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Influence of sidewalls on the centerline small-scale turbulence of a turbulent high-aspect-ratio rectangular jet

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ABSTRACT

This study experimentally investigates the influence of placing two parallel sidewalls confining a high-aspect-ratio rectangular jet on the centerline turbulence of various scales, such as the Kolmogorov and Taylor scales. Measurements were made by hot-wire anemometry at a jet-exit Reynolds number of 7000. It is found that the small-scale turbulence of the jet configured with sidewalls appears to statistically differ from that without sidewalls in both the near-field and far-field flow. The Kolmogorov scale is found to attain the asymptotic state over a shorter axial distance than does the Taylor scale. This suggests that the extent of influence of varying the boundary conditions on the large-scale flow is stronger than that on the small-scale turbulence.

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1. Introduction

Plane or planar jet has received significant attention in research due to its important role in understanding fundamental turbulence theory and wide-range industrial applications [1,2]. A plane jet is commonly generated from a rectangular nozzle of large aspect ratio (i.e., the ratio of long-side length to the short-side length, denoted as AR) with two parallel sidewalls attached to the short sides of the nozzle at the exit plane (see Fig. 1), so that the jet is forced to entrain/mix the ambient fluid in only the direction normal to the nozzle's long sides. The term planar, for the jet without sidewalls depends, to a large extent, on the AR [3–5]. In Deo et al.'s work [6], the jet issuing from a rectangular slot (AR = 30 and 60) without sidewalls was termed the "rectangular" one, which is reasonable given that the aspect ratio of AR = 30 is comparatively small. If AR is sufficiently large, such as that of Hussain and Clark [7] (AR ≈ 44), Namer and Ötügen [8] (AR ≈ 56), and Hitchman et al. [9] (AR = 60), the jet without sidewalls was described as being "planar". In this study, the jet of AR = 60 without sidewalls is also treated as a planar flow at least over a sufficiently large downstream distance.

Turbulent flows are generally of multiple scales. Thus, much effort has been devoted to assessing the large- and small-scale characteristics of the turbulent plane jet under different conditions. For the large-scale profiles, some featured investigations can be found in [10–16]. Small-scale characteristics in planar jet have also been widely and intensively studied [17–21] since they play a significant role in validating conventional turbulence theory, as these jets may be treated as two dimensional flow in the near-field [10] and quasi-isotropic turbulence in the far-field [22]. For instance, Gutmark and Wygnanski [19] observed the tendency of isotropic turbulence as the flow traveled downstream into the far-field and Antonia et al. [20] confirmed the similarity relations derived from the homogeneous isotropic assumptions, in the far field of their planar jet. In addition, Deo et al. [21] recently investigated the influence of Reynolds number on the turbulence dissipation rate (ε) and the smallest scale (η) of their plane jet. The results have indicated that, for $Re_h \geqslant 1500$, the self-preserving relations $\varepsilon \sim Re_h{}^3(x/h)^{-5/2}$ and $\eta \sim Re_h{}^{-3/4}(x/h)^{5/8}$ become valid at $x/h \geqslant 20$.

Moreover, previous investigations have confirmed that environmental boundary conditions have a significant effect on the evolution of turbulent jets [6–9,14–16,23–25]. The first direct study on the effect of sidewalls on a plane jet at $Re_h = 7230$ was conducted by Hitchman et al. [9]. The growth and decay rates of the mean centerline velocity, together with the average kinetic momentum flux, of the jets with and without sidewalls were discussed. The results, however, were not conclusive, because their jet demonstrated a modest decrease in momentum flux with increasing axial distance. Later, Deo et al. [6] studied the turbulent jets issuing from

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Nomenclature

AR	ratio of long-side length to short-side length
C_η	scale coefficient between η and x (Eq. (7))
C_λ	scale coefficient between λ and x (Eq. (8))
C_ε	scale coefficient between ε and x (Eq. (6))
f_c	cut-off frequency (kHz)
f_K	Kolmogorov frequency (kHz)
f_{Km}	measured Kolmogorov frequency (kHz)
f_s	sampling frequency (kHz)
h	slot height (mm)
K_ε	scale coefficient of Eq. (4)
K_u	slope of Eq. (5)
l_0	length-scale of the largest eddies (m)
Re_d	diameter-based Reynolds number (circular jet)
Re_h	height-based Reynolds number (plane jet)
u	x component of fluctuating velocity (m/s)
u'	r.m.s. axial velocity (m/s)
u_m	measured streamwise velocity (m/s)
u_0	velocity scale of the largest eddies (m/s)
U_c	centerline mean velocity (m/s)
$U_{o,c}$	centerline mean velocity at the plane of exit (m/s)
w	slot span (mm)
x_0	x-location of the virtual origin (m)

Greek symbols

γ	ratio of true dissipation rate to measured dissipation rate (N/(m^2 s))
η	Kolmogorov length scale (m)
η_m	measured Kolmogorov scale (m)
λ	Taylor scale (m)
ν	kinetic viscosity (N s/m^2)
ε	turbulent energy dissipation rate (N/(m^2 s))
ε_m	measured dissipation rate (N/(m^2 s))
ε_n	noise contribution of the dissipation rate (N/(m^2 s))
τ_0	time-scale of largest eddies (s)
Φ_u	power spectrum of velocity fluctuation

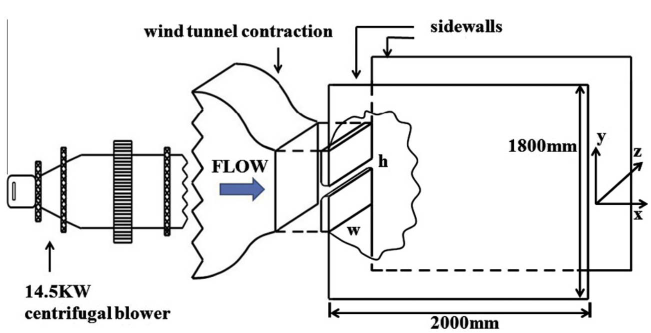

Fig. 1. Schematics of the experimental setups for the present plane jet.

rectangular nozzles of high-aspect ratio with and without sidewalls in more detail, including the lateral and streamwise profiles of the mean velocity, centerline velocity spectra, turbulence intensity, and fluctuating-velocity skewness and flatness factors. It was shown that the jets with and without sidewalls were statistically different throughout the entire flow field. The presence of sidewalls was found to have a profound effect on both the near- and far-field flow. Nevertheless, all these investigations on the effect of sidewalls or boundary conditions focused only on the large-scale flow properties. The sidewall effect on the small-scale characteristics of planar jets is yet to be investigated.

Recently, Mi et al. [26] carried out a study on a circular turbulent jet under different initial conditions and observed that the inflow condition appears to impact notably on the large-scale characteristics but to have considerably weaker influence on the smallest-scale turbulence. These authors however have not looked at the impact of the surrounding boundary condition. Assuming their observation applicable to the latter case and generic for any flows, we would anticipate that, for a rectangular jet, the extent of influence of varying the boundary conditions on the large-scale flow ought to be significantly stronger than that on the small-scale turbulence. Accordingly, some particular findings of Deo et al. [6] for the large-scale characteristics may not apply fully to the smallest-scale turbulence. For instance, the centerline dissipation rate of turbulence kinetic energy (ε), typically representing the smallest-scales, should not well follow the centerline behavior of the mean velocity (U_c). Namely, the dissipation ε might not undertake the same route of the centerline evolution of U_c over a certain downstream distance where the self-preserving scaling of the plane jet occurs in the mid region and then, after an apparent transition, the axisymmetric jet scaling unmistakably occurs in the far-field region, which was observed by Deo et al. [6]. The above is nevertheless only our deduction—whether it is true or not ought to be validated by experiment. Perhaps it is also necessary to check whether the observation of Mi et al. [26] from the circular jet can work in the plane jet.

The present work is designated to fill those gaps. Specifically, we aim to study the sidewall or boundary effect on the centerline small-scale characteristics of a turbulent plane jet, including the centerline variations of the turbulent energy dissipation rate ε, Kolmogorov scale η and Taylor scale λ.

2. Self-preserving relations of centerline ε, η and λ

For any turbulent flow, the turbulent kinetic energy is normally cascaded down from the large-scale turbulence to the small-scale turbulence and finally dissipated by viscous action forces at the smallest scales of turbulence. Hence, at sufficiently high Reynolds numbers, the rate of dissipation (the end of the sequence of processes) is determined by the transfer of energy from the largest eddies (the first process in the sequence). These eddies have energy of order u_0^2 and time scale $\tau_0 = l_0/u_0$, so that the rate of transfer of energy is supposed to scale as $u_0^2/\tau_0 = u_0^3/l_0$. (Here u_0 and l_0 stand for the characteristic velocity and length scales, respectively.) Consequently, the dissipation rate ε scales as u_0^3/l_0 in free shear flows. For a turbulent plane jet

$$\varepsilon = K_\varepsilon U_c^3/y_{0.5}. \tag{1}$$

Here $y_{0.5}$ is the local half width at which the mean velocity is $0.5U_c$ and K_ε is the scale coefficient to be evaluated by experiment.

In the self-preserving region, the centerline velocity U_c follows the well-known self-similar relation [21]

$$[U_{o,c}/U_c]^2 = K_u(x/h + x_0/h), \tag{2}$$

where K_u and x_0 are the slope and the x-location of the virtual origin of linearized $[U_{o,c}/U_c]^2$. Substituting (2) into (1) leads to

$$\varepsilon[hU_{o,c}^{-3}] = C_\varepsilon(x/h)^{-5/2} \tag{3}$$

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