Arch. Mech., 32, 4, pp. 447-453, Warszawa 1980

On the spectral bahaviour of turbulence in premixed flames

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THE INTERACTION phenomenon between the turbulence of the premixed inflammable flow, and the flame propagating in it, has been studied from the point of view of the flame and, also, from that of the turbulence itself. Introduction of the micro-scale effect is interpreted as a possible explication of the discrepancy which exists between the theoretical values of the turbulent propagation speed of the premixed flame — predicted by the wrinkled laminar flame model — and the experimental values of this speed. Finally, with the aim of clarifying the concept of flame generated turbulence, we report our experimental results about the influence of the heat emission on the spectral distribution of the turbulent kinetic energy.

Rozważono zagadnienie wzajemnego oddziaływania między turbulencją przygotowanego przepływu zapalnego a rozchodzącym się w nim płomieniem zarówno z punktu widzenia płomienia jak i samej turbulencji. Wprowadzenie efektu mikroskali tłumaczy się jako ewentualne wyjaśnienie rozbieżności jaka występuje między teoretycznymi wartościami prędkości propagacji turbulencji w przygotowanym płomieniu (przewidzianej na podstawie zafalowanego modelu laminarnego płomienia) oraz eksperymentalnie uzyskanymi wartościami tej prędkości. Na zakończenie, dla wyjaśnienia turbulencji generowanej przez płomień, podano wyniki własnych prac eksperymentalnych dotyczących wpływu emisji cieplnej na rozkład widmowy energii kinetycznej turbulencji.

Рассматривается проблема взаимодействия турбулентности подготовленного возгораемого течения с расходящимся в нем пламенем, как с точки зрения пламени, так и самой трубулентности. Введение эффекта микромасштаба объясняется как возможное выяснение расхождений между теоретическими значениями скорости распространения турбулентности в подготовленном пламени (предполагаемой на основании завихренной модели ламинарного пламени) и экспериментально полученными значениями скорости. В заключение с целью выяснения генерируемой пламенем трубулентности, приведены результаты экспериментальных работ авторов, касающиеся влияния тепловой эмиссии на спектр кинетической турбулентности.

1. Introduction

THE INVESTIGATIONS of flame propagation in a turbulent flow consisting of a homogeneous mixture of fuel and combustion have a twofold aspect: they are concerned with the influence of turbulence on the flame characteristics and also with the influence of the flame upon incident turbulence. Thus the wrinkled laminar flame model, which was initially intended to explain the influence of turbulence on combustion, has later been extended to the second aspect, i.e. to the influence of combustion on turbulence.

The extension of this model, which only considered the influence of turbulence macroscalar fraction, has been analysed to account for the discrepancies between the theoretical and experimental values of turbulent flame propagation velocity. The values predicted by this model were much smaller than the experimental ones. The assumption of an additional turbulence caused by the flame, which would add to incident turbulence and increase its influence upon the flame, was then put forward to explain these discrepancies.

In a previous study (GÖKALP [6]) we suggested to introduce the influence of the microscalar fraction of the turbulence of flame propagation velocity to explain the discrepancy between the values of the velocity predicted by the wrinkled laminar flame model and the experimental values.

The present paper is concerned with the second aspect of this problem of interactions, i.e. the influence of combustion upon turbulence. After a brief description of the only theoretical attempt in this field, that of ESCHENROEDER [4], we report our experimental results concerning the influence of temperature on turbulence and, in particular, on the spectral distribution of turbulent kinetic energy.

This study is connected with the investigations of turbulent combustion in premixed systems through two simplifying assumptions. The first one consists in neglecting the chemical reactions and in considering the rise in temperature of turbulent flow (thus simulating the heat emission due to chemical reactions). The second simplification is that of a relatively low temperature range. This is justified by the characteristics of our flame which is a "cold", feebly exothermic flame with a maximum temperature not exceeding 550°C. Attention is confined here to such a flame in order to make possible the use of the conventional methods of measuring the turbulence in a flame, i.e. hot-wire anemometry.

2. Heat release influence on turbulent energy spectrum

In an incompressible flow the equation describing the behaviour of the isotropic three-dimensional turbulent energy spectrum as a function of time and wave numbers is as follows (HINZE [8]):

$$\frac{\partial}{\partial t}\int_0^k E(k,t)dk = \int_0^k F(k,t)dk - 2\nu\int_0^k k^2E(k,t)dk, \tag{2.1}$$

where $E(k, t)$ is the energy-spectrum function and $F(k, t)$ the transfer-spectrum function. The left-hand side of this equation represents the change of the kinetic energy and of the dissipation in the eddies with wave numbers between 0 and k. The term $\int_0^k F(k,t)dk$ may be interpreted as the transfer energy to or from the turbulence in this wave number region or as the interaction of eddies in the wave number region 0 to k. The last term in the right-hand side represents the dissipation of energy into heat.

Equation (2.1) may be extended to the case in which energy is supplied continuously to the flow. This extension reads

$$\frac{\partial}{\partial t}\int_0^k E(k,t)dk = \int_0^k F(k,t)dk - 2\nu\int_0^k k^2E(k,t)\,dk + H_k(k,t), \tag{2.2}$$

where $H_k(k, t)$ is the energy supplied to turbulence in the wave number region from 0 to k of the spectrum. In the turbulent combustion case $H_k(k, t)$ will represent the energy transferred to the turbulence by chemical heat release.

Equation (2.2) from which $E(k, t)$ is to be deduced contains two other unknowns: $F(k, t)$ and $H_k(k, t)$. In the abscence of an external source of energy various hypotheses have been suggested to connect $F(k, t)$ with $E(k, t)$. Among the most important ones are those of Obukoff, Kovazsnay, Heisenberg and Von Kármán. When a source of energy is present (exothermal reactions in the turbulent combustion case), the only hypothesis proposed is that of ESCHENROEDER [4] who represented $H_k(k, t)$ by

$$\int_0^k H_k(k, t)dk = \frac{4K}{9} \int_0^k \int_0^k E(k, t)E(k, t)dkdk \ldots, \tag{2.3}$$

where K is a function of mean density, temperature and composition.

After introducing into Eq. (2.2) this expression, Eschenroeder resolved it separately for the inertial part and for the viscous part of the three-dimensional spectrum. For the inertial region he represented $F(k, t)$ by the modified hypothesis of Obukoff:

$$\int_0^k F(k, t)dk = -2\alpha \left[\int_0^k \{kE(k, t)\}^{1/2} dk \int_k^\infty E(k, t)dk \right], \tag{2.4}$$

where α is a constant. For the region of the spectrum where the viscous forces are comparable with the inertial ones he used the hypothesis of Heisenberg to connect $F(k, t)$ with $E(k, t)$:

$$\int_0^k F(k, t)^{1/2} dk = -2\alpha' \left\{ \int_k^\infty \frac{E(k, t)}{k^2} dk \right\} \left[\int_0^k k^2 E(k, t)dk \right], \tag{2.5}$$

where α' is another constant. In this last region $H_k(k, t)$ was represented by a modified form of Eq. (2.3):

$$\int_0^k H_k(k, t)dk = \frac{4k\beta}{9} \int_0^k \frac{E(k, t)}{k^2} dk \int_0^k k^2 E(k, t)dk \tag{2.6}$$

with $\beta \sim 1$.

This theoretical attempt of Eschenroeder predicts an intensification of the turbulence and also a new spectral distribution of turbulent kinetic energy under the influence of chemical heat release. Following Eschenroeder, the exothermal source exerts its influence most intensively in the energy containing region of the spectrum. Therefore the greatest distorsion occurs in a region surronding the spectral peak. Moreover, this additional energy tends to shift the transition to viscous action toward ever smaller eddies, that is to say the microscale is decreased for a given integral scale and the turbulent field becomes more predominantly inertial in nature.

It was our aim to test these predictions concerning turbulent spectral behaviour with heat release in the case of a simple temperature elevation of an initially cold turbulent flow.

For this purpose we established a turbulent flow into a brass tube of 50 mm in diameter and 700 mm in length. The turbulence was created by a perforated plate with a mesh diameter of 9 mm and an equivalent bar diameter of 3.8 mm; the flow was heated by an electric resistance providing a maximum temperature of 600°C.

The turbulence was measured with the aid of a temperature compensated anemometric bridge (DISA 55 M14) connected with a high temperature hot-wire (Pt/Rh, 2.2 mm in length and 10 microns in diameter) so as to eliminate temperature fluctuations. Spectral analyses were made using a real time spectrum analyser/digital integrator (Saicor 51).

All measurements were performed at one and the same point of the axis, 600 mm (or 160 mesh length) apart from the perforated plate. These measurements concern the axial velocity fluctuation and its spectrum. The cold flow turbulence at this point was one of a weak intensity, 3% (this measured value is also obtained by the Frenkiel expression for grid turbulence), and of a relatively large scale (about the total turbulent energy being included between 0 and 2000 Hz). The cold flow Reynolds number based on the tube diameter was 37000 and the one based on mesh diameter was 6600. The integral length scale, deduced from the cold flow one-dimensional spectrum, was 4.4 mm and the Taylor microscale, deduced from the Dryden estimation for isotropic turbulence, was found to be equal to 0.9 mm. The turbulence Reynolds number for a mean flow of 11 m/s at 25°C was equal to 22.

In spite of the temperature compensation associated with a relatively high over-heating ratio (0.4), we did not succeed in eliminating completely the high frequency temperature fluctuations. Thus there exists the possibility of contamination of the velocity fluctuation by the high frequency temperature fluctuations. With this reservation, the results concerning the turbulent kinetic energy spectrum behaviour up to 400°C were presented in a previous study (GÖKALP [7]).

The spectrum for $T = 25°C$ was in perfect agreement with that reported by VAN ATTA and CHEN [10]. Up to a 400°C temperature of the flow, they observed an increase in the absolute intensity of the axial fluctuation which passed from 37 cm/s at 25°C and for $\bar{U}_1 = 11$ m/s $(u_1/\bar{U}_1 = 3.36\%)$ to 49 cm/s at 400°C and for $\bar{U}_1 = 16.8$ m/s $(u_1/\bar{U}_1 = 2.91\%)$. This phenomenon occurred in connection with a spectral redistribution of the kinetic energy: the portion of the spectrum up to about 800 Hz became more energetic, the mid-range frequencies between 800 Hz and 1700 Hz less energetic, and above 1700 Hz no visible variations were observed. The transition to the portion of the spectrum less energetic than the cold one occurred at the same wave numbers as those observed by WOOLDRIDGE and MUZZY [11].

The results presented here (with the same reservation about the contamination of the velocity signal by the high frequency temperature fluctuations) concern the measurements of the one-dimensional spectrum at 500°C and 550°C. At 500°C the following phenomenon was observed: the spectral distribution was visibly the same as the one at 400°C. Approaching the limits of our apparatus (the hot-wire and the compensator) in order to increase the temperature, we finally attained 550°C. At this temperature we observed that the low frequencies became slightly less energetic and that the mid-range frequencies tended to be slightly more energetic than at 400°C (Fig. 1). Moreover, the ab-

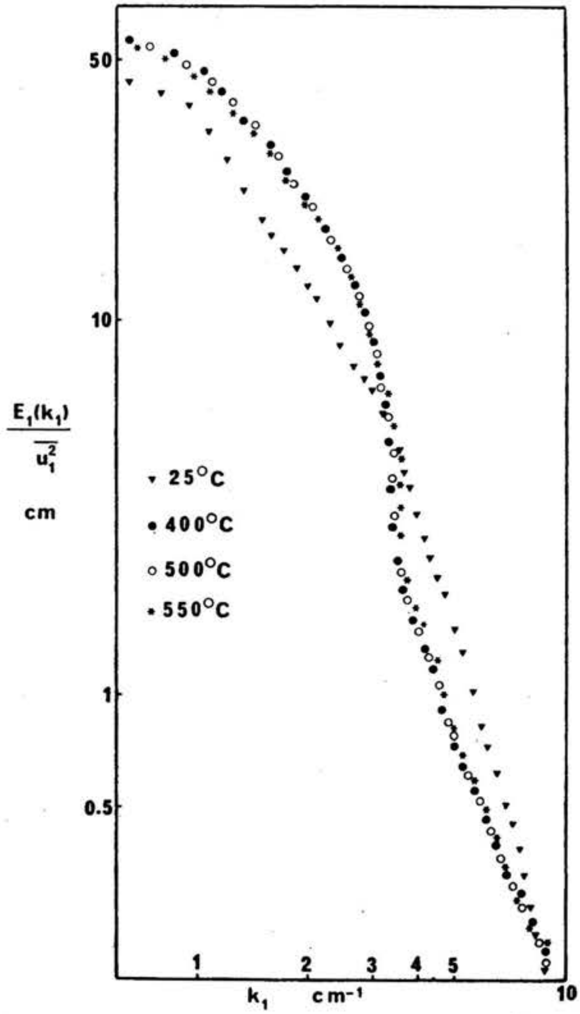

FIG. 1. Behaviour of the one-dimensional normalized spectra with temperature.

solute velocity of the axial fluctuation stagnated at 500°C ($u_1' = 50$ cm/s at $\overline{U}_1 = 18$ cm/s) and was slightly reduced at 550°C ($u_1' = 46.5$ cm/s at $\overline{U}_1 = 18.6$ m/s).

The results of the complete series ranging from 25°C to 550°C are represented in Fig. 2 by a linear-log plot with the ordinate $k_1 E_1(k_1)$ and the abscissa proportional to log k_1. This representation is very sensitive to changes in energy distribution. The area under any section of the $k_1 E_1(k_1)$ plot represents the fraction of total energy in that wave number range. Between 25°C and 400°C the energy increases except for the high frequencies and the second maximum, which gives an idea of the most energetic eddies' dimensions, is displaced towards the lowest frequencies, as was predicted by Eschenroeder. At 500°C the same distribution as for 400°C is obtained. At 550°C a weak energy reduction is observed in low frequencies; the second maximum is slightly shifted towards the mid-range frequencies. The high frequencies remain always unaltered.

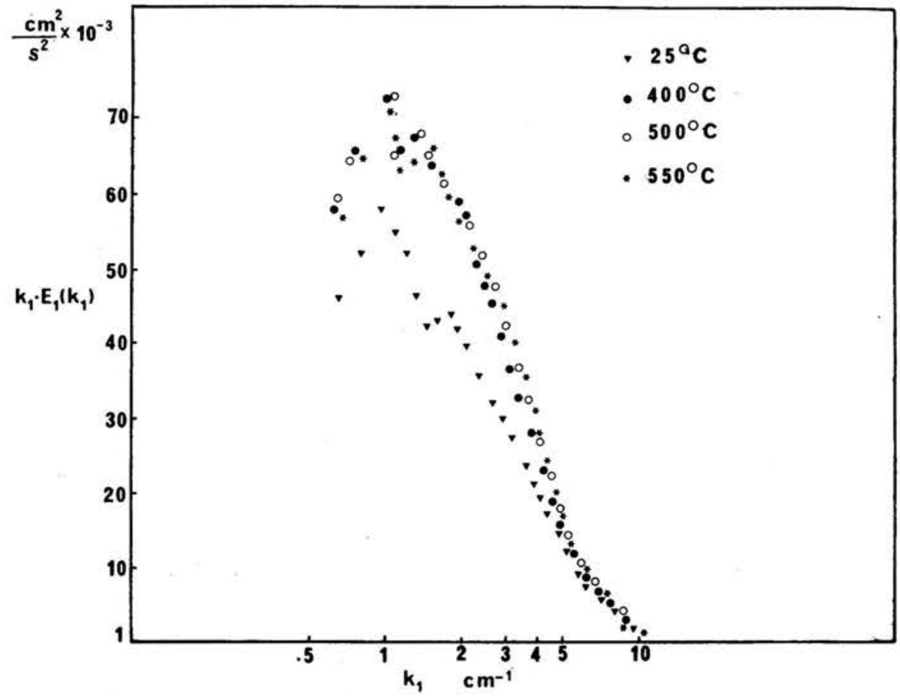

FIG. 2. Semi-log representation of the turbulent kinetic energy behaviour with temperature.

The results for these last two temperatures suggest a certain turbulence attenuation occurring only at low frequencies. As we cannot proceed to comparisons with other results, we abstain from drawing whatever conclusions on this last observation. However, we are wondering whether in the vast domain of turbulence another phenomenon does not occur, where a negative production of turbulence energy could be observed. In such a case we could make an analogy with our observations.

Such a phenomenon occurs effectively in some disymmetrical flows like a wall yet. Here there is a region where the point with $-\overline{u_1 u_2} = 0$ and that with $d\overline{U}_1/dx_2 = 0$ do not coincide. In the region between these two points the shear stress and the mean velocity gradient have opposite signs. If turbulence shear stress is expressed in terms of $d\overline{U}_1/dx_2$ by means of an eddy viscosity ε_m, which implies the assumption of a gradient type of momentum transport, at the point when $d\overline{U}_1/dx_2 = 0$ the shear stress should be zero, which is not the case.

The explanation given by HINZE [9] is that turbulent transport cannot be of the gradient type only. Hence, the contribution of turbulence to shear stress consists of two parts:

$$(2.7) \qquad -\overline{u_1 u_2} = \Sigma_m(d\overline{U}_1/dx_2) - \overline{u_1 u_2^*}.$$

The first term on the right-hand side expresses the contribution of small scale turbulence, the second term the contribution of larger scale turbulence, or of the transport of momentum over distances where the mean velocity gradient can no longer be considered as being constant, while also the effect of inhomogeneity of the turbulence is felt.

On the other hand, the term $A = -\varrho u'_\alpha u'_\beta (\partial \overline{U}_\beta / dx_\alpha)$ occurring on the right-hand side of the equations for the mean energy and the turbulent energy with opposite signs describes the mutual exchange of energy of the mean and fluctuating motion (Monin and Yaglom, 1971). If at a given point of space $A > 0$, then the turbulent energy density at this point increases at the expense of the energy of the mean motion. If, on the contrary, $A < 0$, then the energy density of mean flow increases at the expense of the energy of the fluctuations.

Monin and Yaglom state that if the turbulence has some external source of energy, for example if it is caused by artificial mixing of the fluid, or in the case of a compressible fluid, if it arises because of the presence of density fluctuations produced by the influx of heat, then the possibility for the turbulent energy to be converted into energy of the mean motion, i.e. the possibility that $A < 0$, is not excluded.

In other words, the conclusion that for stationary turbulence production must compensate dissipation is right for the whole flow, but not necessarily right for each point of the flow (ESKINAZI, [5]; BÉGUIER, [1]). Since in the wall jet case the product $(-\overline{u_1 u_2})$ $(d\overline{U}_1/dx_2)$ appears with an opposite sign in the energy equation of the mean motion, this might suggest a transfer of energy from turbulence to the mean motion.

The spectral analyses of this phenomenon by BÉGUIER [2] show the responsibility of the only big eddies in this negative production of energy. The same conclusion is drawn by BÉGUIER, FULACHIER and KEFFER [3] for the temperature fluctuations with negative production in the case of a heat crenel.

Thus our observation of turbulence energy removal from the only macroscalar fraction for 550°C is somewhat grounded.

References

1. C. BÉGUIER, J. Méc., **4**, 3, 1965.
2. C. BÉGUIER, C. R. Acad. Sc., **268**, Sér .A, p. 69, Paris 1969.
3. C. BÉGUIER, L. FULACHIER and J. F. KEFFER, C.R.Acad. Sc., **283**, Sér. B, p. 417, Paris 1976.
4. A. Q. ESCHENROEDER, AIAA J., 3, p. 1839, 1965.
5. S. ESKENAZI, J. Méc., **3**, 3, 1964.
6. I. GÖKALP, Revue Générale Therm. [to appear 1977].
7. I. GÖKALP, Paper presented at the Sixth Colloquium on Gas Dynamics of Explosions and Rective Systems, 22–26 August, Stokholm 1977.
8. J. O. HINZE, *Turbulence*, McGraw Hill, 1959.
9. J. O. HINZE, Appl. Sci. Res., **22**, p. 163, 1970.
10. C. W. VAN ATTA and W. Y. CHEN, J. Fluid Mech., **38**, p. 743, 1969.
11. C. E. WOOLDRIDGE and R. J. MUZZY, AIAA J., **4**, p. 2009, 1966.

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Received October 27, 1977.