Transactions, **SMiRT-25**
Charlotte, NC, USA, August 4-9, 2019
Division III

IMPROVED DESIGN OF A T-JUNCTION BASED ON CFD ANALYSES

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ABSTRACT

The mixing of cold and hot water in the mixing area of T-junctions involves complex heat transfer mechanisms in the fluid and in the structure parts as well. In particular, at high Reynolds numbers the turbulent mixing at a T-junction leads to high temperature fluctuations at the inner wall of the pipes. If the frequency of those fluctuations falls into a certain bandwidth, i.e. high enough to cause significant temperature gradients in the pipe wall and slow enough to overcome the thermal inertia of the pipe material, heat conduction will cause highly transient thermal loads in the pipe wall. This phenomenon, which in this case is due to turbulence, is called High Cycle Thermal Fatigue (HCTF). It causes a very high number of load cycles and a lot of damage cases can be traced back to HCTF.

Also in the case, which is presented in this work, a root cause analysis involving CFD simulations revealed, that HCTF is the driving physical mechanism behind the damages at a T-junction. Based on this finding the T-junction was redesigned to improve its mixing efficiency and to minimize thermal loads at the inner walls of the T-junction. Finally, the efficiency of the design changes was verified by CFD simulations.

INTRODUCTION

The following paper presents the contribution of TUEV NORD concerning the improvement of the design of a T-junction of one of TUEV NORD’s customers. The T-junction mixes warm and cold streams of condensate water. The cold water flows in the horizontal main line with 4’’ diameter and the warm water approaches the main line in a smaller vertical branch with 3’’ diameter from below (see figure 1). Both water flows are mixed in the mixing zone of the T-junction. Exactly in that region cracks occurred repeatedly within a small period of time and the T-junction had to be replaced. The cracks were always very similar. They occurred directly at the branch on one side of the horizontal main line. Furthermore, they showed a small inclination in the flow direction. Hence, a systematic failure had to be assumed and to avoid future damages the design of the T-junction had to be improved.

The first step was a root cause analysis to identify the physical phenomena that leads to the observed behaviour. On the basis of these results design changes should be developed to avoid the cracks. Therefore, the material of the T-junction was examined in a preliminary study, TUEV (2016). As a result thermal fatigue was identified as the physical damage mechanism. To develop countermeasures and to prove their effectiveness the root cause had to be known more precisely. That was the content of a further study whose results are presented in the following sections.

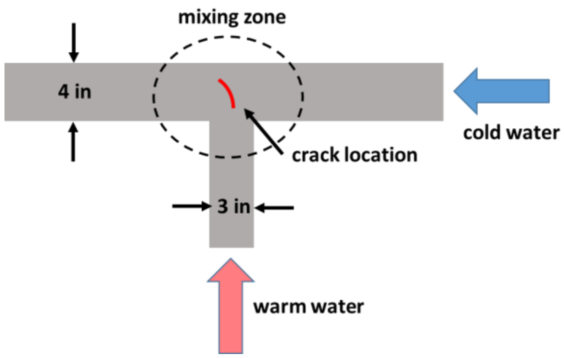

Figure 1. Sketch of the T-junction with crack location

ROOT CAUSE ANALYSIS

There exist several possible sources of thermal fatigue. On the one hand single changes of operation, like e.g. start-up or shut-down processes, can lead to significant thermal loads on the structure. On the other hand also operational fluctuations can cause thermal loads. To distinguish between these sources thermal shock analyses were performed. It was found that a very high number of load cases (> 10^6 cycles) would be necessary before the admissible limit of load cycles is reached. So, it was possible to exclude single events as a root cause, because the facility, to which the T-junction belongs, works mainly in stationary operation and such a high number of single events never occurs.

To examine whether operational fluctuations might be a root cause, a parameter study with time averaged CFD (Computational Fluid Dynamics) simulations was performed. The objective was to examine the mixing of warm and cold water inside the mixing zone of the T-junction under varying mass flows. The geometrical model of the fluid region in the T-junction is shown in figure 2.

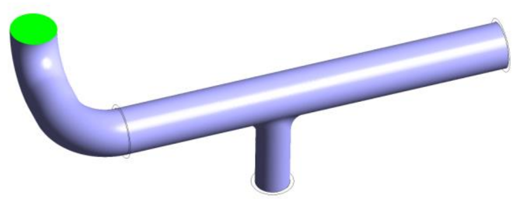

Figure 2. Geometrical model of the fluid region in the T-junction

In usual operation mode the cold water mass flow rate was 8 t/h and the warm water mass flow rate was 15 t/h. That leads to the distribution of cold and warm water inside the T-junction that is shown in figure 3. The flow regime that can be observed is called an impinging jet regime, Kimura et al. (2007). The warm water enters the mixing zone from below and hits the opposite wall quite undisturbed.

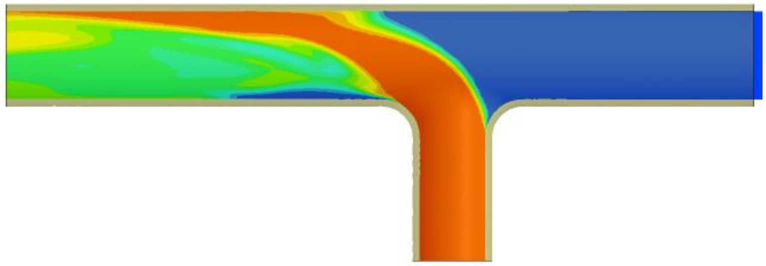

Figure 3. Temperatures in a vertical cut through the T-junction (cold water: 8 t/h, warm water: 15 t/h)

Because the influence of variations of the mass flow rates should be examined, the cold mass flow rate was successively increased up to 15 t/h and the warm mass flow rate was decreased to 8 t/h. The next figure 4 shows the flow regime, which develops for 11 t/h cold and 12 t/h warm water mass flows.

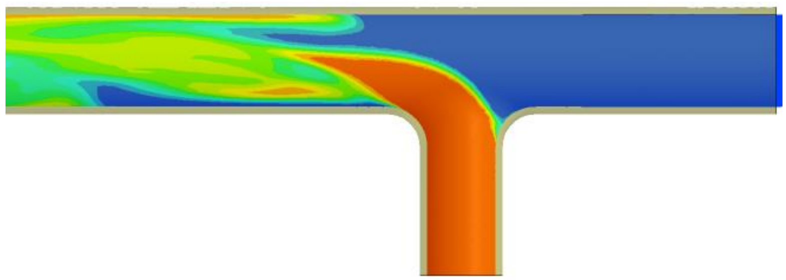

Figure 4. Temperatures in a vertical cut through the T-junction (cold water: 11 t/h, warm water: 12 t/h)

In this case the warm water is deflected such that the jet enters the horizontal line in the center. Compared to figure 3 the temperature distribution shows that the warm water is mixed more effectively with the cold water in the horizontal line.

Figure 5 shows a third flow regime. Here, the mass flow rates were 15 t/h (cold) and 8 t/h (warm). Under these conditions a wall jet develops, i.e. the warm water doesn't separate from the pipe wall in the T-junction.

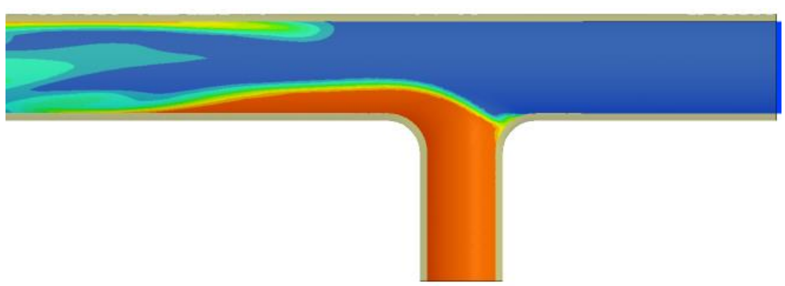

Figure 5. Temperatures in a vertical cut through the T-junction (cold water: 15 t/h, warm water: 8 t/h)

It depends on the ratio of the cold and warm mass flow rate, which flow regime occurs. A study of the influence of different junction geometries and flow parameters on the mixing behaviour is contained in the report VEB (1987). Due to this report the optimal mixing will be achieved, if the ratio between the fluid velocity in the branch u_b and the fluid velocity in the main line u_m becomes the value two, i.e.

$$\frac{u_b}{u_m} = 2. \tag{1}$$

This situation is displayed in figure 4, in which the warm water jet is deflected towards the center of the main line. So, due to both studies, the CFD parameter study as well as report VEB (1987), it is preferable to inject the warm water in the middle of the main line. This can be achieved for instance by adjusting the mass flow rates, such that equation (1) is fulfilled.

However, a view at the temperatures at the pipe wall reveals that the observed location of the cracks doesn't fit to the boundaries between warm and cold water (figure 6). In particular in the default case (cold: 8 t/h, warm: 15 t/h) only cold temperatures are observed near the crack location. Furthermore, due to the operator there are no significant deviations from the default operation. By considering this, also small operational fluctuation can be excluded as root cause for the damages of the T-junction.

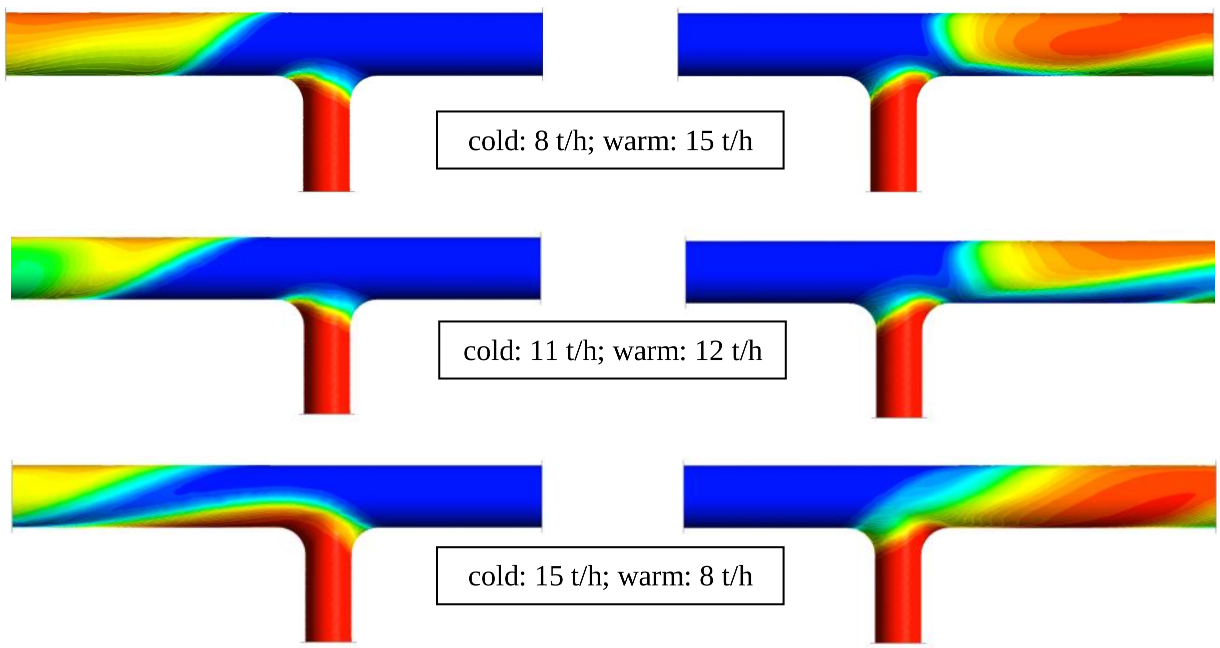

Figure 6. Wall temperatures at both sides of the T-junction

So far, single events and slight deviations from the default operation condition were excluded as cause for the cracks in the T-junction. However, another possibility are turbulence induced temperature fluctuations in the T-junction.

Mixing of two turbulent flows with different temperatures generates highly transient eddies which yield high frequency temperature fluctuations. These fluctuations can lead to significant thermal loads if the frequencies are in an intermediate bandwidth. Very low frequency temperature fluctuations do not produce relevant temperature gradients over the wall thickness, because thermal diffusivity homogenizes the wall temperature. If the frequency is too high, the thermal inertia of the material will not follow the temperature changes. Relevant frequencies are typically between 0.1 and 10 Hz, Kasahara (2012) and Zboray et al. (2011). This phenomenon is called High Cycle Thermal Fatigue (HCTF) and it can provoke a large number of load cylces in a comparatively short period of time.

In 1998 there was a leak in an elbow of a reactor coolant system in the French nuclear power reactor Civaux, see e.g. Chapuliot (2005). The elbow was located downstream of a T-junction. Warm (180° C) and cold (20° C) water were mixed in the T-junction and the flow velocity ratio was about 4:1. Furthermore, not only the elbow was damaged. More damages were found, particularly at the T-junction. Finally, HCTF has been identified as the root cause for the leakage.

There is a noticeable similarity between the Civaux case and the cracks that were examined in this study. In both cases the fluid temperatures and the fluid velocities as well were comparable. Moreover, in the preliminary study it was stated that the inner surface of the T-junction was rough and destroyed in a microscale layer. Such kind of surface structures (so-called elephant skin, Kasahara (2012)) is another indication for HCTF.

The previous time-averaged CFD simulations were not suitable to verify HCTF as the damage cause, because the turbulent fluctuations are removed by the averaging operation in such kind of simulations. For this reason only the averaged temperatures are visible in figure 6. In order to visualize the turbulent fluctuations at least the most relevant eddies have to be resolved in the simulation. Simulations that resolve solely the relevant eddies are called Large Eddy Simulations (LES). Large Eddy Simulations are not time-averaged. Instead a spatial filter operation is used to remove the smaller eddies. The dropped subgrid scales have to be considered in the equations by a so-called subgrid model.

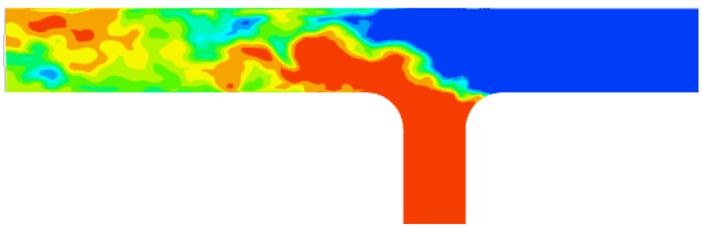

Figure 7. Temperatures in a Large Eddy Simulation (cold water: 8 t/h, warm water: 15 t/h)

Figure 7 shows a snapshot of a Large Eddy Simulation for the default configuration. In comparison to figure 3, which shows the corresponding time-averaged results, the eddies are clearly visible in figure 7. In particular, the region in the center of the T-junction, in which the cracks occur, is a place were strong turbulent fluctuations take place.

So, taking into account all information gathered so far, the very probable reason for the cracks in the T-junction is thermal fatigue due to HCTF.

COUNTERMEASURES AND IMPROVED DESIGN

Because turbulent fluctuation cannot be avoided completely in turbulent flows, only their impact on the T-junction can be influenced by countermeasures. Therefore, possible countermeasures are:

- reduction of the turbulence intensity,
- changing the frequency spectrum,
- changing the flow regime or
- geometrical optimization.

A reduction of the turbulence intensity may be achieved by decreased flow rates or larger pipe diameters. But these would have required major constructive changes in the facility. Therefore, the focus was set on different measures.

In order to change the frequency spectrum, a more detailed spectral analysis would have been necessary. Such an analysis was not available at that moment. Furthermore, it would have been required to verify the effectiveness of corresponding countermeasures. So again, other more efficient countermeasures were needed.

Due to VEB (1987) the best mixing effect will be obtained in a T-junction, if the fluid velocity ratios fulfill equation (1). Furthermore, the goal of constructive changes could be to avoid the direct contact of the injected warm water with the wall of the main pipe in order to minimize the thermal fluctuations at the wall. For this purpose, a design that is called “elephant nose” is proposed in Suzuki et al. (2005).

The T-junction was redesigned based on these principles. The final design is shown in figure 8. The T-junction was equipped with an inner pipe that injects the warm water into the center of the main pipe. Furthermore, the cross section of the main pipe was decreased at the outlet, such that its diameter equals the diameter of the inner pipe to improve the ratio between the fluid velocities. Changing the mass flow rates themselves was not an option due to operational boundary conditions. Moreover, the narrowed cross section at the transition from the T-junction to the 4’’ main pipe has an effect like a jet pump which further increases the mixing efficiency.

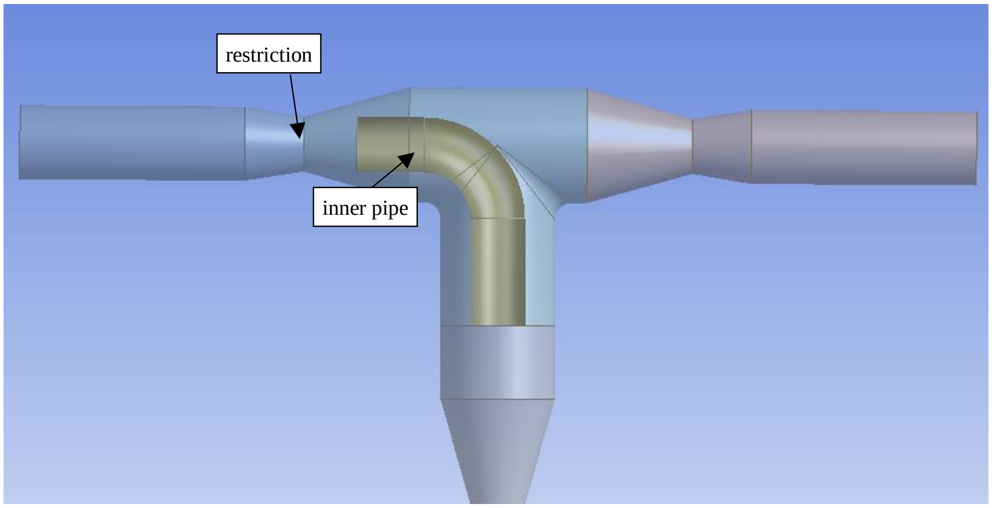

Figure 8. New design of the T-junction

The effectiveness of the design changes was assessed by means of CFD simulations. A comparison between a first design and the final design is presented in the figures 9 and 10.

Figure 9. Average temperatures considering a first redesign attempt (left: side view; right: top view)

Figure 10. Average temperatures considering the final design (left: side view; right: top view)

The temperature distribution in figure 9 reveals that the first approach didn't have the desired effect. The horizontal section of the inner pipe was too short such that the warm water jet was directed towards the wall. So, the goal to avoid a direct interaction of the wall and the jet was not achieved. Therefore, the new design was optimized. The horizontal section of the inner pipe was longer in the final design. Moreover, the inner diameter of the inner pipe was decreased. In the end, the warm water jet is injected into the center of the main pipe and the water which is in contact with the pipe wall is better mixed (figure 10). So, the goals were reached.

CONCLUSIONS

The turbulent mixing of two flows of warm and cold water in a T-junction led to thermal fatigue and the development of cracks. By means of CFD simulations and structural analyses single events and small operational fluctuation with low characteristic frequencies could be excluded as root causes. Instead a phenomenon called High Cycle Thermal Fatigue was identified as the driving physical mechanism. Thus, the thermal loads on the inner wall of the T-junction were caused very probably by turbulent fluctuations in the mixing zone of the T-junction. In order to reduce the thermal loads a new design of the T-junction has been developed. The new design is based on several principles. First, the ratio of the fluid velocities was changed to improve the mixing efficiency. Moreover, an inner pipe based on the elephant nose principle was added in the T-junction. This measure should prevent the direct contact of the warm water jet with the walls of the T-junction. Finally, the principle of a jet pump was used for further improvement of the mixing of the water streams at the outlet of the T-junction. The efficiency of the new design has been verified by CFD simulations.

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