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Influence of acoustic resonance on mixing enhancement in confined mixing layers

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ABSTRACT

Extraordinarily rapid mixing has surprisingly been achieved in confined mixing layers by active forcing within an optimal narrow frequency band (Wang, PhD Dissertation, 1999; Wang, Chem. Eng. Sci., 2003; Wang, AIChE J., 2006). However, the corresponding mechanism of the large receptivity and rapid mixing is still unclear so far. Since it is found that the optimal frequency that corresponds to the rapid mixing is independent of Reynolds number or bulk flow velocity, we postulate that some type of resonance of the experimental setup or fluid-structure interaction might be the cause. In this manuscript, the possible influence of acoustic resonance and fluid-structure interactions are investigated by both parametric study through flow visualization and finite element method (FEM). The results reveal the optimal forcing frequency of the fast mixing is tightly related to a complicated acoustic resonance mechanism of the entire water tunnel system, and when the confined mixing layers are forced under the resonance frequency, ultrafast mixing can be observed. This finding may lead to new technology for mixing and heat transfer enhancement.

1. Introduction

Aims of research in fluid mechanics are not only to understand and model relevant physical, chemical or biological processes, but also to control flow and enhance mixing, heat and mass transfer, such as in combustion [1,2], chemical and biological processes [3] and acoustic noise reduction [4,5]. Mixing enhancement in free shear layers (mixing layer, wake and jet), has been investigated for several decades. Because of their importance in energy, chemical, automotive and aerospace industries, etc, plenty of efforts have been made to understand the mechanism of mixing and the effective ways to enhance mixing based on the flow receptivity in incompressible flows [6–14], compressible flows [12,15–20] or reactive flows [2,21,22] etc.

In plane free mixing layers, the Kelvin-Helmholtz (K-H) instability, vortex merging and subharmonic mode are believed to be the most effective mechanism for mixing enhancement [8,9]. Unfortunately, the enhancement in mixing layer is still limited. Fiedler et al. [23] reported when the forcing intensity exceeds 6.5%, the spreading rate of mixing layers no more increases with the increasing of the forcing intensity due to a saturation phenomenon caused by nonlinear effect. At the same velocity ratio, compared to the neutral case, the spreading rate of mixing layers is only about two times larger under the subharmonic forcing [17]. Recently, Wiltse et al. [13,19] used a spanwise array of heater as actuators at the upstream of trailing edge to enhance the mixing effect. By strengthening the streamwise vortices, only three times mixing enhancement can be achieved. Therefore the methodology of mixing augmentation in free shear layers has not been widely applied in industries because of its limited capability of enhancing mixing, although the free shear layers have the advantages of plug flows in chemical industries [11].

Fortunately, Wang [11,12,24] reported that the aforementioned saturation limit due to the nonlinear effect could be overcome in confined mixing layers under forcing at a specific narrow frequency band. The spreading rate of the mixing layer increases with the forcing intensity without the nonlinear saturation. Since the spreading rate is related to the fluid entrainment, a larger spreading rate normally indicates a stronger entrainment and faster transport of scalar on large scales. At a sufficiently high forcing intensity, the spreading angle, i.e. the spreading rate of the

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mixing layer can reach almost quasi 180°. When the forcing intensity is sufficiently high, even if the basic flow is laminar and the Reynolds number $Re = 400$ (defined by the diameter of the mixing chamber and the bulk flow velocity), Oboukhov–Corrsin spectrum (-5/3 law) can also be observed [24]. Drastic turbulent mixing is achieved immediately at the inlet of mixing chamber and small scale structures are rapidly generated together with the initial large scale structures. The increased small scales by the rapid cascade process will then increase the rate of creation of small scale structures between two chemicals to enhance their molecular diffusion eventually. This is very important for mixing on molecule level which is crucial for chemical reactions.

Surprisingly, the optimal forcing frequency corresponding to the highest spreading rate happens to be in a narrow frequency band (near 6 Hz,) which is independent of Reynolds number and velocity ratio of the flows. This is a great advantage in practical applications, for mixing mass and heat transfer, since the control process can be significantly simplified.

However, the cause and mechanism of the optimal narrow frequency band is yet to be understood. The drastic mixing should be accompanied and dominated by the intensive flow fluctuations which could be induced by either flow instability (absolute or convective) or resonance [25,26]. Although Wang [12] observed that the corner flow instability plays an important role in the dynamics of the rapid mixing, it should not be the cause of the narrow optimal frequency band, under which the shear layers have the largest initial spreading rate. This is because the most unstable frequency of corner flow instability is tightly related to the bulk flow velocity (or Re) and pressure gradient [27–34].

Since this narrow frequency band is independent of Re, intuition attributes the phenomenon of the fast mixing and high receptivity to some kinds of resonance of the flow system. However, although resonances have been widely studied in mixing enhancement in nozzle of combustors and closed cavity [25,35], none of them has reported the aforementioned phenomenon of rapid mixing. In addition, since the optimal frequency is very low, whether the optimal frequency is due to acoustic resonance or some other kind of resonance, should be elucidated. Therefore, in this manuscript, we attempt to explore the relations between acoustic resonances and the optimal frequency for the fast mixing. In Section 2, the experimental apparatus and procedure are introduced. Then, two types of resonance are investigated experimentally in Section 3. One is the acoustic resonance that propagates in the water tunnel. The other is the vibrations caused by fluid-structure interactions. At last, FEM analysis on acoustic eigenfrequency in the fluid is carried out and compared with the experimental results.

2. Experimental setup and procedures

2.1. Experimental setup

The experimental setup is designed to be similar to that by Wang [11,24] to ensure the previous work is repeatable, as shown in Fig. 1(*a*). The water tunnel is consisted of two water supply tubings, a settling chamber, contraction nozzle, mixing chamber and drain pipes. In order to avoid external disturbance, gravity driven flow is adopted by using two 416 L water tanks, which are lifted 2.5 m over the test section. One is filled with pure water and the other is filled with aqueous fluorescent dye solution for flow visualization. The waste solution is drained to another water tank (568 L). Two sets of rotameters are used to control the flow rate in the two streams respectively. Each set is constituted with one 7510 series (2–20 Gallon per Minute, or GPM) and one 7511 series (0.2–2

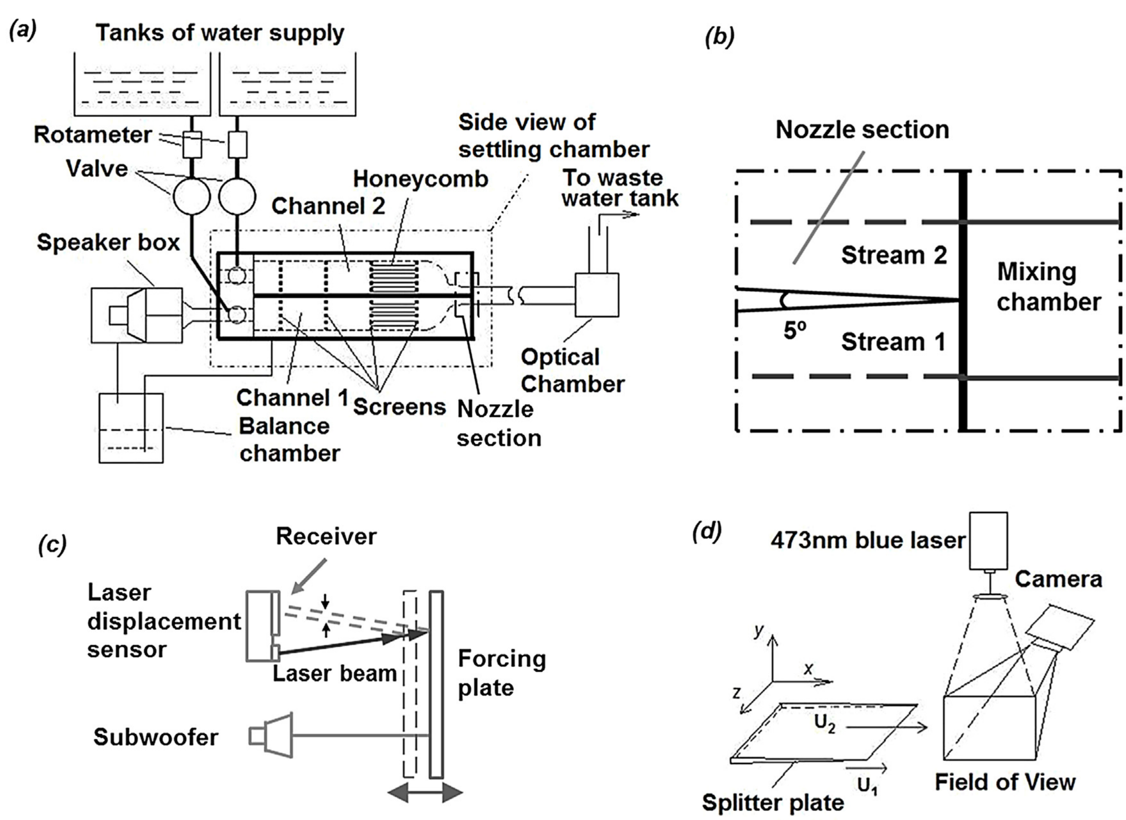

Fig. 1. Diagram of the experimental setup. (*a*) Components and constitutions of water tunnel. (*b*) Diagram of trailing edge in the nozzle section of (*a*). (*c*) Schematic of laser displacement sensor to monitor the movement of a forcing plate. (*d*) Definitions of the coordinate system and the position of FOV of flow visualizations.