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Experimental study and Large Eddy Simulation of thermal mixing phenomena of a parallel jet with perforated obstacles

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Thermal mixing and flow field due to two parallel jets which have different temperatures are investigated both experimentally and numerically. The perforated passive obstacles are used with different geometrical specifications. They are located in front of the jets to control flow field and mixing behavior of the jets. An experimental setup designed and manufactured and Large Eddy Simulation turbulence model with the WALE subgrid-scale stress model were used to simulate same experimental conditions. Three perforated obstacles (POs) with different porosity values were used in the study and these obstacles inserted into a rectangular cross-section confined channel. Results demonstrated that increasing the values of temperature differences enhance thermal mixing performance along the channel. The best mixing quality was captured at the same flow rates of the jets. The perforated obstacle has significant positive effect on the mixing performance and this effect increase with higher porosity values. Dominant frequency of mixing region was found as 5 Hz in all cases. The temperature profiles showed that as porosity decreases thermal oscillations are starting to reach the wall. Both 2D and 3D velocity profiles demonstrated that using of POs reduces the domination of turbulence area in the channel.

1. Introduction

The mixing of fluids at different temperatures in a channel leads to temperature fluctuations that may cause thermal fatigue in the in surrounding surfaces. Turbulent mixing of fluids in a confined domain is of significant interest for many engineering applications. The thermal striping phenomena in a domain, where hot and cold fluid join and mix, however not completely, resulting in significant temperature fluctuations near the surrounding walls. Fluctuations in the wall temperature can cause cyclical thermal stresses and subsequently fatigue cracking of the wall. This may constitute a threat in many industrial applications. For instance; in a nuclear power plant, during reactor operation, temperature fluctuations in the coolant close to a structure may occur in many areas such as core outlet zone, lower part of hot pool, free surface of pool, secondary circuit, and water/steam interface in steam generators. High-cycle thermal fatigue was found to be a cause of the cracks in the connecting pipes and the middle-stage heat exchanger shell at the Tsuruga-2 PWR (Japan) in 1999: two coolants flows-lower temperature main flow inside the inner cylinder of the heat exchanger (HE) and higher temperature bypass flow outside the inner cylinder were mixed. Repair of the damage interrupted the reactor operation program. In 1993, at the BN-600 reactor a sodium leak on the purification loop of primary circuit was observed. Metallurgical expertise showed that it was due to thermal fatigue caused by a fluctuating mixing of hot and cold sodium [1]. Such industrial cases showed that thermal fluctuations can lead dangerous thermomechanical problems in some systems if protective measures are not taken. That's why the conditions that affects thermal mixing phenomena is an important topic that need to be understood.

Kok et al. [2–5] made various investigations on thermal mixing characteristics of parallel jet. One of these studies is numerical and others are experimental. In one experimental work they build an artificial neural network (ANN) model with limited number of experimental measurements for a forward model. In these papers mainly they study effects of ratio of flow rate of hot and cold jet, temperature difference between hot and cold jet, inclination angle

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Nomenclature

$\dot{m}$	Mass flow rate (kg/s)
n	Number of jet
S_t	Standard deviation of fluid temperature
t	Time (s)
T	Temperature of fluid (K)
ΔT	Temperature difference between hot and cold fluid (K)
u	Velocity component (m/s)
$\overline{u}$	Filtered velocity component
ρ	Density of fluid (kg/m^3)
ρ_0	Reference density (kg/m^3)
p	Pressure (Pa)
S_M	Gravitational body force (kg·m/s^2)
g	Gravitational acceleration (m/s^2)
σ_{ij}	Stress tensor (N/m^2)
μ_t	Turbulent subgrid viscosity (kg/m·s)
μ	Molecular viscosity (kg/m·s)
τ_{ij}	Subgrid-scale stress (N/m^2)
h	Enthalpy (kJ/kg)
k_{eff}	Effective thermal conductivity (W/m·K)
k	Thermal conductivity (W/m·K)
c_p	Constant pressure specific heat (kJ/kg·K)
Pr_t	Subgrid Prandtl number
S_{ij}^d	Deviatoric part of rate-of-strain tensor
L_s	Mixing length for sub grid
κ	Von Karman constant
d	Distance to the closest wall (m)
V	Volume of the computational cell (m^3)
C_w	WALE constant

Subscript

h	Hot flow
c	Cold flow
avg	Average
i	Direction index (i = x, y or z)
j	Direction index (j = x, y or z)

of the confined test channel, passive obstacle location in the channel and geometric shape of the passive obstacle. Results of these studies showed that in general mixing performance increase with increasing values of temperature difference between hot and cold jet. Also mixing efficiency increase with increasing inclination angle of the channel. They observed that inserting passive element into the channel effects behavior of the flow and thermal mixing. So these kinds of obstacle can be used as control parameter.

Jin and Leong [6] carried out an experimental study to analyze behavior oscillating and steady flows through a metal foam structure. In the experiments, an auto-balance compressor was used to supply steady flows to the system and oscillating flow generator was used to provide flow oscillation. The obtained results were showed that flow resistance in the metal foams increases with increasing form coefficient and decreasing permeability. An experimental and numerical investigation was performed by Hayes et al. [7] to analyze flow characteristics through a perforated medium. The results were revealed that show favorable agreement between existing Nusselt correlations for heat transfer in a matrix heat exchanger as well as between NTU per plate correlations. Hooman and Gurgenci [8] performed a numerical investigation effects of viscous dissipation and boundary conditions on forced convection in a parallel plate channel filled with saturated porous medium. Analytical expressions of temperature profile and the asymptotic Nusselt number were also presented in the study. The results presented that the Brinkman number has an important effect on the developing Nusselt number. At all considered conditions porous medium shape factor was effected from Nusselt number.

Hooman et al. [9] made an analytical study on the first and the second law of fully developed forced convection inside a channel filled with porous medium. In the analysis three different temperature boundary conditions were used. The authors asserts that the results of this study will allow to evaluate, compare and optimize different channels designs in terms of heat transfer, pressure drop, and entropy generation. Jiang and Lu [10] carried out a numerical study and theoretical analyses to investigate thermal boundary phenomena of heat transfer in porous media. The results showed that the temperature distribution at the contact interface is non-uniform for the porous media with a zero-thickness waterproof wall. However, in the porous media with a finite-thickness waterproof wall the heat flux distribution at the contact interface is non-uniform, while the temperature distribution at the contact interface is uniform.

Wang and Mujumdar [11] studied the three-dimensional flow and mixing characteristics of multiple and multi-confined turbulent opposing jets in a pipe, numerically. Standard k-ε turbulence model was used as turbulence model. They concluded that multiple opposing jets can achieve better mixing than single opposing jets. Wang et al. [12], made a numerical investigation to study the mixing performance of opposing jets in a confined channel. Some new geometric conditions were performed to increase effectiveness of mixing. They observed that dissimilar inlet momenta and unequal slot width could significantly improve the mixing performance; this improvement depended strongly on the operating conditions and geometric configurations. Addition of baffles in the exit of the channel increases the mixing quality. The pressure loss was found to depend strongly on the mixer geometry and operating conditions.

Chandran et al. [13] made a numerical investigation of thermal striping phenomena of a two-jet water model. In the model the jets impinge on a lattice plate. Simulations were carried out for different velocity ratios of hot and cold jets and various location of lattice plate. Also numerical data were validated with available experimental results. Consequently, jets with unity velocity ratio showed maximum temperature fluctuations. Cold jet dominated and hot jet dominated flow demonstrated high and low temperature fluctuations, respectively.

Jung and Yoo [14] carried out Large Eddy Simulations to investigate the effect of inlet thermal intensities (T_{rms}/T) on thermal mixing of the triple jet flow. Smagorinsky-Lilly and the *k-l* sub-grid scale models were used in the turbulence model. It is found that LES predict faster decay of mean temperature along the axis of the central jet. The inlet values of thermal intensity and the sub-grid scale models had no effect on the solution. Cao et al. [15] use Large Eddy Simulation (LES) to study the flow characteristics and temperature fluctuation behavior of a triple-jet model. Numerical data validated with experimental results of Nishimura et al. [16]. The flow field that demonstrated in numerical results showed that many vortices are closely related with the temperature fluctuation behavior. Also the results showed that amplitudes of temperature fluctuation are different in flow field, while the frequency of temperature fluctuation remains constant at all monitoring position.