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Scalar transport in the near field between two coaxial square air jets

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ABSTRACT

The scalar transport in the near field of two square coaxial free air jet flow has been experimentally investigated. In order to study the entrainment and mixing processes taking place between the two jets, heat was used as a scalar. A triple sensor probe was used consisting of an X-wire probe for the point measurement of two velocity components and a single cold wire probe, for the simultaneous recording of instantaneous temperature. From the velocity and temperature signals the momentum and heat flux components were calculated. Eddy diffusivities of heat and momentum were directly evaluated from the experimental data. These diffusivities for all streamwise positions reach a maximum in the interaction region between the two jets; the maximum values increase with the downstream distance in the near field. The quadrant splitting technique applied to turbulent fluxes of momentum and the scalar revealed that the positive contributions to these transport terms are much larger than the negative ones. The quadrant splitting data confirmed that the flow is dominated by large scale coherent structures, which are intermittent in character and permitted the association of the scalar transport with vortical structures occurring in the near field of the coaxial jet flow. A proposed simplified mechanistic flow picture, which shows the passage of a vortex series through the mixing layer in the near field of the jets, is in agreement with the dominant characteristics of the flow.

1. Introduction

Jets find widespread applications in engineering processes, such as dispersion, mixing, direct heat transfer, reacting flows and combustion. It has been established that rectangular jets enhance entrainment and mixing processes in comparison to circular or elliptical configurations. Furthermore, the investigation of the flow phenomena in the near field of rectangular configurations is of interest since they influence the mixing processes further downstream. Enhanced mixing in rectangular configurations is accomplished by the entrainment achieved by large scale coherent structures generated at the flat sides and by the small scale mixing near the corners (e.g. Gutmark et al. [1], Grinstein et al. [2], Grinstein [3], Zaman [4], Quinn [5]).

Circular coaxial jets are often used in industry and there is an extensive literature about the mechanisms of mixing and entrainment. Champagne and Wygnanski [6] measured profiles of streamwise velocity, turbulence intensity and Reynolds stresses for various velocity ratios and a wide range of Reynolds numbers of a coaxial circular jet, using hot wire anemometry. Ko and Kwan [7] and Kwan and Ko [8] studied experimentally circular coaxial jets at downstream distances up to $Z/D = 7$. They provided detailed information about the different regions in the development of the coaxial circular jet. Dahm et al. [9] presented numerical and experimental results using laser induced fluorescence in coaxial circular jets. They reported that different near-field vortex patterns arise, with different interaction dynamics, for different velocity ratios and absolute velocities of the two streams. Sadr and Klewicki [10] investigated the near field of coaxial circular jets in the region up to $Z/D = 6$. They reported the occurrence of two trains of vortices shed from the inner jet wall in the near-exit region of the inner mixing layer. Villermaux and Rehab [11] studied the mixing processes in circular water coaxial jets. A correlation was established between their mixing time and the Reynolds and Schmidt numbers. Pietri et al. [12] performed simultaneous measurements of two velocity components and temperature, using Laser Doppler Anemometry for the velocity measurements and a cold wire for the temperature measurements in a slightly heated circular jet in a coflow. Their measurements were carried out in the far field ($Z/D \geqslant 4.5$).

Fewer studies refer to coaxial rectangular jets. Bitting et al. [13] performed high resolution reactive Mie scattering laser sheet visualizations, two color particle image velocimetry and hot wire anemometry measurements in coaxial circular and square jets at

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Nomenclature

C_p	specific heat of air at constant pressure (J K^{-1} kg^{-1})
D	side length of the inner square jet (m)
D_o	side length of the outer square jet (m)
E_1, E_2	X-wire probe voltages (V)
E_T	cold wire voltage (V)
E_H	eddy diffusivity for heat (m^2 s^{-1})
E_M	eddy diffusivity for momentum (m^2 s^{-1})
k_T	calibration constant of cold wire (K/V)
$Pr_T = E_M/E_H$	turbulent Prandtl number
$Re = U_{in}D\rho/\mu$	Reynolds number
Ri	Richardson number
T, $\overline{T}$, T'	instantaneous, mean and fluctuation of temperature (K)
T_a	ambient temperature (K)
T_c	calibration constant of cold wire (K)
$\overline{T'^2}$	variance of temperature fluctuations (K^2)
T'_{rms}	rms-value of temperature fluctuations (K)
T_{in}	inner jet temperature at the exit (K)
T_o	outer jet temperature at the exit (K)
U, $\overline{U}$, u	instantaneous, mean and fluctuation of streamwise velocity (m s^{-1})
u_{rms}	rms value of u (m s^{-1})
U_{in}	inner jet velocity at the exit (m s^{-1})
U_o	outer jet velocity at the exit (m s^{-1})
$\overline{u^2}$,$\overline{v^2}$,$\overline{uv}$	Reynolds stresses (m^2 s^{-1})
$\overline{uT'}$,$\overline{vT'}$	turbulent fluxes (m K s^{-1})
x, y, z	spanwise (transverse), lateral and streamwise coordinate (m)
V, $\overline{V}$, v	instantaneous, mean and fluctuation of spanwise velocity (m s^{-1})
v_{rms}	rms-value of v (m s^{-1})
Greek	
α	thermal diffusivity of air (m^2 s^{-1})
ΔT_e	$= T_{in} - T_o$ temperature difference at the exit of the coaxial jets (K)
ΔU_e	$= U_{in} - U_o$ velocity difference at the exit of the coaxial jets (m^2 s^{-1})
$\eta = \mu/\rho$	kinematic viscosity of air (m^2 s^{-1})
μ	dynamic viscosity of air (kg m^{-1} s^{-1})
ρ	density of air (kg m^{-3})
ρ_o	density of air at the exit of the outer jet (kg m^{-3})
Other	
$\varnothing$	the diameter of the holes (mm)

the Reynolds numbers 19,000 and 29,000. They reported that coaxial square jet configurations achieve higher mixing enhancement, than the reference coaxial circular jet used in their study. Nikitopoulos et al. [14] applied laser sheet visualizations and hot-wire measurements, compared the flow field of various coaxial square jets with equivalent coaxial circular jets at the Reynolds number 19,000 (same hydraulic diameter, same *Re*, and the same velocity ratio). They reported a moderate enhancement of mixing for the coaxial square jets.

The cited literature shows that considerable knowledge has been accumulated concerning momentum transport in rectangular configurations. There is a deficit, however, to relate this information with scalar transport. This study is focused on the scalar transport in the near field between two coaxial square air jets and provides insight into the association of this transport with known coherent structures. Data of instantaneous velocity and temperature were acquired, which allowed the direct evaluation of fluxes of turbulent quantities and the eddy diffusivities for heat and momentum, which are related to the scalar transport. Moreover, the application of the quadrant splitting technique to velocity and temperature signals permitted the association of the scalar field with occurring coherent structures.

2. Experimental setup

Fig. 1(a) presents schematically the two coaxial square jets together with certain construction details. The side length of the inner square nozzle was 50 mm and the side of the outer nozzle was 107 mm. The contraction ratio (entrance area over exit area) of the inner nozzle was 43.56 and the one of the outer nozzle was 12.93. Special care was paid during the design of the nozzles to assure uniform and low turbulence level exit flow. The cross sectional area ratio of the outer to the inner nozzle was 3.58. During the measurements, the inner jet flow was heated 3–5 °C above the temperature of the outer jet flow. The temperature difference between the coaxial jets was selected in such a way that the temperature fluctuations could be measured with sufficient accuracy and that the temperature difference should be low enough so that buoyancy effects remain negligible. To this purpose, the Richardson Number, *Ri*, of the present flow, defined by the equation,

$$Ri = \frac{g(\rho - \rho_o)\, D}{U_{in}^2\, \rho_o} \qquad (1)$$

has been evaluated. In Eq. (1), index "o" refers to the outer jet, ρ is the air density, D the inner jet side length and U_{in} the flow velocity at the exit of the inner jet. The estimated *Ri*-number is of the order of 10^{-4} indicating that buoyancy effects can be considered negligible.

The origin of the coordinate system was considered at the exit and at the symmetry axis of the nozzles, as it is shown in Fig. 1(b) and (c). The triple-wire probe, which is described below in this paragraph, recorded simultaneously the streamwise velocity $U(t) = \overline{U} + u(t)$, the transverse velocity component $V(t) = \overline{V} + v(t)$ and the temperature $T(t) = \overline{T} + T'(t)$, at the same position in the flow field. The overbar denotes the local time average values of the corresponding quantities; $u(t)$, $v(t)$ and $T'(t)$ are the corresponding fluctuating components. The streamwise velocity was the one parallel to the z-axis, while the transverse velocity component V was the velocity parallel to the x-axis (Fig. 1(b) and (c)). For this experiment, $V > 0$ means that fluid moves from the inner toward the outer jet or toward the environment, while $V < 0$ means that the inner jet is entrained by fluid from the outer jet or the environment. The Reynolds number based on the width of the inner jet, D, and the corresponding velocity of the inner jet, $U_{in} = 6.7$ m s^{-1}, was $Re = U_{in}D/\eta = 21{,}000$. The outer jet velocity was $U_o = 0.5$ m s^{-1} and the velocity ratio of the inner to the outer jet was $U_{in}/U_o = 13.4$.

A triple-wire probe, schematically shown in Fig. 2, was used for the instantaneous measurement of two velocity components and the corresponding instantaneous temperature at the same position in the flow field. The probe consisted of a DANTEC 55P61 X-hot wire probe and a DANTEC 55P31 resistance thermometer. The wires of the X-hot wire probe for the measurement of the two velocity components were platinum-plated tungsten wires, with a length of 1.25 mm and a diameter of 5 μm, separated by a