A NUMERICAL STUDY ON THE MIXING CHARACTERISTICS OF OPPOSED JETS

Peng Xu[*a)], Shuxia Qiu[*] & Arun S. Mujumdar[**]
[*]*College of Science, China Jiliang University, Hangzhou, 310018, China*
[**]*Department of Mechanical Engineering, National University of Singapore,117576 , Singapore*

Summary The opposed-jet configurations of simple geometry and well-controlled boundaries have been employed in a number of industrial applications due to rapid and high-effective mixing performance of viscous fluids. A numerical study has been performed on the two-dimensional opposed jets to gain basic understanding of the mixing properties and hydrodynamics characteristics, where the fluid temperature is used as a passive tracer to evaluate the mixing rate. The potential effect of periodic oscillations induced by pulsation show on the mixing efficiency is examined. Parametric studies are also conducted for the optimization of both steady and unsteady opposed jets.

INTRODUCTION

Due to rapid and high-effective mixing performance of viscous fluids, the opposed-jet configurations with simple geometry and well-controlled boundaries have been utilized in a number of industrial applications such as gas or liquid mixing, fuel combustion, reaction injection molding, pharmaceutical crystallization, particle synthesis, coal gasification, absorption, dust collection, liquid-liquid extraction, chemical processing in reactors and drying technology etc [1]. Various experimental and numerical studies have been conducted to improve the mixing performance of the opposed jets [2-4]. From the previous literature review, it can be found that the speed and efficiency of the mixing in opposed jets are determined by the characteristics of the flow, e.g. the Reynolds number, the inflow conditions and the mixer geometry. Therefore, a better understanding of the mixing rate is mandatory for the optimization of these processes.

Previous studies have mainly focused on optimizing transport processes associated with steady opposed jets impinging normally against each other [5-7]. As the periodic oscillations induced by mechanical pulsation show the features such as flow instability, higher turbulence levels, chaotic mixing and nonlinear dynamic response of boundary layers, flow pulsation has been employed in impinging jets for heat and mass transfer enhancement [8-10]. Thus, the objective of the current work is to evaluate the effect of flow pulsation on heat and mass transfer properties of turbulent opposed impinging jets. A mathematical model is developed for the two-dimensional opposed jets with computational fluid dynamic approach. The hydrodynamics characteristics are examined for better understand the mixing properties in opposed jets.

MATHEMATICAL MODELING

The mathematical model is developed for a two dimensional opposed-jet configuration. Two opposed slot-nozzles of width w impinging normally against each other, and the distance between the opposed jets is H. The fluid (air) is assumed to be incompressible and Newtonian with temperature-dependent fluid properties. Fluid temperature at the cross-section is used as a passive tracer to evaluate the flow mixing characteristics. The cold and hot flows are supplied axially to the nozzles by the upper and lower inlets respectively. A sinusoidal pulsation with flat velocity profile is applied at the inlets. The confinement wall is considered adiabatic, and the no-slip condition is imposed. The pressure outlet boundary condition is adopted at the outlet plane.

The mixing parameter can be defined as $M=1-\delta_T/T_{ave}$, where δ_T is the standard deviation of the fluid temperature at any specific cross-section in the exit channel and T_{ave} is the averaged temperature on the cross-section. The mixing parameter M can be used as a measurement of mixing degree of the opposed jet flows, and M=1 represents a complete mixing effect.

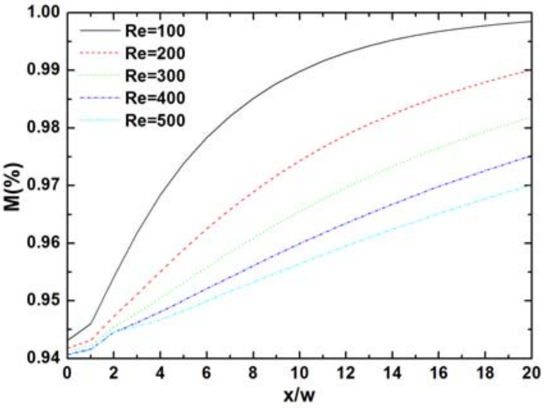
RESULTS AND DISCUSSION

Figure 1 indicates the effect of jet flow Reynolds number on the mixing parameter. In the laminar flow regime, the mixing rate reduces with increase of Reynolds number. Two main reasons may make contributions to the mixing performance of opposed jets. One is the shear-induced flow motion, which can be enhanced by increased jet flow rate. The other is the residence time in the exit channel, increased Reynolds number can reduce this residence time. In laminar flow regime, the latter effect takes a dominant position as the flow rate is relatively low.

In order to improve mixing performance, the sinusoidal flow pulsations are induced at jet inlets. Figure 2 show the comparison of mixing rate along the exit channel between the *steady* and *pulse*d opposed-jet flows. It can be clearly seen in figure 2 that the introduction of flow pulsations can significantly enhance the mixing rate and improve the mixing performance of opposed jets compared with that of steady case. It can be also found that the mixing rate can be further reduced by increasing the pulsation amplitude.

---

a) Corresponding author. Email: xupenghust@yahoo.com.cn



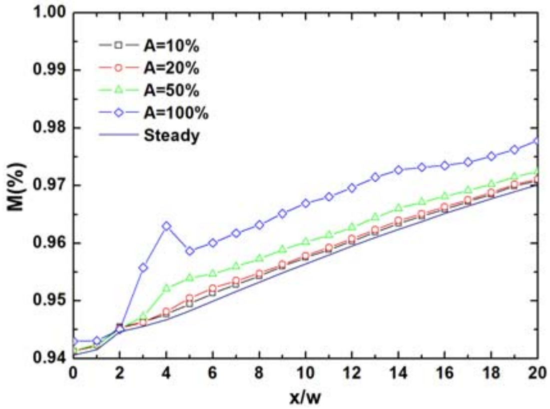


Fig. 1. The distribution of mixing rate in steady opposed jets along the exit channel under different Reynolds number.
Fig. 2. Effect of flow pulsations on the mixing rate along the exit channel at *Re*=500.

CONCLUDING REMARKS

In the present work, the flow and mixing characteristics of opposed jet flows have been investigated. The numerical results indicate that increased Reynolds number can reduce the mixing rate and the sinusoidal flow pulsations can significantly improve the mixing performance of opposed jets in laminar flow regime.

ACKNOWLEDGEMENTS

This work was supported by Zhejiang Provincial Natural Science Foundation of China through Grant no. Y6110343 and Qianjiang Program of Zhejiang Province through Grant no. 2011R10092.

References

[1] Tamir A.: Impinging-stream reactors: fundamentals and applications. Elsevier. Amsterdam 1994.

[2] Wang S.J., Devahastin S., Mujumdar A.S.: Effect of temperature difference on flow and mixing characteristics of laminar confined opposing jets. *Appl Therm Eng* **26**:519-529, 2006.

[3] Ciani A., Kreutner W., Frouzakis C.E., et al.: An experimental and numerical study of the structure and stability of laminar opposed-jet flows. *Comput Fluids* **39**:114-124, 2010.

[4] Hasan N., Khan S.A.: Two-dimensional interactions of non-isothermal counter-flowing streams in an adiabatic channel with aiding and opposing buoyancy. *Int J Heat Mass Transf* **54**:1150-1167, 2011.

[5] Chou C.-P., Chen J.-Y., Janicka J., Mastorakos E.: Modeling of turbulent opposed-jet mixing flows with k-ε model and second-order closure. *Int J Heat Mass Transf* **47**:1023-1035, 2004.

[6] Geyer D., Kempf A., Dreizler A., Janicka J.: Turbulent opposed-jet flames: A critical benchmark experiment for combustion LES. *Combustion and Flame* **143**:524-548, 2005.

[7] Pawlowski R.P., Salinger A.G., Shadis J.N., Mountziaris T.J.: Bifurcation and stability analysis of laminar isothermal counterflowing jets. *Journal of Fluid Mechanics* **551**:117-139, 2006.

[8] Hofmann H.M., Movileanu D.L., Kind M., Martin H.: Influence of a pulsation on heat transfer and flow structure in submerged impinging jets. *Int J Heat Mass Transf* **50**:3638-3648, 2007.

[9] Xu P., Mujumdar A.S., Poh H.J., Yu B.M.: Heat transfer under a pulsed slot turbulent impinging jet at large temperature differences. *Therm Sci* **14**:271-281, 2010.

[10] Xu P., Yu B.M., Qiu S.X., et al.: Turbulent impinging jet heat transfer enhancement due to intermittent pulsation. *Int J Therm Sci* **49**:1247-1252, 2010.