenomenon was observed with characteristics which agree with those suggested by linear stability analyses. The decay of the "memory" of the turbulence in the fully turbulent region, was found to be similar to that observed in grid turbulence and in a forced flow boundary layer. The important scales of the turbulence were found to vary relatively slowly with distance normal to the wall, outside the sublayer, indicating a fairly uniform turbulence structure.

NOMENCLATURE

T, instantaneous temperature;
g, specific gravitational force;
β, coefficient of cubical expansion;
ν, kinematic viscosity;
r_1, distance between probes in x direction;
r_2, distance between probes in y direction;
x, distance from leading edge of plate;
y, distance normally away from plate;
Gr_x, $= g\beta(T_W - T_\infty)x^3/\nu^2$, local Grashof number;
δ, thermal boundary-layer thickness;
u, instantaneous velocity in x direction;

$$R_{T'}(r_2), \quad = \frac{\overline{T'(y)T'(y+r_2)}}{[\overline{T'^2(y)}]^{1/2}[\overline{T'^2(y+r_2)}]^{1/2}};$$

$$R_{T'}(r_1,\tau), \quad = \frac{\overline{T'(x,t)T'(x+r_1,t+\tau)}}{[\overline{T'^2(x,t)}]^{1/2}[\overline{T'^2(x+r_1,t+\tau)}]^{1/2}};$$

$$R_{u'T'}, \quad = \frac{\overline{u'T'}}{(\overline{u'^2})^{1/2}(\overline{T'^2})^{1/2}};$$

τ, delay time.

Subscripts

W, conditions on surface of plate;
∞, conditions outside boundary layer.

Superscripts

$\bar{}$, mean value;
$'$, fluctuating part.

1. INTRODUCTION

THE PRESENT authors are not aware of any existing works on correlations in a natural convection boundary layer. There are however several important works dealing with forced flows [1–6] etc.

The notation used in this work follows that of Tritton rather than that of Favre *et al.* The space–time correlation in the direction of the mean flow reported by Sabot and Comte-Bellot [1, 2] refers to conditions in a pipe but they may be expected to be generally similar to the correlations in a boundary layer. The scalar nature of temperature means that the temperature–temperature correlations are less extensive than the velocity–velocity correlations so that only a few of the correlations reported by Tritton are comparable with the present work. The work of Favre *et al.* has covered a range of correlations and in particular [4] deals with space–time correlations of temperature in a forced flow boundary layer.

The present work reports (i) spatial-correlations of temperature fluctuations in a direction normal to the surface, (ii) space–time correlations of temperature fluctuations in the direction of the mean flow and (iii) the $u'T'$ correlations. From these correlations, some of the scales of the turbulence are determined.

The work was carried out in the department of Mechanical Engineering at Queen Mary College, London, as a part of a more general research undertaken by one of the authors in the Heat Transfer Laboratory of E.N.S.M.A., Poitiers.

2. EXPERIMENTAL ARRANGEMENT

The vertical plate 0.6 m wide and 2.75 m high used to generate the natural convection boundary layer in this work was originally constructed from the work of Cheesewright [7]. The plate was maintained at a constant temperature of approximately 62°C by electrical heaters sandwiched between the two halves of the plate. Side walls of perspex extended 0.26 m normal to the plate from its vertical edges, over its full length.

The temperature of the laboratory in which the plate was situated, was thermostatically controlled but it was not possible to eliminate a small gradient 1.5–2.0°C/m in the vertical direction.

A traversing gear described by Smith [8] permitted traverses to be made perpendicularly to the surface of the plate (in the y direction) at different vertical positions (x direction). The resolution of the position indication was 0.002 mm $0 < y < 10$ mm, 0.1 mm

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$0 < y < 300$ mm and 0.1 mm $0 < x < 2.8$ m. An additional traverse mechanism allowed a second probe to be traversed both in the x and y directions relative to the main probe. The maximum separations and resolutions were 150 and 0.1 mm, and 110 and 0.1 mm in the two directions respectively.

The temperature–temperature correlation measurements were made with thermocouple probes (chromel–alumel, 12.5 μm dia butt jointed). The temperature–velocity correlations were made with a hot wire anemometer probe DISA 55 F01 and a thermocouple used in close proximity. A standard DISA 55 D01 unit was used with the anemometer probe.

The output signals were recorded in digital form using the system described by Hall [9]. A sampling rate of 100 Hz was used throughout and the standard length of record was six min.

The calibration of the anemometer was made by measuring the anemometer output voltage E when the probe was exposed to different velocities and temperatures. The calibration data was fitted by the least squares method to a surface of the form $u = f(E, T)$ and this together with the thermocouple calibration (40.0 μV/°C) was used to calculate the temperature and velocity directly from the digitally sampled anemometer and thermocouple output signals.

All the calculations on the data were carried out on the ICL 1904 computer at Queen Mary College. The correlations, both direct and time delayed, were determined by direct multiplication.

3. RESULTS AND DISCUSSION

It is conventional to make distance normal to the wall dimensionless with respect to a boundary layer thickness δ. The choice of an appropriate δ is particularly difficult in this problem. If we take δ to be the distance at which 99% of the mean temperature drop across the boundary layer has occured, it has a value of approximately 120 mm in the fully turbulent part of the boundary layer ($Gr_x > 2 \times 10^{10}$) but is very ill defined. If we take δ to be a distance at which no further disturbances of the ambient temperature can be seen, it depends on the accuracy of the measurement but is between 150 and 200 mm. If it had been possible to measure the shear stress at the surface of the plate, τ_W, in the experiment, we could have made y dimensionless with respect to y^+ but this was not possible. Further possibilities include δ_h the enthalpy thickness of the layer as defined by Warner and Arpaci [10] and $y_N = (T_W - T_\infty)/(\partial T/\partial y)_{y=0}$ as defined by Fujii [11] and used by Smith [8].

None of the above possibilities has proved to be wholely satisfactory, particularly in the transition region so that for this work we have chosen to leave the results in terms of dimensional distances. If it is desired to make the results for the fully turbulent region dimensionless, a value of $\delta = 150$ mm could be used since measurements are reported for only one x position in this region.

3.1. *Spatial correlations normal to the wall*

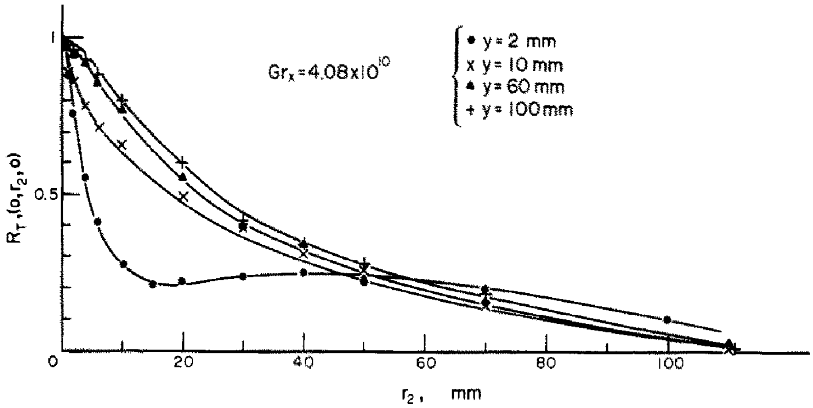
3.1.1. *The fully turbulent zone* ($Gr_x > 2 \times 10^{10}$). Figure 1(a) shows the curves of $R_{T'}$ as a function of the spatial separation r_2, for different distances y of the fixed probe from the wall. At small values of r_2 and at a small distance y from the wall ($y = 2$ mm) the coefficient $R_{T'}$ decreases very rapidly with r_2, but at larger values of r_2 ($r_2 > 15$ *mm*) it remains almost constant at a value of approximately 0.2. This is explained by the fact that at $y = 2$ mm the fixed probe is within the viscous sublayer. If the main correlation between the sublayer and the main flow is assumed to be one of intermittent "bursts" and these "bursts" are an important factor in maintaining the larger scale structure of the main flow, we would expect the correlation between a point in the sublayer and a point in the main flow to be relatively independent of the exact position in the main flow. If the curves of $R_{T'}$ had been extended to values of r_2 greater than 150 mm then $R_{T'}$ would have tended to zero as the moving probe came out of the boundary layer.

At larger values of y (10, 60, 100 mm) the rate of decrease of $R_{T'}$ with r_2 is smaller but this decrease continues with increase in r_2 so that $R_{T'}$ tends to zero at larger r_2. Again, the zero is associated with the moving probe coming outside the boundary layer. It is also notable that the value of $R_{T'}$ for a given r_2 increases with increasing y even in the main flow region. This suggests the increasing relative importance of the large scale eddies as we go towards the outer edge of the boundary layer.

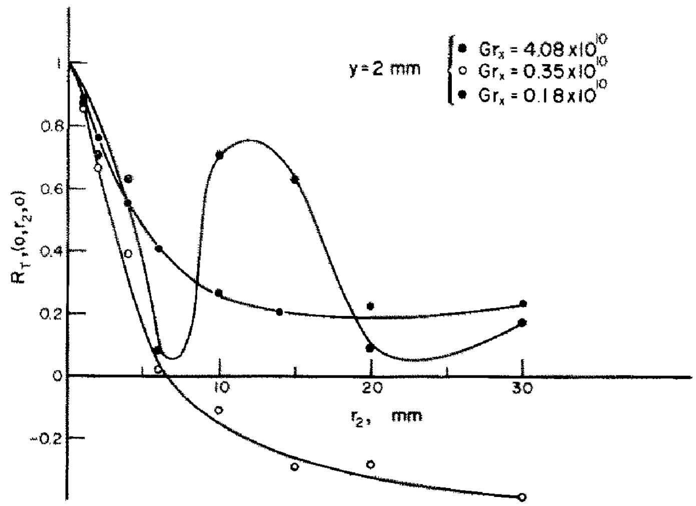
3.1.2. *The transition region*. In this region the values of the correlation coefficient $R_{T'}$ as a function of the spatial separation r_2 have been determined for two different x positions. The results obtained with the fixed probe at 2 mm from the wall are shown in Fig. 1(b). The data in Fig. 1(b) shows much more variation than those for the fully turbulent region, but nonetheless an attempt has been made to draw a continuous curve through the data points.

The curve of $R_{T'}(r_2)$ corresponding to a Grashof number of about 0.35×10^{10} tends towards negative values when r_2 is greater than 7 mm. In fact this data refers to a part of the transition region in which the lateral extent of the boundary layer is increasing very rapidly and the outer part of the layer is dominated by the colder ambient fluid entrained in this growth process. Thus the negative values of $R_{T'}$ are not surprising.

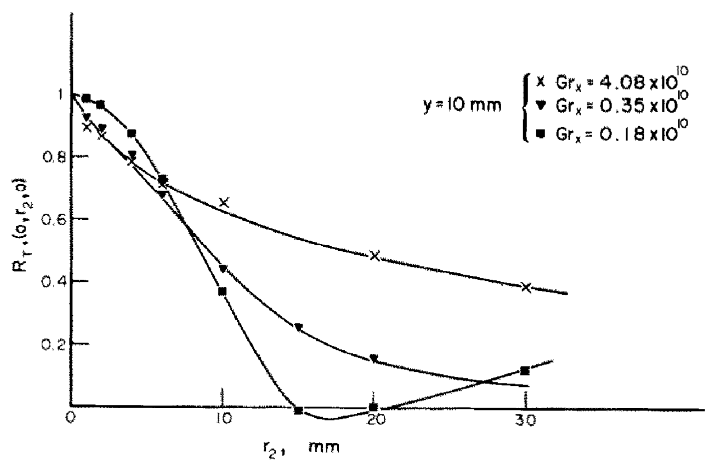
The curve of $R_{T'}(r_2)$ for the other vertical position ($Gr_x = 0.18 \times 10^{10}$) shows a strong oscillatory behavior as r_2 increases. The existence of a periodicity in space under similar conditions has been remarked upon by Sum-Ping and Cheesewright [12], Eskinazi [13] and Doan-Kim-Son [14] but a more complete explanation can perhaps be obtained from the results of stability calculation by Gebhart [15]. At $Gr_x = 0.18 \times 10^{10}$ stability calculations suggest that amplification of random disturbances is just becoming important in the region of the outer inflection point in the profile of mean velocity. Gebhart has pointed out that this



(a) Fully turbulent zone.



(b) Transition region.



(c) Transition region.

FIG. 1. Spatial correlations normal to the wall.

amplification process in natural convection is very frequency sensitive and effectively only a narrow band of frequencies is amplified, the remaining disturbances being "filtered" out. The fixed probe at $y = 2$ mm will be in a region influenced mainly by any disturbances naturally present in the boundary layer but the moving probe, when it is at $r_2 \simeq 7$ mm will be influenced by the selectively amplified disturbances, thus the correlation between the two positions will not be good. When the moving probe is at greater r_2 ($\simeq 12$ mm) it is outside the region of selectively amplified disturbances and the natural disturbances present are likely to correlate well with those at the fixed probe. The final decay of the correlation coefficient at $r_2 \simeq 20$ mm is indicative of the outer edge of the boundary layer.

The above explanation is supported by the RMS values of the fluctuations recorded by the fixed and moving probes. For $r_2 = 7$ mm $(\overline{T'^2})^{1/2}_{\text{mobile}}$ is larger

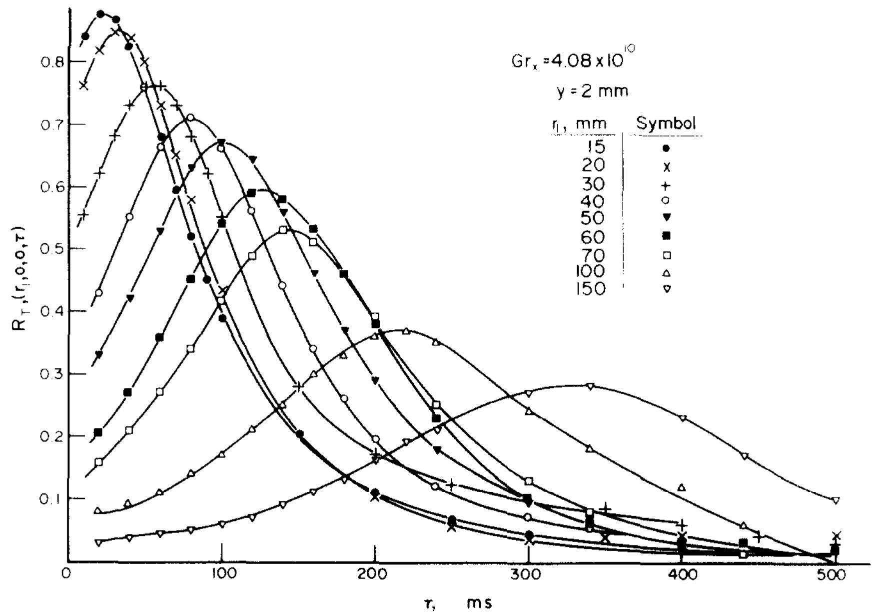


FIG. 2(a).

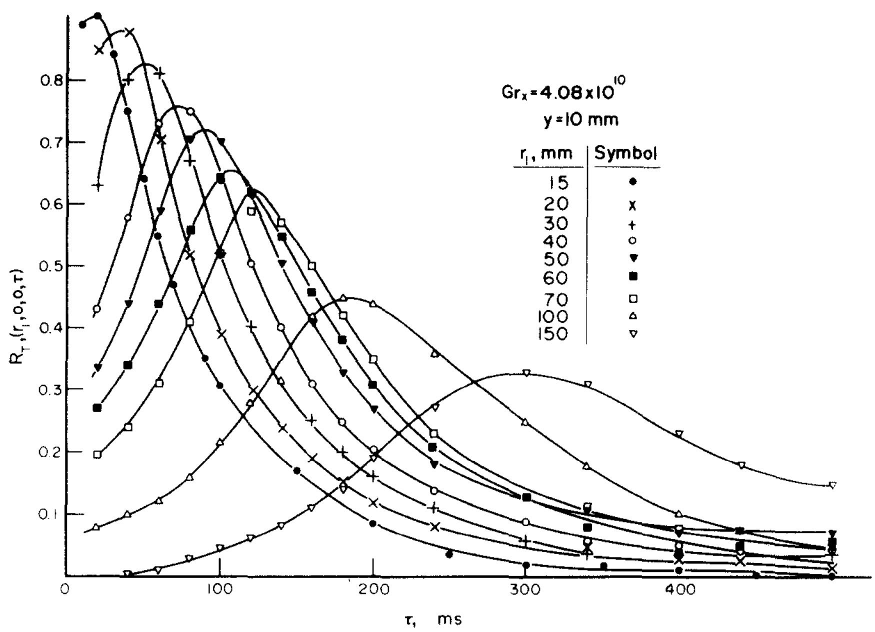


FIG. 2(b).

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than $(\overline{T'^2})^{1/2}_{\text{fixed}}$ while for $r_2 = 10$ mm and 15 mm $(\overline{T'^2})^{1/2}_{\text{mobile}} \simeq (\overline{T'^2})^{1/2}_{\text{fixed}}$ and for $r_2 = 20$ mm and 30 mm $(\overline{T'^2})^{1/2}_{\text{mobile}}$ is less than $(\overline{T'^2})^{1/2}_{\text{fixed}}$.

The correlations $R_{T'}(r_2)$ in Fig. 1(c) do not show the same oscillatory behavior as in Fig. 1(b) because the fixed probe at $y = 10$ mm is already outside the region of amplified disturbance.

The problem of the characteristics of the transition region will be returned to again in the consideration of the longitudinal space–time correlation.

3.2. *Longitudinal space–time correlations (in the direction of the mean flow)*

3.2.1. *The fully turbulent zone* ($\text{Gr}_x > 2 \times 10^{10}$). The curves of longitudinal space–time correlation coefficient $R_{T'}$ for various spatial separations r_1 as a function of the delay time are shown in Figs. 2(a–f). Each figure corresponds to a different distance y of the probes from the wall. The curves show the way in which the coherence of the temperature fluctuations changes as we follow the direction of the mean flow.

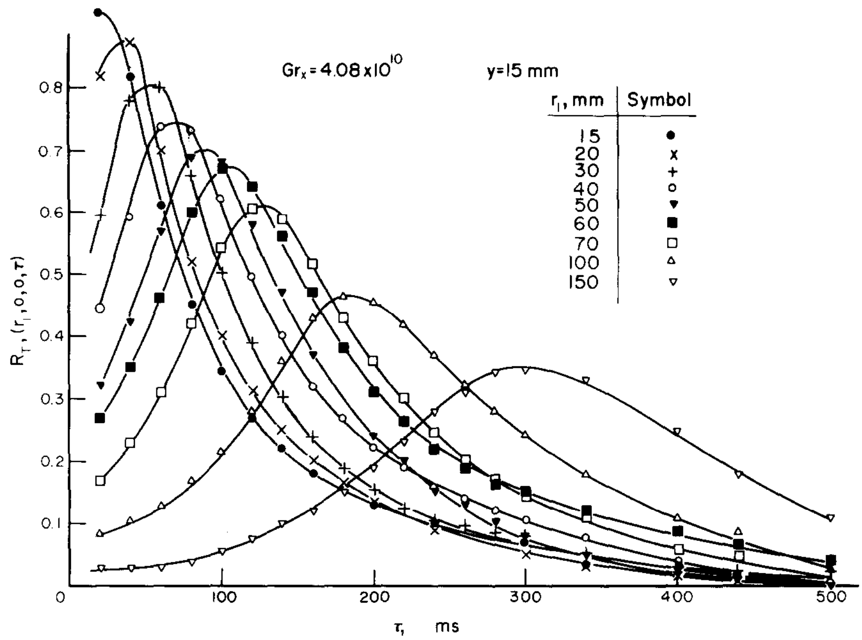

FIG. 2(c).

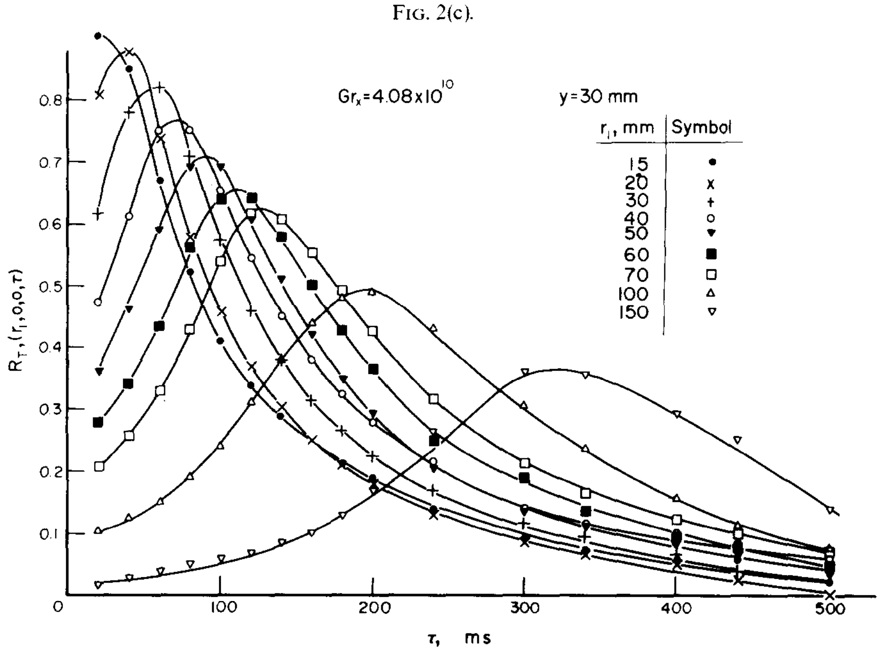

FIG. 2(d).

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All the figures show that for each separation r_1, a maximum value of the coefficient $R_{T'}$ is obtained with a delay time τ_m which we call the optimum delay time. This optimum delay time τ_m increases with increasing separation r_1 while at the same time the maximum value of $R_{T'}$ decreases. It is however notable that $R_{T'}$ max is still quite large (*ca.* 0.3) at values of r_1 equal to the boundary-layer thickness.

Some caution must be used in assessing the actual values of τ_m for large r_1 because the radius of curvature of the curves $R_{T'}(r_1)$ increases with increasing r_1. Nonetheless it is believed that the trends shown by the results are genuine.

The "transit velocity" of fluctuations given by r_1/τ_m decreases gradually as r_1 increases. It is believed that this represents a change from the correlation being dominated by the small eddies for small r_1 to being dominated by the large eddies at large r_1. A comparison of the "transit velocities" with profiles of mean velocity reported by Smith [8] and Doan-Kim-Son [14] shows that for all y values the "transit velocity" for small r_1 is greater than the local mean velocity while for large r_1 it is slightly smaller than the local mean velocity. The extent of these deviations from the local mean velocity is least for a value of y approximating to the peak in the profile of mean velocity ($y = 10$ mm).

It is intended to investigate the significance of these

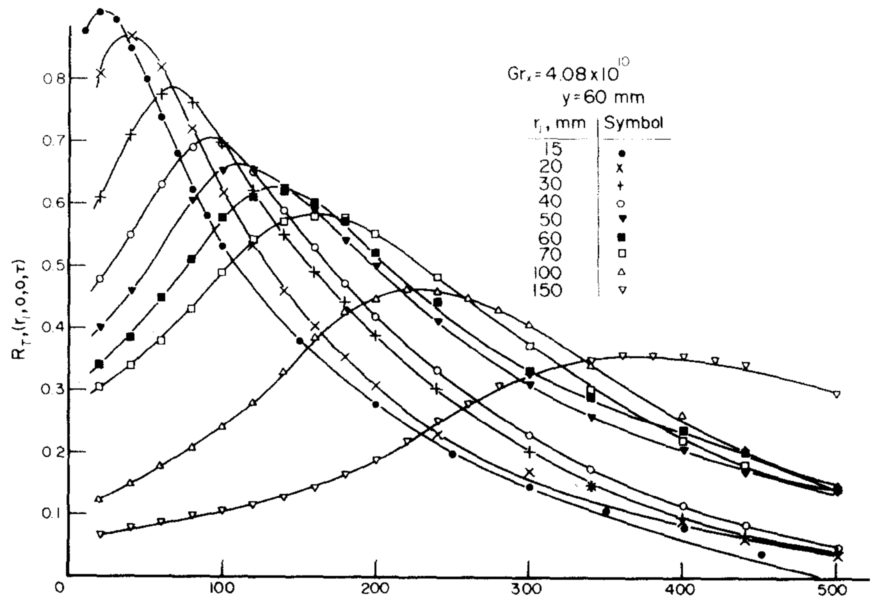

FIG. 2(e).

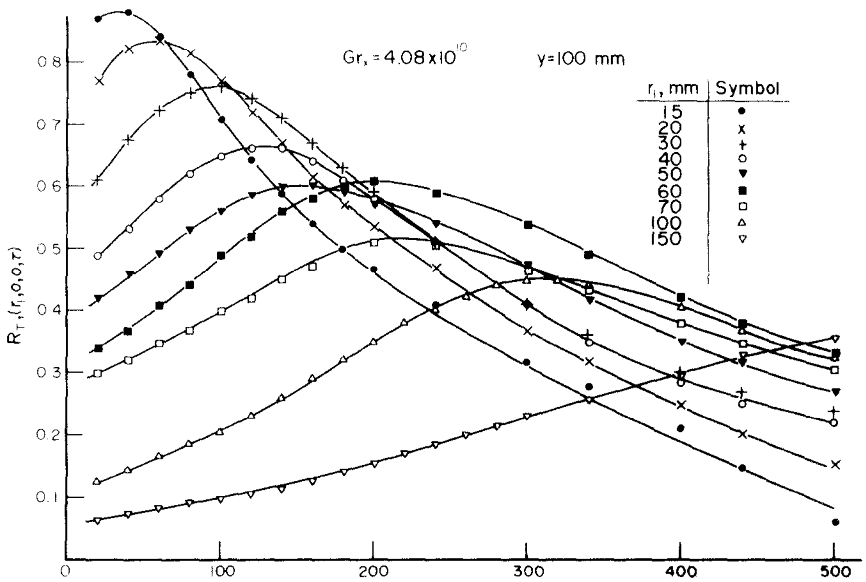

FIG. 2(f).

FIG. 2(a)–(f). Fully turbulent zone: examples of space–time correlations in the direction of the mean flow.

"transit velocities" in future work in which filtered space–time correlations will be determined.

The envelope of the maxima of the curves of $R_{T'}$ gives a curve passing through the point $R_{T'} = 1$, $r_1 = 0$. These curves have not been drawn in on Figs. 2(a–f) but their nature can be clearly seen. They represent the coherence of the turbulence and it is notable that the coherence tends to zero more slowly in this flow than in homogeneous turbulence [1].

The decay of the maximum correlations can also be represented as a function of r_1, a form in which it is often referred to as the memory of the turbulence.

Such curves, for different values of y are shown in Fig. 3. It is notable that the curves for different values of y are almost coincident except for $y = 2$ mm and $y = 100$ mm, both of which are lower. For $y = 2$ mm, both the fixed and the moving probes are in the viscous sublayer and it is believed that this region is less affected by large eddies, which accounts for the lower correlation. For $y = 100$ mm the probes are in the outer, intermittent, region of the boundary layer and this is responsible for the reduced correlation.

The curve for $y = 10$ mm is presented in dimensionless form in Fig. 4 where a comparison is made with similar data for (i) grid turbulence, and (ii) a forced flow boundary layer. The space variable used is that

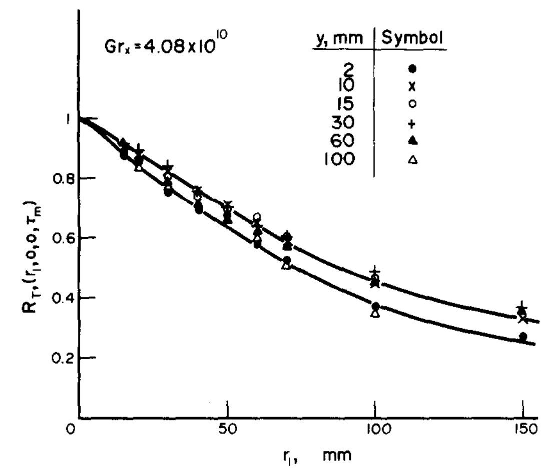

FIG. 3. Fully turbulent zone: space–time correlation coefficient with optimum delay τ_m, for various values of y.

suggested by Dumas *et al.* [6], $\xi = (r_1/L_x)\cdot\overline{(u'^2)}^{1/2}/\bar{u}$ where the value of the longitudinal scale of the turbulence L_x is given in Section 3.3. and $\overline{(u'^2)}^{1/2}/\bar{u}$ has been determined from the results presented in the Section 3.4. below. The coherence of turbulence in a free convection flow is slightly more important than in a forced convection one.

3.2.2. *The transition region.* In Fig. 5(a) the curves of the longitudinal space–time correlation $R_{T'}$ for $x = 1$ m, $y = 2$ mm are presented. The correlation oscillates between negative and positive values with the amplitude of the fluctuations diminishing with increasing delay time although the frequency seems to remain constant (*ca.* 3.5 Hz). This frequency also appears dominantly in the transition region [8, 14] and it is notable that the idea of a dominant frequency is also apparent in the work of Gebhart [15] who talks about "filtering" or frequency selective amplification in the transition process.

The apparent disorder of the curves in Fig. 5(a) contrasts with the highly ordered curves for $x = 1$ m, $y = 10$ mm shown in Fig. 5(b). This is not unexpected because the position represented by the data in Fig. 5(b) is very close to the region where the frequency selective amplification of Gebhart should be most pronounced (around the outer inflexion point in the profile of mean velocity). Again the frequency suggested by the data is approx. 3.5 Hz.

A final set of data for the transition region $x = 0.8$ m, $y = 10$ mm, is shown in Fig. 5(c). The same periodicity is present but again the curves are relatively disordered, indicating that the frequency selective amplification is not as strong. It is notable that at $x = 0.8$ m, $y = 2$ mm no meaningful longitudinal correlations could be obtained.

The lateral and longitudinal variations of the "memory" of the turbulence, derived from the above data, are shown in Figs. 6 and 7 respectively.

3.3. *Scales of turbulence*

The mean dimension of the large structures in the longitudinal direction is given by:

$$L_x = \int_0^\infty R_{T'}(r_1)\,dr_1.$$

In practice, the upper limit of this integral cannot be taken as infinity but it must be taken as a definite distance r_1^* because, the values of $R_{T'}$ are still quite large at the largest value of r_1 which could be achieved in the experiments and the extrapolation to zero of the $R_{T'}(r_1)$ curve would be difficult to realize without the large error.

The values of the length scale L_x shown in Fig. 8 have been determined with $r_1^* = 150$ mm. The variation of L_x with y would not be significantly different if the true limit of the integral had been used.

With an analogous method, the normal scale of turbulence L_y has been determined. It is about 1/3 of L_x.

The dissipation by molecular viscosity of the kinetic energy of turbulence is characterized by the dissipation length λ_T. For a homogeneous flow and small values of

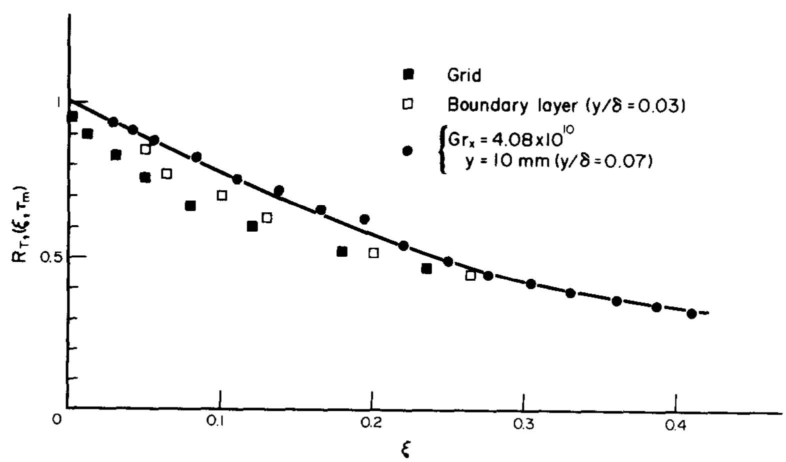

FIG. 4. Comparison between the present data and the results of Dumas *et al.* [6] obtained in forced convection.

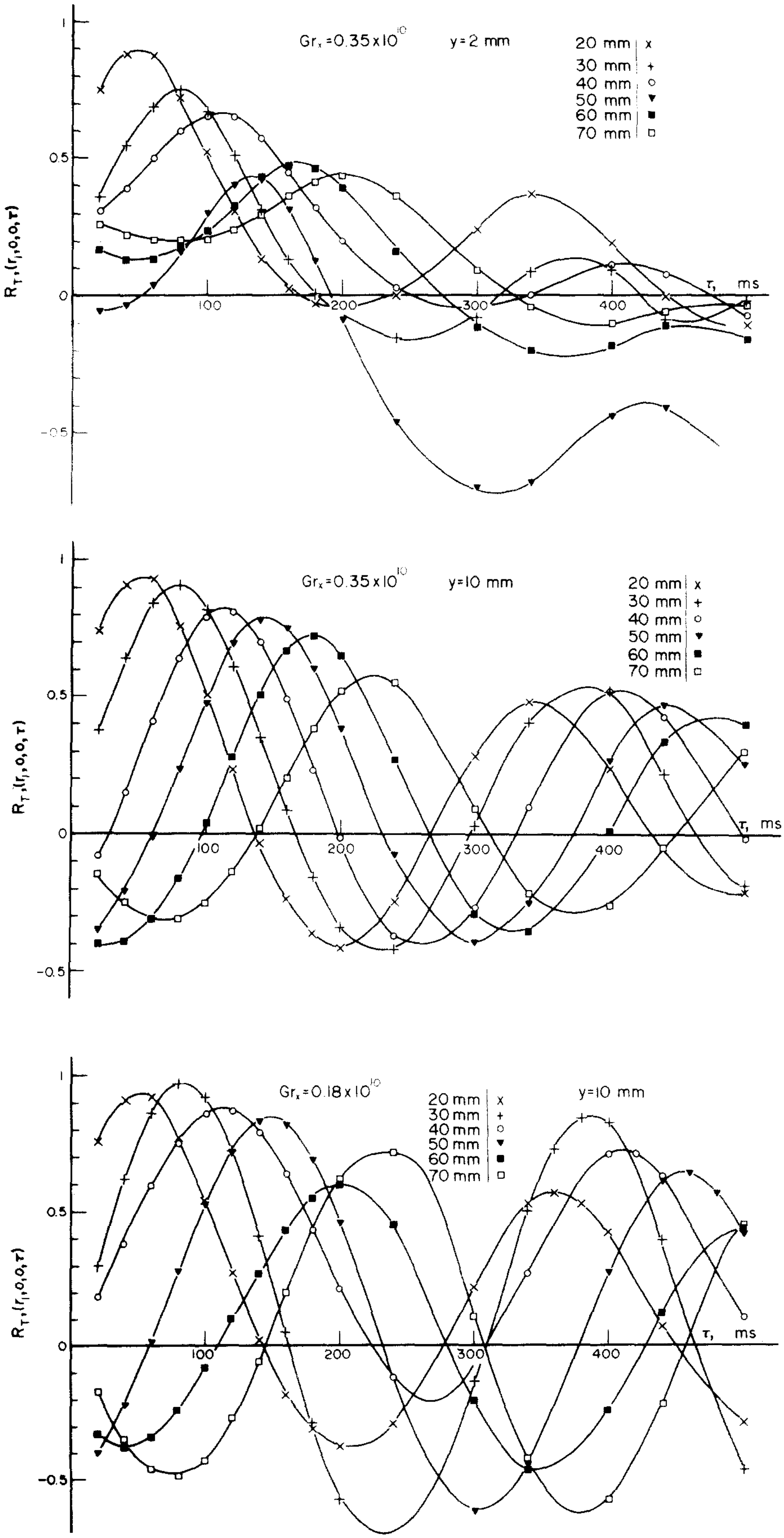

FIG. 5(a)–(c). Transition region: examples of space–time correlations in the direction of the mean flow.

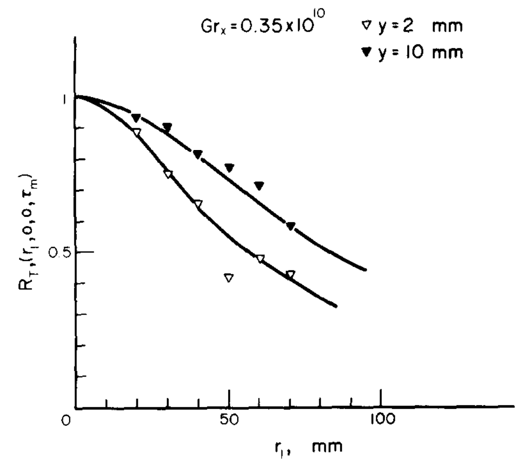

FIG. 6. Transition region: space–time correlation coefficient with optimum delay τ_m, for various values of y.

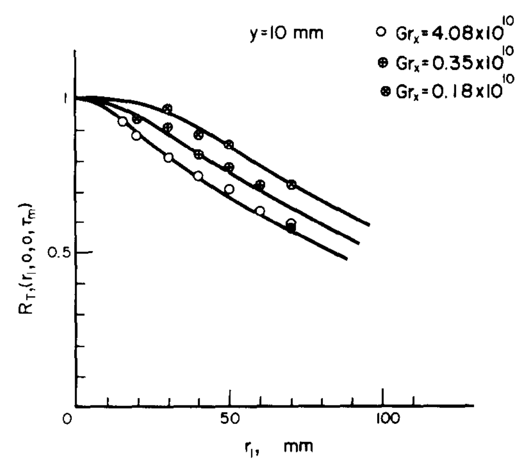

FIG. 7. Comparison of space–time correlation coefficients with optimum delay τ_m in the fully turbulent zone and in the transition region.

r_2, Hinze [16] proposed the following expression to permit the calculation of λ_T from the curves $R_{T'}(r_2)$

$$R_{T'} = 1 - \frac{r_2^2}{\lambda_T^2}.$$

The dissipation length λ_T increases slightly with y (Fig. 8) which implies that the dissipation of energy diminishes in proportion.

3.4. *The correlation between the temperature fluctuations and the velocity fluctuations*

In the present work it has only been possible to measure the component of velocity parallel to the wall, u. Thus only the correlation $u'T'$ can be presented.

Figure 9 shows $R_{u'T'}$ as a function of the distance from the wall and several remarks can be made about this curve. (i) The correlation is positive for all values of y. This is to be expected because an increase in the temperature of an element of fluid will increase the buoyancy force on it and hence will increase its upward velocity. Conversely a decrease in the temperature will decrease the buoyancy and decrease the velocity. (ii) In the viscous sublayer $R_{u'T'}$ increases rapidly, implying that the fluctuations of temperature and velocity are well correlated. This is to be expected because this is a region in which inertia effects may be neglected and the flow is governed by a balance between the buoyancy forces and the wall shear. A similar effect has been observed in a study of the temperature and velocity fields in a forced convection boundary layer by Fulachier [17]. Measurements of the spectra of temperature and velocity fluctuations in a sublayer of a natural convection boundary layer by Doan-Kim-Son [14] and Smith [8] further support this picture of the sublayer since they show that the spectra are closely similar and the fluctuations are in phase with one another. (iii) At large distances from the wall $R_{u'T'}$ seems to vary only slowly with y but the relatively large value ($\simeq 0.6$) implies that the fluctuations of temperature and velocity are still closely linked to one another.

Distributions of $R_{u'T'}$ for two values of x in the transition region are shown in Fig. 10. The data are somewhat scattered but some trends may still be distinguished. The high degree of correlation near the wall is still present as well as a peak in the correlation around $y = 15$ mm. However, for the transition region data, $R_{u'T'}$ fall rapidly to zero for $y > 40$ mm unlike the turbulent zone data where it remains nearly constant.

4. CONCLUSION

Examination of experimental data for the correlations coefficients of temperature and velocity fluctuations in the fully turbulent zone and in the tran-

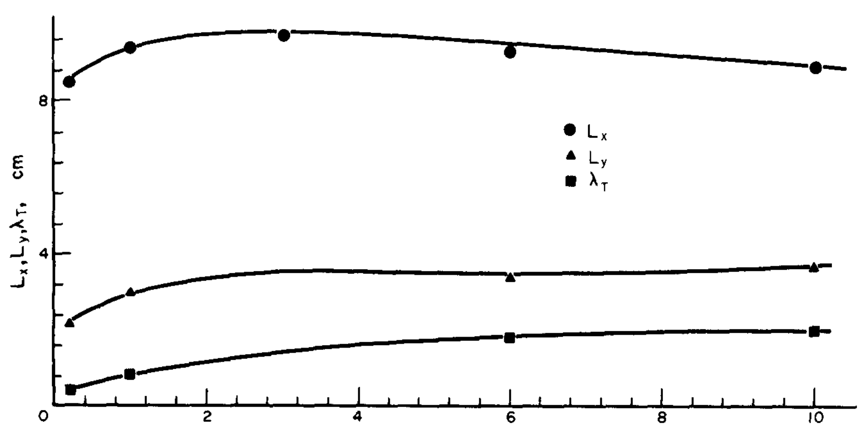

FIG. 8. Variation of the correlation lengths and the dissipation length.

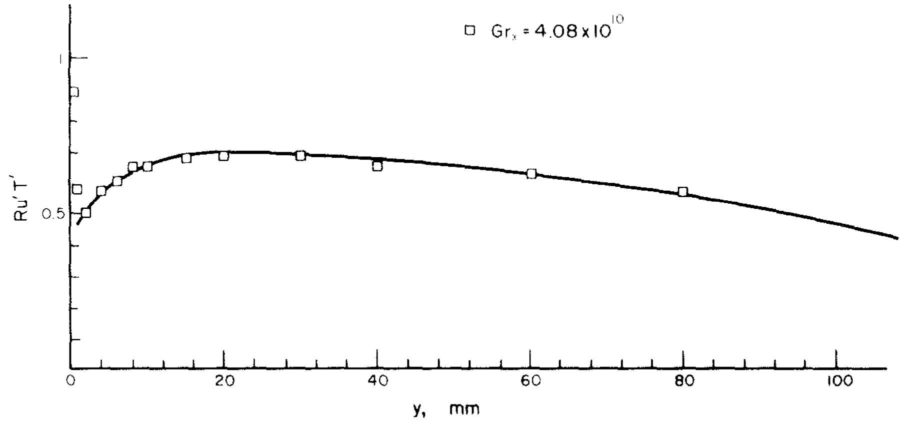

FIG. 9. Fully turbulent zone: distribution of correlation coefficient $R_{u'T'}$ across the boundary layer.

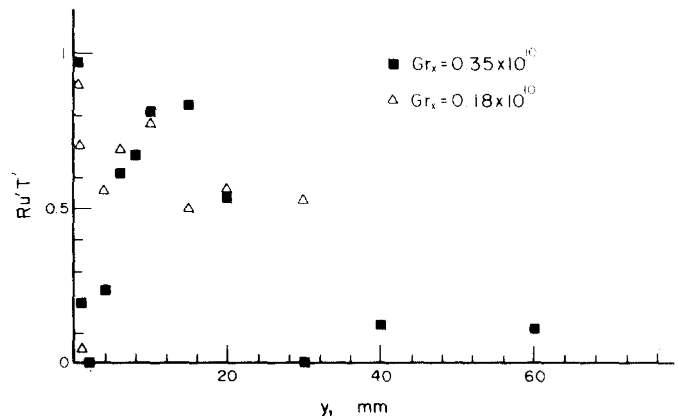

FIG. 10. Transition region: distribution of correlation coefficient $R_{u'T'}$ across the boundary layer.

sition region has suggested some essential features:

A relative independence between the main flow and the sublayer was detected.

A strongly periodic phenomenon was observed in the transition region.

The correlation coefficient measured with a longitudinal separation reaches a maximum for an optimum time delay.

The "memory" of the turbulence is more important in the transition region than that in the fully turbulent zone.

The scales of the turbulence are significant.

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MESURE DE CORRELATION ESPACE-TEMPS DANS UNE COUCHE LIMITE DE CONVECTION NATURELLE TURBULENTE

Résumé—On mesure des corrélations spatiales normalement à la paroi et des corrélations espace-temps pour les fluctuations de température. On note l'indépendance relative de l'écoulement dans la sous-couche vis-à-vis de l'extérieur. Dans la région de transition, un phénomène fortement périodique est observé, avec des caractéristiques conformes à celles suggérées par des analyses de stabilité linéaire. La perte de "mémoire" de la turbulence dans la région pleinement turbulente parait semblable à celle observée dans une turbulence de grille et dans une couche limite d'écoulement forcé. Les échelles importantes de la turbulence varient relativement lentement avec la distance normale à la paroi, hors de la sous-couche, indiquant une structure de turbulence parfaitement uniforme.

MESSUNGEN DER ORT-ZEIT-WECHSELBEZIEHUNGEN IN EINER TURBULENTEN GRENZSCHICHT BEI FREIER KONVEKTION

Zusammenfassung—Es wurden quer zur Wand örtliche Wechselbeziehungen und in Längsrichtung örtlich-zeitliche Wechselbeziehungen von Temperaturänderungen gemessen. Eine relative Unabhängigkeit der Strömung in der Unterschicht von der Strömung außerhalb dieser Schicht wurde festgestellt. Im Übergangsgebiet wurde eine stark periodische Erscheinung beobachtet, deren Eigenschaften mit denen übereinstimmen, die durch lineare Stabilitätsanalysen vorgeschlagen werden. Der Zerfall des "Gedächtnisses" der Turbulenz im voll turbulenten Gebiet wurde ähnlich dem befunden, den man bei Turbulenz an Gittern und in Grenzschichten bei erzwungener Strömung beobachtet. Es wurde gefunden, daß die bedeutenden Stufen der Turbulenz sich relativ langsam mit dem Abstand von der Wand verändern, wobei sich außerhalb der Unterschicht eine ziemlich gleichförmige turbulente Struktur zeigt.

ИЗМЕРЕНИЯ ПРОСТРАНСТВЕННО-ВРЕМЕННЫХ КОРРЕЛЯЦИЙ В ТУРБУЛЕНТНОМ ПОГРАНИЧНОМ СЛОЕ ПРИ ЕСТЕСТВЕННОЙ КОНВЕКЦИИ

Аннотация — Получены пространственные корреляции по нормали к стенке и продольные пространственно-временные корреляции температурных пульсаций. Отмечена относительная независимость течения в подслое от внешнего течения. В переходной области наблюдался строго периодический процесс, характеристики которого согласуются с характеристиками, полученными из линейной теории устойчивости. Найдено, что затухание «памяти» турбулентности в полностью турбулентной области аналогично затуханию турбулентности за решеткой и в пограничном слое при вынужденном течении. Установлено, что основные масштабы турбулентности сравнительно медленно изменяются с расстоянием по нормали к стенке вне подслоя, что указывает на довольно однородную структуру турбулентности.