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Thermal mixing in T-junctions

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Temperature fluctuations occur due to thermal mixing of hot and cold streams in the T-junctions of the piping system in nuclear power plants. Temperature fluctuations cause thermal fatigue of piping system. In the present work, thermal mixing experiments are carried out on a T-junction with water. Velocity and temperature fields are measured using hot film anemometer (HFA). Three dimensional steady state computational fluid dynamics (CFD) simulations have been carried out to predict the velocity and temperature fields. The predicted velocity and temperature fields are in good agreement with the experimental measurements.

1. Introduction

Thermal mixing is one of the causes of thermal fatigue failure in nuclear power plants. Thermal mixing characterizes the phenomenon where hot and cold flow streams join, mix and result in temperature fluctuations. The temperature fluctuations cause cyclic thermal stresses and subsequent fatigue cracking of the pipe wall. Thus prediction of thermal field in piping system is an important aspect from the nuclear reactor safety point of view. In order to assess the structural strength, stability and life of such T-junctions, it is essential to know the following: (i) magnitude of the temperature fluctuations, (ii) characteristic frequencies of temperature fluctuations, (iii) regions of pipe wall that experience the temperature fluctuations, (iv) attenuation of the temperature fluctuations in the boundary layer near the pipe wall. These were the basic goals of the present work. Thermal mixing experiments in T-junctions were reported previously. These investigations include flow visualization, temperature measurements using thermocouples and velocity measurements. In these experiments, temperature fluctuations were measured at selected locations in the pipes. Also numerical studies using CFD were carried out. Thermal mixing was modeled using large eddy simulation (LES) and direct numerical simulation (DNS), which required extensive computational capacity and time. In the present study, cross flow thermal mixing experiments were performed in T-junctions and temperature measurements are carried out in the mixing region using the HFA. Three dimensional steady state CFD simulations were carried out to predict the velocity and temperature fields.

2. Previous work

Table 1 shows various experimental and numerical investigations of the hydrodynamics of the T-junctions in the published literature.

McFarland and Landy (1980) carried out water tests with 3 different configurations of a T-junction. They discussed transient and steady state data for pressure and temperature of fluid, and compared it with visual observations of the mixing processes in the T-junction configurations. They concluded that good mixing between similar fluids can be obtained within a reasonable length ($L/D<10$) without considerable pressure losses.

Maruyama et al. (1981) experimentally investigated the mixing of two fluid streams meeting at a T-junction. They derived an empirical correlation for the jet trajectory that is applicable over a wide range of pipe diameters and velocity ratios. Also, they described an analytical procedure for determining optimum mixing conditions based on entrainment of fluid due to mixing.

Maruyama et al. (1982) found out mixing conditions based on cross-sectional temperature distribution in the main pipe. They investigated mixing conditions for two fluid streams at an oblique branch as a function of branch angle. They also studied the dependence of the degree of mixing on the jet angle by comparing

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Table 1
Previous literature

Reference	Type of flows	Main pipe fluid	Branch pipe fluid	Main pipe diameter (m)	Branch pipe (jet) Diameter (m)	Velocity ratio (V_h/V_c)	Main study details					
							Expt.	CFD	V	V'	T	T'
McFarland and Landy (1980)	Cross	NaOH soln	Water (hot) with indicator	0.09	0.018	0.39–1.58	✓				✓	✓
Maruyama et al. (1981)	Cross	Air (35 °C)	Air (25 °C)	0.051	0.005–0.013	2–5	✓		✓		✓	
Maruyama et al. (1982)	Cross, tangential	Air, Water	Air, Water	0.1	0.0042–0.0113	3.5–12	✓		✓		✓	
Andreopoulos (1983)	Cross	Air	Air	Duct: 1.5 × 1.5	0.05	0.25–2	✓				✓	
Rzezonka and Kastl (1984)	Cross	Liquid Na (cold)	Liquid Na (hot)	0.30	0.15	0.5–2.65	✓				✓	
Sherif and Pletcher (1989)	Cross	Water	Water	Duct: 0.61 × 1.067	0.014	1–7	✓				✓	✓
Tang et al. (1993)	Cross	Air	Air	3.81	0.95	0.5–0.8	✓				✓	
Fukushima and Fukagata (2003)	Cross	Water (hot)	Water (cold)	0.1	0.05	2.0	✓	✓ (DNS)	✓	✓	✓	✓
Zughbi and Khokhar (2003)	Cross, counter, multiple	Water (cold)	Water (hot)	0.0254	0.00635	2.5–25	✓	✓	✓		✓	
Igarashi and Tanaka (2003)	Cross	Water (hot)	Water (cold)	0.15	0.05	0.5–5	✓	✓			✓	✓
Noguchi and Tanimoto (2003)	Cross	Water (hot)	Water (cold)	0.102	0.0204	5–50	✓	✓			✓	✓
Ogawa et al. (2005)	Cross	Water (48 °C)	Water (33 °C)	0.15	0.05	0.7–4.35	✓	✓			✓	✓
Hu and Kazimi (2006)	Cross, impinging	Water (cold)	Water (hot)	0.102	0.102	4.7	✓	✓			✓	✓
Wang and Mujumdar (2007)	Cross	Water (22.7 °C)	Water (29.9 °C)	0.05	0.024	0.45, 0.61		✓	✓		✓	
Tilly and Sousa (2008)	Cross	Air (110 °C)	Air (30 °C)	Duct: 0.3 × 0.25 × 0.5	Jet slot: 0.25 × 0.015	0.01	✓					✓
Kamide et al., (2009)	Cross	Water (48 °C)	Water (33 °C)	0.15	0.05	0.5–4.5	✓	✓	✓	✓	✓	✓
Walker et al. (2009)	Cross	Water	Water	0.051	0.051	0.4–1.67	✓	✓	✓	✓	✓	✓
Frank et al. (2010) (For Experiments: cited Andersson et al. 2006)	Cross	Water (15 °C)	Water (30 °C)	0.14	0.1	1	✓	✓ (LES)	✓	✓	✓ ✓	✓ ✓
Simoneau et al. (2010)	Cross	Liquid Na (cold)	Liquid Na (hot)	0.494	0.068	0.5	✓	✓ (LES)			✓	✓
Kuczaj et al. (2010) (for experiments: cited Andersson et al., 2006)	Cross	Water (15 °C)	Water (30 °C)	0.14	0.1	4	✓	✓ (LES)	✓	✓	✓	✓

the experimental results for the optimal velocity ratio. The optimal conditions and the trajectory of the deflected jet were correlated by extending the equations for a tee junction. They concluded that for rapid mixing, the oblique branch should be at an angle of 45° to the main pipe.

Andreopolus (1983) has carried out the wind tunnel experiments by issuing a heated jet into a cold stream at velocity ratios 0.25–2. He noted that at low velocity ratios, early mixing between the hot jet and cold cross stream resulted in non-uniform temperature distribution. He reported that the extra rate of strain due to streamline curvature and temperature gradients in the normal and longitudinal directions affected the rate of generation of temperature fluctuations. Also the rate of generation of turbulent heat fluxes was found to depend on velocity and temperature gradient.

Sherif and Pletcher (1989) carried out experiments by discharging heated turbulent jets into a cross flowing stream in a water channel. Velocity ratios of 1, 4 and 7 were used and jet discharge temperatures were 28–42 °C. They reported that a double peak pattern was observed in the temperature fluctuation profiles. One peak usually occurred in the wake, while other peak occurred above the jet centerline in the region of high temperature gradient. They concluded that wall temperature was influenced by jet temperature in low velocity ratio jet. Also for low velocity ratio cases, mixing was not as good as in high velocity ratio cases.

Zughbi and Khokhar (2003) carried out numerical and experimental investigations of mixing in pipelines with cross and impinging T-junction configurations. Cold water flowing in main pipe is mixed with hot water flowing through the branch pipe. They measured temperature fields to quantify degree of mixing. They reported that the angle at which the jet was injected determined whether the jet impinges on the opposite wall. Also jet angle affects the mixing length. They showed that the pipe length required to achieve 95% mixing was found to be a function of V_h/V_c, d/D and angle of injection. By experimentations and simulations, they proved that for 90° tees, there was poor mixing at certain velocity ratios. They concluded that for a velocity ratio of 17.1, the 95% mixing length was found to be shortest for an angle of 45° or 165°. This optimum angle was found to change with the velocity ratio.

Igarashi et al. (2003) investigated the temperature and velocity distribution in the mixing tee. Fluid temperature and flow velocity distributions were measured by movable thermocouples and particle image velocimetry (PIV). Also, they applied an in-house direct numerical simulation (DNS) code ‘DINUS-3’ to understand the mixing phenomenon. In the wall jet case, wake region was formed behind the jet exiting from the branch pipe.