THE SHEAR LAYERS OF A 2D JET EXCITED BY SMALL FLEXIBLE WIRES

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ABSTRACT

The shear layers of a 2D hot jet, interacting with flexible fine wires, are investigated experimentally. The jet width is 15mm, and the jet nozzle has an aspect ratio of 20:1. The ratio of the jet-exit density to the ambient is 0.8, and the Reynolds number of the jet is 3000 approximately. In each shear layer of the 2D jet flow, a fine wire of diameter 0.23mm is flexibly mounted along the span-wise direction. The natural frequency of the wire is regulated by the tension in the wire. The interaction of the wires and the jet flow is investigated by temperature measurements and flow visualization. It is found that the flexible wires are more likely to vibrate when they are mounted in the shear layers with high mean velocity gradient rather than in the potential core. The flexible wires when located in the shear layers have significant influence on the jet flow. With the wires being still in the shear layers, the jet potential core becomes longer, and temperature fluctuations in the near field are suppressed slightly. With the wires vibrating in the shear layers, the jet flow is influenced profoundly; the potential core becomes much shorter, the coherent structures in the shear layers appear closer to the jet nozzle, and the hot jet spreads more heat in the cross-stream direction and the temperature fluctuations in the shear layers increase significantly. Furthermore, the temperature spectra of the hot jet become line-dominated with the spectral peaks occurring at the natural frequency of the wire and its harmonics. Thus, the dominant frequency of the jet can be controlled by adjusting the natural frequency of the wire, through adjusting the wire tension in the experiment.

INTRODUCTION

The large-scale coherent structures in a free shear layer play a key role in transports of mass, momentum, and heat of the shear layer. Mixing of fluids in the two streams can be enhanced by a rapid growth of the large-scale vortical structures and high-level turbulence in the shear layers. Much information of the phenomena of the shear layer structures has been accumulated, but how to manipulate the shear layer, for example to enhance/reduce the turbulence intensity of a shear flow, is still of interest.

It has long been known that a jet is sensitive to external acoustic excitation or mechanical perturbation. Based on the concept, acoustic, and mechanical means have been used to manipulate jet flows. For instance of acoustic excitation, Crow and Champagne (1971) found that periodic acoustic forcing at the jet exit reduced the potential core of a round jet, changed the turbulence intensity profiles, and increased the jet spreading angle. Among mechanical means for flow control, small cylinder (wire) has been proven to be effective in changing the turbulence intensity of jet flows. Tong and Warhaft (1994) used a fine ring to suppress turbulence intensity, by a maximum of 30%, of a round jet. Rajagopalan and Antonia (1998) reduced the growth rate, the momentum thickness and the turbulence intensity of a plane jet using small cylinders. In the foregoing two examples, the wires were rigidly fixed, motionless in the jet flows. Instead of rigid and motionless wire, a flexible wire was applied by Vandsburger and Ding (1995) for turbulent control of mixing layers.

The present paper is to illustrate that the coherent structures in the shear layers and temperature distributions of a plane hot jet can be manipulated by means of small wires. After a brief description of the facility and instrumentation, experimental results of flow visualization, and temperature measurements are presented. It is founded that the wires have quite different effects on the jet flow depending on the wires are motionless or vibrating in the flow. Descriptions of the flow structures, mean temperature, jet-spreading rate, temperature fluctuations, and spectral analysis of the unexcited/excited jet are given to discuss the influence of the wires on the flow.

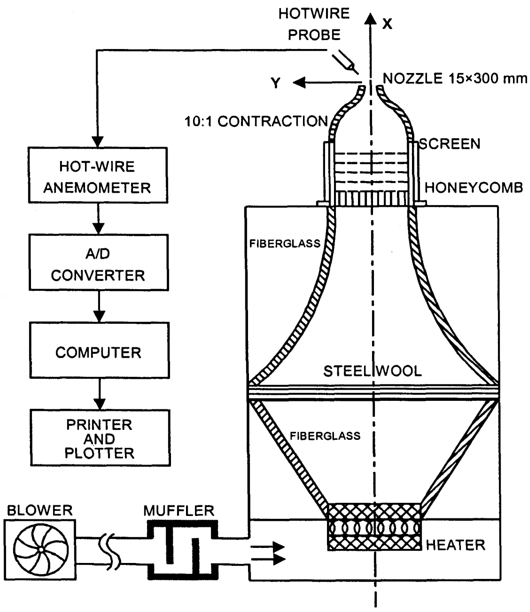


Figure 1: The jet facility

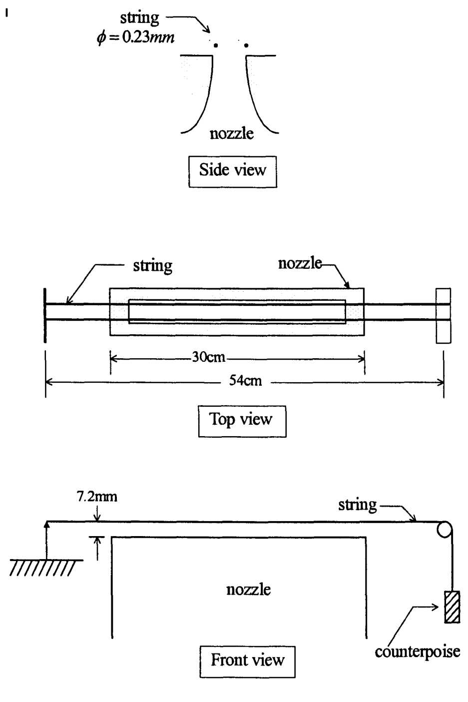


Figure 2: The installation of the two wires in the shear layers.

EXPERIMENTAL APPARATUS

The facility used to produce a plane hot jet is shown in Fig. 1. The nozzle, pointing vertically up, has a size of 15 x 300mm, giving an aspect ratio of 20. Airflow for the jet is driven by a variable speed blower through a long duct and an acoustic muffler to reduce blower noise. The airflow can be heated by an electric heater packed with aluminum wool. We reminder the reader that the stream-wise, transverse, and span-wise coordinates are denoted by X, Y, and Z, respectively, which are normalized by the jet width H=15mm. In each shear layer of the jet, a metal wire 0.23 mm in diameter (0.015 jet width) and 540mm long is mounted along the jet span-wise direction, as shown in Figure 2. The wires are flexibly mounted so that they may vibrate in the flow. Counterpoises are used to adjust the wire tension, and hence the nature frequency of the wire.

The hot jet flow can be visualized by using Schlieren optics, since density gradient exists in the hot jet. In the study, A typical Schlieren optical system (see Liepmann and Roshko, 1957, for instance) was set up for flow visualization of the hot jet.

The wire motion was monitored by a detector coil, PASCO Model WA-9613. The detector coil converts the velocity component in the X-Y plane of the wire segment near the coil into electric signal. The signal after being amplified was collected by a data acquisition system.

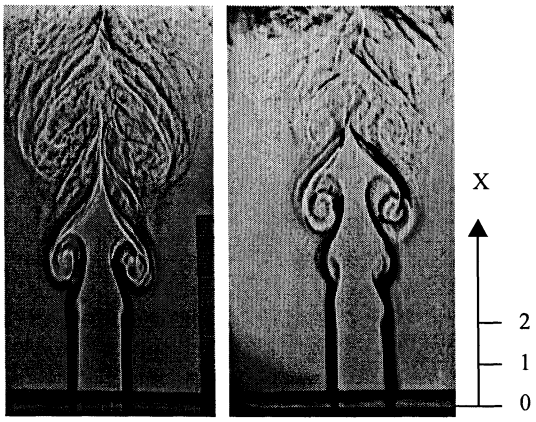
A DANTEC hot anemometer in constant current mode was used to collect local unsteady temperature data. The sensor was platinum-plated tungsten wire of 1 μm in diameter and 0.4 mm long. The frequency response of the wire in constant current mode for temperature measurement was about 2 kHz, which is adequate for the present experiments. The temperature signals were digitized at a sampling rate of 2048 data/second by a 12 bit A/D converter and transmitted to a PC-586 computer for data storage and processing. The uncertainty of the output voltage collected from the anemometer due to digitization is 3×10^{-4} Volt, and the uncertainty of temperature measurements is 0.26 ^{0}C. For spectral data, the software MATLAB was used to obtain autospectral (power spectral) density function of the temperature fluctuations. Additionally, a spectrum analyzer AND AD3524, with a setting of frequency resolution Δf=0.125Hz, was used to monitor the spectra of the jet temperature and the wire vibration.

RESULTS AND DISCUSSION

Throughout the experiments, the jet exit temperature T_j was fixed at 110°C, and the ambient temperature T_∞ was 27°C, giving a density ratio S of about 0.8. The jet exit velocity U_j was fixed at 4 m/s. The corresponding Reynolds number, Re(=U_jH/ν), is 3000 approximately, where the kinematic viscosity, ν, is evaluated at the average of the jet exit and the ambient temperatures. The jet is initially laminar.

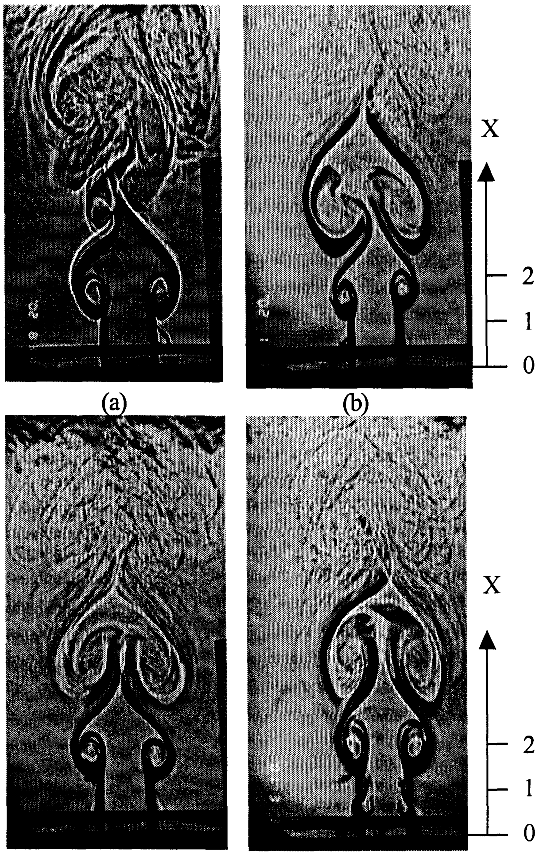
Flow visualization

Figure 3(a) is a Schieren image of the hot jet without any wire in the flow. It is shown that the flow structure is symmetrical with respect to the center plane Y=0. For the region close the nozzle 0<X<2, the shear layers are relatively "quiet"; no vortices are observed. The vertical, dark lines in the Schlieren image are a result of high velocity gradient in the shear layers. Around X=2, wave structures appear in the shear layers, and then big vortices centered at X≈2.7 form. The jet becomes relatively turbulent downstream, after the vortical structures.



(a) (b)

Figure 3: Schieren image of the hot jet, (a) without wires (b) with two still wires at X=0.48 and Y=±0.5.



(c) (d)

Figure 4: Schieren image of the hot jet with vibrating wires, (a) the natural frequency of the wires=37Hz (b) 64Hz (c) 83Hz (d) 98Hz.

Figure 3(b) is a Schieren image of the hot jet under the same jet-exit conditions, but two small wire of diameter 0.23mm were inserted respectively in the two shear layers, motionless along the spanwise direction (denoted as the Z-direction, normal to plane of paper). It is noted that the two wires are located at X=0.48 and Y=±0.5 in the shear layers (Y=0 corresponds to the centerline of the jet on each Schlieren image). They are not seen in the picture because of relatively small diameter (0.015 jet width). The small wires, which are motionless in the shear layers, are considered as a perturbation to the jet flow. With the perturbation, the vortical structures appear smaller and form slightly downstream, and the potential core looks longer compared with the jet without the wires. It is noted that no change of the flow structure has been observed, if the wires are located in the potential core, where no velocity gradient exists although mean velocity is higher.

In further experiments, the wires are flexibly mounted, instead of being rigidly fixed and motionless, in the shear layers. The natural frequency of the two wires (both wires were set at the same natural frequency in the present experiment) can be adjusted so that they may vibrate in the jet flow for certain natural frequencies. it is found that the wire response to the jet flow is dependent on the wire location and the natural frequency of the wire, f_n. When the wire was mounted in the potential core or in the shear layer with small mean velocity gradient, no wire vibration was detected. Even given an initial perturbation to the wire at these locations, the amplitude of the perturbed wire decayed exponentially to zero. Under this circumstance, the wires have no impact on the jet flow. If the wire was in the shear layer at a location of high mean velocity gradient, the wire was found to vibrate in the flow at the natural frequency of the wires. And, the vibration amplitude depends on the natural frequency and location of the wires. For instance, the wire with f_n=37Hz was found to vibrate in the hot jet when it was located in the region 0.37<Y<0.63 and X=0.48, with a maximum amplitude about 7 mm (measured at Z=0) when Y=0.5. If f_n=135Hz, the wire was observed to vibrate only when it was mounted near Y=0.5 for X=0.48, and the vibration amplitude was about 3 mm. When the wire natural frequency was above 143Hz, no wire vibration was observed in the jet flow. It is thus concluded that the flexible wires are more likely to vibrate in the flow with lower natural frequency, and mounted at a location with high velocity gradient. In the following experiments of wire vibration in the flow, the wires were mounted at X=0.48 (for instance) and Y=0.5 (where maximum velocity gradient exists for the given X).

With the wires vibrating in the shear layers, Schlieren images of the hot jet are shown in Fig. 4 for different natural frequencies of the wires. While the jet flows in Fig. 4 basically maintain symmetric with respect to the center plane Y=0, and look similar for these different natural frequencies, they appear significantly different from the jet flows without vibrating wires as shown in Fig. 3. With the vibrating wires in the flow, big coherent vortices develop much closer to the nozzle, the originally laminar jet becomes turbulent after a shorter transition region.

From the flow visualization, it is thus illustrated that the small wires, as a perturbation to the jet flow, may alter the flow structures if mounted at appropriate location. Depending on whether the wires are motionless or vibrate in the shear layers, the flow structures change in different direction. While the motionless wires can slightly defer the development of the vortical structures, the vibrating wires strongly promote the early formation of the vortical structures and accelerate the jet into fully turbulent state. The finding provides another evidence that a local disturbance at appropriate location can have significant influence on global flow structures. Beside the flow visualization, the effects of the wires on the jet flow are quantitatively examined by temperature measurement and spectral analysis.

Spectral data

The corresponding temperature spectra for the jets of Figs. 3(a) and 3(b) are shown in Figs. 5 and 6, respectively. As shown in Fig. 5 for the case of no wire in the flow, there exists a spectral peak around f_p =116 Hz, representing the dominant frequency of the large vortices in the shear layers. It is observed that the amplitude of the peak increases along the streamwise direction in the region close to the nozzle, from X=0 to X=2.4 as indicated in the figure.

With the wires being motionless in the shear layers, the spectral peak disappears as shown in Fig. 6. It is thus illustrated that the growth of the dominant mode f_p along the X-direction is subdued in the developing region by the still wires. As a result, the development of large vortical structures is deferred, as already seen in the Schlieren images. Similar effect of still wire on the development of vortical structures in shear layers has been also found in a wake. In Strykowski and Sreenivasan's experiment (1990), a small cylinder in the shear layer of a wake can completely suppress vortex shedding behind a circular cylinder.

With the wires vibrating in the shear layers, the jet shows line-dominated spectra with peaks at nf_n, as shown in Fig. 7 for f_n=37Hz, which is significant different in character from the spectra for the jet without vibrating wires. It can be seen that the original dominant mode, f_p =116 Hz, of the natural hot jet disappears in the spectra. The dominant frequency of the flow is now related to the natural frequency of the wires, not to the original dominant frequency of the natural hot jet. This finding suggests that adjusting the nature frequency of the wires can control the dominant frequency in the flow.

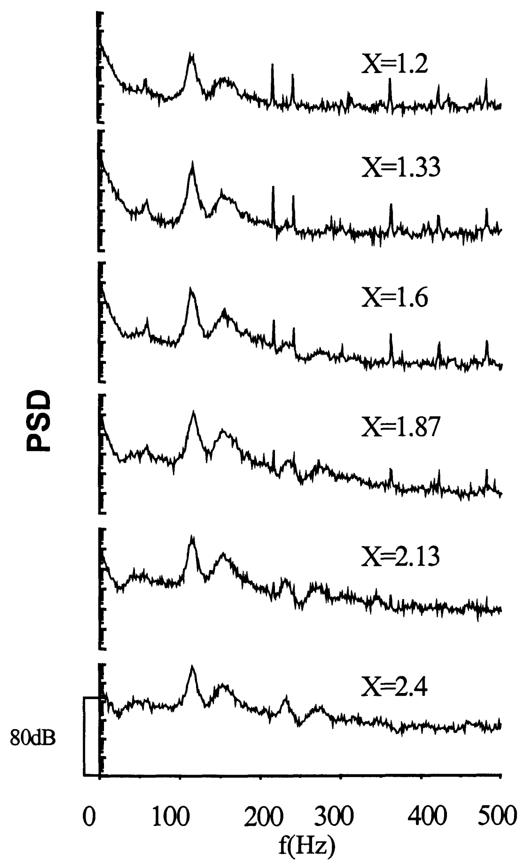


Figure 5: Temperature spectra of the hot jet without wires. Temperature probe at Y=0.5.

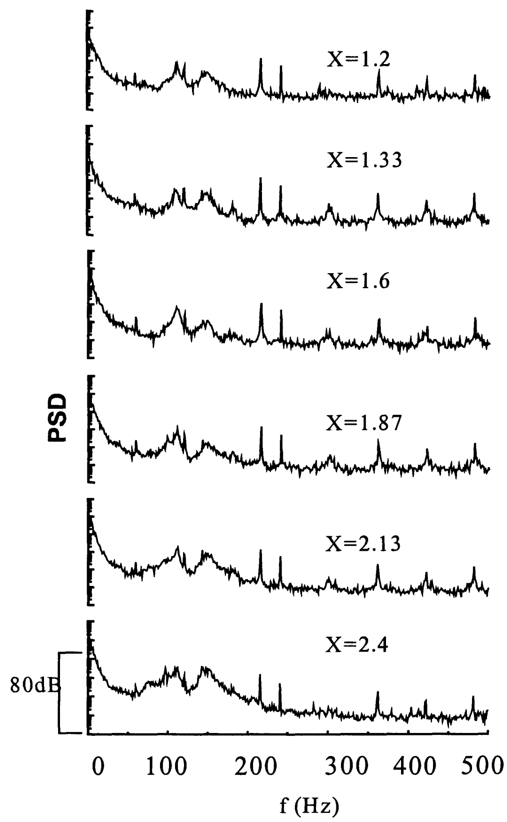


Figure 6: Temperature spectra of the hot jet with still wires at X=0.48 and Y=±0.5.

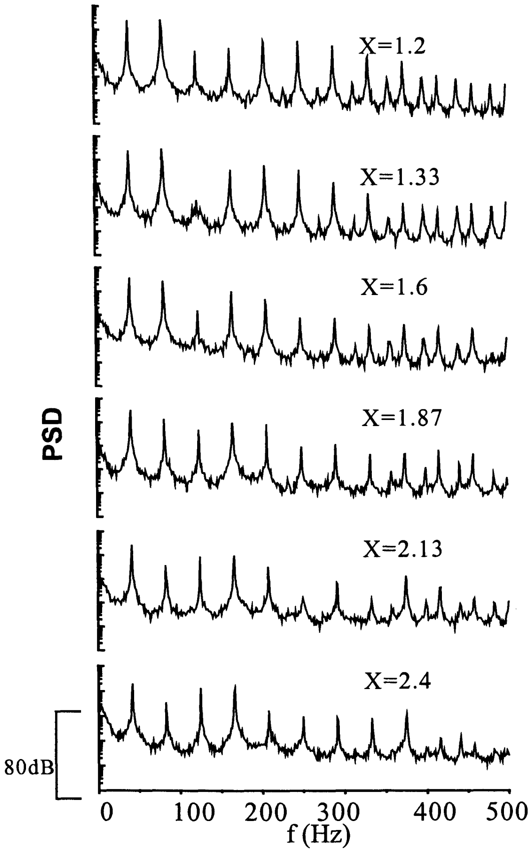


Figure 7: Temperature spectra of the hot jet with vibrating wires, the wire natural frequency=37Hz.

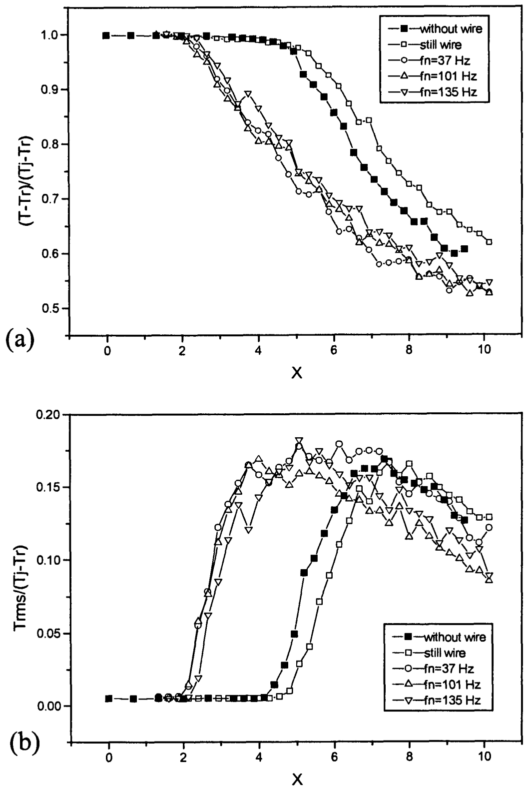


Figure 8: Temperature distribution along the centerline (a) mean values (b) temperature fluctuations

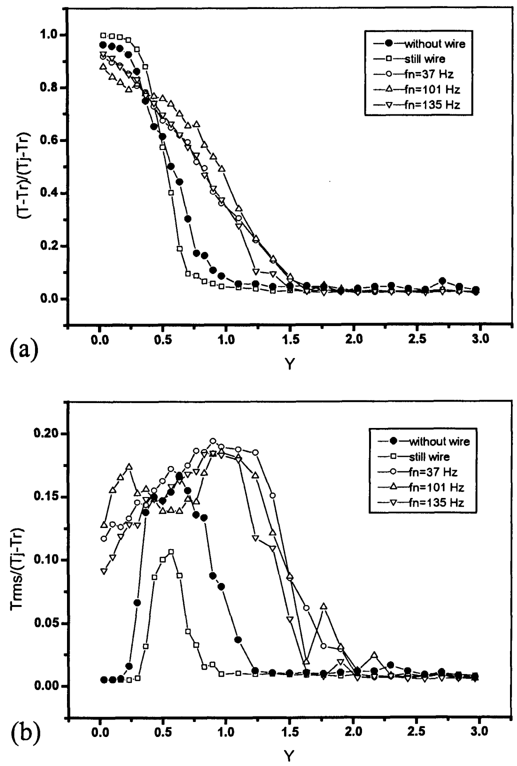


Figure 9: Temperature distribution along the Y-direction, at X=3 (a) mean values (b) temperature fluctuations

Temperature field

The temperature distributions of the jet along the centerline are shown in Fig.8a and Fig. 8b for mean temperature and temperature fluctuations, respectively. The mean temperatures decay, after $X \approx 4$, more slowly with the wires motionless in the shear layers than without any wire. Correspondingly, significant rise of temperature fluctuations occurs at larger X, i.e. more downstream, for the case with still wires. The persistence of the jet exit condition with the still wires suggests a longer potential core, as seen in the flow visualization, though the change is relatively slight under the present test conditions.

With the wires vibrating in the shear layers, the mean temperatures begin to significantly drop at $X \approx 2$, much closer to the nozzle compared to the temperature for the unexcited hot jet. Correspondingly, temperature fluctuations increase significantly after $X \approx 2$. The data suggests a reduction of potential core, about 50% shorter than that of the unexcited jet. In addition, it can be seen from the figure that once the wires vibrate in the shear layers, the temperature distributions along the centerline are basically similar regardless the difference of the wire natural frequencies, though the natural frequency determines the dominant frequency in the flow as illustrated in the spectral analysis.

The temperature distributions along the transverse (Y-) direction, at X=3 for example, are shown in Fig. 9. With the vibrating wires in the flow, mean temperatures higher than the ambient are detected for larger Y as shown in Fig.9(a), and the region with substantial fluctuations enlarges significantly, including 0<X<1.5, as shown in Fig.9(b). This distribution implies more jet spreading due to the vibration wires. As an indication of jet spreading, the half jet widths are shown in Fig. 10. It becomes clear that the vibrating wires in the shear layers can enhance the jet spreading, while the still wires have little effect on the jet spreading.

From the temperature measurements, it is concluded that the temperature of the jet is redistributed with the wires in the shear layers. Especially, wire vibration has profound influence on the temperature distributions of the hot jet; increase temperature fluctuation, heat spread rate, and shorten the potential core.

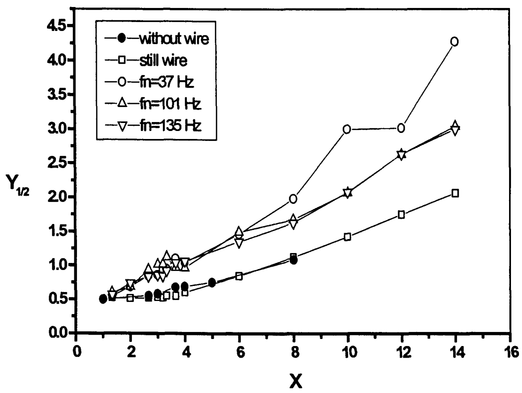


Figure 10: The jet-half width versus the X-coordinate

CONCLUSION

Two small wires of diameter 0.23mm (0.015 jet width) are used to excite a hot jet flow. The small wires, each in the shear layers and near the nozzle, can influence the vortical structures in the shear layers, the dominant frequency in the flow, and the temperature distributions of the hot jet. The wires can have opposite effects on the jet flow depending on the wires being motionless or vibrating in the shear layers. Some experimental findings are described as follows:

(1) On the wire response to the jet flow: the flexible wires are more likely to vibrate in the flow when they are located in the shear layers at a location with high velocity gradient. Wire vibrations in the shear layers occur only for the wires of low natural frequency.

(2) On the flow structures in the near field of the jet: while still wires delay slightly the formation of large vortical structures, vibrating wires promote early formation of the large vortical structure. The potential core of the jet with still wires becomes slightly longer than that of a natural jet. While perturbed by vibrating wires, the potential core becomes shorter, only about 50% of the potential core of the unexcited jet.

(3) On the spectra of the jet: the jet shows line-dominated spectra with vibrating wires while the spectra are broad band for the jet without vibrating wires. Once the wires vibrate in the shear layers, the dominant frequency of the jet flow is related to the natural frequency of the wires, not to the original dominant frequency in the flow. Therefore, adjusting the nature frequency of the wires can control the dominant frequency in the flow.

(4) On the temperature field: with the small wires motionless in each shear layer, the temperature fluctuations of the jet decrease in the near field, 2<X<5. With the wires vibrating in the shear layers, temperature fluctuations increase in the near field, and the hot jet spreads more heat.

ACKNOWLEDGMENTS

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