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International Journal of Heat and Mass Transfer 46 (2003) 3983–3990

International Journal of HEAT and MASS TRANSFER

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Instantaneous energy separation in a free jet—Part II. Total temperature measurement

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Received 1 November 2002; received in revised form 2 May 2003

Abstract

The mechanism of energy separation in a free jet and its enhancement by acoustic excitation are investigated using an experimental technique to measure instantaneous velocity and total temperature simultaneously. The measured velocity and total temperature data are analyzed and compared by both time-averaged and spectral methods. By introducing the skewness of the total temperature fluctuation, the characteristics of energy separation can be identified. The results show that the frequencies of dominant total temperature fluctuation coincide with those of velocity fluctuation which represent the passing frequencies of vortices at give locations. This confirms that the mechanism of energy separation is induced by the motion of the coherent vortical structure which generates pressure fluctuation with the flow field. Spectral analysis of the data with acoustic excitation indicate that the enhancement of energy separation by acoustic excitation should result from vortex pairing processes induced by the acoustic excitation.

1. Introduction

"Energy separation", the re-distribution of the total energy (temperature) in a flowing fluid without external work or heat, has the potential to heat or cool a fluid without using a conventional heating or cooling system. It generally occurs where velocity is high enough that the dynamic temperature of a flowing fluid is not negligible. However, current obtainable temperature difference between the hotter and colder regions is not large enough for a practical engineering application. To increase the obtainable temperature differences, it is essential to understand the mechanisms of energy separation. Although it has been observed in various flow situations since the first observation by Ranque [1], its mechanism has not been clearly understood until Eckert [2] proposed a physical model of energy separation. He suggested two possible mechanisms: (1) the imbalance between energy transports by viscous shear work and heat conduction and (2) the pressure work done by moving vortices within a flow field. He indicated that the latter is much stronger in a flow where a large scale coherent structure occurs including shear layers, jets and flows across a cylinder. He also pointed out that instantaneous flow and thermal information is required to understand the mechanism due to its unsteady characteristics.

The scope of the present study is confined to a jet flow. Even so, the results will be a good foundation for understanding energy separation in various unsteady vortex flows. Energy separation in a jet flow was firstly observed by Goldstein et al. [3], when measuring time-averaged recovery temperature on an adiabatic flat plate exposed to an impinging jet. They found significant minima in the radial distribution of the recovery temperature and concluded that these could be due to energy separation caused by the motion of ring vortices around the jet. Fox et al. [4,5] investigated energy separation in both free and impinging jets. The time-averaged total temperature of the free jet and the wall temperature on the impingement plate were measured.

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doi:10.1016/S0017-9310(03)00244-8

Nomenclature

A, B, n	calibration constants for each wire of the dual-wire probe
c_p	specific heat of a fluid
D	nozzle exit diameter
E	output voltage from the anemometer
f	frequency of velocity and total temperature fluctuation
f_{ex}	frequency of external acoustic excitation
r	radial coordinate
S	energy separation factor, $\frac{T_t - T_{t,o}}{2U_e^2/c_p}$
S_m	energy separation factor based on time mean total temperature
S_{rms}	normalized total temperature fluctuation, $\frac{T_{t,s}}{2U_e^2/c_p}$
Sk	skewness in Eq. (5)
Sr_D	Strouhal number of velocity and temperature fluctuations, $\frac{fD}{U_e}$
Sr_{ex}	Strouhal number of acoustic excitation, $\frac{f_{ex}D}{U_e}$
t	time
T_r	recovery temperature
T_s	static temperature
T_t	total temperature
$T_{t,m}$	time mean of total temperature
$T_{t,o}$	total temperature of the jet at the nozzle exit
$T_{t,s}$	root-mean-square (RMS) value of total temperature
T_w	wire temperature
u, U	velocity
U_e	mean velocity at the nozzle exit
z	axial coordinate
η	recovery temperature ratio, $\frac{T_r}{T_t}$

In addition, the pressure fluctuation signal in the impinging jet was measured using a microphone. Fox and Kurosaka [6] extended these previous studies to a supersonic jet. They found the pressure difference across shock waves induced additional energy separation. Seol and Goldstein [7] tried to enhance the amount of energy separation by applying external acoustic excitation around a free jet. They measured total temperature distribution of a free jet with acoustic excitation and found that the temperature differences were significantly enhanced at certain excitation frequencies. However, the detailed mechanism of the enhancement was not clearly shown.

As reviewed above, most of previous studies on energy separation were based on time-averaged total temperature measurement. The lack of instantaneous information limits the understanding of energy separation. Recently a few studies investigated instantaneous mechanism of energy separation. Experiments to measure instantaneous total temperature were performed in the wake of a circular cylinder [8], and a turbine blade [9]. Han et al. [10] and Han and Goldstein [11] performed numerical studies on energy separation in a shear layer and jet by solving the two-dimensional unsteady Navier–Stokes equations and total energy conservation equations.

In the present study, the mechanism of energy separation and its enhancement in a free jet is investigated with instantaneous velocity and total temperature measurements. Even though the results are obtained only for free jet, they not only explain the mechanism in the jet, but also provide useful information to interpret energy separation in other unsteady vortex flows. The present study consists of two parts: (1) flow measurement and visualization, and (2) total temperature measurement. In the first part [12], the motion of the coherent vortical structure and its response to acoustic excitation are studied by instantaneous velocity measurement and flow visualization. In this second part, instantaneous total temperature is performed and compared with the instantaneous velocity data. Comparison between the results of spectral analysis on instantaneous velocity and total temperature data provide a bridge from the motion of the coherent structure to the total temperature fluctuation. It also reveals the enhancement mechanism from acoustic excitation.

2. Theoretical background

There are two main reasons why it is very difficult to measure rapidly fluctuating temperature in a high speed flow. One is due to the thermal inertia of conventional temperature sensors, which need to be reach thermal equilibrium with the surroundings. The other rises from the effect of the stagnation of a fluid. Several temperatures of a flowing fluid can be defined. The static temperature (T_s) is the temperature measured by a sensor moving at the same velocity of the fluid. It represents the thermal internal energy of the fluid. The total temperature (T_t) is measured with a stationary sensor when the fluid is stagnated adiabatically so that its kinetic energy is converted into thermal energy. The total temperature represents the total energy—the summation of thermal and kinetic energy. Even though the two temperatures suggest two different physical quantities respectively,

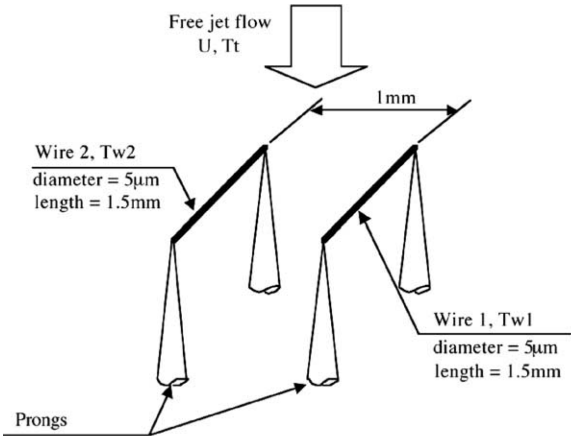

Fig. 1. Conceptual diagram of a dual-wire sensor.

they are eventually the same in low velocity flows where the kinetic energy is small. However, they should be carefully distinguished, if the velocity is large enough so that the kinetic energy is no longer negligible.

In real flow situations, a fluid cannot be stagnated adiabatically due to its viscosity and thermal conductivity. Therefore, the temperature measured with a stationary sensor is lower than its total temperature. This measured temperature is the recovery temperature (T_r). It depends not only on the temperature (either static or total) and velocity of the fluid, but also on the fluid properties and sensor geometry.

In order to avoid those difficulties, a dual-wire sensor is developed in the present study. The dual-wire probe consists of two geometrically identical parallel wires operating in constant temperature mode at different working temperatures. The dual-wire probe is built based on a boundary layer "X" wire probe (TSI, 1243-T1.5). Two 5 μm tungsten wires separated by 1 mm are set parallel to each other instead of being perpendicular as in the original model. The probe is exposed to flows as shown in Fig. 1. To maximize the sensitivity to the temperature fluctuation without losing stability of the anemometer, 1.5 and 1.2 overheat ratios are chosen. If the wires are exposed to the same flow and thermal conditions, heat transfer around each wire can be described by a modified King's law as follows;

$$\text{Wire 1:}\quad U^{n_1} = \frac{1}{B_1}\left(-A_1 + \frac{E_1^2}{T_{w_1} - T_r}\right) \tag{1}$$

$$\text{Wire 2:}\quad U^{n_2} = \frac{1}{B_2}\left(-A_2 + \frac{E_2^2}{T_{w_2} - T_r}\right) \tag{2}$$

where E is the output voltage from the anemometer and A, B and n are constants determined by calibration. Eqs. (1) and (2) can be combined by eliminating the velocity U, and reduced as follows,

$$\left[\frac{1}{B_1}\left(-A_1 + \frac{E_1^2}{T_{w_1} - T_r}\right)\right]^{\frac{1}{n_1}} - \left[\frac{1}{B_2}\left(-A_2 + \frac{E_2^2}{T_{w_2} - T_r}\right)\right]^{\frac{1}{n_2}} = 0 \tag{3}$$

By solving Eq. (3), the value of the recovery temperature T_r can be determined. Then U can also be determined by inserting the obtained value of T_r into either Eq. (1) or (2). Introducing recovery temperature ratio (η), defined by,

$$\eta = \frac{T_r}{T_t} \tag{4}$$

the total temperature of the flow (T_t) can be calculated with known values of U and T_r. Detailed calibration and measurement procedures with the uncertainty analysis can be found in [13].

3. Experimental apparatus

The experimental apparatus includes three parts—jet generation system, acoustic excitation system and measurement system. An air jet is issued from a bell shaped nozzle whose diameter is 20 mm. The total temperature at the nozzle exit ($T_{t,o}$) is controlled to be the room temperature (T_{amb}) within ±0.05 °C. All systems are described in detail in the first part of the present study [12]. Throughout the measurements, the Reynolds number of the jet (Re_D) is fixed at 1.2×10^5. Acoustic waves are applied around the jet with three excitation Strouhal numbers—0, 0.3 and 0.9 ($Sr_{ex} = 0$ is the case without acoustic excitation). The uncertainty in T_t throughout the measurement is less than 0.35 K.

4. Results and discussion

Fig. 2 shows the measured velocity and total temperature distributions with the dual-wire sensor without acoustic excitation. The time averaged energy separation factor profiles show good agreements with previous results [7] except the fact that the energy separation factor at very low velocity region (where $r/D > 1$) fluctuates little bit. This can be explained with the inherent defects of hot-wire anemometers in very low velocity regions where natural convection around the wires is no longer negligible. The biggest energy separation is observed at $z/D = 0.5$ (maximum $S_m \approx 0.2$ and minimum $S_m \approx -0.3$) and the total temperature fluctuation reaches about 200% of its dynamic temperature. Similar results for the total temperature fluctuation were reported by Ng et al. [8] in the wake of a circular cylinder. As the flow goes downstream, the locations of maximum total temperature fluctuation are observed at further outside

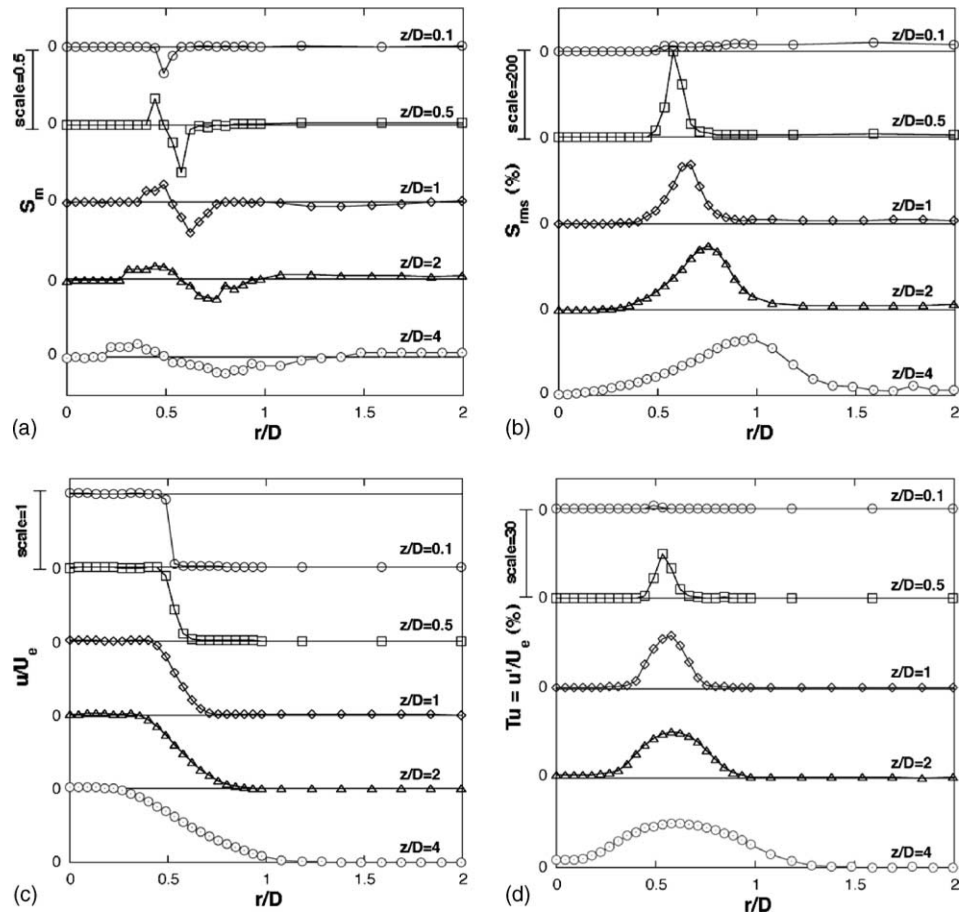

Fig. 2. Total temperature distribution without acoustic excitation: (a) time averaged energy separation factor, (b) RMS value of energy separation factor, (c) time averaged axial velocity and (d) RMS value of axial velocity.

than the locations of maximum velocity fluctuation shown in Fig. 2(d). This trend agrees with a numerical prediction by Han and Goldstein [11].

The results of spectral analysis on the dual-wire data without acoustic excitation are presented in Fig. 3. At $z/D = 0.5$, throughout the measured frequency range, no dominant frequency can be identified in either spectra except three peaks around $Sr_D \approx 1.25$. These peaks are expected to come from the fluctuation of the probe due to the vortex shedding from the supporter of the probe. Where $z/D \geqslant 1$, note the coincidence of dominant frequencies in velocity and total temperature spectra. In both velocity and total temperature spectra, spectral densities around $Sr_D \approx 0.6$ increase significantly at $z/D = 1$ and the frequency of the maximum spectral density moves to $Sr_D \approx 0.4$. As already shown in the first part of the present study [12], a dominant frequency in the velocity power spectra represents the passing frequency of ring vortices at a given streamwise location. Therefore, the total temperature fluctuating frequency is the same as the vortex passing frequency. This fact confirms that energy separation in a free jet is caused by the motion of the coherent vortical structure, which generates pressure fluctuation within the flow field.

Seol and Goldstein [7] suggested that the energy separation very near the nozzle exit, e.g. $z/D = 0.1$, might come from the energy separation within the boundary layer inside the nozzle. However, their time-averaged results could not provide enough information to verify the suggestion. To examine the suggestion, time-averaged and RMS values of velocity and total temperature data at several locations are calculated and compared in Table 1. The locations where the parameters calculated are depicted in Fig. 4. To characterize the characteristics of velocity and total temperature fluctuations at Point A, two additional locations (Points B and C) are chosen. Energy separation at Points B and C is due to the vortex motion as discussed above. Skewness (Sk) is a parameter to describe the symmetry of fluctuating signal with respect to its mean value. For the total temperature, the skewness (Sk) is defined as follows;

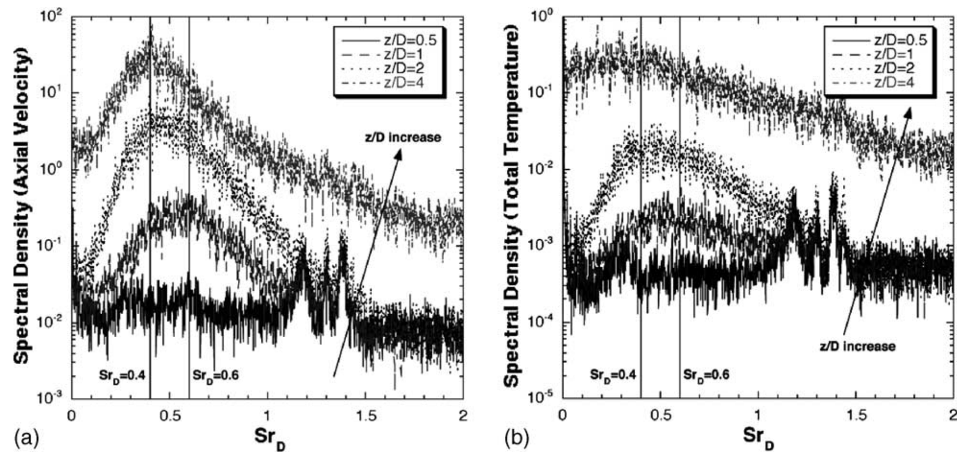

Fig. 3. Power spectra of velocity and total temperature without acoustic excitation: (a) velocity fluctuation, (b) total temperature fluctuation.

Table 1
Calculated values of skewness

Point	z/D	r/D	U_m/U_e	U_{rms}/U_e (%)	S_m	S_{rms} (%)	Sk
A	0.1	0.49	0.92	1.2	−0.17	3.4	0.1749
B	1	0.40	1.02	2.5	0.073	4.4	0.6328
C	1	0.62	0.20	14.3	−0.20	133	−1.4270

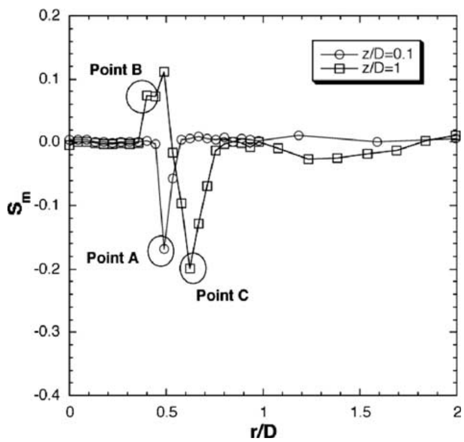

Fig. 4. Skewness calculation points.

$$Sk = \frac{1}{\tau}\int_0^\tau \left(\frac{T_t - T_{t,m}}{T_{t,rms}}\right)^3 dt \qquad (5)$$

where τ is a time interval, $T_{t,m}$ and $T_{t,rms}$ are time mean and RMS value of the total temperature respectively. When Sk is close to 0, fluctuating signal is close to symmetry with respect to its mean value. However, for relatively large positive or negative values of Sk, the fluctuating signal has frequently larger or smaller values respectively than its mean value. Details of the concept of the skewness can be found in [14].

Time-averaged velocity, turbulent intensity and total temperature fluctuation at Point A are very similar to those at Point B, but the skewness value at Point B is 3.6 times larger than that at Point A. When Point A and C are compared, all other parameters are different even they have similar time-averaged energy separation factor. Note that Point C has negative skewness value contrary to the other two Points suggesting the total temperature fluctuation at this point is skewed in the opposite side (i.e. smaller than the mean value). Based on the physical model suggested by Eckert [2], energy separation within a boundary layer is a diffusion process resulted from the imbalance between heat conduction and viscous dissipation. Therefore, the corresponding total temperature should fluctuate only due to turbulence. Contrary to this, energy separation within a flow with moving vortices is an advective process, and the corresponding total temperature fluctuation is contributed by both turbulence and large scale coherent structure motion. Recent numerical studies [5,10,11] showed that the fluctuation could be very asymmetric with respect to the time-averaged values. The present experimental results confirm the previous theoretical and numerical studies, and also show that energy separation within a flow with moving vortices has relatively larger skewness values than energy separation within a boundary layer due to the imbalance between heat conduction and viscous dissipation.

The results with acoustic excitation are shown in Fig. 5. When $Sr_{ex} = 0.3$ (Fig. 5(a) and (b)), the total temperature distribution and fluctuation are very similar to the results without acoustic excitation. However, the effect of acoustic excitation becomes noticeable, when $Sr_{ex} = 0.9$ (Fig. 5(c) and (d)). Even the effect of acoustic excitation is negligible until $z/D = 0.5$, the amount of energy separation and the total temperature fluctuation increase significantly at $z/D = 1.0$. Not only the magnitude of energy separation, the width of energy separation region is getting wider than that without acoustic excitation. This kind of intensification of energy separation is still observable to $z/D = 4.0$.

The velocity and total temperature power spectra with acoustic excitation are presented in Figs. 6 and 7. Even with acoustic excitation, the frequencies of dominant velocity and total temperature fluctuations are match very well for each case. In Fig. 6 (when $Sr_{ex} = 0.3$), there is a very sharp and noticeable peak at $Sr_D = 0.3$, and it must represent the excitation signal. However, acoustic excitation with the excitation frequency of $Sr_{ex} = 0.3$ does not change the dominant frequencies of velocity and total temperature fluctuations. It only results in more rapid development of the total temperature fluctuation, as already observed with the velocity power spectra in [12]. As the excitation Strouhal number is increased to 0.9, the power spectra of the velocity and temperature show some changes (See Fig. 7). Similar to the case of $Sr_{ex} = 0.3$, a sharp peak is observed at $Sr_D = 0.9$ which is representing the excitation signal. Until $z/D = 0.5$, even though the spectral densities of the total temperature slightly increase, not much change in the spectrum is observed. However, unlike the cases without acoustic excitation and with the excitation of $Sr_{ex} = 0.3$, the Strouhal number of dominant fluctuation is changed to 0.45 at $z/D \geqslant 1$. At $z/D = 4$, fluctuations of small scale eddies (i.e. high frequency fluctuation) are getting stronger than the other cases.

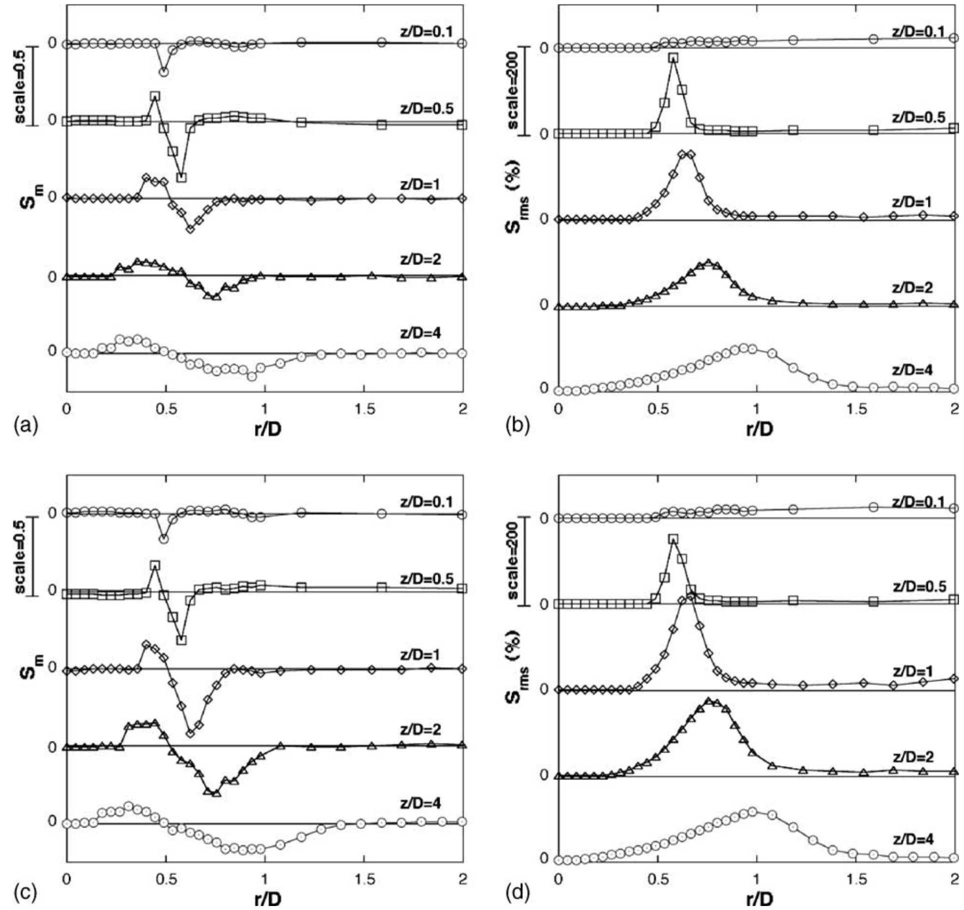

Fig. 5. Total temperature distribution with acoustic excitation: (a) time averaged energy separation factor when $Sr_{ex} = 0.3$, (b) RMS value of energy separation factor when $Sr_{ex} = 0.3$, (c) time averaged energy separation factor when $Sr_{ex} = 0.9$ and (d) RMS value of energy separation factor when $Sr_{ex} = 0.9$.

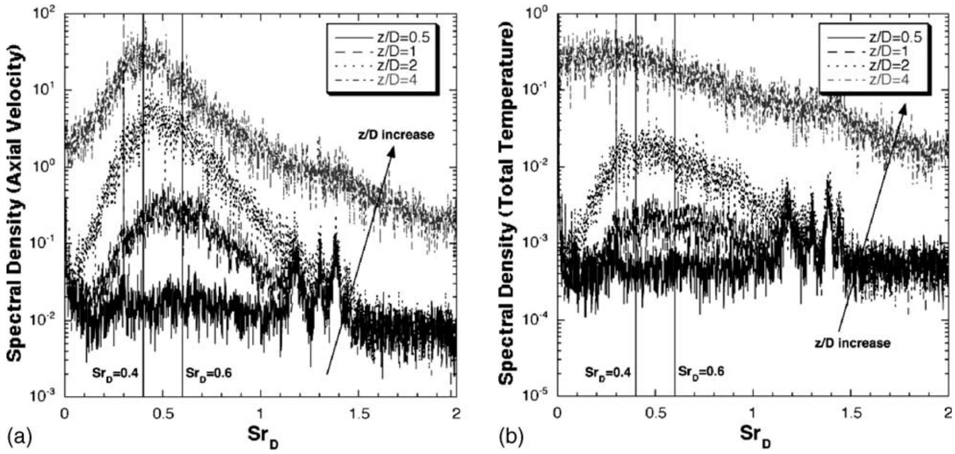

Fig. 6. Power spectra of velocity and total temperature when $Sr_{ex} = 0.3$: (a) velocity fluctuation, (b) total temperature fluctuation.

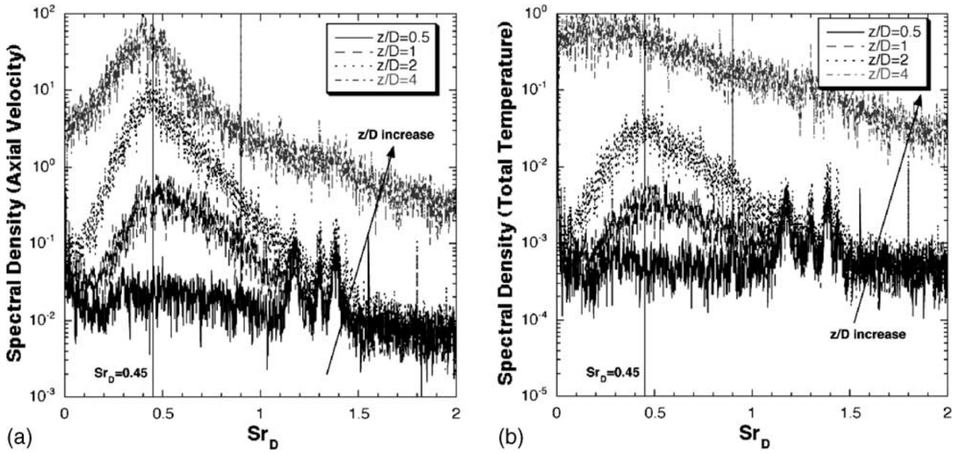

Fig. 7. Power spectra of velocity and total temperature when $Sr_{ex} = 0.9$: (a) velocity fluctuation, (b) total temperature fluctuation.

5. Conclusions

Instantaneous velocity and total temperature fields of a free jet are measured to investigate the mechanism of energy separation and its intensification by acoustic excitation. Simultaneous velocity and total temperature are measured using two parallel constant temperature hot-wire anemometers. Conclusions from the present study can be summarized as follows;

1. The maximum total temperature fluctuations throughout the measured cases reach about 200% of the dynamic temperature. The maximum total temperature fluctuations are located at outer radial position than the maximum turbulent intensity points at a given axial location.
2. In the results of spectral analysis, the frequencies of dominant total temperature fluctuation coincide with those of velocity fluctuation. From the results in [12], this shows that the frequencies of dominant velocity fluctuation represent the passing frequencies of ring vortices at a given axial location. Therefore, the total temperature fluctuating frequencies are the same as the vortex passing frequencies. It is well known that the development of vortices induces pressure fluctuations in flow fields. It can be confirmed from the observation above that energy separation in a free jet is caused by the motion of the coherent vortical structure which generates pressure fluctuation within the flow field.
3. By computing the skewness of the total temperature fluctuation, the characteristics of energy separation can be identified.
   a. The fluctuation of total temperature comes from the energy imbalance between viscous shear work and heat conduction. Since the amount of

fluctuation should be very small and randomly fluctuated, the skewness value should be small.

b. When energy separation is induced by the motion of the coherent structure, the total temperature fluctuation is very asymmetric and the skewness is relatively large positive or negative numbers.

4. An acoustic excitation of $Sr_{ex} = 0.9$ intensifies energy separation for $1.0 \leqslant z/D \leqslant 4.0$. The results of spectral analysis in [12] show that the vortex motions at these locations are strengthened through vortex pairings induced by acoustic excitation. Therefore, the intensification of energy separation comes from strong and more regular vortex pairing process induced by acoustic excitation.

Acknowledgements

The authors would like to appreciate the support by the Engineering Research Program of the Office of Basic Energy Sciences at the US Department of Energy.

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