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Experimental analysis of internal energy transport in the presence of coherent motion

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Abstract—The paper presents the internal energy budget in the initial region of the slightly heated free round jet in the presence of column-mode coherent structures. The budget was obtained by the quantitative evaluation of the shares of particular streams of internal energy transported in the flow-field considered. The input data for calculations have been obtained by the hot-wire measurements of three components of instantaneous velocity and instantaneous temperature. All the terms of the internal energy budget have been determined experimentally except the pressure-velocity term which was treated as a closing quantity. The results of the study suggest, that the internal energy of the flow is determined by the mutual balance of convection realized by the mean, oscillatory and random components of motion accompanied by the work of pressure–velocity correlations. It appears furthermore, that the heat transfer in the initial jet area is realized mainly by random fluctuations of proper turbulence motion, generated, however, in substantial part by coherent structures existing in the flow-field considered. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

The problem formulated in this paper concerns the qualitative description of the interaction between the coherent structures and the turbulent fields of velocity and temperature. The numerical modelling of turbulent flow-fields which is nowadays a basic tool for engineering calculations requires a quantitative knowledge of particular fluxes of energy and heat, which are transported by turbulent and organized motion. Such a research, which should form a basis for further improvement of turbulence models, has been earlier undertaken at the Institute of Thermal Machinery in the domain of analysis of turbulence kinetic energy budget [1]. The bibliography available contains the studies of heat transfer processes in the classical fully-developed flows [2–4], but till now no information concerning the heat transport properties in the presence of organized motion has been found. This research was, therefore, performed in order to fill this gap and it was intended to obtain a description of the internal energy transport realized by the mean motion. This internal energy budget may be treated as a quantitative evaluation of the shares of particular streams of internal energy transported in the flow-field considered. The balance of internal energy is coupled to the kinetic energy transport equation by the dissipation term, which may be regarded as a heat source distributed throughout the flow. That is why it has been decided to choose the free, round jet as a sample object of study, because the earlier results concerning the kinetic energy budget [1] could be used as a starting point and a reference level.

✠Professor Elsner died 15 August 1996.

2. FORMULATION OF MEAN INTERNAL ENERGY BALANCE EQUATION

The comprehensive analysis of the energy transfer properties of turbulent flow requires the knowledge of the behaviour of the so called total energy E_{tot}, which is a sum of both the kinetic (or mechanical) energy E_{kin} and the internal energy (neglecting the potential energy), i.e.:

$$E_{tot} = E_{kin} + E_{int}. \quad (1)$$

In the case of the real fluid, kinetic energy is interrelated to the internal one by both the dissipation and the compressibility effects. As it is well known [5], it is possible to derive the separate balance equations for both the total and kinetic energies, which then may be used to determine the internal energy balance

NOMENCLATURE

AME	advection of mean internal energy	U, u	velocity
c_v, c_p	specific heat capacity of air at constant volume and constant pressure, respectively	x, r, ϕ	cylindrical coordinate system
CFE	coherent flux of internal energy	α	thermal diffusivity
D	exit nozzle diameter	ε	dissipation of turbulence kinetic energy
DEK	dissipation of kinetic energy	θ, v	temperature
DHC	diffusion of heat by conduction	λ_s	wavelength of coherent structure
E_{int}, C_{int}	specific internal energy	μ	dynamic viscosity
E_{kin}	specific kinetic energy	ρ	density
E_{tot}	specific total energy	ν	kinetic viscosity
P, p	pressure	$(\bar{\ })$	time-mean average
PVC	work done by pressure–velocity correlations	$(\tilde{\ })$	oscillatory component
Re_D	Reynolds number based on the exit nozzle diameter	$(')$	random component.
St_D	Strouhal number		
TFE	turbulent flux of internal energy		
		Subscripts	
		o	nozzle outlet
		r	radial direction
		x	axial direction
		ϕ	circumferential direction.

equation and this way has been chosen to be followed in this analysis.

Each of the physical flow-field quantities was treated as a superposition of mean $(\bar{\ })$, periodic $(\tilde{\ })$ and random $(')$ components, i.e.:

$$\begin{aligned} U_i &= \bar{U}_i + \tilde{u}_i + u'_i \\ p &= \bar{p} + \tilde{p} + p' \\ \theta &= \bar{\theta} + \tilde{v} + v' \end{aligned} \tag{2}$$

where $i = x, r, \phi$ stands for the axisymmetric coordinates applied. If one assumes the relatively small velocity range, as well as the moderate overheat of the jet, then it will be possible to consider the flow as incompressible with the constant physical properties, such as viscosity ν, thermal diffusivity α, etc.

Subtracting the kinetic energy equation from the total energy one, then neglecting the internal volumetric heating and assuming the air to be a perfect gas, the resultant transport equation of the internal energy may be written as:

$$\begin{aligned} \frac{D(E_{int})}{Dt} &= c_v\left[\frac{\partial\theta}{\partial t} + U_x\frac{\partial\theta}{\partial x} + U_r\frac{\partial\theta}{\partial r} + U_\phi\frac{\partial\theta}{r\,\partial\phi}\right] \\ &= c_p\alpha\nabla^2\theta + \varepsilon - \frac{1}{\rho}\left[\frac{\partial P}{\partial t} + U_x\frac{\partial P}{\partial x} + U_r\frac{\partial P}{\partial r}\right. \\ &\quad \left. + U_\phi\frac{\partial P}{r\,\partial\phi}\right] \end{aligned} \tag{3}$$

where c_V, c_P denote the specific heat capacity at constant volume and pressure, respectively, and the viscous dissipation term expressed as:

$$\begin{aligned} \varepsilon = \frac{\mu}{\rho}\Bigg\{2\left[\left(\frac{\partial U_x}{\partial x}\right)^2 + \left(\frac{\partial U_r}{\partial r}\right)^2 + \left(\frac{\partial U_\phi}{r\partial\phi} + \frac{U_r}{r}\right)^2\right] \\ + \left(\frac{\partial U_x}{\partial r} + \frac{\partial U_r}{\partial x}\right)^2 + \left(\frac{\partial U_r}{r\partial\phi} + \frac{\partial U_\phi}{\partial x}\right)^2 \\ + \left(\frac{\partial U_\phi}{\partial r} + \frac{\partial U_r}{r\partial\phi} - \frac{U_\phi}{r}\right)^2\Bigg\}. \end{aligned} \tag{4}$$

Following the relation (2) the instantaneous value of internal energy may be expressed with the use of triple decomposition concept as:

$$E_{int} = \bar{E}_{int} + \tilde{e}_{int} + e'_{int} \tag{5}$$

where only the internal energy of the mean motion will be of interest in this paper, because the time-mean values of oscillatory and random components of internal energy equal zero, i.e.:

$$\overline{\tilde{e}_{int}} = \overline{e'}_{int} = 0.$$

Bearing in mind the above statement, the time-averaging of equation (3) was applied, which for the case of axisymmetric jet ($\partial/\partial\phi = 0$) gave finally the following form of the transport equation of the internal energy of the mean motion:

$$c_v\left[\bar{U}_x\frac{\partial\bar{\theta}}{\partial x}+\bar{U}_r\frac{\partial\bar{\theta}}{\partial r}+\bar{U}_\phi\frac{\partial\bar{\theta}}{r\partial\phi}\right]$$
1

$$+c_v\left[\frac{\partial\overline{\tilde{u}_x\tilde{v}}}{\partial x}+\frac{1}{r}\frac{\partial(r\overline{\tilde{u}_r\tilde{v}})}{\partial r}+\frac{\partial\overline{\tilde{u}_\phi\tilde{v}}}{r\partial\phi}\right]$$
2

$$+c_v\left[\frac{\partial\overline{u'_xv'}}{\partial x}+\frac{1}{r}\frac{\partial(r\overline{u'_rv'})}{\partial r}+\frac{\partial\overline{u'_\phi v'}}{r\partial\phi}\right]-c_p\alpha\nabla^2\bar{\theta}-(\bar{\varepsilon})$$
3 4 5

$$+\frac{1}{\rho}\left\{\frac{\partial}{\partial x}(\bar{P}\bar{U}_x+\overline{\tilde{p}\tilde{u}_x}+\overline{p'u'_x})\right.$$

$$+\frac{\partial}{r\partial r}\left[(r\bar{P}\bar{U}_r+\overline{\tilde{p}\tilde{u}_r}+\overline{p'u'_r})\right]+\frac{\partial}{r\partial\phi}(\bar{P}\bar{U}_\phi$$
6

$$\left.+\overline{\tilde{p}\tilde{u}_\phi}+\overline{p'u'_\phi})\right\}=0. \qquad (6)$$

Taking into account the structure of the above equation, its particular terms were interpreted as follows (the abbreviations given in brackets):

(1) advection of mean internal energy (AME);
(2) coherent flux of internal energy (CFE);
(3) turbulent flux of internal energy (TFE);
(4) diffusion of heat by conduction (DHC);
(5) dissipation of kinetic energy (DEK);
(6) work done by pressure–velocity correlations term (PVC).

3. EXPERIMENTAL CONDITIONS

The object of the research was the non-isothermal round jet issuing from the contoured nozzle of $D = 0.04$ [m] at the constant exit velocity corresponding to the

$$Re = 4\cdot 10^4.$$

The overheat of the flowing medium (i.e. the difference between the ambient $\bar{\theta}_a$ and exit air temperature $\bar{\theta}_o$) was kept at the constant level

$$\Delta\bar{\theta} = 40\,[^\circ\mathrm{C}]$$

i.e. the experiment was confined to 'weakly-non-isothermal' range because of the requirements resulting from the hot-wire technique.

The free, round jet reveals a multi-modality of the coherent motion [6, 7] and that is why the flow had to be externally stimulated with the harmonic acoustic wave of the frequency f given by the Strouhal number

$$St = \frac{fD}{U_o} = 0.42.$$

The above value corresponds the so-called 'column-mode', which on one hand is characterized by the largest amplitudes attained and on the other by the absence of pairing, which could disturb the mechanism analyzed. The acoustic jet stabilization cancelled the random dispersion of size and shedding frequency of coherent vortices and furthermore enabled one to use the acoustic pressure as a reference signal in phase-averaging procedure.

In the course of experiment the three components of instantaneous velocity together with the instantaneous temperature have been recorded with the use of a combined, four-wire sensor, shown schematically in Fig. 1. The triple-wire gold-plated DANTEC 55P91 probe used for velocity measurements was composed of 5 μm sensing elements with active length equal to 1.2 mm, while the DANTEC P31 temperature probe utilized a 1 μm wire of 0.6 mm length. The measuring volume occupied by the wires could be approximated by the sphere with 2 mm diameter, while the proper distances among the particular wires allowed to avoid their thermal and aerodynamic interference. The signals from hot-wire bridges were digitized together with the acoustic pressure signal and then processed numerically with the use of time and phase-averaging [8] in order to split the signal according to the triple decomposition [see equation (2)] idea. The location of the above cross-sections is indicated at the plot of periodical component of temperature variance $\overline{\tilde{v}^2}$ (Fig. 2), measured along the centerline of the mixing layer. The $\overline{\tilde{v}^2}$ might be regarded as an overall measure of the intensity of mixing processes realized by coherent vortex and because of its relation to the spatial coherence of the structure analyzed it was used to localize the measuring cross-sections. As can be seen in Fig. 2, the three test cross-sections selected for the analysis were located in the areas characterized by the growth ($x/D = 1.5$), the maximum spatial coherence ($x/D = 2.5$) and the decay ($x/D = 4$) of the column-mode vortices. The above main cross-sections were accompanied by auxiliary measuring planes, which were needed to calculate the gradients of particular quantities in transport equation analyzed. The Δx distance was selected as $\Delta x/\lambda_s = 0.08$ (i.e. $\Delta x/D = 0.125$), because the results of preliminary measurements [9, 10] as well as literature data [11, 12] have shown that this value was on one hand sufficiently small in comparison with the wavelength λ_s of the column-mode structures and on the other it was large enough to obtain accurate estimation of the particular gradients in equation (6).

4. ANALYSIS OF PARTICULAR TERMS OF INTERNAL ENERGY BUDGET

The instantaneous temperature and velocity time-series recorded during the measurements after proper processing [8, 13] allowed to calculate the values of first four terms of equation (6) in all the measuring points. The dissipation of kinetic energy of turbulence

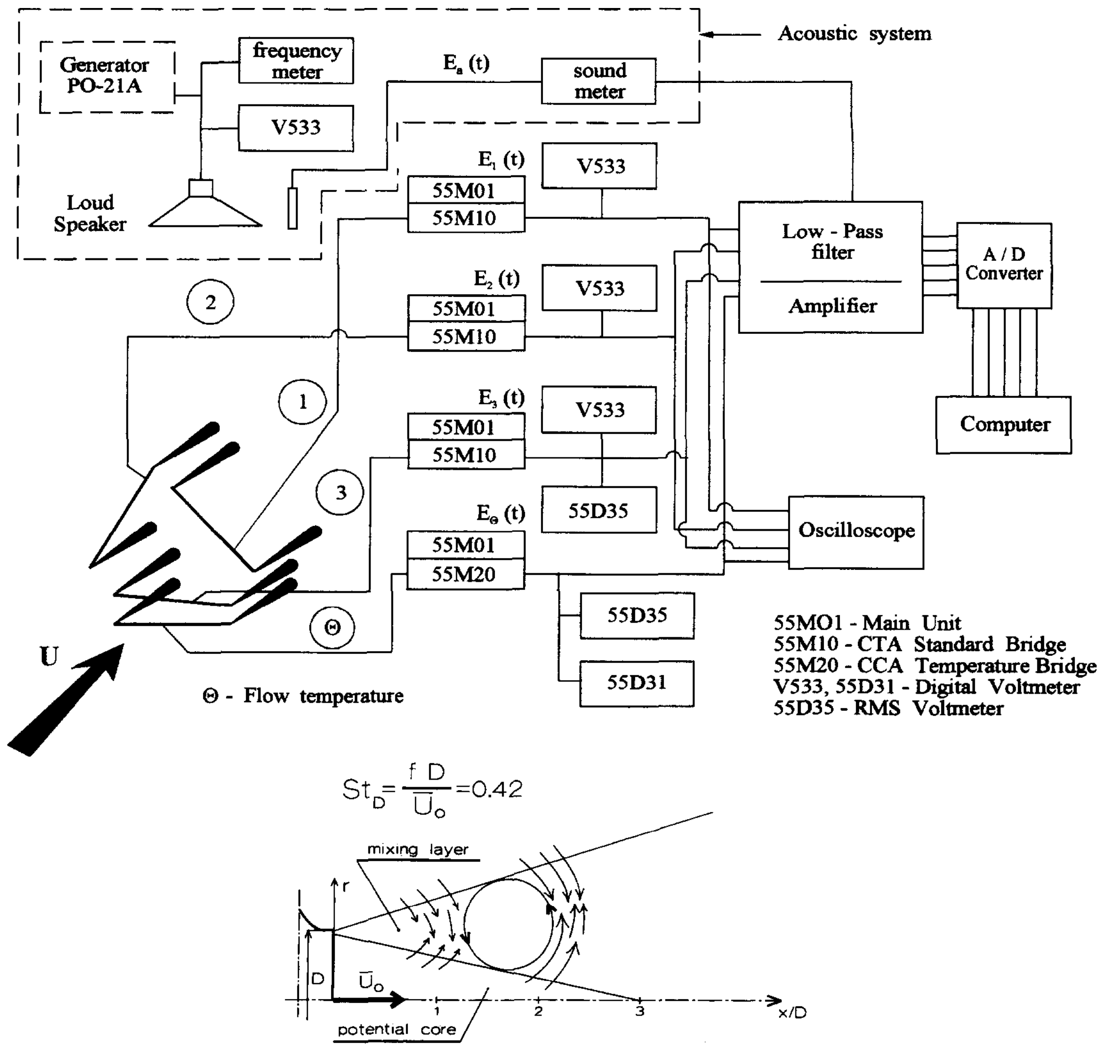

Fig. 1. The sketch of hot-wire probe and apparatus (a); and the coordinate system applied (b).

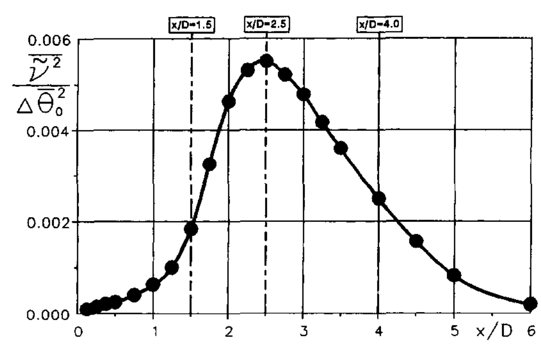

Fig. 2. The distribution of periodical component of temperature variance measured along the centerline of the mixing layer ($r/D = 0.5$).

[term 5 of equation (6)] was taken from [1], while the work done by pressure–velocity correlations (term 6) has been calculated as a closing quantity of the internal energy transport equation.

The radial distributions of term 1, i.e. the advection of internal energy by the mean motion (AME—advection of mean internal energy) has been presented at Fig. 3 as the total value (AME_X&R), as well as the axial (AME_$x \equiv c_v \bar{U}_x \; \partial\bar{\theta}/\partial x$) and radial (AME_$R \equiv c_v \bar{U}_r \; \partial\bar{\theta}/\partial x$) components. As it comes out from the above data the radial advection (AME_R) which increases the energy level throughout the control volume plays a minor role in transport processes considered. The dominant part of internal energy advection realized by the mean motion is performed in the axial direction and the contribution of the (AME_X) term to the energy balance depends strongly on the radial coordinate. As it results from the analysis of equation (6) the behaviour of advection term is determined mainly by the longitudinal mean-temperature gradient $\partial\bar{\theta}/\partial x$, and the above quantity has been calculated from mean-temperature profiles measured at the main control planes as well as at the auxiliary ones [13]. One may easily notice the evident similarity of radial distributions of longitudinal advection (AME_X—Fig. 3) at all the cross-sections considered, which reveal the three distinctly different areas located along the radial coordinate. The first

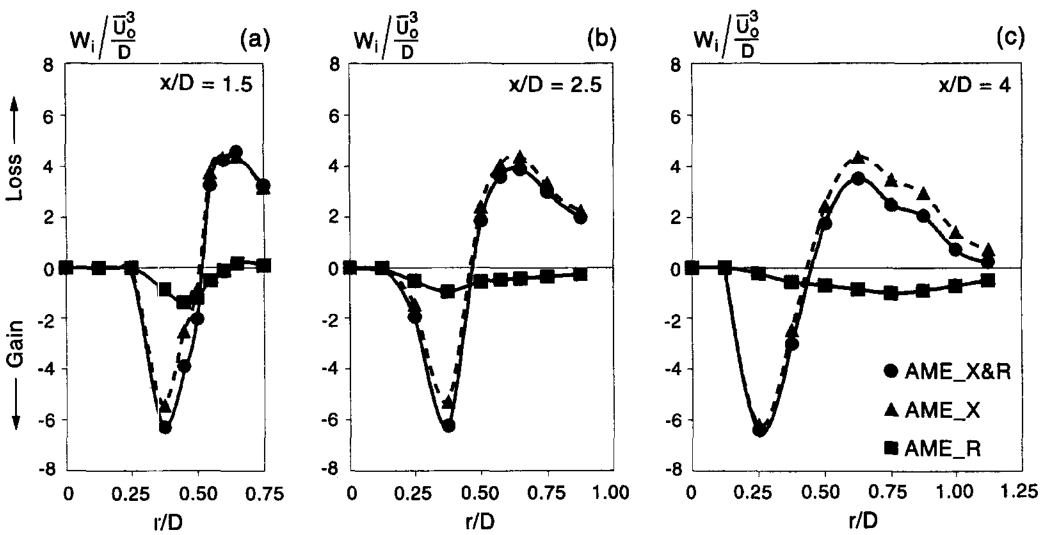

Fig. 3. Radial distributions of axial radial and total advection of mean internal energy (AME) at the cross-section: (a) $x/D = 1.5$; (b) $x/D = 2.5$; (c) $x/D = 4$.

zone characterized by the constant value of mean temperature $\bar{\theta}$ inside the potential core, reveals zero value of axial and radial convection, and the radial extent of this area diminishes in consecutive cross-sections. The intense spreading of temperature wake and the resulting negative mean-temperature gradient $\partial\bar{\theta}/\partial x$ create the next area located between the border of potential core and the radial coordinate $r/D \approx 0.5$, where advection gives the energy gain inside the control volume The third zone located at the area $r/D > 0.5$ is characterized by the positive value of $\partial\bar{\theta}/\partial x$ and, as a consequence, by the loss of internal energy caused by the action of longitudinal advection. The dominant role of the term (AME_X) leads to the fact, that the total advection of internal energy (AME_X&R) reveals the same characteristic behaviour in all the control-planes analyzed. One should notice, however, that in the last cross-section ($x/D = 4$) the total advection reaches the zero level at much smaller radial distance than its axial component because in the outer jet region of this plane the terms (AME_X) and (AME_R) bring the opposite contributions into the internal energy budget.

The second term of equation (6) is the coherent flux of internal energy (CFE) which may be understood as an internal energy stream transported by the coherent motion or as a 'coherent advection'. The radial distributions of the total coherent energy flux (CFE_X&R), as well as, of its axial (CFE_X) and radial (CFE_R) components presented at Fig. 4 reveal quite a different behaviour in comparison with the advection realized by the mean motion. First of all, the radial transport performed by CFE_R term plays a dominant role while the values of axial advection term (CFE_X) oscillate around zero in all the cross-sections considered. The second important difference is the opposite contribution brought by the (CFE) term into the internal energy budget in comparison with the (AME) flux. As can be seen at Fig. 4, the coherent advection extracts the energy in the inner jet area and brings about the energy gain in the zone determined by the $r/d > 0.5$ radial coordinate. One should notice, however, that when the point of observation is being moved downstream the area of positive (CFE) values evidently prevail over the negative ones [see Figs 4(a–c)].

This tendency may be most clearly observed in $x/D = 4$ cross-section [Fig. 4(c)] where the intense action of viscous forces in the outer jet region cancels the periodic motion and diminishes evidently the negative internal energy flux transported by coherent structures. The more favourable conditions of phase coherence characteristic for the inner jet region increase the positive (CFE) flux and the highest values of both gain and loss of internal energy are encountered in the $x/D = 2.5$ cross-section characterized by the highest share of organized motion in the overall kinetic energy of velocity fluctuations. One should also notice that the radial advection performed by oscillatory motion is intense enough to be noticed even in the area of potential core, where the internal energy advection realized by the mean motion was not traceable [comp. Figs. 3(c) and 4(c).

A similar behaviour (see Fig. 5) is revealed by the term 3 denoted here as TFE (turbulent flux of internal energy) which can be identified with the heat advection performed by turbulent (random) motion. Following the previous analyses, the total heat flux transported by turbulent motion (TFE_X&R), as well as, its axial (TFE_X) and radial (TFE_R) components have been presented at Fig. 5. One may observe the dominance of radial component (TFE_R) of turbulent advection, which extracts the internal energy in the inner jet region and leads to the energy gain in the outer flow area. It should be noticed however, that the increase of internal energy level is less visible when

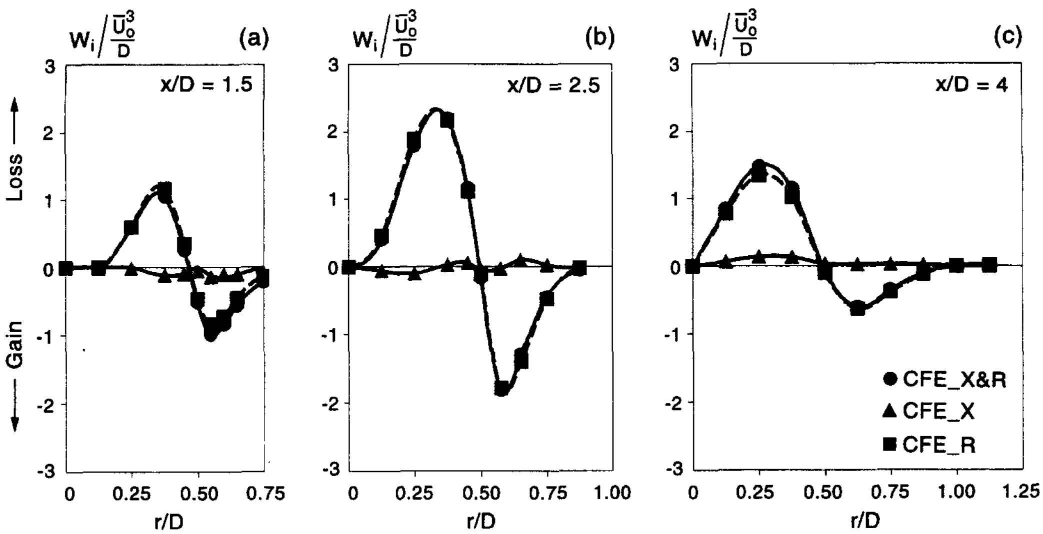

Fig. 4. Radial distributions of axial, radial and total coherent fluxes of internal energy (CFE) at the cross-sections: (a) $x/D = 1.5$; (b) $x/D = 2.5$; (c) $x/D = 4$.

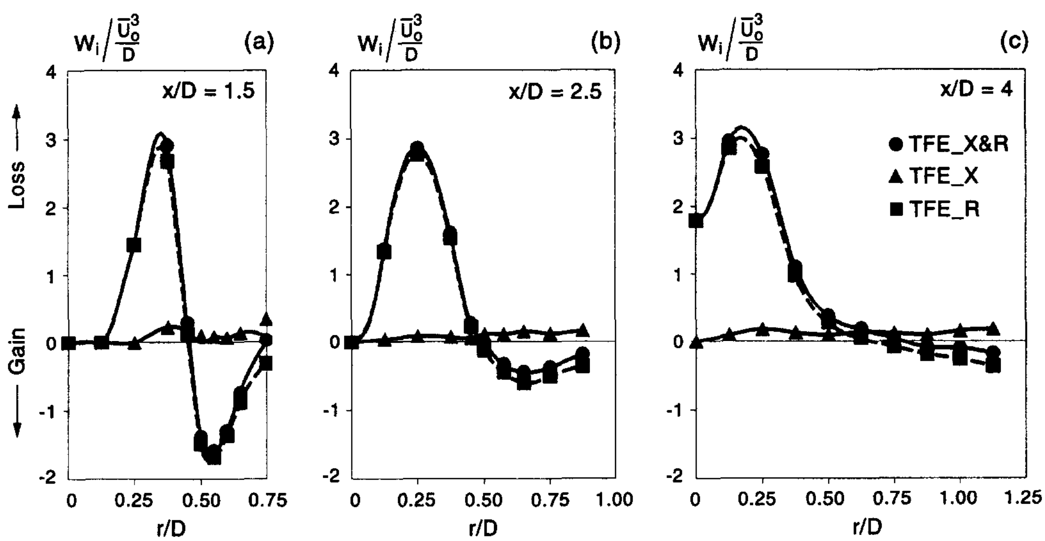

Fig. 5. Radial distributions of axial, radial and total turbulent fluxes of internal energy (TFE) at the cross-sections: (a) $x/D = 1.5$; (b) $x/D = 2.5$; (c) $x/D = 4$.

the structures gradually lose their spatial coherence in the outer jet boundary, due to the action of viscous forces [see Figs. 5(a–c)]. The maximum amplitudes of positive turbulent advection inside the jet are always bigger than the ones revealed by (CFE) term, that suggests the indirect role of coherent structures in heat transfer processes i.e. the above processes seem to be realized in greater extent by random turbulence generated due to the action of coherent motion. A similar observation concerns the inner region of the $x/D = 2.5$ plane where the maximum coherence of organized motion is accompanied by the minimum intensity of random advection of internal energy [see Fig. 5(b)]. One may notice therefore, that the growth [$x/D = 1.5$—Fig. 5(a)] and decay [$x/D = 4$—Fig. 5(c)] of coherent structures create the more favourable conditions for random turbulence generation than the ones existing in the region of maximum spatial coherence of coherent vortex [$x/D = 2.5$—Fig. 5(b)].

The next two pictures present the radial distributions of internal energy transported by conduction (Fig. 6—term 4—designed as DHC—diffusion of heat by conduction), as well as, the dissipation term (Fig. 7—term 5—marked as DKE—dissipation of kinetic energy). The dissipation increases of course the energy contents of the control volume, while the DHC term leads to the loss of internal energy in the prevailing part of each cross-section considered. It should be noticed, however, that both these heat fluxes are in general three orders of magnitude smaller than the terms discussed previously and that is why their role in the energy budget is

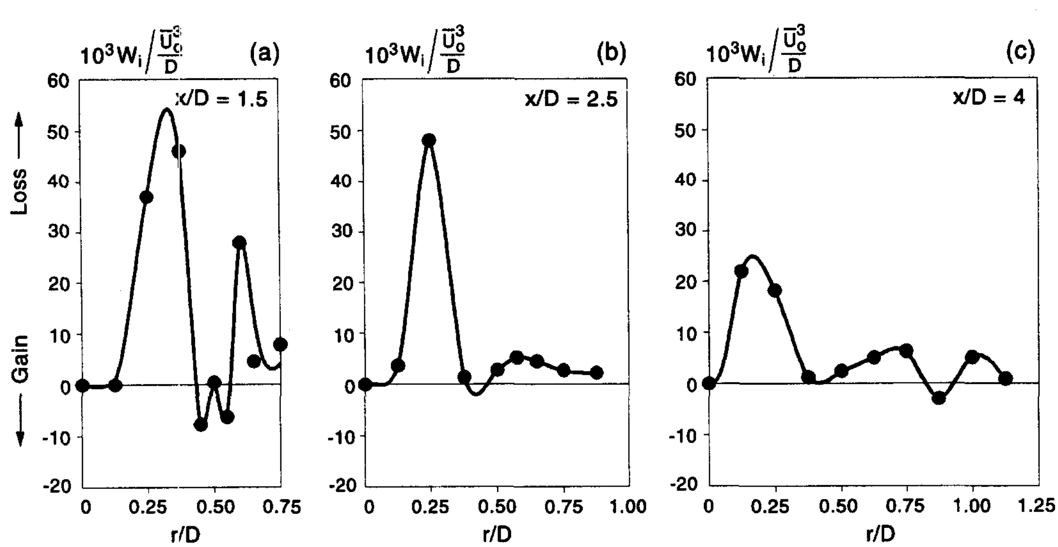

Fig. 6. Radial distributions of diffusion of heat by conduction (DHC) at the cross-section: (a) $x/D = 1.5$; (b) $x/D = 2.5$; (c) $x/D = 4$.

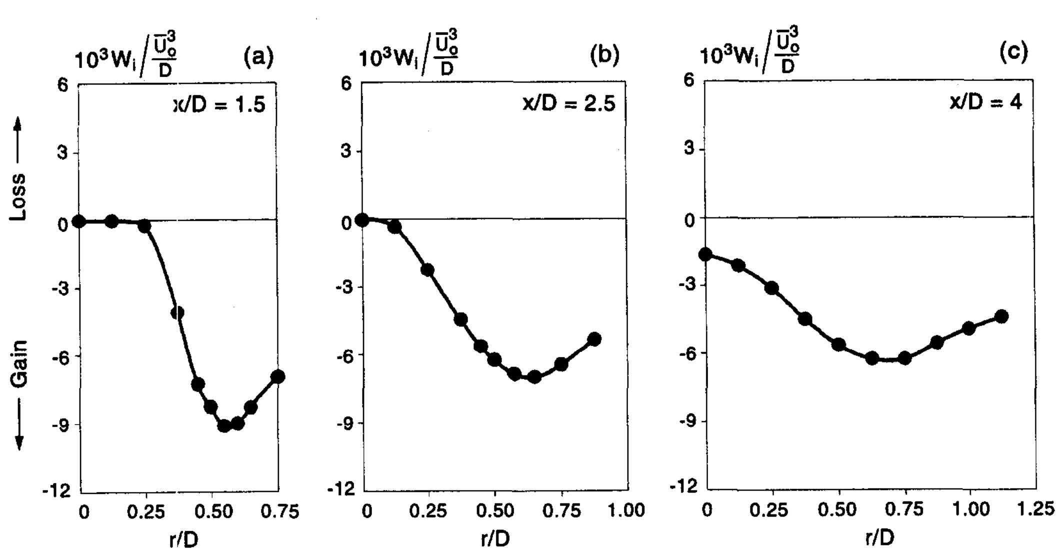

Fig. 7. Radial distributions of viscous dissipation of kinetic energy (DKE) at the cross-sections: (a) $x/D = 1.5$; (b) $x/D = 2.5$; (c) $x/D = 4.0$.

negligible. Furthermore, the low values of the DHC term and the computational errors lead to the substantial scatter of data most clearly visible around the $r/D = 0.5$ coordinate in the $x/D = 1.5$ cross-section [see Fig. 6(a)].

Term '6' of equation (6) containing the pressure–velocity correlations could not be determined experimentally and has been regarded as a closing quantity in the internal energy balance. It plays, therefore, an exceptional role in the present analysis, because one may expect that its physically justified distributions may be treated as a verification of the correct determination of the remaining terms. The additional reason that makes the analysis of this term so essential is the important role of pressure–velocity correlations in transport processes realized by turbulent flows. In the small-scale random turbulence, the above correlations are responsible for the kinetic energy redistribution among the particular flow-field directions and for the resulting tendency towards isotropy [2]. In the case of the turbulent flow field which is characterized by the presence of the organized motion the role of the above correlations is still unexplained despite the fact that this problem was a matter of intense theoretical and numerical research [14].

The radial distributions of work done by pressure velocity correlations (PVC) have been presented at Fig. 8 for the consecutive cross-sections. As can be seen at Figs. 8(a,b), inside the potential core the PVC term equals zero, while in the area neighbouring to the core it reveals the negative sign, i.e. represents the energy gain. One may expect therefore that in the

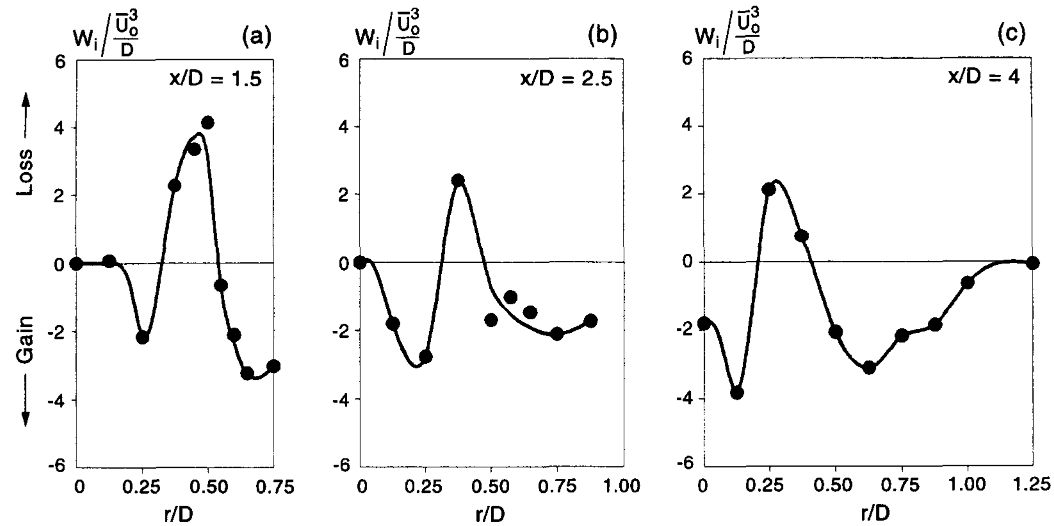

Fig. 8. Radial distributions of work done by pressure–velocity correlations (PVC) at the cross-sections: (a) $x/D = 1.5$; (b) $x/D = 2.5$; (c) $x/D = 4.0$.

inner jet region the positive velocity fluctuations are accompanied by negative pressure oscillations and vice-versa. Furthermore, one may notice at Fig. 8 the rapid change of PVC sign in the central jet area, caused probably by the vorticity dominance which results in turn in the appearance of additional inertia forces disturbing the pressure field. The amplitude of positive PVC which is well correlated with the maximum values of vorticity in particular cross-sections [13] as well as the gradual shift of positive PVC peak towards the inner part of the jet where the vortices preserve their coherence, may be treated as an additional confirmation of the above statement. The radial distributions of PVC term presented at Fig. 8 reveal the quantitative and qualitative agreement with the data from [1, 14] that allows to presume that the particular terms of the internal energy budget have been calculated correctly. Furthermore, the substantial values of the work performed by pressure–velocity correlations (comparable with terms 1–3) suggest the important role of PVC term in heat transport processes taking place in the flow-field considered.

5. CONCLUDING REMARKS

The summary of the above considerations may be found at Fig. 9, presenting the radial distributions of all the particular terms of the budget of the internal energy transported by the mean flow. According to previous statements, the results obtained at Fig. 9 reveal the negligible role of both the terms 4 (heat flux transported by conduction) and 5 (dissipation of kinetic energy) in transport processes considered. The influence of potential core may be observed only in

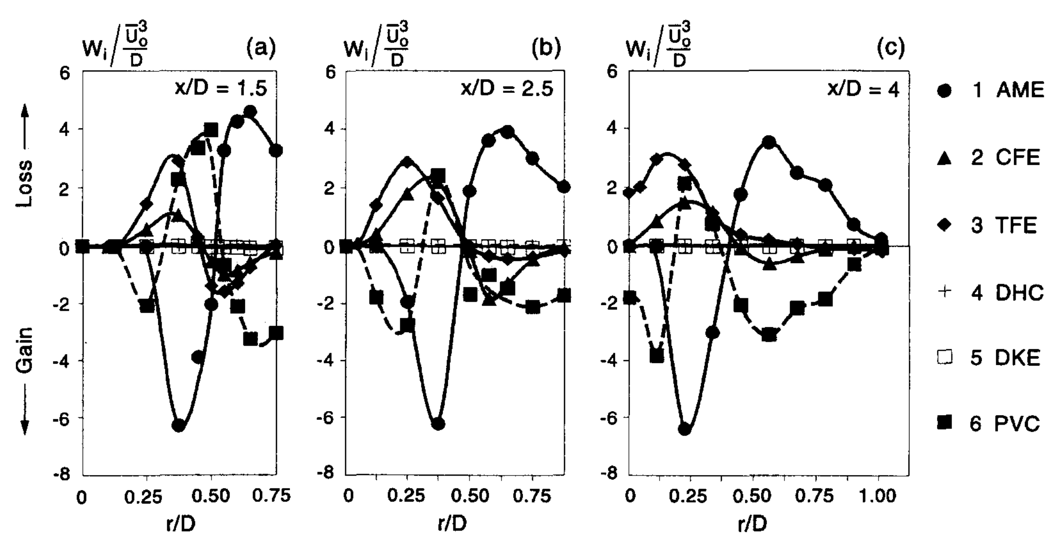

Fig. 9. Budget of the internal energy of the mean-motion at the cross-sections: (a) $x/D = 1.5$; (b) $x/D = 2.5$; (c) $x/D = 2.5$.

two cross-sections closest to the jet exit [Figs. 9(a,b)] while in the $x/D = 4$ plane [Fig. 9(c)] the intense transport processes take place even at the jet axis. Outside the potential core the three distinct zones characterized by different behaviour of energy transfer processes may be observed. In the area adjacent either to the potential core (see measuring planes $x/D = 1.5$ and 2.5) or to the jet axis (cross-section $x/D = 4$) where the zero value of longitudinal temperature gradient $\partial\bar{\theta}/\partial x$ exists, the internal energy transport is realized mainly by the random fluctuations of proper turbulent motion (term 3) as well by the term 6 (work done by pressure-velocity correlations) where the latter one represents the energy gain. The next zone, which spreads radially up to the distance $r/D \approx 0.5$ is in turn dominated by convection of the mean motion, which increases the energy level of the control volume, due to the gradual cooling of the medium (negative value of AME at $r/D \approx 0.5$). The above internal energy stream is counterbalanced in this area by as many as three energy fluxes, i.e. convection realized by oscillatory (term 2) and random (term 3) motion, as well as, by the work performed by pressure–velocity correlations (term 6).

The outer zone of the jet ($r/D > 0.5$) is in turn characterized by the positive sign of $\partial\bar{\theta}/\partial x$ [10] and the resulting loss of energy due to the convection of the mean motion is counterbalanced mainly by the work of pressure–velocity correlations. The loss of spatial coherence characteristic for the outer jet boundary results in the diminishing role of convection processes realized both by oscillatory (term 2) and random motion (term 3) in this area.

Summing up the above observations, one may conclude that the internal energy budget results from the mutual balance of convection realized by the mean (term 1), oscillatory (term 2) and random (term 3) components of motion accompanied by the work of pressure–velocity correlations (term 6). The remaining parts of internal energy balance, i.e. heat conduction (term 4) and dissipation play a minor role in transport processes considered. It should be noticed, however, that the coherent heat flux is comparable with the random one only in the zone of maximum spatial coherence of the organized motion ($x/d = 2.5$).

The dominance of the internal energy stream transported by random turbulence observed in the prevailing area of the jet confirms the earlier conclusions concerning the indirect role of coherent structures in heat transfer processes. One may conclude therefore, that the heat transfer in the initial jet area is realized mainly by random fluctuations of proper turbulence motion, generated however in a substantial part, by the coherent structures existing in the flow field considered.

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