On velocity and temperature fluctuations generated by a turbulent grid in open vertical channel

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ABSTRACT:

We analyze experimentally the statistical properties of velocity and temperature fluctuations in a free turbulent flow generated downstream of two grids placed at the inlet of a large vertical open channel. One of the grids with mesh spacing M_θ is heated so that a mean temperature rise across the grid of about 10K, while the other said dynamic grid with mesh spacing is not heated, hence the thermal mesh size was smaller than the momentum mesh size ($M > M_\theta$). Considerations will here be restricted to fluids heated from below for which buoyancy effects form the only source of motion. With this arrangement, the velocity, and temperature and their respective variances are measured by the hot wire anemometry. A flow either with decreased or increased velocity and temperature variances is observed. Beyond $x/M = 10$ downstream of the grid, the usual grid velocity decay in wind tunnel is not observed. Furthermore, up to approximately $x/M = 16.66$ from the turbulent grid, the mean temperature variance decreases and evolves in agreement with the ones generally observed in fully developed wind tunnel grid turbulence and a behavior consistent with the existence of scaling laws is obtained. However, beyond this distance, an increase temperature variance was noticed. So that the decomposition of the temperature variance in power law is no longer observed.

Key words : Experiment; Open vertical channel; Grid turbulence; Free convection

1 Introduction

The simplest turbulent flow is that for which the statistical properties of the field are invariant to rotation or reflection of the Cartesian coordinate system. This notion, isotropic turbulence, was introduced by Taylor in [1] and has been fruitful in permitting relatively detailed analytical studies .
Although the turbulence found in natural and technological flows is ordinarily far from isotropic, many features of diverse turbulent flows, especially the spatially local features, seem to be moderately universal. Decaying homogeneous and isotropic turbulence with and without heating continues to be

the basis reference for the development of many theories and turbulence models. The earlier work of Batchelor [2] and Corrsin [3] has been revisited by a number of authors (e.g. George [4] , Gonzalez and Fall [5] , Lavoie and al [6] and more recently by Antonia and al [7] and Lee and al [8] , the list is far to be exhaustive .This new interest provided the motivation for the present study. The oceanic and atmospheric microstructural transport, problems of environmental engineering, and a plethora of more specific subjects require an understanding of how the scalar quantities can evolve in presence of dynamically active buoyancy forces. However the majority of the models currently available are based on measurements or observations of flows for which there is a dominant influence of forced convection. Much uncertainty remains as to the exact role of buoyancy forces in the dynamics of turbulent motion and scalar transport. In this work, we investigate the dynamic and thermal fluctuations behavior in decaying grid where the flow is not caused by a dynamic engine (wind tunnel) but rather by a thermal engine here the positive buoyant. It is clear that mixing of scalar quantities is at the core of phenomena such as dispersion of pollutants, combustion and air conditioning, also understanding thermal fluctuation behavior is a necessary first step in understanding the mixing turbulent heat processes. Due to these motifs, our main focus is on scalar fluctuations, all the more that there is a paucity of information in the literature on the form of temperature fluctuations in the turbulent free flow . In order to introduce a temperature fluctuation field with initial integral scale smaller than that of the turbulence field, a thermal grid with thinner with mesh M_θ smaller than turbulence grid mesh M, was inserted downstream of the flow. Generally a scalar fluctuation may be produced by imposing a mean linear scalar gradient on the grid flow and a thermal fluctuation may be produced by using an array of finely heated wires in proximity to the grid (or heating the grid itself. Since the work began with Corrsin and coworkers (e.g. Mills et al [9,10]), there have been fewer studies on the scalar decay rate than there have been on the velocity decay rate. Even when experimental studies have been conducted in the scalar transport, it has been treated as ‘‘passive’’ scalar, having no dynamical effect on the flow. In all usually experiments a passive linear cross-stream temperature gradient $\beta = dT/dz$ is constant and its value was independent of downstream position. It should be noted that one of the most relevant experimental studies, mainly by Warhaft and al [11] , Sirivat and al [12], up to recent progress in modeling scalar fluctuations in homogeneous grid turbulence by Viswanathan and Pope [13] that the decaying thermal variance is sensitive to the initial conditions of the flow and depends on the method of heating the grid. They concluded that this may be avoided by heating the flow either downstream of the grid with an array of fine wires, known as a ‘‘mandoline’’, or upstream in the plenum with an array of wire ribbons, known as a ‘‘toaster’’(e.g. Sirivat and Warhaft [12]). It may be observed that although several studies have been conducted in the wind tunnel , to our knowledge no studying has heretofore been investigated in turbulent free convection. The flow generated in present experiment was so that buoyancy was the sole source of motion, and production of turbulent kinetic energy by mean shear was negligible compared to production by buoyancy. One of our objectives, is to check whether the decays of the turbulent energies kinetic and thermal follow a power law when the buoyancy is the only source of motion.

2 Apparatus And Method Of Approach

In this study we have examined the dynamic and thermal characteristics for different positions behind the turbulence grid. The temperature measurements and two velocity components were performed into a turbulent grid at Fluid Mechanics Laboratory (Ecole Centrale de Nantes) by Pavageau [14] . The laboratory experiments were conducted with air as the working fluid; the facility designed for this study was a vertical open tunnel with a total height of 13m, and square cross-section of constant dimensions 3 m x 3 m. The large cross-section area allowed for a large homogeneous core to persist to the end of the tunnel in spite of the development of the boundary layers. A sketch with dimensions is shown in figure l. This channel of study is divided into two parts situated on either side of the plane grids. The first part of the channel 3 meters high is located in the basement of the building, it was used to obtain a fully developed flow at the entrance to the second part of the channel. to reduce vortex and lateral mean velocity fluctuations the air then passed through a set of honeycombs. The second part of the channel is the test portion; it extends from the grid to the exit of the tunnel outlet. The walls 10 cm thick, painted white to reduce the radiation effect, they consist of two metal sheets of thickness 2mm. Containing glass wool, these walls limit the heat transfer between inside and outside the channel. Flow was generated using the thermal grid to mesh $M_{\theta} = 10cm$, electrically heated. The grid consists of a perpendicular arrangement of two sets of 29 resistive rods 15 mm in diameter. The circuit could also be controlled manually to maintain a fixed power supply to the grid, since a constant power (80kw) input is required to maintain the temperature rise of about 10K across the grid needed for generating stationary temperature fluctuations. The turbulent grid located at some centimeters of thermal grid is bi-planar to mesh M=30cm, it consists of 20 flat rectangular bar of 3cm thickness and 6cm width. Its role is essentially creating and piloting turbulence. Its coefficient solidity is 34. The flow generated in this manner was so that buoyancy was the sole source of motion, and production of turbulent kinetic energy by mean shear was negligible compared to production by buoyancy. The present experimental set-up is a compromise for having a known free turbulence field at a reasonably high Re. The mean flow velocity in the middle flow was about $\langle \mathrm{U} \rangle \sim 0.55\ \mathrm{ms}^{-1}$. The Reynolds number based on M and $\langle \mathrm{U} \rangle$ was about $\mathrm{R_M} \cong 10769$ and the corresponding Peclet number $P_e = P_r R_M$, was about 7753.68 , Pr = 0.725 for the working fluid, air. The mean temperature increase ΔT, relative to ambient, varied from 10 to 5.5 K with increasing x. The resulting temperature fluctuations were inconveniently small, but this ensured negligible influence of density variations upon the fully developed turbulent velocity field, as attested by both turbulence level and velocity correlation measurements. The simultaneously recorded hot- and cold-wire signals were used to calculate the true velocity and temperature fluctuations. Instantaneous temperature measurements within the flow were made with Wollaston-process platinum wires of 1 μm in diameter and 2 mm length. The cold wires were operated in the constant current mode without compensation for thermal inertial, and with a current as low as 140 μA ensuring that the velocity sensitivity of the cold wires was negligible for existing experimental conditions. Velocity fluctuations were measured with tungsten hot wires 5 μm in diameter and 3 mm in long. (For further design details refer to Pavageau [27] .

3 Experiment results and discussion

Results refer to a Cartesian coordinate system with its origin located at the center of the upper surface of the turbulent grid , which coincides with the zy plane. The z-axis is parallel to the cross section and the x-axis is pointing upwards. All measurements were taken at the plane of symmetry (y = 0). The mean temperature is normalized with the mean ambient value corresponding to each vertical station. And mean velocity is normalized with a mean velocity obtained at inlet of a channel. The average vertical gradient of the ambient mean temperature was estimated to be about 1 Km^{-1} , representative of a permanent stratification. The mean temperature vertical gradient in the tunnel was nearly constant within the investigated area of the tower, equal to $-0.3\ Km^{-1}$, thus representative of an unstable thermal stratification. First we shall present the salient characteristics of the velocity field and then we examine the characteristics of the temperature field and their transverse homogeneity variances, finally the results of the longitudinal evolution of the temperature variance will be presented.

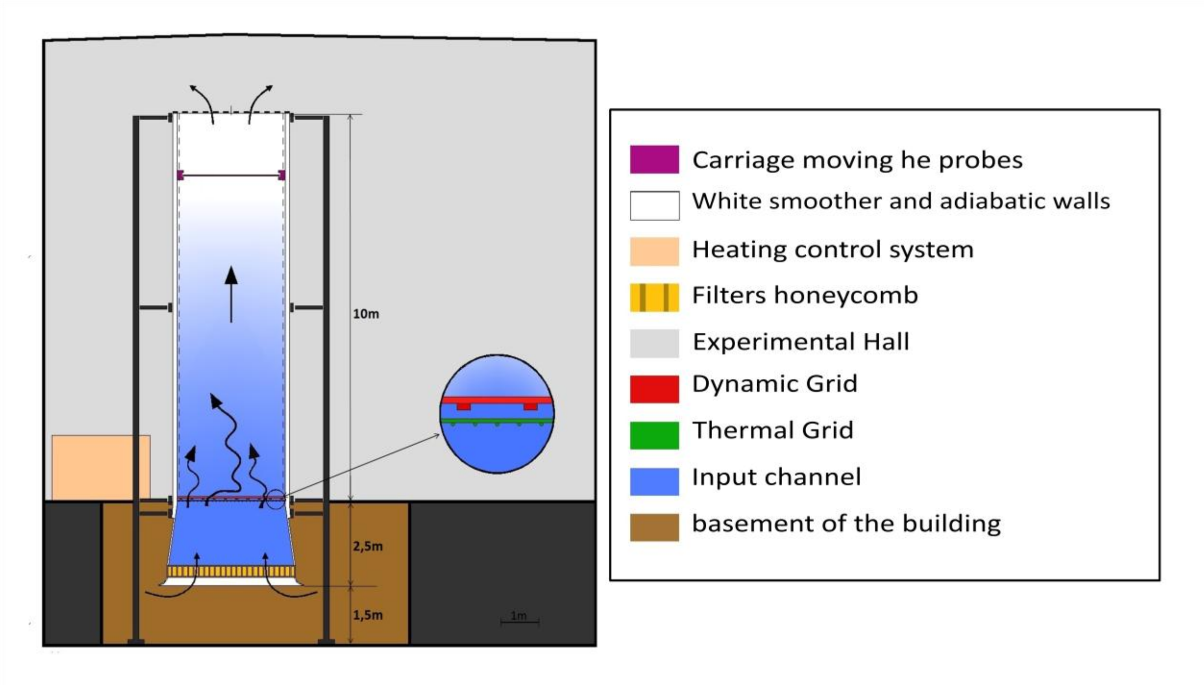

Figure. 1 Cross section in the xOz plane showing The different parts of the experimental apparatus. The dimension ratios are not represented faithfully in this drawing

3.1 Flow field

Usually systematic checks on the homogeneity of the flow are carried out before undertaking any statistical analysis for which homogeneity is required. Ertunc and al [16] studied the lateral inhomogeneous in turbulence from a grid made of horizontal and vertical bars in a biplane configuration. They reported the presence of lateral inhomogeneity in the turbulence intensity even at x/M as large as 80. They suggested that for the inhomogeneity to be negligible, adjacent 'wakes' emanating from the bars should overlap appreciably. The recent DNS of Djenidi and Tardu [17] of grid-generated turbulence, where the grid is made up of independent flat square elements with a solidity of 25% showed that while the lateral inhomogeneity was high in the region close to the grid (x/ M < 10), it decreased significantly with increasing distance. However, the downstream extent was only x/M =15, not long enough for the turbulence to reach a complete (lateral) homogeneous state.
Their work, which shows for the first time that ergodicity is well satisfied in grid turbulence in planes perpendicular to the mean flow. Finally, according Sirivat and Warhaft [12], for the heated turbulent grid experiments good transverse homogeneity is never attained. An example of transverse profiles

of dimensionless mean longitudinal velocity component at different sections downstream of the grid is shown in figure 2. Near the walls the mean longitudinal velocity tends to increase with altitude, while it decreases for the central area (4.5 < z/M > 7.5). The reduction velocity in the central area is attributed to the entrained air into the more elevated velocity areas near channel walls. The same comments were reported in Habib [18] (2002) Furthermore the transverse distribution of the mean longitudinal velocity component is not quite symmetrical relative to the axis of the channel, due probably to the initial conditions. This asymmetric behavior is conserved and propagated in the streamwise flow as shown in Uberoi and Wallis [19] Despite a smooth axial deceleration observed in the middle of the flow of the test section, the transversal flow field is similar to that for a conventional forced grid flow. Figure 2 (bis) shows the plot of longitudinal velocity variance, the values have been obtained by averaging value per section over the core of the flows. This results put forward an increase in the variance of the velocity fluctuations with the distance from the grids in contrast to what is usually observed for grid turbulence in forced convection. Assuming transverse homogeneity, since dissipation ϵ_u was the dominant term in the balance of the transport equation of the longitudinal velocity variance. It did balance the total production of turbulent energy by buoyancy and mean gradient in the lower region of the flow. While dissipation and production were approximately evenly balanced from 3 m onwards as production by mean gradient increased.

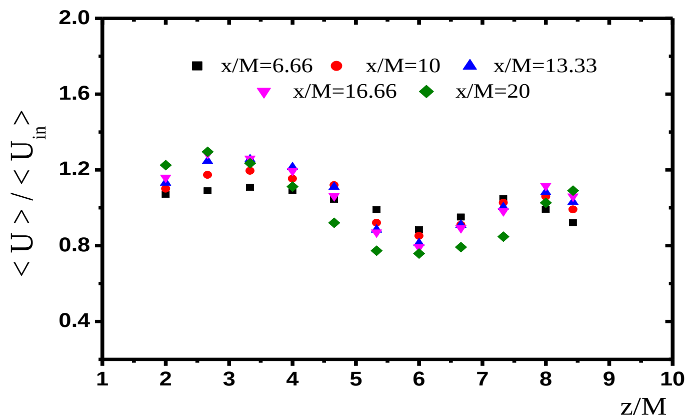

Figure. 2 Transversal (cross-stream) profiles of mean vertical velocity component at five positions downstreame grid

Figure 3(a) shows the transverse profiles of the longitudinal turbulent intensities $I_u = \langle u^2\rangle^{1/2}/\langle U\rangle$, the cross-stream turbulent intensities $I_w = \langle w^2\rangle^{1/2}/\langle U\rangle$ and the anisotropy I_u/I_w at x / M = 13.33 downstream of the turbulent grid. These figures reveal that both I_u and I_w increase in the central region of the flow 4,5 < z/M > 7 and decrease elsewhere. The typical transversal standard deviations across the flow at x/M = 13.33 of *2%* of the average intensities. The variance $\langle u^2\rangle$ of the longitudinal component velocity fluctuations decreased across the lower investigated part of the flow up to about 3 m downstream of the turbulent grid and then increased with height the channel (its evolution is not represented here. Figure 3 (b) helps us to characterize the behavior isotropy. In spite of the data scattering, this plot is interesting; the ratio of longitudinal component of velocity fluctuations and the two components of transversal velocity fluctuations $\langle v^2\rangle^{1/2} \approx \langle w^2\rangle^{1/2}$along the transverse axis is always greater than unity. At 13.33 mesh lengths downstream of the grid, I_u/I_w has a nearly constant mean value 1.17. This ratio remained close to 1.2 in the lower part of the flow, which is similar to the value found in the classical case of grid generated turbulence for a non-contracted tunnel (Comte- Bellot and Corrsin [15]).A good agreement with the results of Gibson and Dakos [20] obtained in a wind tunnel is noted. These authors also argue that a small anisotropy (10%) is often found for a grid-generated turbulence.

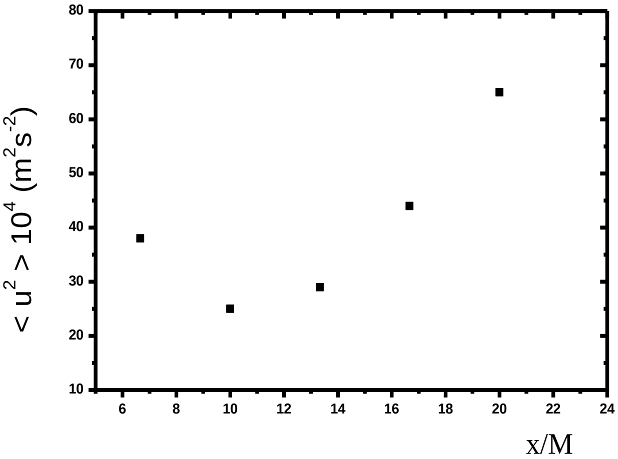

Figure 2(bis). Longitudinal velocity variance

Recent study conducted by Lavoie et al [6] have reported that the combined effect of a more isotropic flow and a less intense vortex shedding by carefully modifying the grid reduces the dependence on the initial conditions. Since there is no mean shear and hence no production of initial turbulent kinetic energy, the turbulence in this flow ought quite simply to decays. Many studies (e.g. Comte-Bellot and Corrsin [15], Mohamed and LaRue [21] ; Lavoie et al. [6]) have shown that the decay of the turbulent kinetic energy follows a power law $u'^2 \propto (x - x_0)^{n_u}$ where x_0 is the virtual origin for the grid turbulence and n_u is the decay exponent. In the present case the usual decay is not observed everywhere (a prime denotes the root mean-square value) . In the area $x/M < 10$ downstream of the grid we observe that turbulence decays and increases after that. Commonly accepted power laws in a forced flow will not be examined in our study.

3.2 Evolution of the thermal field

Figures 4 show the dimensionless transverse mean temperature profile at different stations downstream of the grid. There is a small asymmetry in the horizontal profiles which is possibly due to the proximity of the laboratory wall on the left side of the tunnel. The centerline temperature decreases along the channel, this behavior reflects the transverse transport of the energy originally imparted to the fluid at the centerline toward the channel walls. In spite of a lighter transverse inhomogeneous in the flow, the mean temperature field remains spatially uniform throughout the channel, this result is in agreement with the results of Haaland and Sparrow [22].

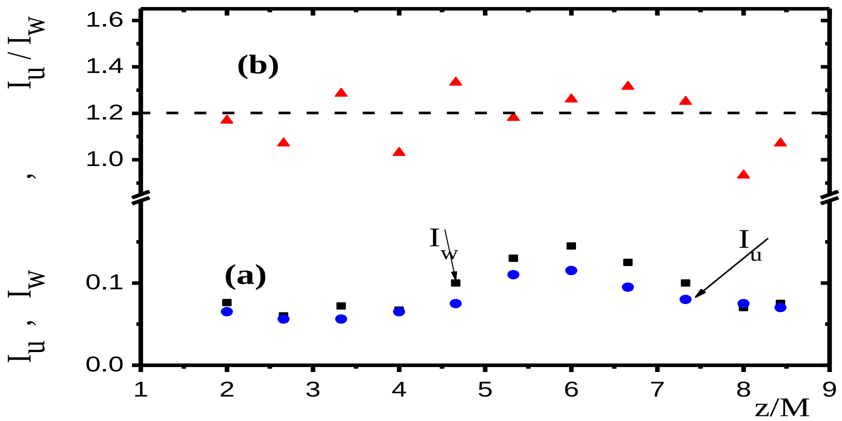

Figure 3. (a) Transversal profiles of longitudinal (Iu) and cross-stream (Iw) turbulent intensities in the fully developed area flow, at x/M=13.33. The dashed line represents the contraction case in wind tunnel (Compte-Bellot and Corrsin [15]), (b) the ratio of the longitudinal to transversal intensities at x/M=13.33.

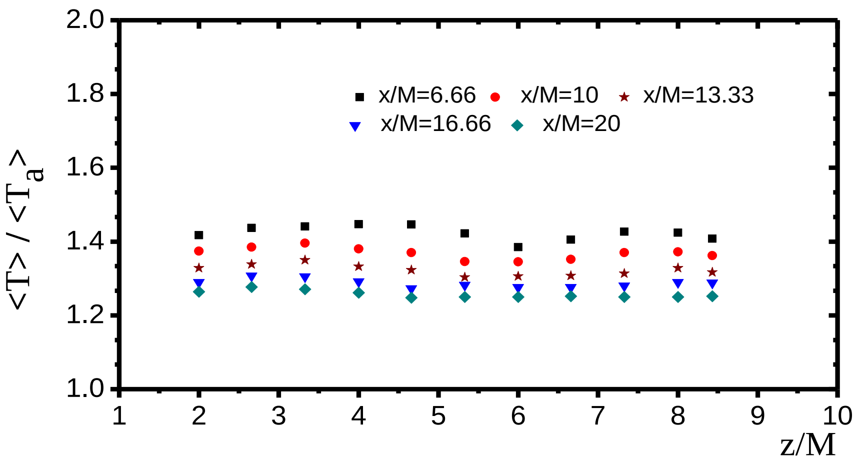

Figure 4. A mean Transverse temperature profiles at five positions downstream of the turbulent grid.

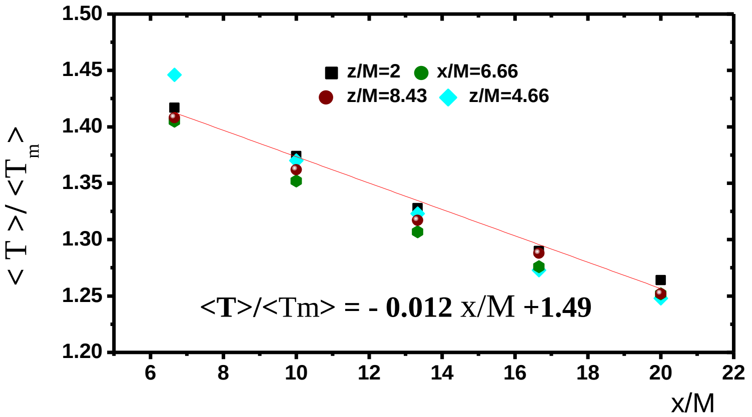

Figure 5. Longitudinal mean temperature evolution at various transversal positions

At $x/M = 6.66$, the typical standard deviation of $\langle T\rangle/\langle T_m\rangle$ is approximately 2% of the mean. Figure 5 shows the evolution of longitudinal mean temperature downstream the turbulent grid at various transversal positions. Although there is some scatter, a straight line produces the best fit to the data. Linear interpolation is used to confirm that the mean vertical thermal gradient in the inner study channel is negative.

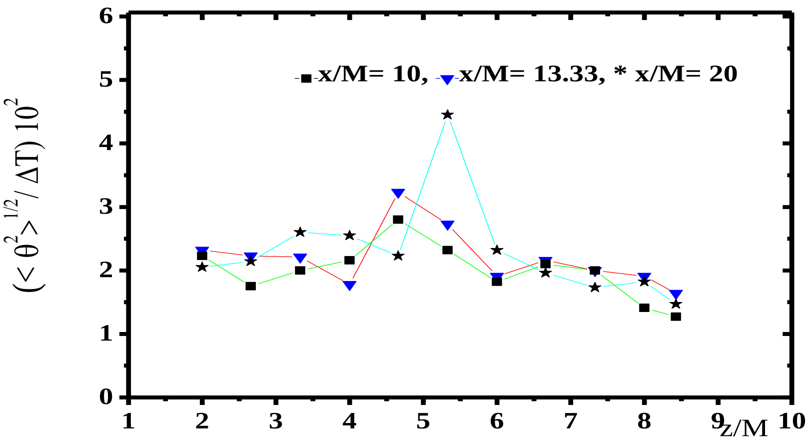

Figure 6. Transverse profiles of temperature r.m.s. (Homogeneous turbulence field)

3.3 Temperature-fluctuations

Although theoretical prediction of Corrsin [3] has had remarkable confirmation for decaying grid turbulence in which the temperature gradient was produced by differentially heating the bars of the grid Wiskind.[23], Alexopoulos and Keffer [24], Venkataramani and Chevray [25],), the streamwise evolution of the mean temperature variance $\langle\theta^2\rangle$ in wind channel flows is poorly understood from both experimental and theoretical viewpoints. Figure 6 shows the transverse profiles of the thermal r.m.s., where ΔT is the temperature difference across the grid, we note here that the distribution is inhomogeneous. Indeed, for the heated grid experiments good homogeneity is never attained, this may be in part due to the strong coherence between u and θ fields. We note also that owing to anisotropy of the larger scales, the thermal variance increased almost linearly with the distance from the grid. In the vicinity of the central axis we note the presence of a main peak variance. In such an experiment as has been shown by Warhaft and Lumley [11], there is coupling between the temperature fluctuations and the longitudinal velocity. This coupling probably also affects the evolution of the mean temperature variance $\langle\theta^2\rangle$ in the cross-stream direction. Figures 8 (a) and (b) shows the plot of longitudinal thermal variance for present case and previous works mentioned above respectively. For two figures the values have been obtained by averaging over the core of the flows. Wiskind [23], Alexopoulos and Keffer [24] showed an increase after about $x/M \approx 50$ but the rates are different, Venkataramani and Chevray [25] shows a dramatic increase followed by an equally dramatic decrease in the longitudinal thermal r.m.s. , but their experiment only extends to $x/M \approx 50$. Part of the reason for the large scatter in these data probably lies in the method of generating the thermal profile. Assuming transverse homogeneity the transport equation of the temperature variance $\langle\theta^2\rangle$ are by Tennekes and Lumley [26]

$$\langle\theta^2\rangle/dt \cong k_\theta - \epsilon_\theta \qquad (1)$$

Here ϵ_θ is the temperature-dissipation term, K_θ is the eddy diffusivity. Equation previous shows that there is both production and dissipation of $\langle\theta^2\rangle$. Also the analysis made by Pavageau[14] on the balance of the transport temperature variance equation, chows that temperature-dissipation ϵ_θ is the dominate term in this balance, it is quite clear that after x/M=13.33 the temperature variance increases as production begins to dominate dissipation.

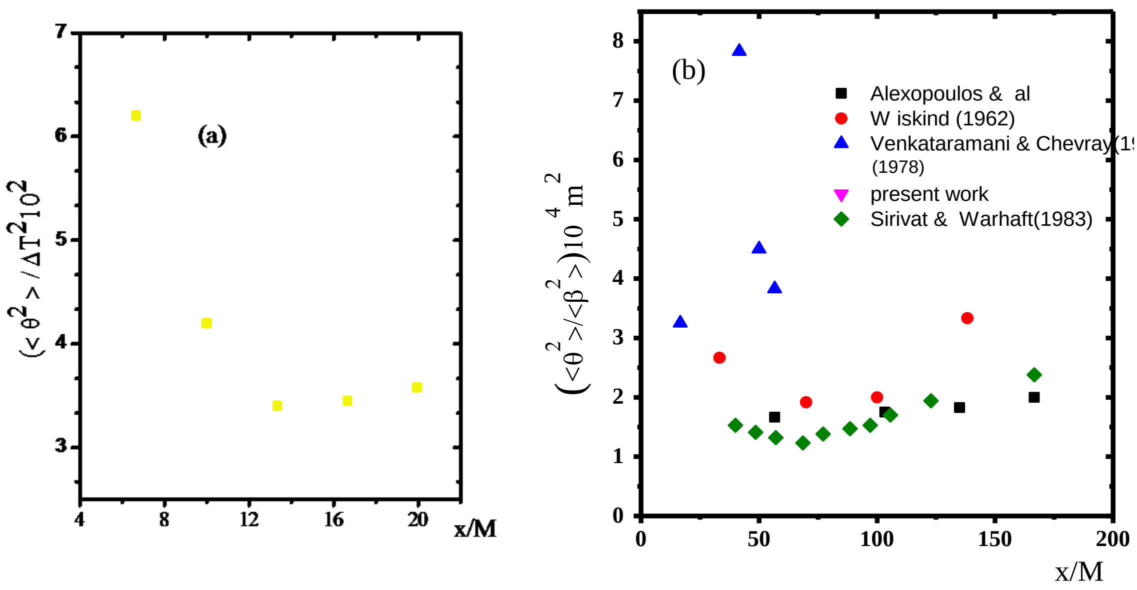

Figure 8. The longitudinal thermal variances, (a) in present work ,
(b) for the above-cited experiments extracted from Sirivat and Warhaft [12],
β is a passieve linear cross-stream temperature gradient.

It is now accepted (in forced convection) When a passive scalar is introduced the scalar variance $\langle\theta^2\rangle$, like the velocity variance $\langle u^2\rangle$, also decays as a power law (e.g. Sreenivasan and al. [28], George [29], Antonia et al. [7]):

$$\langle\theta^2\rangle/\langle\Delta T^2\rangle = A(x)(x/M - x_0/M)^{-n_\theta} \qquad (2)$$

where $\langle\theta^2\rangle/\langle\Delta T^2\rangle$ is the downstream dimensionless variance temperature, A is the decay coefficient which depends on initial conditions, x is the coordinate, positive in the downstream direction with origin at the grid and n_θ is the decay exponent. Here a value for x_0/M=0 is assumed and the method of least squares is used to obtain the corresponding values for A and n_θ. In figure 9 a log-log scale is used, streamwise variations in the vicinity of the central channel axis illustrate a downstream decay of variance temperature . A form for the decay power-law expression is written as:

$$\langle\theta^2\rangle/\langle\Delta T^2\rangle = -0.881(x/M)^{-0.674} \quad (3)$$

This equation, valid until x / M = 13.33 ,beyond the variance increase and any similarity is then possible.

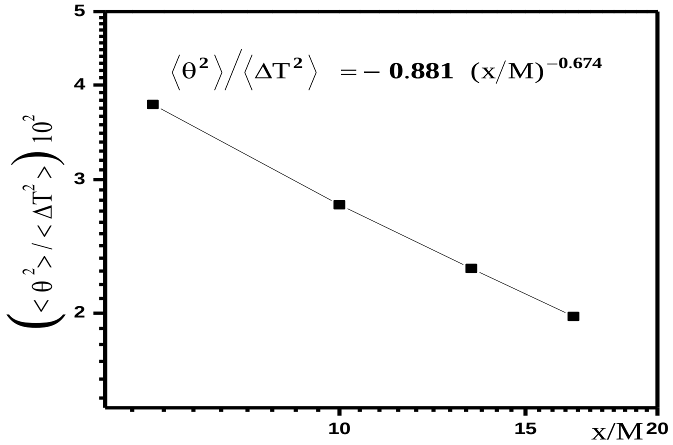

Figure 9. Decay of temperature variance in central axix downstream the grid (—■—z/M= 5)

4 Conclusion

The experiments analysis of results put forward an increase in the variance of the velocity fluctuations with the distance from the grids in contrast to what is usually observed for grid turbulence in forced convection. Also, we did not observe the streamwise decay of temperature variance typical of grid turbulence in forced convection. Instead, an increase in temperature variance was noticed starting at 4 m downstream of the grid and the decay of temperature variance in power law is no longer observed.
It is clear that the scalar transport (here temperature), problems of environmental engineering, and a plethora of more specific subjects require an understanding of how the scalar quantities can evolve in presence of dynamically active buoyancy forces, however the usual models of closure of turbulent equations come mainly from experiments conducted in mixed or forced convection . For turbulent free flow of natural convection, the question of the validity of the physical analysis that is made through these equations remains posed. This point should deserve attention in future works.
- We hope that, through this work, one will find incentives to examination of the degree of applicability of customarily used models for turbulent free convection.
- Besides that, assuming the homogeneity of the flow, velocity and temperature variances obtained in this experiment can enable to get a reference values for the average rate of the temperature or velocity dissipation, values important in modeling free turbulent convection.

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