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T-junction experiment with high temperature and high pressure to investigate flow rate influence on mixing characteristics

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ABSTRACT

Thermal fatigue is one of the typical phenomena of fluid-structure interaction. It is a degradation mechanism to the piping materials and mostly found close to mixing tees where flow streams with temperature difference are mixed. At the University of Stuttgart, experiments have been performed at the Fluid-Structure-Interaction (FSI) test facility for investigating thermal fatigue effect close to a horizontal T-junction. The cold water flow of the branch pipe line (20 °C) and the hot water flow of the main pipe line (max. 280 °C) are mixed in a horizontally oriented 90° T-junction at pressure $p = 75$ bar. Particularly for simulating the rimmed weld root of a weld connection in the mixing region, a weld seam model is installed in the pipe line downstream of the T-junction.

In this investigation, 48 micro-thermocouples are installed in six measurement cross-sections close to the T-junction to capture the near-wall fluid temperatures. The temperature signals are recorded with 100 Hz. The experiments are performed with different flow rates in the main pipe line respectively branch pipe line. For each flow condition, measurements are conducted with continuous and periodic cold flow injection from the branch pipe. The temperature measurement data are analyzed and discussed from the view point of their relevance to thermal fatigue. The flow mixing characteristics are discussed on the basis of different measurement positions. The results show that the inlet flow rates is a crucial factor on the mixing behavior at the T-junction. The potential of thermal fatigue in the mixing region changes with variation of the inlet flow rate. Furthermore, variation of the flow rate shows a different impact in continuous mixing processes compared to periodical mixing processes.

1. Introduction

In 1998, an incident has been reported in the French nuclear power plant Civeaux. Several through-cracks have been found in the piping system of the reactor unit 1, and coolant in the circuit was leaking with 30 m^3/h (Chapuliot et al., 2005). Such kind of damages are created by the degradation mechanism called thermal fatigue, which is created by the high frequency temperature fluctuations in the mixing tees of piping systems, where flow streams with different temperature are mixed. Recent research also shows that the weld connections in the mixing region downstream of the mixing tees have a high potential for initiation and growth of cracks (Sbitti and Taheri, 2010). To investigate the effect of thermal fatigue in the thermal-mixing pipe flow, researches are usually performed with three methods: thermal hydraulic experimental investigations, numerical simulations in computer fluid dynamics and structure material analyses (Metzner and Wilke, 2005). In France, the FATHER mock-up has been constructed evaluate the fatigue loading for initiation of high cycle thermal fatigue in a mixing T-junction pipe (Courtin, 2013). Coupled with the FATHER experiments, Taheri et al. have investigated the growth of the fatigue crack close to a weld seam in the mixing zone of the thermal mixing process with the impact of weld residual stresses (Taheri and Fatemi, 2017; Taheri et al., 2017). Their results confirm the high risk of thermal fatigue to the weld seams due to temperature fluctuations in the mixing flow. At Japan Atomic Energy Agency, the WATLON set-up has been constructed to investigate mixing characteristics at a vertical T-junction. Kamide et al. have concluded the classification of flow pattern with flow field visualization in the experiments (Kamide et al., 2009). Based on the WATLON experiments, numerical simulations have been performed with different codes (Tanaka et al., 2009; Utanohara et al., 2016a). Another T-junction test facility, the T-Cubic facility, has been constructed at the Institute of Nuclear Safety Systems, Inc., Fukui, Japan. The experiment at T-Cubic facility focuses on the temperature fluctuations in the piping materials in the mixing region (Miyoshi et al., 2014). Parallel with the experiments, Utanohara et al. have performed LES calculations to verify the temperature distributions and velocity profile in the mixing flow

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Nomenclature

d	diameter of branch pipe (38.9 mm)
D	diameter of main pipe (71.8 mm)
D_m	diameter of the stratified pipe flow [mm]
f	measurement cross-section branch pipe
F	measurement cross-section main pipe
FT	thermocouple position
g	gravity constant (9.81 m/s^2)
$\dot{M}_b$	flow rate in the branch pipe [g/s]
$\dot{M}_m$	flow rate in the main pipe [g/s]
Re_b	Reynolds number in branch pipe [-]
Re_m	Reynolds number in main pipe [-]
Ri	Richardson number
T_b	temperature in branch pipe flow [°C]
T_m	temperature in main pipe flow [°C]
T_{mean}	mean temperature [°C]
T_{mixing}	temperature in the mixing flow [°C]
T_{RMS}	RMS temperature fluctuation [K]
$\bar{u}_b$	mean velocity in branch pipe [m/s]
$\bar{u}_m$	mean velocity in main pipe [m/s]
u_{mix}	velocity of mixing flow [m/s]
x	Cartesian coordinates, main pipe flow direction
θ	angular position [°]
ρ_b	density in branch pipe flow [kg/m^3]
ρ_m	density in main pipe flow [kg/m^3]

(Utanohara et al., 2016b). In Sweden, T-junction mixing-flow tests have been performed at the Älvkarleby Laboratory of Vattenfall Research and Development (VRD) for CFD benchmark (Smith et al., 2009). With the Vattenfall benchmark, several different numerical works have been performed with different models (Höhne, 2014; Zhang and Lu, 2014).

In Germany, the Fluid-Structure-Interaction (FSI) test facility is constructed to investigate the thermal fatigue effect in the thermal mixing process at high temperature and high pressure (see Fig. 1). The FSI test facility is operated jointly by the Institute of Nuclear Technology and Energy Systems (IKE) and the Materials Testing Institute (MPA) at the University of Stuttgart (Kuschewski et al., 2013). It is a modularly constructed DN80 (D = 71.8 mm) main pipe line circuit connected with a DN40 (d = 38.9 mm) branch pipe line at a horizontal T-junction. Unlike the most of other experimental investigations above, the temperature difference between the mixing flows can reach the maximum of 260 K, and the maximal operating pressure at the FSI test facility is 75 bar.

In the previous work (Zhou et al., 2016, 2017a), the experimental investigation at FSI test facility concentrated on the thermal fatigue effect to the dissimilar weld seam, which is a weld connection between austenitic and ferritic stainless steel. Weld seam modules have been constructed, equipped thermocouple technique, and installed in the main pipe circuit. Temperature measurement data have been analyzed and discussed with the relevance to thermal fatigue. After the experiments, the weld seam modules have been cut open for metallographic investigations. The results of the fractographic investigations confirmed the conclusion of the thermocouple measurement.

The major aim of this work is to investigate the influence of the inlet flow rates on the thermal flow mixing behavior at the 90° T-junction. To reach this aim, temperature measurements are performed by using the thermocouple measuring technique. The experiments are conducted with variation of the flow rate in the main and branch pipe line respectively. Thermal fatigue effect and reverse flow phenomenon are discussed by means of the temperature measurement data from experiments with variation of the flow rate in the inlet flow. Fig. 2

2. Experimental setup

In this work, thermal fatigue effect in the mixing flow is investigated with the thermocouple (TC)-module (Zhou et al., 2018), which is installed in the test section downstream of the T-junction (see Fig. 1). With periodically switching of the two-way valve COAX-I, the cold flow in the branch pipe line can be periodically injected into the T-junction, so that an **A**rtificially **I**nduced **P**eriodical **TE**mperature **C**hange (AIPTEC) is created in the mixing flow. In one of the previous investigation on AIPTEC, the combination of 30 s injection and 30 s bypass can created the highest temperature fluctuation in the mixing flow and therefore the highest potential for material damage due to thermal fatigue (Zhou et al., 2017b). Since the thermal fatigue effect and the thermal flow mixing behavior are different in the experiments with AIPTEC and continuous cold flow injection, the experiments in this work are all performed with 30 s/30 s AIPTEC in comparison with the continuous cold flow injection.

This investigation concentrates on the flow rate influence on the thermal fatigue effect and flow mixing behavior close to the T-junction. The flow rates in the main respectively branch pipe are varied in this investigation. The flow rate in the main pipe line is measured and controlled by a flow meter and a control valve downstream of the circulation pump. Same devices are installed downstream of the booster pump to measure and control the flow rate in the branch pipe line. The flow rates in this investigation are shown in Table 1. The results of case 2 have been presented in one of the previous work (Zhou et al., 2018). However, this case is an important reference case and will be shown in this work compared with the other cases. Each case is performed with AIPTEC and continuous cold flow injection. The measurements with AIPTEC are conducted for at least 120 periods. The experiments with

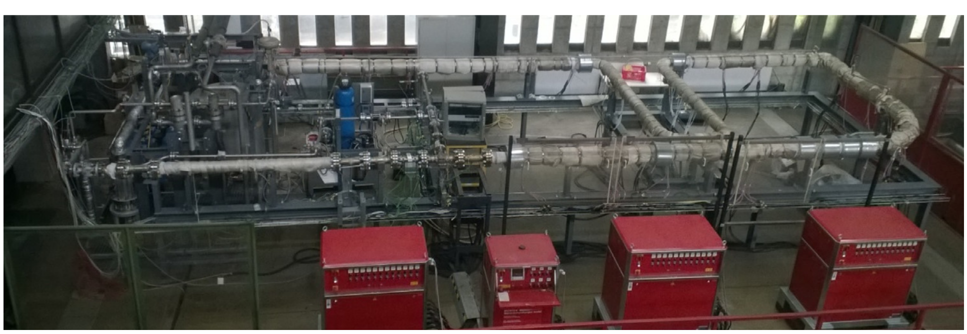

Fig. 1. IKE/MPA fluid-structure-interaction (FSI) test facility.