Structure of Grid Turbulence through a Heated Screen*

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Measurements of mean values and turbulent intensities of velocity and temperature fluctuations of grid turbulence have been made in a developing region just after an electrically heated screen. The air velocity is set as 1 m/s. The electric current to the screen is adjusted to be the downstream temperature (T_a) 32°C, 100°C or 150°C. Hot-wire anemometry with compensation for temperature variation is used to measure velocity with temperature variation. In a developing region, both velocity and temperature distributions become non-uniform at a point just downstream of the heated screen. The distributions recover gradually to the uniform condition in a downstream region. Turbulent energy dissipates with the distance from the heated screen. The dissipation rate is decreased with increasing air temperature.

Key Words: Heat Transfer, Turbulent flow, Fluid Mechanics, Forced Convection, Grid Turbulence

1. Introduction

The role of turbulence on heat transfer processes is one of the fundamental issues of convective heat transfer, thus, it has been widely investigated. Most fundamental research for investigating the detailed structure of turbulent heat transfer has mainly been aimed at elucidating the effect of turbulence on the heat transfer. In these studies, the temperature difference was small enough not to affect the turbulence structure. In other words, the heat has been treated as a "passive scalar" in that the turbulence affects the heat transfer process, though the heat addition does not vary the turbulence structure.

In recent years, heat transfer processes with a relatively high temperature difference have been noted in relation to the heat transfer in combustors and cooling systems in nuclear plants^{(1),(2)}. In these cases, the value of flow properties, such as density and viscosity, varies with temperature variation and, thus, the turbulence structure is supposed to be varied. The heat is, therefore, no longer treated as a passive scalar and the interaction between the heat and the turbulence motion must be taken into account. The turbulence structure with a relatively high temperature difference, therefore, can not be deduced from experimental results with a low temperature difference⁽²⁾. In order to elucidate the interaction between the heat and the turbulence structure, the present authors have investigated the structure of a flat-plate turbulent boundary layer with high heat flux from the flat plate⁽³⁾. Although the results shed some additional light on the interaction between the heat and the turbulence structure, they suggested that more fundamental studies are necessary to elucidate the interaction of heat and the turbulence structure. In the present study, then, grid turbulence is examined, since the isothermal grid turbulence is a one-dimensional turbulent flow with simple decay due to a viscous dissipation. Furthermore, the grid turbulence has been used to elucidate the fundamental structure of isothermal turbulent flow⁽⁴⁾. This suggests that the grid turbulence is suitable for fundamental study of the interaction between the heat and the turbulence structure with a high temperature difference.

When the grid turbulence is used, the heat should be added uniformly at a cross section to form a one-dimensional flow field with heat addition. In the present study, a fine-wire screen is used as a heating device. The diameter of the wire is small enough not to form vortexes. By using the fine-wire screen, the one-dimensional flow field with velocity and temperature

* Received 23rd August, 1991. Paper No. 90-0100 A

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ture fluctuations may be obtained after the developing region. However, experimental investigations on the grid turbulence with heat addition by a fine-wire heating screen are few, and the fundamental characteristics, such as the length of the developing region, have not yet been elucidated, although a few studies^{(5),(6)} have been performed in cases when the temperature may have been treated as a passive scalar. The present study, then, aims to elucidate the fundamental characteristics of a developing region of the grid turbulence with a relatively high temperature difference between the turbulent flow and the fine-wire heating screen experimentally, as a first step in the study of the turbulence structure with strong heat addition.

2. Experimental Apparatus and Procedure

2.1 Apparatus and conditions

Figure 1 shows the test section of the present study. The test section is a cylindrical wind tunnel and was set up vertically. The uniform air flow with low turbulence (turbulent intensity of velocity fluctuation is about 0.3% at the mean flow velocity of 1 m/s)

Table 1 Turbulence-generating grid

	wire diameter (D)	distance between wires (M)	wire Reynolds No. (Re_d)
G1	6 mm	28 mm	362
G2	12	24	724

Fig. 1 Test section

Fig. 2 Probe for velocity and temperature measurements

flows upward from the nozzle. The turbulence-generating grid can be installed at the exit of the nozzle and the turbulence is added. Two grids are used, as shown in Table 1. The wire Reynolds number (Re_d) is defined as follows.

$$Re_d = \frac{U_{ref} D}{\nu} \quad (1)$$

$$U_{ref} = \frac{\text{volume flow rate}}{\text{cross-sectional area of the test section}}$$

D : grid diameter

The heating screen is set 340 mm downstream from the turbulence-generating grid. The wire of the heating screen is made of Fe/Cr wire with diameter (d) = 0.4 mm. One heating unit is formed by normally crossing wires, as shown in Fig. 1. The distance between wires is 5 mm. The wire Reynolds number is 24 in the isothermal case, when U_{ref} is 1 m/s. The heating screen consists of five heating units.

The reference velocity (U_0) is set to 1.0 m/s at $x = 150$ mm, where the turbulence added by the grid becomes nearly uniform. The reference temperature (T_a) is defined as a mean temperature at $x = 600$ mm, where the temperature becomes almost uniform. T_a is set as 32°C (room temperature), 100°C and 150°C. When the screen is heated, the nonuniform temperature profile is formed just downstream of the screen. In order to elucidate the downstream variation of the flow field, the measurement has been made at two typical locations, that is, location A and location B in Fig. 1. Location A is located downstream of the wire, where the effect of the wire is most significant. Location B, on the other hand, is located at the center of the wires, where the effect of the wire is less significant.

2.2 Measurement method of velocity and temperature

Hot-wire anemometry with temperature compensation (Kanomax System 7000) was used to measure velocity and temperature simultaneously. The probe with hot and cold wires which was designed for this study, is shown in Fig. 2. Platinum-iridium wires (diameter = 12.7 μ m) were used as hot and cold wires. The hot wire is used to detect the velocity as a sensor of the hot-wire anemometry. The cold wire is used to detect the temperature as a sensor of the resistance thermometry. As shown in Fig. 2, the hot wire (length = 1.5 mm) is located 2 mm downstream of the cold wire (length = 2.5 mm). The probe is inserted into the test section from the downstream side in order to minimize the disturbance to the flow field. The support of the probe was water cooled, since the support is located in the hot flow.

Equation 2 shows King's equation⁽⁷⁾, which indicates the basic concept of the present measurement:

$$V^2 = (C_1 + C_2 U^{0.5})(T_{\text{wire}} - T_f). \quad (2)$$

V : output voltage

U : velocity

T_{wire} : wire temperature

T_f : fluid temperature

C_1, C_2 : coefficient

The hot-wire anemometry compensates the effect of temperature on velocity data by the term $T_{\text{wire}} - T_f$, where T_f is measured by a cold wire. Coefficients C_1 and C_2 are treated as constants, although they are not constant in general. In order to estimate the influence of setting C_1 and C_2 constant, the relationship between the velocity and the output voltage were measured by varying the flow velocity and flow temperature. The results are shown in Fig. 3. The output voltage of each temperature varies linearly with the variation of velocity since the linearizer is used. In addition, Figure 3 shows that the relationship between the output voltage and the velocity can be shown by one straight line, regardless of the temperature, when the effect of temperature variation on the velocity data is compensated. This indicates that the effect of temperature variation on the velocity data is compensated sufficiently in the present temperature range, nevertheless, C_1 and C_2 are set as constant values and it is confirmed that a reasonable velocity measurement can be made.

The minimum scale of temperature fluctuation which can be analyzed is about 2.5 mm, since the length of the cold wire is 2.5 mm. When the velocity is 1 m/s, the maximum frequency to be analyzed, corresponding to the scale of 2.5 mm, is about 400 s^{-1} . Similarly, the maximum frequency of velocity fluctuation which can be analyzed is estimated to be about 670 1/s, since the length of the hot wire is 1.5 mm. The distance between the hot and cold wires is 2 mm, thus,

Fig. 3 Calibration of velocity measurement

the time difference between two wires is estimated to be 2 ms, assuming Taylor's hypothesis, when the velocity is 1 m/s. The autocorrelation coefficient of temperature fluctuation with 2 ms delay is over -3 db in most cases in the present study, and this suggests that the two signals of velocity and temperature fluctuations have enough simultaneity. In the present study, the mean value and turbulent intensity of fluctuation are mainly discussed, then, the effect of the small scale turbulence, which is not large enough for simultaneous measurement, is considered to be negligible.

When the temperature fluctuation is measured by a resistance thermometer, the higher-frequency signal is attenuated by thermal inertia, then the signal is compensated electrically. Strictly speaking, the time constant for compensation should be set accurately at every moment since the time constant varies with temperature and velocity fluctuations. Following the theory of Collis and Williams⁽⁸⁾, the time constant is estimated to be $5.5 \text{ ms} \pm 20\%$ in the temperature range between 50°C and 200°C when the velocity is assumed to be 1 m/s. In the present study, the discussion is focused on characteristics of mean value and turbulent intensity of velocity and temperature fluctuations as well as on intuitive observation of signals. The effect of low-frequency and large-scale turbulence on the present parameters is much greater than that of high frequency and small scale turbulence. This suggests that the time constant can be set as a constant value at each location, though the temperature and velocity fluctuate. Thus, the time constant is set as the value calculated by Collis and Williams' equation using a mean temperature and mean velocity.

3. Results and Discussion

3.1 Characteristics of turbulence generating grid

Figure 4 shows the decay of turbulence generated by the turbulence-generating grids. In order to confirm the characteristics of grid turbulence, the heating screen was not installed. The turbulence energy is estimated as $(u'/U_a)^2$, since the value of turbulent intensity of velocity fluctuation of other directions are nearly the same in the case of the grid turbulence. U_a is the mean velocity at $x=600 \text{ mm}$, which is the furthest measurement location from the heating screen. U_a is constant in all measurement regions, hence, it is equal to $U_0=1.0 \text{ m/s}$. The inverse values of the turbulence energy $(U_a/u')^2$ of both G 1 and G 2 linearly decrease with increasing x . This indicates that both grids (G 1 and G 2) generate typical characteristics of grid turbulence. The diameter of the bar and the distance between bars of the G 1 grid

are almost the same as those of the grid used by Batchelor and Townsend⁽⁴⁾; therefore, the gradients of the decay line are nearly the same. The diameter of the bars of the G2 grid is larger than that of Batchelor and Townsend and the turbulence decay becomes slower. Groth and Johansson⁽⁹⁾ have investigated experimentally the turbulence structure of a flow through a turbulence generating grid and an attenuating screen. Their turbulence decay is close to that of the G2 grid. From these results, it is confirmed that the turbulence generated by G1 or G2 can be treated as a typical grid turbulence.

3.2 Profiles of temperature and velocity

In this section, signals of velocity and temperature fluctuations (u and t), mean velocity and temperature ($\bar{u}$ and $\bar{T}$) and turbulent intensity of velocity and temperature fluctuations (u' and t') are shown. These results of G1 and of G2 are qualitatively the same, thus, the results of G2 are shown as typical ones.

3.2.1 Signals Figure 5 shows the signals of velocity and temperature fluctuations (u and t) at position B of $x=370$ mm, which is the measurement location nearest the heating screen. In this case, the temperature T_a is set at 150°C . The fluctuation of about a 5 ms period is clearly seen in both velocity and

Fig. 4 Characteristics of turbulence-generating grids

Fig. 5 Signals of velocity and temperature fluctuations

temperature signals. It is also clear that the velocity and temperature fluctuations show a positive correlation in that both signals vary in the same trend. This means that the high-temperature fluid is fast and vice versa. The same correlation was observed in other cases, for example, at position A and $T_a=100^\circ\text{C}$. Matushima et al.⁽³⁾ revealed that the temperature and velocity correlation is negative in the case of a flat-plate turbulent boundary layer with heat addition from the flat plate. This suggests that the correlation between the velocity and the temperature fluctuations depends on the flow field.

3.2.2 Mean temperature profile Figure 6 shows the streamwise profile of mean temperature. The profile of $T_a=100^\circ\text{C}$ and that of $T_a=150^\circ\text{C}$ are qualitatively the same. At position A, the temperature just downstream of the heating screen is higher than T_a , since the A position is just above the heating wire. The temperature increases gradually with increasing T_a and reaches T_a at about $x=560$ mm. On the other hand, the temperature just downstream of the heating screen at position B is lower than T_a since the position B is at the center of the heating wires. With increasing x , the temperature increases gradually and reaches T_a at about $x=560$ mm. These results indicate that the temperature is nonuniform just downstream of the heating screen and becomes uniform with increasing x .

3.2.3 Turbulent intensity of temperature fluctuation Figure 7 shows the streamwise profile of turbulent intensity of temperature fluctuation (t'). At position A, the temperature fluctuation is small since most of the fluid parcel through A position is heated up. On the other hand, the high-temperature fluid parcel and low-temperature fluid parcel pass through position B alternately; then the turbulent intensity of temperature fluctuation becomes high. At position A, the turbulent intensity of temperature fluctuation reaches a maximum. This suggests that lower temperature reaches the A position at this

Fig. 6 Mean temperature profile

position. The turbulent intensity of temperature fluctuation decreases monotonically with a further decrease in x . This suggests that the temperature fields become uniform. The value of t' in the case of $T_a=150^\circ\text{C}$ is larger than that in the case of $T_a=100^\circ\text{C}$, since the temperature difference between the high-temperature fluid parcel and low-temperature fluid parcel is larger.

3.2.4 Mean velocity Figure 8 shows the streamwise profile of mean velocity ($\bar{U}$). When the heating screen is not installed, $\bar{U}$ is constant in all measurement regions, keeping $\bar{U} = U_0 = 1.0 \text{ m/s}$. When the heating screen is installed without heating ($T_a = 32^\circ\text{C}$), the velocities at the A and B positions are nearly the same as each other at the region downstream from $x = 480 \text{ mm}$. On the other hand, the velocity decreases with decreasing x from $x = 480 \text{ mm}$ at position A and vice versa at position B. The A position is in the wake region of the wire of the heating screen just downstream of the screen because the A position is above the wire. Consequently, the velocity decreases. On the other hand, the velocity at position B increases because the B position is at the center of the wires.

In the case of $T_a = 150^\circ\text{C}$, the mean velocities at

Fig. 7 Profile of turbulent intensity of temperature fluctuation

Fig. 8 Mean velocity profile

the A and B positions are nearly the same as each other at the region downstream from $x = 540 \text{ mm}$. The mean velocity in this region is 1.4 times larger than that in the case of $T_a = 32^\circ\text{C}$. This ratio corresponds to that of T_a ($423 \text{ K}/305 \text{ K} = 1.39$). This means that the increase in the mean velocity is attributed to the overall increase in the volume, that is, decrease in the density, with temperature increase. With decreasing x from $x = 540 \text{ mm}$, the mean velocity at position A increases and that at position B decreases, contrary to the case of $T_a = 32^\circ\text{C}$. At position A, the air density decreases with the heating of the heating screen and the velocity increases due to the effects of thermal expansion and/or buoyancy force. Since the increase in velocity due to the heating overcomes the velocity decrease due to the wake of the wire of the screen, the velocity increases.

In the case of $T_a = 100^\circ\text{C}$ the mean velocities at the A and B positions are the same as each other at the region downstream from $x = 540 \text{ mm}$. The value of the mean velocity increases corresponding to the volume increase as compared with that of $T_a = 32^\circ\text{C}$ as well as in the case of $T_a = 150^\circ\text{C}$. The mean velocities at the A and B positions increase with decreasing x from $x = 540 \text{ mm}$. The condition $T_a = 100^\circ\text{C}$ is the intermediate condition between $T_a = 32$ and 150°C . Then, the velocity profiles at the A and B positions show the intermediate profiles between $T_a = 32$ and 150°C .

3.2.5 Turbulent intensity of velocity fluctuation

Figure 9 shows the streamwise profile of turbulent intensity of velocity fluctuation (u'). The ordinate is normalized by U_a . When the heating screen is not installed, the turbulent intensity gradually decreases with x , as expected. The decreasing trend is nearly the same as that measured by Groth and Johansson⁽⁹⁾, which is shown by a dashed and dotted line in Fig. 9. When the heating screen is installed, the turbulent intensity increases just downstream of the heating grid ($x = 370 \text{ mm}$) even though the screen is not heated. The turbulent intensity decreases significantly with increasing x and it becomes smaller than that in the case without the heating screen in the downstream region from $x = 440 \text{ mm}$. The dotted line shows the turbulence decay through a grid and a screen as measured by Groth and Johansson⁽⁹⁾. This result corresponds to the present results of the isothermal flow through a grid and a heating screen. These indicate that the screen attenuate the turbulence and the turbulent intensity becomes lower than that without the screen in the downstream region. The scale of turbulence made by the heating screen seems to be smaller than that made by the grid, and the turbulence made by the heating screen decays rapidly. At the same

time, the scale of the part of turbulence made by the grid becomes small at the screen, and this turbulence also decays rapidly, as pointed out by Groth and Johansson. Then, the turbulent intensity becomes less than that without the screen in the downstream region. In the case of $T_a=100^\circ\text{C}$, the turbulent intensity increases as compared to that in the isothermal flow. The fluid around the wire of the heating screen is heated up and the density of the fluid decreases. On the other hand, the fluid flowing in the middle of the wires is not affected by the heating. As a result, the high-temperature fluid parcel and the low-temperature fluid parcel are formed. As shown in Fig. 5, the high-temperature fluid parcel is faster than the low-temperature fluid parcel. The high turbulent intensity should be obtained since the high- and low-temperature fluid parcels are mixed intermittently. The turbulence decays with increasing x .

In the case of $T_a=150^\circ\text{C}$, the turbulent intensity just downstream of the screen is less than that in the case of $T_a=100^\circ\text{C}$. This appears to begin to show the effect of the increase in the kinematic viscosity.

3.3 Decay of turbulent energy

Figure 10 shows the decay of turbulent energy. When the heating screen is not installed, the inverse value of turbulent energy $(U_a/u')^2$ linearly increases

Fig. 9 Profile of turbulent intensity of velocity fluctuation

Fig. 10 Decay of turbulent energy

with increasing x . As mentioned in Section 3.1, this result is closer to that of Groth and Johansson than that of Batchelor and Townsend. The value of $(U_a/u')^2$ of the isothermal flow with a grid and screen increases linearly much faster than that without a screen. This result corresponds to that with a grid and screen of Groth and Johansson. It is significant that the gradient of the line changes at $x=480$ mm and the gradient becomes small in the downstream region at the A position. At position B, the gradient changes at $x=550$ mm. Similar change in the gradient has been reported by Tsuji⁽¹⁰⁾ in the flow passing through two screens. The gradient and the position where the gradient changes are not the same in the A and B positions. This shows the nonuniformity of the flow field. When T_a is increased, the turbulent energy just downstream of the screen increases and the value of $(U_a/u')^2$ decreases as compared with that of the isothermal flow. In the downstream region from $x=480$ mm, $(U_a/u')^2$ increases linearly in both the $T_a=100$ and 150° cases. The change in gradient, which is seen in the case of the isothermal flow, cannot be seen in the present experimental region. The gradient becomes low with an increase in T_a . No qualitative difference was observed between position A and position B, though the values are not the same. When T_a is increased, the kinematic viscosity of the air increases. As shown in Fig. 6, the air temperature just downstream of the screen reaches 200°C in the case of $T_a=150^\circ\text{C}$. In this case, the kinematic viscosity increases to about 2.2 times the ambient air ($T_a=32^\circ\text{C}$). Then, the high-frequency and small-scale turbulence decays faster than that in the ambient air. On the other hand, the large-scale turbulence is generated due to the intermittent mixing of high-temperature fluid parcels and low-temperature fluid parcels as mentioned in Section 3.2.5. This large-scale turbulence decays slowly, and the gradient of the decay line becomes low.

As shown in Fig. 10, the turbulent energy decays linearly regardless of T_a . This suggests that the decay process simply depends on the viscous dissipation, similar to the grid turbulence of the isothermal flow. In other words, the decay process can be shown as follows.

$$(U_a/u')^2 = k_1 x + k_2 \quad (2)$$

$$\{(U_a/u')^2/k_1\} = x - x_0 \quad (3)$$

$$(x_0 = -k_2/k_1: \text{virtual origin})$$

The linearity of decay curves can be examined by using Eq. (3). The results are shown in Fig. 11. In the case of an isothermal flow with a screen, the gradient of the decay line changes, as shown in Fig. 10. Equation (3) is fit for the upstream-side decay line since the present study focuses on the developing region

Fig. 11 Decay of normalized turbulent energy

from just downstream of the screen. Figure 11 shows that the experimental results in $T_a = 32^\circ\text{C}$ deviate from the straight line of Eq. (3) in the downstream region from the middle location ($x - x_0 = 120$ in A position, $x - x_0 = 180$ in B position), reflecting on the change in gradient of the decay lines. In the case of $T_a = 100^\circ\text{C}$, the experimental results fit well with the line of Eq. (3). This indicates that simple linear decay takes place in all measurement regions. In the case of $T_a = 150^\circ\text{C}$, the experimental results do not fit with Eq. (3) just downstream of the screen. This suggests that simple linear decay does not take place there since the large-scale turbulence is supposed to be generated. In the region downstream from $x - x_0 = 60$ mm, however, the experimental results fit well with Eq. (3); thus, it seems that the turbulence structure gradually becomes to the simple dissipation process with increasing x .

The virtual origin x_0 is about -122 mm in the case of the isothermal flow with the G2 grid and without the screen. When the screen is installed, x_0 is about $382 \text{ mm} \pm 10\%$ regardless of T_a . Therefore, it appears that the virtual origin does not depend on T_a , unlike as the gradient of the decay line, but depends on the characteristics of the heating screen.

4. Conclusions

The experimental investigation of the structure of grid turbulence with heating by a heating screen has been conducted as basic research on the interaction between heat and flow motion. The discussion is focused on the structure of a developing region near the heating screen. The conclusions are:

- (1) The signals of velocity and temperature fluctuations show a positive correlation in that the high-temperature fluid parcel is fast and vice versa.
- (2) Just downstream of the heating screen, the thermal field becomes nonuniform due to the intermittent mixing of high-temperature fluid parcels and low-temperature fluid parcels. The velocity of high-

temperature fluid parcels is faster than that of the low-temperature fluid parcels due to the acceleration by thermal expansion or buoyancy effect. As a result, the flow field becomes nonuniform. The nonuniform flow field recovers to a uniform flow field with increasing downstream distance. However, the distance to recover the flow field becomes longer with increasing temperature of the heating wire.

- (3) The decay of the inverse value of the turbulent energy shows the typical linear decay of grid turbulence due to viscous dissipation, though the flow and thermal fields are nonuniform. The gradient of the decay line decreases with increasing heating temperature. These results indicate that the decay process is the simple linear decay similar to the isothermal grid turbulence, regardless of heating temperature, though the decay rate becomes low with an increase in the heating temperature.

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