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Upstream nozzle shaping effects on near field flow in round turbulent free jets

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Abstract

Isothermal, incompressible round turbulent free jets of air, issuing from a sharp-edged orifice and from a contoured nozzle into still air surroundings, have been used to study the effects of upstream nozzle shaping on near field jet evolution experimentally. The Reynolds number, based on the diameter of the orifice or the nozzle, was 1.84×10^5 in both jets. Hot-wire anemometry and a pitot-static tube were used to obtain the measured quantities which included the mean streamwise velocity, the turbulent Reynolds normal and shear stresses, the autocorrelation coefficients and one-dimensional energy spectra of the fluctuating streamwise velocity and the mean static pressure. The mean streamwise velocity decay on the jet centerline and the jet half-velocity widths were obtained from the mean streamwise velocity data. To the extent that the results showed that mixing in the sharp-edged orifice round jet was higher than in the contoured nozzle round jet, upstream nozzle shaping was found to affect jet evolution in the near flow field. The distribution of the autocorrelation coefficients of the streamwise fluctuating velocity showed a marked difference in the evolution of the two jets, one of which had a uniform, and the other a non-uniform, exit plane mean streamwise velocity profile. The one-dimensional energy spectra results and also those of the distribution of the autocorrelation coefficients indicated the presence of coherent structures in the near field of the jets and the sharp-edged orifice jet was found to be more "energetic" than the contoured nozzle jet.

Keywords: Jets; Nozzles; Mixing; Turbulence

1. Introduction

The round geometry, because of the ease with which it can be produced, is found in many applications in engineering. Jets which issue from round nozzles into essentially unbounded surroundings are useful in a number of areas of technical interest. This jet flow configuration has, consequently, been and continues to be the subject of many contributions to basic fluid mechanics research. A round jet can emanate from a pipe, from a nozzle with smoothly contracting shaping upstream of the nozzle exit plane or from a sharp-edged orifice. These three different exit conditions lead, of course, to different developments of the flow downstream of the nozzle or orifice exit plane. Depending upon the requirements of the applications in which the jets are used, one or the other of the three exit conditions mentioned previously may be used. Regardless of the exit shape used, the flow field of a round jet can be divided into

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three regions, namely, an initial or flow development region, referred to as the potential core when the exit velocity profile is top hat, a transition region and a fully developed region. Detailed experimental studies of the fully developed region have been carried out by Wygnanski and Fiedler [1] and by Rodi [2], among others, and, more recently, by Panchapakesan and Lumley [3]. The mean flow and turbulence quantities show self-similar distributions in the fully developed region and this has facilitated the analytic treatment of the jet in this region. Such analyses can be found, for example, in Rajaratnam [4] and in Schlichting [5]. The near and transition regions of the jet have been studied by Sami et al. [6], Hill [7], Boguslawski and Popiel [8] and Obot et al. [9], among others. The study of Sami et al. [6] presented mean flow, mean static pressure and turbulence data for a round jet issuing from a smoothly contoured nozzle. Mass entrainment data for the flow of a round jet issuing from a short converging nozzle were provided by the study of Hill [7]. The round jet issuing from a long circular pipe, with a fully developed turbulent velocity profile, was studied by Boguslawski and Popiel [8] and the study contributed mean flow and turbulence data. Mean streamwise velocity data, from which the spreading and entrainment rates in a jet issuing from a square-edged orifice were obtained, were provided by the study of Obot et al. [9].

The effects of nozzle upstream shaping or initial conditions on the downstream development of round jets have not been totally ignored in the extant literature. The important role played by the initial conditions in the spatial and temporal evolution of jets has indeed been recognized for some time now. Quinn and Militzer [10], in an experimental and numerical study of the near flow field of round jets issuing from a sharp-edged orifice and from a contoured nozzle, have shown by means of mean flow and time-averaged turbulence and mean static pressure data that mixing is higher in a sharp-edged orifice jet than in a contoured nozzle jet. Mi et al. [11] did a comparative study of mixing in round jets issuing from a contoured nozzle, an orifice plate and a pipe and concluded, by means of flow visualization, mean and time-averaged fluctuating temperature data and one-dimensional energy spectra of the fluctuating streamwise velocity, that the highest mixing occurs in the orifice plate jet and that the mixing in the contoured nozzle jet is, in turn, higher than that in the pipe jet.

It is noteworthy that the data in all of the aforementioned studies were acquired along lines of symmetry and were presented as profiles. While information contained in such profiles is useful and has contributed to the knowledge base on round jets, more complete information about the evolution of the jet can be obtained from data acquired across entire planes at selected streamwise locations. The present study was undertaken to extend the scope of the experimental part of the work reported in Quinn and Militzer [10]. The objective was to determine the effects of the upstream shaping of the nozzle, namely, sharp-edged orifice versus contoured nozzle, on the downstream development of round turbulent free jets in the near flow field. The data, obtained across entire streamwise planes, used to achieve the stated objective of the study include the mean streamwise velocity, the mean static pressure, time-averaged turbulence statistics and the autocorrelations and one-dimensional spectra of the streamwise fluctuating velocity. The jet half-velocity widths and the mean streamwise velocity decay on the jet centerline have been obtained from the mean streamwise velocity data and are used to assess mixing in the two jets.

2. Experimental details

The jet flow facility used for the present study is shown in Fig. 1. It consists of a small centrifugal fan, a diffuser, a settling chamber, a three-dimensional contraction and a screen cage. The fan, which drew air from a room adjacent to the laboratory and delivered it to the sharp-edged orifice or contoured nozzle via the diffuser, settling chamber and contraction, was supported on anti-vibration neoprene pads. The diffuser was fitted with a baffle at its upstream end, honeycomb and mesh-wire screens. The settling chamber, a plywood box, of 0.762 m $\times$ 0.762 m cross-section and 1.054 m in length, was also fitted with mesh-wire screens. The three-dimensional contraction had a contour which is a third-degree polynomial that had zero derivatives as end conditions. The contraction, 0.523 m in length, had a circular cross-section, with 0.762 m diameter at its upstream end, and a 0.305 m $\times$ 0.305 m square cross-section at its downstream end. The sharp-edged orifice, which is shown in Fig. 2, or the contoured nozzle, which is shown in Fig. 3, capped the downstream end of the contraction, which was flush with a 2.438 m $\times$ 2.438 m plywood wall. The Cartesian coordinate system used is shown in Fig. 2. The streamwise (X) coordinate is perpendicular to the spanwise (Y) and lateral (Z) coordinates and forms a right-hand system with them. The contraction ratio was 283. The plywood wall formed one side of a screen cage which extended 3.658 m downstream from the wall. The experiments were performed in a 7.70 m $\times$ 7.01 m $\times$ 2.87 m room.