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Enhancement of laminar flow mixing using a pair of staggered lateral synthetic jets

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ABSTRACT

In the work reported in this paper, laminar flow mixing between two parallel water streams, which are injected into a rectangular channel at a net flow Reynolds number of 83, is enhanced using a pair of staggered lateral synthetic jets (LSJ) located on the opposite walls of the mixing channel. The synthetic jet pair is operated 180° out-of-phase at a range of actuation frequencies, f, and dimensionless stroke length, L. Our results show that an excellent mixing is obtained when a relatively high value of f or L is used. The dominant mixing enhancement mechanisms are identified, which are found to change as the LSJ actuation parameters vary. Quantitative comparison with the opposing LSJ pair configuration reveals that the staggered configuration slightly outperforms the opposing configuration at moderate levels of f or L. As f or L increase further, however, a similar mixing performance is obtained from both configurations.

1. Introduction

Synthetic jets are zero-mass-flux jets, which are synthesized from an ambient fluid. A typical synthetic jet actuator consists of a cavity, an oscillating membrane and an orifice on one of the cavity walls. As a result of the periodic volume change of the cavity, a train of vortical structures are produced, which propagate away from the orifice at their own self-induced velocity [1–5]. These vortical structures are capable of entraining the ambient fluid into their cores, thereby providing an effective mechanism in transporting mass and momentum across a flow field. Together with their unique feature of injecting vorticity and momentum into the flow field without the need of an external fluid source, synthetic jets bear many potential promises to the control and management of fluid flows.

A large volume of research has been carried out to study the behaviour of synthetic jets for the purpose of delaying flow separation over aerodynamic bodies [6–8]. Recently, heat transfer enhanced by synthetic jets has been studied, mainly focusing on jet impinging cooling [9,10] and heat transfer within micro-channels [11,12]. Although the concept of using synthetic jets for enhancement of liquid mixing has been proposed [13,14], it has not been explored experimentally and an in-depth understanding of the flow physics involved is also lacking. Exploitation of new mixing technologies will be beneficial for designing more effective mixing devices for many applications, such as inline mixers for viscous fluids and bi-sensors, in which the level of mixing is suppressed by their inherent low Reynolds numbers.

Recently, the authors of this paper have successfully demonstrated the use of a lateral synthetic jet (LSJ) pair in enhancing the mixing between two parallel fluid streams at a net flow Reynolds number of 83 [15]. The synthetic jet pair is located directly opposite to each other on the side-walls of a rectangular mixing channel. Since the synthetic jet pair is operated 180° out-of-phase, the net flow rate in the mixing channel further downstream is essentially time invariant. At relatively high synthetic jet actuation frequencies or amplitudes, a mixing degree of more than 0.9 is obtained at downstream locations of the jet orifices. The alternative formation of vortex pairs from each jet orifice due to the 180° out-of-phase actuation of the jet pair and the interaction between the vortex pairs from the opposing orifices are found to play a significant role in the resultant good mixing.

Despite the rapid mixing demonstrated by the opposing LSJ pair configuration, it is of a practical interest to investigate if a different spatial arrangement of the two jet orifices would yield an improved level of mixing, hence leading to the design of a more efficient mixing device. Therefore, in this paper the effect of a pair of staggered lateral synthetic jets on the mixing between two water streams in the same mixing channel is examined using the Planar Laser Induced Fluorescence technique (PLIF) and Particle Image Velocimetry (PIV). The distance between the centres of the left and right jet is fixed as 8 mm, which is equal to the width of the

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A	area of cross-section, m^2
c	tracer concentration, mg/l
d	width of jet orifice, m
f	actuation frequency, Hz
h	width of mixing channel, m
L	dimensionless stroke length
Re	Reynolds number
R_v	velocity ratio
Str	Strouhal number
T	period of synthetic jet actuation, s
t	time, s
U, u	velocity, m/s
x, y	coordinate, m
Subscript	
n	net flow in the mixing channel

mixing channel. A streamwise offset between the two orifices can be favourable by allowing a stronger interaction between the vortical structures produced by each orifice in accordance to a 180° out-of-phase actuation of the jet pair.

2. Experimental setup and methods

2.1. The experimental setup

This experiment is carried out in the same experimental setup used by the authors in their study of the opposing synthetic jet pair [16], except that the opposing synthetic jet pair is replaced by a staggered one. Two water streams are introduced into the mixing channel via a reversed Y-shape confluence unit. The rectangular mixing channel, which is made of Perspex, has a width of $h = 8$ mm, a depth of 40 mm and a length of 1 m. Intensive local perturbations are introduced into the mixing channel via a pair of synthetic jets produced by oscillating pistons attached to two separate cavities, see Fig. 1. The orifice of each synthetic jet is located on the two opposite side-walls of the mixing channel. Each orifice has a width of $d = 4$ mm and a depth extending across the entire depth of the mixing channel. In the present setup, the centres of two orifices are staggered by a streamwise distance of 8 mm, which is equivalent to the width of the mixing channel. The synthetic jet pair is operated 180° out-of-phase at a range of actuation frequencies and displacements. More information about the design of the synthetic jet actuators and the mixing flow rig can be found in [15].

According to the dimensionless analysis carried out by Xia and Zhong [16], the level of mixing in the present setup is determined by four dimensionless parameters. They are the net flow Reynolds number, $Ren = \rho h\bar{U}_n/\mu$, the dimensionless stroke length, $L = \bar{U}_j/fd$, the Strouhal number, $Str = fh/\bar{U}_n$, and the width ratio between the orifice and the mixing channel, d/h. Here, $\bar{U}_n$ is the mean flow velocity in the mixing channel, and $\bar{U}_j$ is the synthetic jet mean blowing velocity over its actuation cycle. In this experiment, the geometry of the mixing channel and the orifices of the synthetic jet actuators are fixed with d/h being equal to 0.5. A relatively high value of d/h, such as the one used here, ensures the formation of vortices with a size comparable to the mixing channel width hence the mixing effectiveness of the synthetic jets.

The coordinate system adopted in this paper is shown in Fig. 2. The location of $y = 0$ coincides with the location of the centres of the oscillating pistons. As such, the centre of the left and the right LSJ orifice is located at $y = -0.5h$, and $0.5h$, respectively. Since the dimension of the LSJ cavities is 126 mm × 126 mm, an offset of $0.5h$ or 4 mm between the centre of the orifice and the centre of the cavity is expected to have a negligible influence on the blowing velocity profile at each orifice exit.

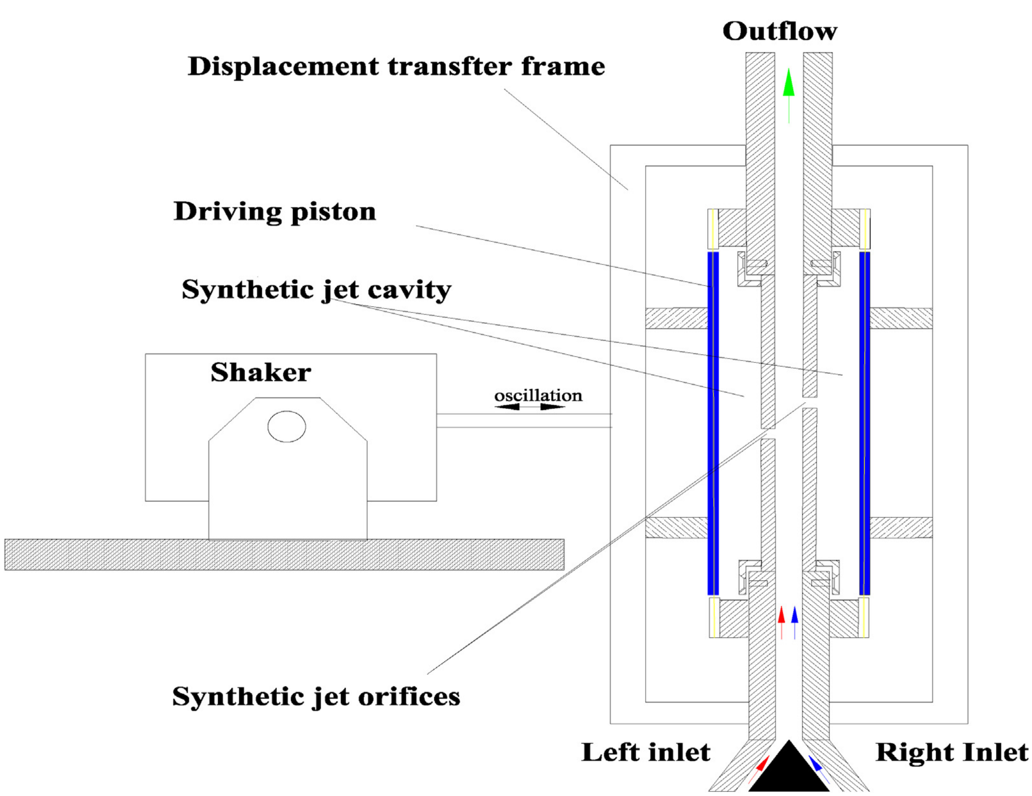

Fig. 1. Schematic of the experimental setup.