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Liquids mixing enhanced by multiple synthetic jet pairs at low Reynolds numbers

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HIGHLIGHTS

- Fast in-line mixing is achieved by using three synthetic jet pairs operated 180° out-of-phase at Reynolds number of 2.
- Folding and stretching of fluid elements as well as sequential segmentation are the primary mixing mechanisms for enhanced mixing.
- Out-of-phase synthetic jet pair configuration has several advantages.
- A functional relationship between the synthetic jet actuation frequency and magnitude to ensure good mixing is found from the experimental data.

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ABSTRACT

In this paper, the effect of three synthetic jet pairs on the mixing between two fluid streams in a planar mixing channel is examined at a net flow Reynolds number of 2. They are mounted transversely to the incoming flow and operated 180° out-of-phase. The PLIF technique is used to provide a visual impression of the effect of synthetic jets on mixing as their operating condition varies, whereas PIV is used to provide the complementary information about the flow structures produced by the synthetic jets and their role in promoting mixing. Our experimental results demonstrate that this inline fluid mixer with a simple design produces an excellent mixing at low Reynolds numbers. It is found that such a good mixing is the result of a significantly increased interfacial area created by these synthetic jet pairs. Based on the degree of mixing deduced from the PLIF data at some distances downstream of the synthetic jets, a functional relationship between the synthetic jet actuation frequency and amplitude is also obtained. This functional relationship can be used for selecting the synthetic jet operating conditions to ensure a good mixing for a scaled version of this fluid mixer.

1. Introduction

Fluid mixing at low Reynolds numbers is challenging since it relies purely on molecular diffusion due to an absence of turbulence in the flow. Consequently, the use of an effective mechanism, either active or passive, which is capable of increasing the interfacial areas between the liquids to be mixed, becomes indispensable to achieve a fast mixing.

The methods commonly used for mixing at low Reynolds numbers are based on principles, such as multi-lamination, flow split-and-recombine and jet mixing. In multi-lamination, fluids to be mixed are forced through narrow gaps so as to increase the interfacial area as well as to decrease the traverse thickness of fluid layers to favor molecular diffusion(Hardt et al., 2002; Melin et al., 2004). In the method of flow split-and-recombine, fluid is fed into passages with complex geometry so as to create chaotic advection (Zalc et al., 2002). These two methods are passive in nature, which are characterized by no additional energy consumption except for the pumping action and the hydrostatic potential. They have the advantage of having simple control systems but at the expense of structural complexity. The jet mixing technique, on the other hand, offers a competitive alternative method with less structural complexity. Jet mixing may involve the use of passive mixing techniques, such as collision of jets (Wong et al., 2004) and eddy formation, and active mixing techniques, such as periodic injection switching (Niu and Lee, 2003) and periodic lateral perturbation (Niu and Lee, 2003). In jet mixing, sequential segmentation generated by out-of-phase periodic injection can enhance mixing effectively (Paik et al., 2003). Sequential segmentation is a process where solvent and solute streams are broken up into segments in the axial direction, which increases the interfacial areas hence favors mixing. Despite the volume of research work on jet mixing (Bothe et al., 2006; Hoffmann et al., 2006; Wong et al.,

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2004), however, the degree of mixing is often found undesirable at Reynolds numbers below, say 300. Hence, there is a need to develop new mixing techniques, which are effective at much lower Reynolds numbers.

A synthetic jet is a zero-mass-flux jet, which is synthesized from the ambient fluid. It is produced by the periodic ejection and ingestion of fluid from an orifice, which is caused by the movement of a diaphragm attached to a cavity. As a result of the periodic volume change of the cavity, a train of vortical structures is produced, which propagates away from the orifice at its own self-induced velocity (Glezer and Amitay, 2002; Holman et al., 2005; Zhou et al., 2009). These vortical structures are capable of entraining the ambient fluid into its 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 as a means of manipulating fluid flows.

Synthetic jets have received intense research attention since 1990's, Many of these studies aim at the potential applications of delaying flow separation over aerodynamic bodies (Jabbal and Zhong, 2008; Shuster and Smith, 2007; Tang et al., 2007; Tesar, 2009; Zhang and Zhong, 2010; Zhong et al., 2007). It is believed that the vortical structures, which are produced by the synthetic jets issuing through a slot or an array of circular orifices upstream of a separated flow, energize the retarded near-wall flow in the boundary layer, hence delaying the flow separation. In more recent years, there has been an increased interest in surface cooling using impinging synthetic jets (Chaudhari et al., 2010; Li et al., 2009; Pavlova and Amitay, 2006; Travaicek and Tesar, 2003). Comparatively, the use of synthetic jets in enhancing fluid mixing has been less well explored.

Synthetic jets issuing into a channel flow through the channel walls are capable of generating intensive local disturbances hence enhancing mixing. This technique is particularly attractive, since the velocity of the synthetic jets can be varied independently of that of the fluid streams to be mixed, allowing effective mixing to be achieved in low Reynolds number flows. Although there have been some preliminary studies of mixing enhancement using synthetic jets (Mautner, 2004; Tesar, 2009), detailed experimental investigations aiming at understanding the flow physics involved are still lacking. Such an improved understanding will be beneficial to the development of more effective mixing devices, which operate at low Reynolds numbers, such as inline flow mixers for viscous fluids and bi-sensors.

Using a pair of synthetic jets located on the opposite walls of a planar mixing channel and operated 180° out of phase, Xia and Zhong (2012b) demonstrated that a homogeneous mixing between two fluid streams can be achieved at a net flow Reynolds number as low as 83. They found that the interaction between the vortices produced by the synthetic jet pair and their subsequent breakup plays a key role in promoting mixing. However, as the net flow Reynolds number reduces, the mixing effectiveness of this method is expected to decrease. As shown by the flow visualization of circular synthetic jets issuing into a quiescent flow at a Reynolds number around 1, only a reciprocating plug flow is formed without any discernible vortical structures (Xia and Zhong, 2012a) Therefore, it is of a practical interest to investigate whether this method remains effective at much lower Reynolds numbers and explore the measures, which can be taken to enhance the level of mixing.

In this paper, the effect of three synthetic jet pairs on the mixing of two fluid streams is examined at a net flow Reynolds number of 2. The experiment is undertaken in the same rig used by Xia and Zhong (2012b) except that sugar solutions are used as the flow media in order to produce lower net flow Reynolds numbers. The three synthetic jet pairs are operated 180° out-of-phase. Their actuation frequency and amplitude are varied to allow the effect of these two parameters on mixing to be assessed. In this study, the PLIF technique provides a visual impression of the effect of synthetic jets on mixing as their operating condition varies, whereas PIV is used to provide complementary information about the flow structures produced by the synthetic jets and their role in promoting mixing. Finally, the extent of mixing is quantified using the dye concentration measured by the PLIF technique at some distances downstream of the synthetic jets.

2. Experimental setup and methods

2.1. The fluid mixer and synthetic jet actuators

An schematic of the synthetic jet fluid mixer used in the present study is shown in Fig. 1. Two separate fluid streams are introduced into the mixing channel via a confluence inlet. The rectangular mixing channel, which is made of Perspex, has a width of $h=8$ mm, a depth of $w=40$ mm and a length of 1 m. More information about the design of this synthetic jet mixer can be found in Xia (2012).

In this study, cane sugar solutions are used as the fluid media in order to obtain desired low Reynolds number flows. Cane sugar solutions with a sugar concentration up to approximately 78% are Newtonian fluid (Quintas et al., 2006), and the viscosity of the solution can be estimated with a good accuracy given the temperature and the sugar mass fraction (Mageean et al., 1991). Sugar solutions are considered as the desirable fluid media for this study because they are cheap to make and their viscosity can be easily adjusted by varying the sugar mass fraction during preparation. The sugar solution used in the present experiment has a mass fraction of 58.2% with a dynamic viscosity of $\mu=5.0\times10^{-2}$ Pa s and a density of 1277 kg/m^3 at 18 °C. Before the experiment, the viscosity coefficient of the sugar solution is also measured with a GILMONT falling ball viscometer. The difference between the estimated and measured viscosity coefficient is found to be less than 3%, confirming that the correlation given by Mageean et al. (1991) is quite accurate.

Intensive lateral perturbations are introduced into the mixing channel using three pairs of synthetic jets mounted transversely to the incoming flow on the two opposite walls of the mixing channel as shown in Fig. 1. The orifice of each synthetic jet has a width of $d=4$ mm and spans the entire depth of the mixing channel. The spacing between the centres of adjacent orifices is chosen to be 16 mm, which is equal to 2 h. The choice of such

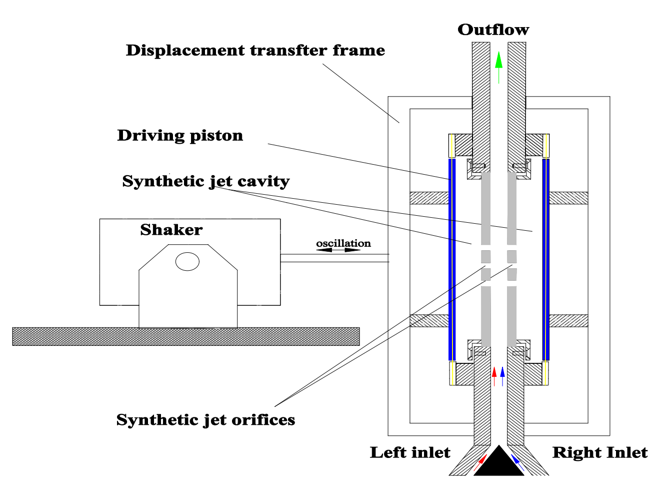

Fig. 1. Schematic of the experimental setup (not to scale).