Title

T-junction cross-flow mixing with thermally driven density stratification

Authors

John Kickhofel

jkickhofel@gmail.com

Horst-Michael Prasser

prasser@lke.mavt.ethz.ch

Laboratory of Nuclear Energy Systems

ETH Zurich

Sonneggstrasse 3, 8057 Zurich

Switzerland

P. Karthick Selvam

karthick.selvam@ike.uni-stuttgart.de

Eckart Laurien

eckart.laurien@ike.uni-stuttgart.de

Rudi Kulenovic

rudi.kulenovic@ike.uni-stuttgart.de

Institute of Nuclear Technology and Energy Systems (IKE), University of Stuttgart

Pfaffenwaldring 31,

70569, Stuttgart,

Germany

Abstract

As a means of further elucidating turbulence- and stratification-driven thermal fatigue in the vicinity of T-junctions in nuclear power plants, a series of experiments have been conducted at the high temperature high pressure fluid-structure interaction T-junction facility of the University of Stuttgart with novel fluid measurement instrumentation. T-junction mixing with large fluid temperature gradients results in complex flow behavior, the result of density driven effects. Deionized water mixing at temperature differences of up to 232 K at 7

MPa pressure have been investigated in a T-junction with main pipe diameter 71.8 mm and branch line diameter 38.9 mm. The experiments have been performed with fixed flow rates of 0.4 kg/s in the main pipe and 0.1 kg/s in the branch line. A novel electrode-mesh sensor compatible with the DN80 PN100 pipeline upstream and downstream of the T-junction has been utilized as a temperature sensor providing a high density information in the pipe cross-section in both space and time. Additionally, in-flow and in-wall thermocouples quantify the damping of thermal fluctuations by the wall material. The results indicate that large inflow temperature differences lead to strong turbulence damping, and ultimately stable stratification extending both downstream and upstream of the T-junction resulting in large local thermal gradients.

Keywords

T-junction mixing, Thermal Fatigue, Fluid Structure Interaction, Wire mesh sensor, Stratification, Turbulent Mixing

1 Introduction

Thermal fatigue is a special case of material fatigue caused not by external mechanical loadings but by thermal loadings resulting in stress generating thermal expansion and contraction within the material. It may be that the material, for example steel piping, is mechanically constrained in some way in which case the fatigue is thermo-mechanical in nature, this is often the case in engineering applications. A typical example of thermal fatigue in the field of power generation is cyclic stresses on pipe walls driven by locally fluctuating internal fluid temperatures. Given appropriate fluctuation amplitude and frequency at the wall, such temperature fluctuations alone may generate crack networks bringing about component failure due. Thermal fatigue is typically manifested when a material is exposed to large, cyclic fluid temperature gradients where the gradients are the result of a thermally stratified fluid or a turbulent mixing process. In contrast to the sinusoidal or semi-variable loadings assumed in most laboratory material testing and theoretical modelling of thermal fatigue, in industrial processes thermal fatigue is the result of variable loading¹ spectra. Such loadings, comprised of a wide range of fluctuation frequencies, may include phenomena such as periodic overloading and also so-called sequence effects.

Cyclic coolant temperature fluctuations have been identified as a cause of cracking and coolant leakage accidents in commercial nuclear power plant piping, especially in the vicinity of T-junctions. High cycle thermal fatigue due to coolant mixing has been responsible for a total of thirteen through-wall cracks in the primary circuit of commercial pressurized water reactor NPPs between 1982 and 1998, shown in Fig. 1 (IAEA 2003). Historical data seems to suggest that thermal fatigue is not merely a lifetime management issue, with many accidents occurring early in the 60-years of envisioned plant lifetime. Up to 2007, the OECD/NEA Piping Failure Data Exchange (OPDE) Project² had recorded 64 non-through-wall crack (wall thinning), 65 leak, and 3 structural failure incidents for which thermal fatigue is believed to be the culprit (Lydell and Riznic 2008). Thermal striping and high cycle thermal fatigue was the focus of the international community in the 1980's and 90's due to cracks that had formed in NPP pressurizer surge lines due to thermal stratification. Prior to that, in the context of liquid metal and molten salt reactors, the issue

¹ Sometimes referred to as complex loading.

² The project covers “piping components of the main safety systems (e.g. ASME Code Class 1, 2 and 3)... [and also] non-safety piping systems that, if leaking, could lead to common-cause initiating events such as internal flooding of vital plant areas.”

was recognized as a potential threat as early as the mid 1970's due to the potentially high temperature gradients and heat transfer coefficients of the moderators (Brunnings 1982; Huebotter 1978). Significant research on thermal fatigue and thermal striping in fast reactor T-junctions as it related to thermo-mechanical codes has been compiled in the IAEA TECDOC 1381, the result of a three year coordinated research topic and computational benchmark exercise (IAEA 2002). A motivating factor in that project was the detection of a crack near a T-junction in the secondary loop of the French Phenix LMFBR in 1991 (Gelineau et al. 2001).

Fig. 1. Through-wall crack incidents and leak rates vs. nuclear power plant age between 1982 and 1998 as compiled by the IAEA in TECDOC 1361 (IAEA 2003).

It was not until the 1998 accident in the RHR of the newly constructed Civaux 1 NPP³ in France, in which a 180 *mm* long through-wall crack in 304L stainless steel downstream of a T-junction in the residual heat removal system resulted in a significant leakage rate of 500 l/min, that the issue of HCTF due to turbulent mixing downstream of T-junctions started to be addressed by researchers en masse and detailed assessment methods developed (Chapuliot et al. 2005; Faigy 2000; Faigy 2002; Faigy 2003; Faigy 2004; Galpin and Simoneau 2011). In the case of the Civaux accident, at the time a 'new phenomena,' an incomplete understanding of locations in the pipe network where turbulent mixing could manifest large amplitude temperature fluctuations at critical frequencies to generate thermal striping, meant the piping network was not of a safe design for the particular operating conditions (Blondet and Faigy 2002). Radu et al. (2007) found semi-analytically that the critical frequencies for the Civaux 1 RHR piping materials were 0.3 and 0.1 Hz for hoop and axial stresses, respectively (Radu et al. 2007). The CEA, Framatome and EdF naturally, intensively investigated the accident at the Civaux 1 plant in 1998 with publications still appearing more than a decade later. Part of their investigation was aimed at crack initiation under thermal fatigue, a major finding was "thermal fatigue appears to be more damaging than uniaxial isothermal fatigue" (Fissolo et al. 2009a; Fissolo et al. 2009b). Impetus to better understand the problem, especially in the vicinity of T-junctions has grown steadily and over the past decade and a half, especially in the field of time resolved fluid dynamic and finite element simulations. Despite this long history, the prediction of thermal fatigue-prone zones remains a challenge.

³ PWR type N4, 1400 MWe

T-junctions prone to large fluid temperature gradients tend to be located in the high pressure injection, feed water makeup, residual heat removal, and emergency core cooling systems of LWRs. Some may exist directly at the hot or cold leg of the RCS in PWRs where small branch lines lead to auxiliary systems. It is in these T-junctions where hot and cold flows may meet, in a so-called ‘joining,’ ‘confluence,’ or, henceforth, ‘cross-flow.’ The most common manifestation of such mixing in LWRs is the case of a hot turbulent flow approaching the T-junction in the main pipe met by a cooler incoming flow from the branch line, see Fig. 2. This type of mixing has been delineated further in published research based on the momentum ratio of the incoming flows (Hosseini et al. 2008; Kamide et al. 2009). These classifications, impinging jet, deflecting jet, turn jet, and wall jet break down when the flows entering a T-junction are of significantly different densities, as when there exist large fluid temperature differences. The flow patterns at high ΔT mixing are not recognizable as any of the traditional jet classifications.

Fig. 2. Schematic of cross-flow mixing in a T-junction from Smith (2013). (Smith et al. 2013)

Cross-flow mixing has been thoroughly investigated in open literature. Naik-Nimbalkar et al. (2010) references at least 16 published cross-flow mixing studies in T-junction since 1980, mostly in the field of nuclear engineering with water used as the working fluid (Naik-Nimbalkar et al. 2010). However, of the many T-junction facilities worldwide few explore mixing between main pipe and branch line fluids with any sizeable temperature difference. Among them are the FATHER and FATHERINO facilities of the CEA, France. These facilities explored temperature differences of up to 160 °C and 75 °C, respectively, and were a direct response to the Civaux 1 accident (Beaufils and Courtin 2011; Braillard and Edelin 2009; Braillard et al. 2007; Courtin 2013; Courtin and Beaufils 2011; Courtin et al. 2011). The experiments with T-junction on Rapid and Emergent Mixing Effects (EXTREME) facility at the National Tsing Hua University can reach a ΔT of 70 K at flow rates suitable to encounter upstream flow in the main pipe (Chen et al. 2012; Chen et al. 2014; Zhang et al. 2015). The EXTREME facility has exhibited mixing more than 0.5 diameters upstream in the main pipe. At the University of Stuttgart in Germany, the Institut für Kernenergetik und Energiesysteme (IKE) and the Materialprüfanstalt (MPA) have since 2011 operated a T-junction facility for the study of fluid-structure-interaction (FSI) in the case of large fluid temperature differences (Kuschewski et al. 2011; Kuschewski et al. 2013). The facility incorporates reactor-grade materials and can reach reactor-like conditions with

ΔT approaching 240 K. Collaboration between the ETH Zurich Laboratory of Nuclear Energy Systems and the University of Stuttgart Institute of Nuclear Technology and Energy Systems (IKE) and Materials Testing Institute (MPA) undertaken within the scope of the research presented herein has seen the Stuttgart T-junction facility taken to its highest operating temperature, resulting in a bulk ΔT of 232 K at 70 bar, during testing of a novel high temperature wire mesh sensor

The phenomena of upstream flow of the cold branch fluid in the main pipe experienced at high ΔT has been described by few publications⁴ (Chen et al. 2012; Chen et al. 2014; Klören and Laurien 2013; Tanaka et al. 2010). Klören found that for $\Delta T = 150$ K in the Stuttgart T-junction geometry, upstream flow proceeds $> 3 D_m$ in the main pipe and $> 25 D_m$ at $\Delta T = 260$ K at the same flow rate conditions measured by the mesh sensor, while large eddy simulations (LES) by Selvam et al. (2015) anticipate upstream flow to be slightly beyond $1.0 D_m$ at $\Delta T = 117$ K with a higher main mass flow rate of 0.4 kg/s.

Section 2 describes the T-junction facility at the University of Stuttgart followed, in Section 3, by a detailed description of the instrumentation installed for the purpose of mixing measurements. Specifically, the description of instrumentation at the facility focuses on the thermocouple module and mesh sensor module. The chosen test matrix, four different flow temperature boundary conditions, and procedure at the facility during and between measurements is found in Section 4. Results and analysis are divided into measurements downstream and upstream of the T-junction in Section 5 and Section 6, respectively.

2 Facility

At the epicenter of the T-junction facility at the University of Stuttgart, known as the Fluid-Structure Interaction (FSI) test facility, is a sharp edged forged 1.4550 (X6 CrNiNb 18-10) austenitic stainless steel T-junction with reduced carbon content in accordance with the German KTA 3201.1 (KTA 1998-06). The facility is shown schematically in Fig. 3 along with the properties of the working fluid, deionized water with electrical conductivity (EC) between 5 and 10 $\mu\text{S}/\text{cm}$. A main pipe with inner diameter $D_m = 71.8$ mm carrying hot water at a constant mass flow rate of 0.4 kg/s (turbulent flow) encounters a perpendicular,

⁴ Here we exclude discussing the minute and highly transient upstream or ‘reverse flow,’ sometimes observed in low ΔT cross-flow mixing studies, e.g. by Tanaka (2010). That phenomena is categorically different from the lengthy upstream flow found at high ΔT , discussed in this paper.

horizontal branch pipe of inner diameter 38.9 mm with room temperature water flowing at a rate of 0.1 kg/s (transition flow). Downstream the flow is then split according to the mass flow rate ratio and recycled back to the T-junction. Flow conditions at the T-junction are such that at low ΔT ($T_m - T_b$) a wall-jet type flow pattern is manifest downstream of the T-junction at these flow rates. At higher ΔT the cold branch line flow quickly sinks to the bottom of the mixing pipe downstream of the T-junction and only weakly mixes with the hotter main flow. More information about the flow behavior at the facility is described in the work of Kuschewski (near wall LED-induced fluorescence (NWLED-IF) experiments), Klören (LES simulations), and, most recently, Selvam (LES simulations) (Kloeren et al. 2012; Klören and Laurien 2013; Kuschewski et al. 2011; Kuschewski et al. 2013; Selvam et al. 2014; Selvam et al. 2015). The hot flow is measured once a minute 1015 mm upstream of the T-junction in the center of the main pipe by a thermocouple (XTM3) while the temperature in the branch flow is measured with the same frequency by an additional thermocouple in the center of the branch line flow 2940 mm upstream of the T-junction (XTM4).

Fig. 3. Piping and instrumentation diagram of the FSI test facility at the University of Stuttgart adapted from Kuschewski (2013) (Kuschewski et al. 2013).

The facility is operated at temperatures up to 256 °C and pressures up to 80 bar. Downstream of the T-junction a hermetically sealed canned motor pump drives the entire circuit. Resistance heating mats along the length of the main pipe inlet run are controlled in real time by a PID controller with reference to thermocouples between the mats and the outer walls of the conduit. Heating of the facility proceeds in the main pipe at a rate of typically 40 °C/hour. Meanwhile, the room temperature flow from the branch line never ceases, such that mixing is always occurring at the T-junction. The flange system used in the main pipe and mixing pipe are standard, specifically DN 80 PN 100, with the exception of the inner diameter, 71.8 mm, which is custom. The piping, with the exception of the T-junction, is comprised of austenitic stainless steel 1.4571 (X6CrNiMoTi17-12-2). In the vicinity of the T-junction in the main and mixing pipe there exist flanged modules, two upstream and three downstream, each 340 mm in length which allow for relatively easy installation of measurement instrumentation at a variety of locations.

3 Instrumentation

3.1 Thermocouple module

Temperature measurements were recorded with a flanged module (TC module) containing 16 0.25 mm diameter K-type thermocouples protruding 2 mm into the flow from the inner pipe wall surface in addition to 8 thermocouples of the same diameter positioned 0.15 mm away from the inner pipe wall surface. The thermocouples recorded data continuously at 100 Hz. The TC module was positioned once immediately downstream of the T-junction and once as the 2nd module downstream of the T-junction such that the in-flow measurement positions are 5.0 and 6.0 resp. 9.7, and 10.7 D_m , while in-wall positions are at 5.5 and 10.2 D_m . Because the TC module had to be rotated when switching between its two positions, the circumferential position of the thermocouples changed. All 24 thermocouples in the module are oriented as shown in Fig. 4, with two different configurations depending on the measurement location. Additional temperature measurements are recorded at 24 positions in the walls of the T-junction itself. These thermocouples are 1 mm diameter K-type and are sampled continuously at 100 Hz. Both the TC module and additional thermocouples installed in the T-junction can be seen in Fig. 6.

Fig. 4. Cross-sectional location of thermocouples downstream of T-junction (viewed looking away from the T-junction) for axial measurement planes 9.7, 10.2, and 10.7 D_m (blue squares) and 5.0, 5.5, and 6.0 D_m (red circles) along with a photograph of the thermocouple module.

3.2 Mesh sensor module

The mesh sensor comprises supplementary packaging including flanges, hoses and feedthrough glands which play a supporting role as it relates to the mesh sensor itself. A drawing of the sensor package is shown in Fig. 5. The mesh sensor utilizes the same electronic principle and data acquisition system as traditional wire mesh sensor technology developed by Prasser (1998) which has seen nearly two decades of implementation in the measurement of single and multiphase flows (Prasser et al. 1998). Wire mesh sensors measure the electrical conductivity (EC) of a medium as analog current detected in a multiplexed-manner where each transmitter electrode is sequentially delivered a square-wave

voltage pulse during which all receiver electrodes are sampled in parallel. Cross-talk between neighboring receivers or transmitters is suppressed by means of low-impedance drivers and inputs for the transmitters and receivers, respectively.

Fig. 5. CAD drawing of sensor package installed in DN80 PN100 flanged pipeline of inner diameter 71.8 mm.

The sensor is characterized by a separation of the pressure barrier construction from the mesh sensor itself (Kickhofel et al. 2015). The result is a flange design which allows for a variety of potential sensor designs to be installed incorporated. Two housing flanges comprise the main components of the sensor package, they act to provide a cavity within the pressure barrier of the facility which is large enough such that a mesh sensor and associated wiring may be mounted. The two flanges, so-called primary and lid flanges, surround and secure the mesh sensor. The primary consequence of the additional space in the conduit provided by the housing flanges is that the gasket which ensures the sealing between the two is of larger diameter than those found in the pipeline itself. The gasket between the housing flanges is of inner/outer diameter 116/140 mm such that the sealing area is similar to that of the standard 90/120 mm gaskets found in DN80 PN100. The result is non-negligible stress in the form of torsion acting on both housing flanges by the pipeline flanges they are connected to. CATIA V5 FEM simulations indicate the necessity of a strong heat treated steel to avoid plastic deformation, therefore the flanges have been manufactured from 1.4418 QT900 (1.4418 X4 CrNiMo 16-5-1). The housing flanges allow for the transport of the mesh sensor as a fully assembled unit which need only be fixed on site between two flanges in the pipeline. A ‘spacer’ module of reduced length was manufactured for adapting the sensor to the Stuttgart FSI test facility, four thermocouples were installed at four circumferential positioned on the outer wall of this shortened module. A photograph of the installed mesh sensor is shown in Fig. 6.

Fig. 6. The mesh sensor package (red box), TC module (blue box), and additional thermocouples (green boxes), are shown installed at the FSI T-junction facility Stuttgart.

Two 10.7 mm diameter conduits are machined into the primary flange perpendicular to the axis of the flow conduit and each other. It is through these conduits that the 16 transmitter and 16 receiver signal carriers (stranded silver coated copper wires insulated with

PTFE) are passed, respectively, from the mesh sensor to the feedthrough glands, there passing through the pressure barrier, and are eventually connected to a D-SUB 25 terminal which is linked to the analog to digital DAQ box. Between the primary flange and the feedthrough glands 20 cm stainless steel hoses are installed to provide physical separation from the heat source (the flow) such that the temperature rating (260 °C) of the glands is respected at all times.

The sensor sandwich is comprised of three stacked concentric ceramic plates, see Fig. 7. In two of the plates, each 3 mm thick, sixteen 0.6 mm deep and 0.6 mm wide grooves are machined to position and retain the electrodes of the mesh sensor. The electrodes are 316L stainless steel capillaries of mean outer diameter 0.57 mm and mean inner diameter 0.31 mm. A third ceramic plate 1.5 mm in thickness ensures electrical separation between the final electrode layer and the lid flange. The free cross-section across both electrode layers is approximately 77%, and the pressure drop coefficient estimated based on Idel'chick (1966) is 0.26 (Idel'chick 1966). A splice between the electrodes in the signal carriers is made by a simple stainless steel crimp, protected by a PEEK heat shrink. Additional design features include two centering pins and four small compression springs, with housings inside the primary flange, for the purpose of maintaining the position of the sensor sandwich.

Fig. 7. Sketch of a single ceramic substrate for positioning 16 electrodes (left). Sensor sandwich comprising three ceramic plates and stainless steel capillary electrodes (right). The orientation of the sensor is shown as if viewed from the T-junction.

The calibration of the sensor relies on a nearby thermocouple to generate a relationship between EC (i.e. raw mesh sensor signal) at a given crossing point versus temperature. Since mixing downstream of the T-junction cannot be excluded (nor can upstream flow at higher temperatures), calibration of some crossing points is a challenge. Full details of the calibration methodology for downstream and upstream sensor positions is presented in Appendix Section 10.1. The resolution of the sensor in terms of EC is high and is limited primarily by electronic noise which was reduced by means of median filtering of the recorded signals, described in Appendix Section 10.2. This systematic error represents only one component of the total measurement error since it relies on a better understanding of the change in EC with temperature than is available based on the particular mean conductivity of the working fluid at the T-junction facility. A larger, and less quantifiable source of error comes from the incomplete knowledge of how the temperature at a given

crossing point varies from that measured by a nearby (a distance $10.7 D_m$ away) thermocouple in the facility being used as a reference. The calibration methodology attempts to alleviate this error. A linear function is used to describe mesh sensor signal as a function of temperature across the range of interest (roughly 60 to 200 °C).

4 Test matrix

Two measurement campaigns were performed, both saw the temperature in the main pipe rise from room temperature to 256 °C in the center of the flow, as measured by the XTM3 thermocouple, over the course of roughly 8 hours at 70 bar. During the first heating the mesh sensor measurement plane was located at $y = 3.5 D_m$ (henceforth, positions are assumed to be on the y-axis), while the TC module was installed such that thermocouples were located at 9.7, 10.2, and 10.7 D_m . The second heating saw the mesh sensor installed upstream of the T-junction at $3.5 D_m$ and the TC module positioned immediately downstream of the T-junction, measuring at 5.0, 5.5, and 6.0 D_m . Both configurations are shown in Fig. 8.

Fig. 8. Configuration of the T-junction facility during the first (top) and second (bottom) measurement campaigns. Main flow travels right to left, gravity is directed into the page.

Readings from all thermocouples in the TC module and T-junction were recorded continuously at 100 Hz during heating of the facility while extra thermocouples installed on the spacer module were sampled at 0.5 Hz. The mesh sensor acquired data repeatedly for a duration of 180 seconds at 10 kHz with 73 seconds downtime between measurements being required for downloading and saving the data to a PC.

Fig. 9. Temperature history recorded once per minute in the center of the main pipe (XTM3) and branch line (XTM4) upstream of the T-junction, dotted lines represent four analyzed fluid temperature test cases.

Heating was occasionally stabilized for some minutes, such that longer measurements with better statistics could be acquired. Four test cases have been isolated for deeper analysis; they are main flow temperatures of 165 ± 1 °C, 181 ± 1 °C, 201 ± 1 °C and 256 ± 1 °C with a branch flow temperature of 22 ± 1 °C. The main pipe and branch line temperature histories are shown in Fig. 9 for both measurement campaigns. Due to instability in the main flow

temperature in the second measurement campaign, the $T_m = 201 \pm 1$ °C case is left unanalyzed. The main and branch mass flow rates were equal for all three test cases: $\dot{m}_m = 0.4$ kg/s and $\dot{m}_b = 0.1$ kg/s. The fluid conditions in all four test cases are enumerated in Table 4-1. The Froude number is defined, along the lines of Eq. 3-15, as,

$$Fr = \frac{U_{mix}}{\sqrt{g'D_m}}, \quad (4-1)$$

where g' is the reduced gravity and the mixture velocity U_{mix} is defined as the sum of superficial velocities,

$$U_{mix} = \dot{m}_m/A\rho_m + \dot{m}_b/A\rho_b, \quad (4-2)$$

where A is the main pipe flow area. The Prandlt number is defined as,

$$Pr = c_p\mu/k, \quad (4-3)$$

where c_p is the specific heat, μ is the dynamic viscosity, and k is the thermal conductivity. It represents the ratio of viscous diffusion rate to thermal diffusion rate. In the branch fluid, Pr is between 6.4 and 6.9 for all test cases while in the far less viscous main flow, in the highest temperature case, Pr is around its minimum in water, 0.83.

Herein the Richardson number is calculated as,

$$Ri = gD_m\varepsilon/U_{mix}^2, \quad (4-4)$$

where $\varepsilon = \Delta\rho/\rho = (\rho_b - \rho_m)/\rho_b$ is the density difference. This definition of the Richardson number is similar to that found in Chapuliot (2005) with the difference being the use of the mixture velocity rather than the branch line velocity (Chapuliot et al. 2005). Finally, the momentum ratio is defined as in (Kamide et al. 2009),

$$p_r = \frac{4\rho_m U_m^2 D_m D_b}{\pi\rho_b U_b^2 D_b^2}. \quad (4-5)$$

Table 4-1. Fluid conditions for each experimental case including Reynolds, Froude and Richardson numbers. Subscript r represents the ratio between main and branch flow water.

*Based on $T_b = 22\text{-}24\text{ }^{\circ}\text{C}$, $\rho_b = 1000.6\text{ kg/m}^3$, $U_b = 0.084\text{ m/s}$.

Test case	T_m [$^{\circ}\text{C}$]	ΔT^* [K]	ρ_m [kg/m^3]	ρ_r^* [-]	ε^* [-]	U_r^* [-]	p_r [-]	Re_m [E4]	Re_r [-]	Fr [-]	Ri [-]
#1	165	143	906.3	0.91	0.094	1.30	3.58	4.27	12.12	1.62	0.50
#2	181	159	889.9	0.89	0.11	1.32	3.64	4.71	13.37	1.52	0.57
#3	201	179	867.6	0.87	0.13	1.35	3.74	5.26	14.94	1.41	0.68
#4	256	232	793.0	0.79	0.21	1.48	4.10	6.81	19.35	1.22	0.98

5 Downstream results

Thermocouple data downstream of the T-junction enables two primary observations to be made; firstly, the manner in which the mixing develops as it progresses from the T-junction downstream is garnered from thermocouples at a range of axial positions from $0.95 D_m$ to $10.7 D_m$, and secondly, the degree to which the walls of the conduit damp the internal fluid temperature fluctuations. Downstream of the T-junction, the average temperature measured in the flow in the TC module at the top of the pipeline from 9.5° to 170.5° is within 14% of the maximum average temperature measured in the same region for all test cases and positions (5 to $10.7 D_m$). In the fourth test case, at the highest main flow temperature of $256 \pm 1\text{ }^{\circ}\text{C}$, the fluid temperature is especially stable in this zone: the minimum temperature measured between 9.5° and 170.5° is 96% of the maximum. The average temperature at bottom of the pipeline is relatively stable across 67.5° (three measurement points) for the first test case, becoming progressively less so in the subsequent cases with increasing ΔT .

Fig. 10. Mean temperature measured by thermocouples protruding 2 mm into the flow at various circumferential positions and distances downstream of the T-junction for each test case.

The RMS of temperature, measured near the wall, 2 mm in the flow by the thermocouple module indicates two peaks for each test case. These peaks in temperature fluctuations represent the ends of the stratified layer between hot main flow and cold branch flow in the pipeline. In the first two test cases, $T_m = 165 \pm 1\text{ }^{\circ}\text{C}$ and $181 \pm 1\text{ }^{\circ}\text{C}$, the stratified layer on the left-side wall lies between 144.5° and 215.5° and on the right-side wall between 279.5°

and 9.5° , at $5 D_m$. In Test #4 the layer is slightly shifted, circumferentially. At the same axial position the mixing between hot and cold flows occurs somewhere between 189.5° - 279.5° and 279.5° - 9.5° . The sparse positioning of the thermocouples combined with the knowledge that the mixing layer between main and branch flows may be very sharp, gained from the mesh sensor, preclude precise conclusions on the amplitude or location of temperature fluctuations based on results from the TC module alone. As mixing progresses downstream of the T-junction, the temperature difference in the flow between the top and bottom of the pipeline shows little change. For example, in the first test case the top-to-bottom ΔT is measured to be at most 110 K at $5 D_m$ and 106 K at $10.7 D_m$.

Fig. 11. RMS of temperature measured by thermocouples protruding 2 mm into the flow at various circumferential positions and distances downstream of the T-junction for each test case.

Thermocouples 0.15 mm from the flow, in the steel wall of the pipeline show strong damping of temperature fluctuations. Fig. 12 shows the strong degree to which temperature fluctuations measured in the wall are damped relative to the thermocouples positioned 2 mm in the flow at $256 \pm 1^\circ \text{C}$. For example, while the highest in-flow T_{RMS} values measured by the TC module were 12.7 to 14.7 K at position 324.5° $5.0 D_m$ and $6.0 D_m$ downstream, respectively, between these two measurements points at $5.5 D_m$, T_{RMS} is only 0.83 K in the wall. This in-wall fluctuation amplitude is only 5.5-6.5% of the nearby in-flow values. In general, elevated T_{RMS} values are damped more than 80%. The strong damping of temperature fluctuations, already within 0.15 mm of wall material is the result of the thermal inertia of the 8.55 mm-thick steel walls of the pipeline. The wall has a strong low-pass effect on the thermal mixing spectrum. The power spectral density of the aforementioned in-flow and in-wall thermocouples are shown in Fig. 13. A peak, apparent in the in-flow spectra centered around 2.5 Hz, corresponding to a Strouhal number of 1.44 (based on main flow parameters and the diameter of the mixing pipe), is strongly damped in the in-wall spectra.

Fig. 12. Test #4 gain-magnitude response of T_{RMS} measured by in-wall thermocouples versus nearby in-flow thermocouples at identical circumferential positions.

Fig. 13. Test #4 normalized power spectral density from in-flow and in-wall thermocouples at 324.5°. The dotted line marks 2.5 Hz, the approximate location of peaking in the in-flow spectra.

Results from the TC module show temperature fluctuations decreasing with downstream distance from the T-junction. This is true both at the top of the pipe, where T_{rms} in the hot fluid is less than 1.5 K across an angle of 67.5°, and at the bottom of the pipe where temperature fluctuations tend to be lower at 10.2 and 10.7 D_m than at 5 and 6 D_m . These results are interpreted as a decreasing in thermal mixing and a sharpening of the stratified interface between the fluids with downstream progression.

The mesh sensor module positioned at 3.5 D_m elucidates the $\bar{T}$ and T_{RMS} profiles within the cross-section of the pipeline. Fig. 14 shows plots of both mean and fluctuating temperature fields as measured by the mesh sensor for all test cases. Density differences between the hot main flow and cold branch flow is seen to play a strong role in the mixing behavior downstream of the T-junction. As the main flow temperature increases (and thereby the water density decreases), the mixing zone downstream of the T-junction, as measured by the extent of elevated temperature fluctuations in the cross-section tends to sharpen and move closer to the bottom of the pipe. As the mixing zone shrinks the amplitude of temperature fluctuations increases to around $T_{RMS} = 10$ K. All tests show similar profiles in which a mixing layer between hot main flow and cold branch flow spans the inner diameter of the pipe. This mixing layer, in the $\bar{T}$ profile, is oriented more or less perpendicular to gravity except in the first test case where the layer appears to be oriented 20° relative to the axis of gravity. Below the mixing layer, cold fluid temperatures (< 75 °C) are measured even in the final test case. This flow profile cannot be categorized within the traditional, low- ΔT cross-flow mixing nomenclature of Kamide (2009).

Fig. 14. Mean (top row) and RMS (bottom row) of temperature in the cross-section of the pipeline measured by the mesh sensor downstream of the T-junction at 3.5 D_m . Viewing orientation is looking away from the T-junction.⁵

⁵ Technical difficulties with the 6th transmitter electrode resulted in an intermittent signal which also affected its neighboring transmitters. Therefore, the average and RMS plots in those three rows of crossing points are compiled not from the whole 180 s measurement but from the portion in which the 6th transmitter was functioning properly. Nonetheless, it is evident a signal of questionable validity remains in the 5th, 6th, and 7th transmitter electrodes and therefore quantitative discussion related to those positions is avoided.

The temperature profile measured in the third and fourth test case, at the highest ΔT , is unreliable in the hot fluid region at the top of the pipeline due to the calibration methodology. In the lower portions of the pipe cross-section, where temperatures are below 200 °C, the temperature profile can be reported with confidence. The zone of average cold fluid at the bottom of the pipe is greatly reduced in area, especially at $T_m = 256$ °C while the minimum average temperatures, at 70–80 °C, are marginally elevated compared to lower ΔT cases. Of all test cases, temperature fluctuation amplitudes are highest in the mixing zone found in the fourth test case and are, furthermore, the most localized.

The power spectral density, computed at the crossing point measuring highest T_{rms} for each test case (see Fig. 15) does not indicate a preferred frequency of mixing except in the fourth test in which frequencies between 1.6 Hz and 2.4 Hz show the highest powers. The spectrum from Test #1 is weighted more towards the high frequencies relative to the other tests. Apart from this, the four spectra are similar in shape. Power spectra at some positions measured by the mesh sensor measurement plane show similarity with spectra from downstream thermocouples at different positions. For example, in Fig. 16, the thermal mixing spectrum from near the wall in the mesh sensor at a circumferential position of 219° is similar to the spectrum 5 D_m downstream at 324.5°, yet is dissimilar to the spectrum downstream at nearly the same circumferential position, 234.5°. This asymmetry may be the result of the swinging motion of the heavy cold flow as it progresses down the main pipe, described by both Klören and Laurien (2011) and Selvam et al. (2015) in mixing cases with lower ΔT (Klören and Laurien 2011; Selvam et al. 2015).

Fig. 15. Ensemble averaged (8x) power spectral density measured by the mesh sensor at crossing-points of highest T_{rms} for each test case.

Fig. 16. Power spectral density measured near the wall by the mesh sensor in Test #4 along with that from a downstream thermocouple measurement showing similarities.

6 Upstream results

Upstream flow in the T-junction, the result of a slow turbulent flow and large density differences between the main and branch flows, is a significant feature of the flow behavior at high ΔT . The formation and progression of upstream flow with increasing ΔT , starting at the T-junction, may be traced by a combination of thermocouples in the walls of the main pipe, on the outside of the main pipe, and by the mesh sensor. Specifically, measurement points are present at -0.96 (1.5 mm from inner wall), -1.58 (1.8 mm from inner wall), -3.5 (mesh sensor module), -5.9 (outer wall), -10.1 (outer wall) and $-40.7 D_m$ (outer wall). The onset of upstream flow has been found to be more akin to a quench than a slow, ramped cooling of the bottom of the conduit. Therefore, thermocouples, even those on the outside wall of the main pipe, measure a sudden plummet in the temperature which can help to localize in time the moment upstream flow reached the measurement location. The thermal inertia of the wall does result in a slightly delayed indicator, for simplicity, however, this is neglected.

The penetration depth of the upstream flow into the main pipe extends more than 2.92 m based on thermocouple readings. The upstream penetration of the cold branch flow, as a function of ΔT between main and branch flow, is shown in Fig. 17. A parasitic effect to the reproducibility of these measurements in another facility is the heating of the upstream flow by the heating mats which are installed around the main pipe starting at approximately $-13.6 D_m$. It is possible that this upstream heating is responsible for the non-linearity of the progression of upstream flow as a function of ΔT .

Fig. 17. Data points represent the ΔT at which upstream flow reached thermocouples or the mesh sensor during both Campaign #1 and #2. Vertical dotted line represents the location at which heating mats surrounding the pipe end.

The upstream flow onset, as measured by the mesh sensor, includes a number of important features. First and foremost is the speed with which the temperature is seen to decrease at the bottom of the main pipe at $-3.5 D_m$, see Fig. 18. A number of crossing points at the bottom of the pipe detect a sudden drop in temperature for which the cold branch line water is responsible. Part of the initial decrease in temperature includes a portion in which the fluid temperature drops from 140 °C to 100 °C at a rate of approximately -130 K/s. Near the wall, the temperature fluctuations recorded at the three chosen crossing points are $T_{RMS}(16,11) = 6.3$ K, and $T_{RMS}(15,11) = 8.4$ K in the first 10 seconds after the onset of upstream flow. The fluctuations are greatly reduced in magnitude some 10's of seconds later,

between 30 and 40 s after the onset of upstream flow, $T_{RMS}(16,11) = 3.1$ K, $T_{RMS}(15,11) = 5.2$ K. A regularly extending and receding upstream flow could result in thermal fatigue in the main pipe analogous to the case of turbulent penetration in the branch line (Kickhofel et al. 2014; Kim et al. 1993). That mixing scenario, coined the Farley-Tihange phenomena after the affected nuclear power plants, sees a cold tongue of water impinging into a branch line filled with much hotter water (USNRC 1988).

Fig. 18. Temperature at three mesh sensor crossing points at the bottom of the main pipe (right) during the onset of upstream flow reaching the sensor location ($-3.5 D_m$).

Average temperature and temperature fluctuations at the chosen boundary conditions of $\Delta T = 143, 159$ and 232 K are typical of stratified flows. The interface between hot and cold fluids is sharp in spite of their progressing in opposite directions.

Fig. 19. Mean (top row) and RMS (bottom row) of temperature in the cross-section of the pipeline measured by the mesh sensor upstream of the T-junction at $-3.5 D_m$. Viewing orientation is looking away from the T-junction.⁶

Mean temperature and fluctuation profiles are shown in Fig. 19 for test cases #1, #2 and #4 upstream of the T-junction. In Test #1 the mesh sensor measures a small amount of upstream flow at the very bottom of the pipe with temperature of approximately 100 °C. Neighboring crossing points sees a mean temperature increase of over 30 K. The highest temperature fluctuations are found in the thin layer between the cold upstream flow and the hot main flow. The remainder of the cross section shows negligible temperature fluctuations. With higher ΔT , and therefore density difference at the T-junction, in Test #2, the amount of upstream flow in the pipe cross section is increased and the temperature gradient between the zone of upstream flow and the hot flow is considerably larger. The RMS of the temperature,

⁶ Technical difficulties with the 6th transmitter electrode resulted in an intermittent signal which also affected its neighboring transmitters. Therefore, the average and RMS plots in those three rows of crossing points are compiled not from the whole 180 s measurement but from the portion in which the 6th transmitter was functioning, in the case of Test #1. Nonetheless, it is evident a signal of questionable validity remains in the 5th, 6th, and 7th transmitter electrodes and therefore quantitative discussion related to those positions is avoided. Insufficient up-time was found in the 6th transmitter electrode in Test #2 and #4, it has therefore been left blank.

however, is decreased compared to the lower ΔT case, which can be interpreted as a more stable stratification. Finally, by including interpretation of the $\bar{T}$ and T_{RMS} profiles from the fourth test case with $T_m = 256$ °C it can be concluded that the fraction of cold fluid in the cross section is increasing with increasing ΔT . It is conceivable that the branch flow is being split between the mixing pipe and main pipe in larger and larger fractions, explaining the decreasing cold flow area with increasing ΔT in the mixing pipe along with the concurrent increase in the main pipe. The symmetry between upstream and downstream stratified temperature profiles is the result of large density gradients between hot and cold flows, potentially exacerbated by the geometry-altering thermal stresses induced by the thermal stratification itself.

7 Global analysis

The maximum thermal gradient in the center of the cross-section downstream of the T-junction is found to be a linearly increasing function of Richardson number over a large range from $Ri = 0.28$ to 0.98 ($\Delta T = 78$ to 232 K), see Fig. 20. In absolute terms, the maximum thermal gradient more than doubles from around 4 K/mm to 9.5 K/mm at $3.5 D_m$. Each data point represents the gradient of temperature from a 5-second time-averaged mesh sensor signal extracted from each consecutive full 180 s measurement during the heating of the facility. Upstream of the T-junction the thermal gradient prior to upstream flow onset is low, around 1 K/mm and increases slowly with Ri number. The onset of upstream flow results in a jump in the maximum thermal gradient found in the centerline (shown with dotted red arrow Fig. 20) to around 8 K/mm. The stratified layer sharpens further resulting in a maximum thermal gradient of around 14.5 ± 1 K/mm between $Ri = 4.5$ and 6.6 , significantly higher than found downstream of the T-junction.

Fig. 20. Maximum average thermal gradient $(\partial \bar{T} / \partial z)_{max}$ across the stratified layer in the center of the pipe cross-section vs. Richardson number. The onset of upstream flow is apparent in the step change (indicated by dotted red arrow) in thermal gradient around

$$Ri = 3.6.$$

As deduced previously in a qualitative sense from $\bar{T}$ profiles measured by the mesh sensor (recall Fig. 14), the cold holdup area (see Appendix Section 10.4) appears to decrease $3.5 D_m$ downstream of the T-junction with increasing ΔT . Fig. 21 shows quantitatively the trend in cold holdup as percentage of the total flow area versus Ri number. Indeed it happens that the cold flow area below the stratified layer shrinks with increasing Ri number while, concurrently, the same holdup area $-3.5 D_m$ upstream of the T-junction increases with Ri number. As the Richardson number increases beyond 6 the holdup area upstream of the T-junction becomes larger than downstream at the same non-dimensional positions ($\pm 3.5 D_m$). As Ri increases, it has steadily less influence on the proportional area of heavier cold flow in the cross-section both upstream and downstream of the T-junction.

Fig. 21. Cold holdup in the pipe cross section vs. Richardson number $3.5D_m$ downstream and $-3.5 D_m$ upstream of the T-junction.

At high main flow temperatures, stratification in the flow results in large thermal stresses in the facility which act to induce a bending moment in the pipeline, which is not anchored (Kweon et al. 2008). This behavior has been investigated in an FEM simulation by the MPA Stuttgart based on temperature profiles from LES simulations with conjugate heat transfer (Schuler et al. 2012). Two simulations were performed based on main flow temperatures of 120 °C and 280 °C. At 120 °C, before the onset of upstream flow, modules downstream of the T-junction rises to a level slightly higher than the T-junction module. Significant upstream flow at $T_m = 280$ °C results in the T-junction module along with the first two upstream modules rising significantly such that downstream modules are inclined. It cannot be excluded that this phenomenon may have an effect on flow mixing behavior in the pipeline.

8 Conclusion

The measurements described herein are party to a series of proof of concept tests performed at the Stuttgart T-junction facility of a new mesh sensor package for high temperature and high pressure flows related to nuclear safety. T-junction mixing with reactor-like temperature differences between main pipe and branch line flows (< 230 °C) has been investigated at bulk temperatures of up to 256 °C. Instrumentation included thermocouples

installed on the pipe outer wall, in-wall, and in-flow as well as a novel mesh sensor capable of measuring high temperature and high pressure flows at high frequency, in this case 10 kHz, with 208 measurements points in the flow with a pitch of 4.48 mm. The mesh sensor package, measuring electrical conductivity, is used here to measure single phase mixing in the T-junction by means of a calibration routine based on the temperature dependence of the electrical conductivity of water. The mesh sensor was installed both downstream and upstream of the T-junction where it elucidated the flow profile in the case of turbulent mixing and stratification. Four boundary conditions, in particular, were investigated. These included mixing at main pipe flow temperatures ranging from $T_m = 165\text{ }^{\circ}\text{C}$ to $256\text{ }^{\circ}\text{C}$. The mixing behavior downstream of the T-junction cannot be described within the usual categorizations of cross-flow mixing in T-junctions.

Downstream of the T-junction according to thermocouple measurements, the average temperature profile near the wall is somewhat static between positions nearer to the T-junction ($5 D_m$) and farther downstream ($10.7 D_m$) while temperature fluctuations tend to decrease with the downstream progression of the flow. The mesh sensor indicates a layer with a high gradient in average temperature between cold fluid in the bottom portion of the pipeline and hot fluid on top. As the main flow temperature increases the interface between the main flow and branch flow in the mixing pipe becomes sharper and contains larger amplitude temperature fluctuations. The area of cold fluid in the cross-section is seen to decrease with increasing T_m such that the highest temperature fluctuations near the wall at the mesh sensor position move downwards along the walls from the middle portion of the pipeline. Damping of temperature fluctuations between a 2 mm distance from the inner wall to 0.15 mm in the wall material is shown to be very strong. The amplitude of the largest temperature fluctuations detected in the wall are measured as only approximately 6% of the nearby in-flow amplitudes.

The upstream flow phenomena, cold flow penetrating more than 3 meters into the main pipe underneath the incoming hot main flow, has been documented in detail. The cold flow rests in a nearly stable way on the very bottom of the pipe with temperature fluctuations residing in a thin layer not thicker than the pitch of the mesh sensor. The mesh sensor indicates the sudden quenching which occurs when the upstream flow arrives at a particular location at the pipe bottom, in this case measured at $-3.5 D_m$ upstream of the T-junction. Furthermore, the cold ‘hold-up’ area of the upstream flow increases with ΔT between the main and branch flows.

Given the evident significance of density driven flow behavior in the vicinity of the T-junction brought about in part by a weaker, transition branch flow, further studies with increased flow rates in the branch line should be performed to understand the flow mixing behavior in this case. The results herein are valuable for CFD validation in the case of reactor fluid conditions.

9 Acknowledgements

The authors would like to gratefully acknowledge the Swiss National Science Foundation and swissnuclear for their generous funding under project #200021_132659 and project #1320, respectively. Furthermore, thanks to the German Academic Exchange Service (DAAD) for providing research fellowship for Karthick Selvam during his stay at IKE, University of Stuttgart. The authors further acknowledge the German Federal Ministry of Education and Research (BMBF) for providing funding to commission the FSI test facility under project number 02NUK009B.

10 Appendix

10.1 Mesh sensor calibration

The mesh sensor measures the EC of a small volume of fluid between each crossing point of the mesh. Typically, single phase mixing experiments, such as studies of turbulent mixing at T-junctions, would utilize a salt tracer to differentiate the main flow from the branch flow and therefore capture the mixing process. The addition of a tracer was not possible at the T-junction facility and therefore the measurements rely on the varying EC of water with temperature. The ion product, $K_w = [H^+][OH^-]$ (also referred to as the dissociation constant), of pure water has been measured by Marshall and Franck (1981) over a wide range of temperatures and pressures and subsequently accepted by the International Association for the Properties of Water and Steam (IAPWS) (Marshall and Franck 1981). Fig. 22 (left) shows the EC of pure water vs. temperature at 7 MPa based on the correlation and coefficients of Marshall.

Fig. 22. EC vs. temperature (left) according to the correlation of Marshall (1981) for pure water, and EC vs. temperature (right) from experiments with NaCl solutions at high pressure from Quist (1967) (Marshall and Franck 1981; Quist and Marshall 1967).

Truly pure water, however, does not exist in an engineering context. Measurements by a handheld meter at the T-junction facility found the circulated water to have EC of 7-9 $\mu\text{S}/\text{cm}$, which, while highly deionized, results in a different shape of the ion product vs. temperature curve. It has been shown, for electrolyte solutions such as NaCl, for example, that EC is nearly linear to 200 °C over a wide range of pressures, see Fig. 22 (right) (Quist and Marshall 1967). The mobility of ions in the water are the dominating contribution, compared to the self-dissociation of H_2O , to the EC as a function of temperature especially at elevated temperatures in the range of interest.⁷ The peak in EC is the result of ionic association counterbalancing the ionic mobility as the density of water continues to decrease with temperature. The nonlinearity of EC as a function of temperature, seen especially below 100 °C, is lost with an increase in impurities. Therefore, a linear behavior of the EC of the water over a range between approximately 80 - 200 °C has been assumed.

The calibration of the mesh sensor at the Stuttgart T-junction is performed using the raw data collected from the full day of heating and cooling the facility with the sensor installed upstream of the T-junction. For the calibration of each crossing point, a single reference thermocouple was chosen. The reference thermocouple, XTM3, described earlier, lies in the center of the flow 765 mm upstream of the mesh sensor. It would be incorrect to assume that the temperature at XTM3 is equal to the temperature across the whole of the mesh sensor plane. A number of factors are at play; firstly, there is no heating of the flow between XTM3 and the mesh sensor plane; some heat losses and mixing can be expected. Secondly, and more importantly, at a Reynolds number of 54,000 (at 200 °C) in the main pipe the flow is not sufficiently turbulent such that a flat temperature profile is achieved in the pipe cross section. A top-to-bottom temperature gradient in the main pipe is expected to exceed 10-15 K at high water temperatures based on thermocouple measurements at the facility. Therefore, a least squares regression was performed to best estimate the reference temperature at each mesh sensor crossing point T_{ij} as a function of reference thermocouple temperature T_r and time t .

⁷ The sharp decrease in viscosity of water vs. temperature as it is heated above room temperature is the reason for increased ionic mobility.

The least squares regression seeks the planar fitting of 3D points of the form $(x, y, T_r(t_{max}))$. The plane $T_r + A + By + Cx$ describes the distribution of temperature in the pipe cross section at the location of the mesh sensor which is known to exhibit a gradient from top to bottom at high temperatures.⁸ We seek the minimum of the function,

$$R^2 = \sum_i^{16} \sum_j^{16} (T_r(t_{max,ij}) + A + By_{ij} + Cx_{ij} - T_{ij}(t_{max,ij}))^2 \quad 10-1$$

$$\frac{\partial(R^2)}{\partial A} = 0, \frac{\partial(R^2)}{\partial B} = 0, \frac{\partial(R^2)}{\partial C} = 0, \quad 10-2$$

where $T_{ij}(t_{max,ij})$ is defined for all i,j crossing points as 240 °C: the temperature corresponding to the maximum signal, and therefore maximum EC, at each crossing point. The reference thermocouple T_r at the time of maximum signal at crossing point i,j , $t_{max,ij}$, varies. In this way a function for the estimated temperature at each crossing point at any given time, $T_{ij} = T_r(t) + A + By_{ij} + Cx_{ij}$, may be generated assuming a planar temperature profile in the cross section at 240 °C. A further step is taken to scale the coefficients B and C with main flow temperature, assuming that the temperature profile in the main pipe must be flat at room temperature (20 °C),

$$B'(t) = -\frac{20}{220}B + \frac{1}{220}T_r(t), \quad 10-3$$

and similarly for $C'(t)$. An example of the relationship between the corrected reference temperature T_{ij} and the mesh sensor signal θ is shown in Fig. 23. Visible is the peak in the EC of the water at 240 °C. The region in which the crossing points are calibrated is where the signal shows linear dependence to the temperature. A linear fit is made in this region for each crossing point which becomes function which converts the raw measured signals to temperatures.

Fig. 23. Plot of raw mesh sensor signal vs. estimated temperature at a crossing point near the top of the pipe. The function which describes the linear fit, shown in red, is that which

⁸ The x-component is included to account for the possibility of upstream swirl influencing the temperature profile along this axis, although a flow straightening device is installed.

converts signal values to temperature at this crossing point for any given measurement dataset.

The presence of cold upstream flow at the sensor precludes the generation of complete calibration data for the crossing points of the sensor at the bottom of the pipe, as in the case of the downstream calibration. We therefore rely on the linear behavior of the EC of the fluid versus temperature in calibrating these crossing points for temperatures that we could otherwise not verify being experienced at those locations (estimated as temperatures above 140 °C).

10.2 Noise filtering

Care has been taken to filter noise from the mesh sensor signal while maintaining integrity of the signal as it relates to fluid temperature fluctuations. Measurements recorded at 10 kHz enable a variety of filtering measures to be implemented while maintaining more than adequate sampling rates. Grounding of the pipeline to the DAQ system and shielded cables was performed to reduce the noise as much as reasonably possible at the T-junction facility. Signal-to-noise ratios of X to X were measured when the pipeline was full of room temperature water. In order to further reduce electronic noise visible in the sensor signal, a median filter approach has been implemented.

The 1-D median filter replaces each value with the median of a windowed range around that value. We have chosen a window size of 14 values (a '14-order' median filter) in order to eliminate large amplitude high frequency electronic noise and glitches observed in some chosen reference signals. More information, such as boundary effects when implementing the filter can be found in textbooks (Arce 2005). Fig. 24 shows a sample signal with and without filtering. Only the very high frequency portions of the spectrum are affected by the filtering.

Fig. 24. A comparison between one seconds of raw signal recorded by the mesh sensor, and the corresponding power spectral density, in the mixing layer downstream of the T-junction with and without median filtering.

By integrating the PSD we find that θ_{RMS} post-filtering is reduced by 3.7%. The power spectrum remains largely unchanged at lower frequencies with 99.3% of the scalar variance retained for a frequency domain of up to 500 Hz. Given the Reynolds number of the flow and eddy turnover times we do not expect fluctuations in the fluid temperature at frequencies above 500 Hz to be meaningful. No noise filtering has been performed on thermocouple signals.

10.3 Frequency response

The frequency response of K-type thermocouples at the Stuttgart T-junction facility has been investigated in the past. The well-known low-pass filtering effect present in the thermocouples is the product of their thermal inertia. Mesh sensor technology is not limited in frequency resolution by thermal inertia, but rather by the flow velocity. We assume that the diffusion timescale is significantly small, such that it can be neglected, and focus entirely on the advection of ions by the flow. The volume-averaging performed by the sensor results in the failure to resolve the true conductivity fluctuation amplitude in the case of high frequency fluctuations transported through the mesh grid.

A simple first-order low pass filter with transfer function

$$H(\omega i) = \frac{1}{1+\tau\omega i} \quad 10-4$$

is sufficient to describe the frequency response of the sensor. The time constant, τ , of the mesh sensor is defined as the quotient of the distance between electrode grids (2.44E-3 m) and the fluid velocity. Assuming a fluid velocity of 0.1 m/s, the real part of Eq. 10-4 is,

$$|H(\omega i)| = \frac{1}{\sqrt{1+(\tau\omega)^2}} \quad 10-5$$

where $\tau = 2.44\text{E-}2$. The gain-magnitude frequency response of the mesh sensor, based on Eq. 9-5 is shown along with the thermocouple response in Fig. 25. Uncertainty in the frequency response of the mesh sensor is the result of variability in local fluid velocity. For example, crossing points very near the wall will exhibit a more damped power spectrum due to a combination of smaller eddies and local fluid velocities.

Fig. 25. Gain-magnitude frequency response of thermocouples at the facility and of the mesh sensor for a number of fluid velocities.

10.4 Calculation of cold holdup area

Cold (branch) flow holdup was calculated as follows. Crossing points measuring below a threshold temperature,

$$T_h = T_m - (T_m - \bar{T}_{t,r,min})/2 \quad (10-6)$$

where T_m is the most recent main flow temperature recorded by reference thermocouple (XTM3) and $\bar{T}_{t,r,min}$ is the minimum average temperature calculated from the five second mesh sensor signal, were labeled as cold flow and given a value of 1 in the 16-by-16 2D holdup matrix. Values above the threshold were set to 0. The 2D holdup matrix is multiplied element-wise by a weight matrix $W_{t,r}$ which takes into account the reduced measurement area of crossing points near the wall of the conduit.

$$A_{holdup} = (\sum_t^{16} \sum_r^{16} \theta_{holdup,t,r} * W_{t,r})A \quad (10-7)$$

where A is the pitch of the sensor squared, 20.14 mm^2 . An example of a 2D holdup matrix is shown for an arbitrary time step in Fig. 26. Note that the plot is not oriented with gravity pointing downwards.

Fig. 26. Instantaneous weighted cold holdup at $Ri = 0.98$ $3.5D_m$ downstream of the T-junction.

Test #1

Test #2

Test #3

Test #4

Test #1

Test #2

Test #3

Test #4

Figure 11. Isobaric variation of specific conductances of 0.01000 *m* NaCl solutions as a function of temperature; pressures of 500 to 4000 bars.