INFLUENCE OF TEMPERATURE DIFFERENCES OF MIXED STREAMS UPON T-JUNCTION DAMAGE

Richard Nekvasil*

The problem of thermal fatigue in pipe connections under the influence of streams mixing is one of the most discussed problems on international conferences. Numerous failures occur in industry as a result of this damage mechanism. It is caused by frequent stress changes developed by an effect of non-stationary thermal fields. The degree of damage is greatly dependent on characteristic of material, geometrical design of a pipe connection in operational conditions. The report is dealing with influence of temperature differences of mixing media streams upon pipe material damage cumulation. It is focused on a perpendicular T-junction made of ferritic steel, which is protected inside with an anticorrosive weld deposit from austenitic steel. Six cases of temperature differences will be considered for particular operational conditions with a step of 50 °C, and the damage cumulation process will be observed. Thanks to it, it will be possible to judge better the meaning of streams temperature differences.

Key words: *thermal fatigue, damage cumulation, steams mixing, fluid structure interaction, CFD, FEM*

1. Introduction

The analysis is carried out for the case of cold medium rapidly entering a heated pipe [1], [2]. This case can take place as a part of a technological process or as a result of a fallback system operation. When pipe walls are cooled, shock thermal changes in surface layers of pipe material take place, thus developing high values of stresses. In their turn, stresses decrease item lifetime and can cause fatigue cracks, which can grow under conditions of cyclic load and may reach limiting level of pipe damage. These states are inadmissible, that is why it is necessary to analyze influence of different operating conditions and determine favourable conditions with minimum pipe damage [3], [4].

The case of pipe thermal damage under influence of streams mixing is very complicated [5], [6]. Combination of two computational methods, which are Computational Fluid Dynamics (CFD) and Finite Element Metod (FEM), was used to solve it. First of all, thermal-hydraulic analyses were carried out in order to determine thermal fields distribution in the item material. The simulation was done using CFX software [9]. Determined thermal fields are used further as boundary conditions; next aim is to specify stress distribution in the item. To simulate this process ANSYS software was used. To use results of thermal-hydraulic analyses in stress analysis it is necessary to interconnect CFD and FEM software. The method of mutual interactions between thermal-hydraulic and structural analyses is called Fluid Structures Interactions (FSI).

* Ing. R. Nekvasil, Ph.D., Institute of Process and Environmental Engineering, Faculty of Mechanical Engineering, Brno University of Technology

2. The procedure of problem solving

It was necessary to create computational models for numerical simulations of streaming and further determination of stresses under particular operational conditions for the pipe with particular geometrical design. Computational model was represented by a 3D model of pipe connection designed according to the drawing documentation. SolidWorks software was used for these purposes. Thermal-hydraulic analysis demanded filling of the model with the working medium, which was done by means of Workbench software.

The computational mesh of a working medium consisted of tetrahedral and prismatic elements (substituting a boundary layer) because more advanced meshing programme was not available. Before the mesh was generated, the areas for boundary conditions application were chosen on account of faster selecting in the process of operational conditions applying.

The computational model of the pipe was created in the programme ANSYS by means of volumes dividing, thus a qualitative mesh comprising hexahedral elements was generated. Similarly, it was necessary to create node groups for applying boundary conditions. The model was exported in the format cdb (text data) and then together with the medium mesh imported to CFX. Here both models were interconnected and all necessary boundary conditions, such as speed, temperatures and pressures, were applied. The calculation was adjusted so, that it was possible to observe changes in the process of media mixing. The simulation was analyzed non-stationarily, with the attention to time dependence, the information was saved in particular steps.

Thermal-hydraulic analyses helped to determine thermal and speed field distributions, which are very important from stress analysis point of view. Temperature values in the nodes of the pipe computational model and pressures on an internal wall in particular steps were exported as text data (cdb) so that stress analyses could be carried out. Exported boundary limits (temperature and pressure) were applied to the same model which was

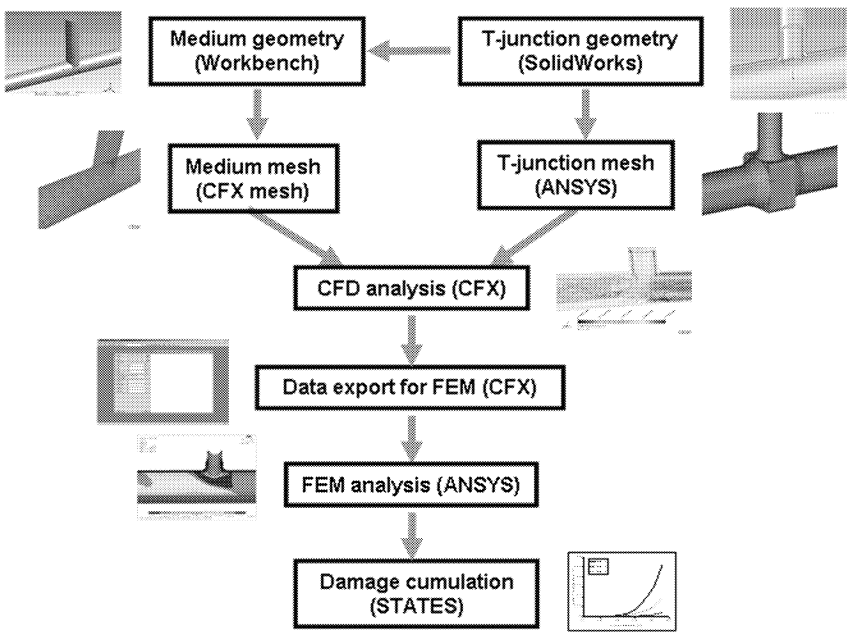

Fig.1: Scheme of calculation procedure

used in CFD analysis. One of the ends of the main pipe was firmly gripped and the two left were loaded by axial forces developed under the influence of internal pressure.

FEM analysis allowed determining stress distribution in the pipe material in particular time steps. Thanks to that, it was possible to find the most loaded places and carry out fatigue analysis for them. Load cycles were determined from time behaviour of stresses. Damage cumulation value was calculated for one case of media streams mixing. Fig. 1 shows the whole procedure of thermal-hydraulic analysis with the following stress analysis and low-cycle fatigue analysis. This procedure is frequently used for solving industrial problems, which couldn't have been thoroughly analyzed before.

2.1. Boundary limits for streaming

The principal step in the whole procedure of creating a complex computational model for the thermal-hydraulic analysis comprised mutual interconnection of both meshes so, that information about temperature changes in contact surfaces as well as pressures applied to them could be exchanged. Further boundary limits were inlet speeds of media and their temperatures. Zero pressure was applied to the output of the pipe, which means that temperature, pressure and speed values were calculated from the input values. Only a half of the pipe connection was modeled, hence it was necessary to apply symmetry conditions (media and pipe) to the area of cut. Advanced turbulence RNG k-ε model [9] was used. From the heat exchange point of view the energy conservation law was used. It was considered that no heat exchange with the environment would take place, because the considered case is thermally isolated. To make it possible to observe changes during streams mixing and determine stress distribution in the pipe at any moment, the problems were being solved non-stationarily. It was necessary to choose proper time intervals.

2.2. Boundary limits for stress analyses

Applied boundary conditions for stress (multifield) analyses were pressure applied to the internal wall, temperature in the volume of pipe material and axial load. Further one of the ends of a main pipe was gripped so that the pipe couldn't be displaced in an axial direction and at the same time could move in radial and normal directions. Since force and torque actions applied to the ends of the pipe were unknown, the axial load developed under internal pressure was applied to the ends. Another condition describing symmetry axis was applied, it imposed zero displacement to the area of cut in the direction perpendicular to the area.

2.3. Conditions for determining damage cumulation

On the basis of stress analyses the most loaded areas were chosen and time changes of stresses caused by media mixing processes were empanelled for these areas. They were further thoroughly assessed from the fatigue damage point of view by means of Rain Flow Method [7]. Three key states were identified for the majority of considered cases, namely initial load (the pipe is heated to the temperature of main stream), maximum thermal gradient (medium starts entering main pipe) and quasi-stationary state of streaming (stationary distribution of thermal fields in pipe material). The sequence of three load states made a load cycle, for which damage cumulation was calculated [5], [6].

Values of damage cumulation were determined by means of STATES programme [10], which was developed on Institute of applied mechanics Brno, Ltd. The input parameters were: stress tensor component values, temperatures for particular load cases (in the selected areas), sequences of load states (load blocks) and mechanical characteristics of the steel. The calculation of σ_{H} stress (stress calculated under the condition of linear functioning of material) was carried out provided that material has elastic properties. The values of σ_{t} (real total strain) and σ (real stress) were approximately derived from the values above using STATES programme. Neuber conception was used for these purposes [7]. To determine damage cumulation Langer lifetime curve, stress safety factor $n_\sigma = 2$ and cycle number safety factor $n_{\mathrm{N}} = 10$ were used. Damage cumulations were calculated for values of the stress tensor and temperatures of separate nodes.

3. Analysis of influence of temperature difference upon T-junction damage

Value of temperature difference of mixing streams is one of the most important aspects having great influence on pipe material damage. Operating temperatures are predetermined by manufacturing technologies peculiar to separate units and they can't be changed. The areas most influenced thermally can be partly changed by pipe connection geometry improvement.

3.1. Analyzed pipe connection geometry and applied boundary conditions

Ferritic pipe with an anticorrosive weld deposit and an insertion was considered. In order to preserve the protective coating the attached pipe is welded to the T-junction by an anticorrosive weld. This type of connection is designated for higher working pressures and aggressive media. Fig. 2 shows geometry of the connection.

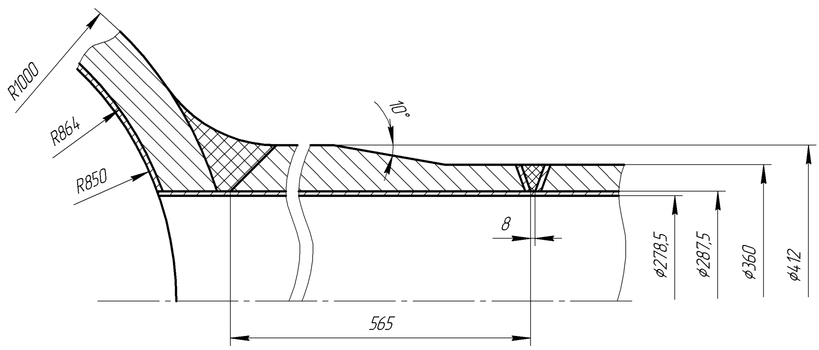

Fig.2: Geometry of the analyzed T-junction

The mesh of the computational model comprised approximately 300 thousand elements. Boundary conditions included speed of working medium streaming in a main pipe equal 8.3 m/s, the temperature varied from 70 to 320 °C, with a constant step for particular simulations equal 50 °C. The medium in the attached pipe streamed with the speed equal to 3.7 m/s and a constant temperature equal to 20 °C. Working medium was water under the pressure of 2.36 MPa.

3.2. Streaming analysis and thermal fields distribution

The process of cold medium stream entering hot pipe was simulated for different temperature differences as well as for stabilization of thermal fields in the pipe material. For the case of lower medium speed in the attached pipe, the stream was drifted away by the stream in the main pipe. As a result the sharp edge and upper part of the main pipe were affected. If the speed of an entering stream is higher, then it is drifted away to the center of the pipe and the main pipe is thus not affected. The last possible case is when the stream from the attached pipe is pushed to the opposite wall of the main pipe. It can happen when the speed of the stream in the main pipe is low, and the stream from the attached pipe flows fast. In this case the lower part of the main pipe is mainly affected [8].

CFD outcomes showed that thermal fields stabilizing process in the analyzed case took approximately 600 s. It can be said that the time is dependent on geometry of the T-junction and streams speed ratio. After 20 s the difference of temperatures on the internal and external surfaces was maximum, which caused maximum stress in the pipe.

In the process of pipe cooling nonuniform cooling of an austenitic weld compared to the ferritic pipe was observed. The reason is different physical characteristics of materials. This effect is of great importance because of stresses developed in the border area of the pipe and an austenitic weld deposit. Nonuniform cooling of both materials will be the subject of the following chapter.

3.3. Analysis of the most loaded areas and determination of damage cumulation

The computational model for stress analysis comprised 105 thousand elements. For the chosen time instants numerical simulations were carried out and stress fields distribution was determined. Since the ferritic pipe was protected with the austenitic weld deposit, stress peaks were observed in the materials border.

Stress analysis showed that there are significant differences in the state of stress between ferritic pipe and austenitic weld deposit, which was expected as materials have different physical characteristics (austenitic material had an extensibility factor twice as large as ferritic steel). The austenitic weld deposit in the border area was more stressed, in some cases higher by an order. When the temperature of both connected pipes is constant (in the beginning of the process) the values of stresses are not outstanding. But if upper layers are cooled rapidly then stresses rise multiply. Dominant stresses are circumferential and longitudinal stresses.

The most unsafe and closely analyzed area was the area of austenitic weld deposition, where differences between stress values in internal and external sides were maximum in all analyzed cases. The attention was paid to the cross section of the weld connection and the border area between austenitic weld deposit and ferritic steel. The next figure shows observed areas, the figures 4 and 5 show stress distribution over thickness in the chosen areas beginning with the internal side and ending with the external side (temperature difference equal to 300 °C and time instant 100 s). Vertical axis corresponds to stress values in Pa, horizontal axis corresponds to the distance in m.

Graphic dependence shows how weld connection is loaded; the dominant component of stress is circumferential. It has tension nature near internal wall and pressure nature near

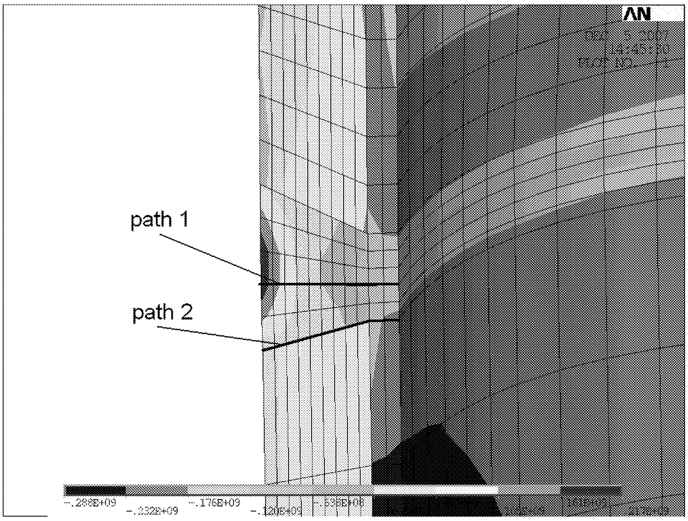

Fig.3: Examined paths of a weld connection

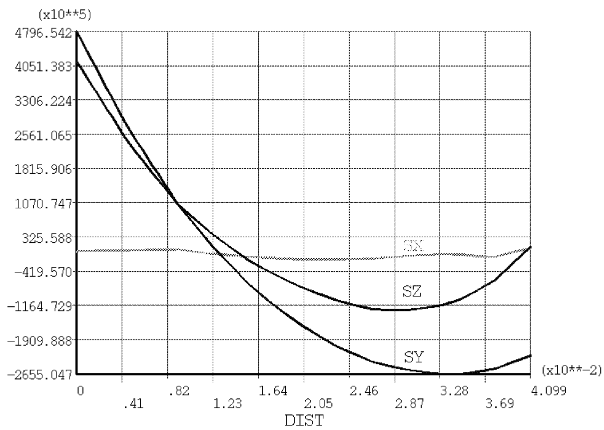

Fig.4: Stress curve for the middle of a weld connection (path 1)

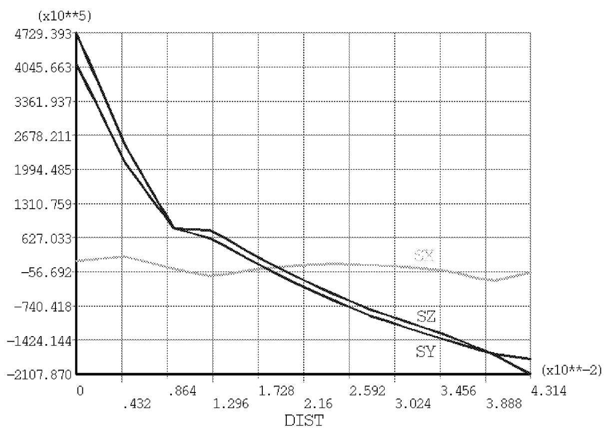

Fig.5: Stress curve for the border area of the weld connection (path 2)

external wall. In light of cracks initiation and propagation this fact is very unfavourable and the design is poor. The only advantage is corrosion resistance in aggressive medium.

The analysis of stress state in the process of cooling showed two most loaded areas which are: the area of weld connection and T-junction connection (see Fig. 6).

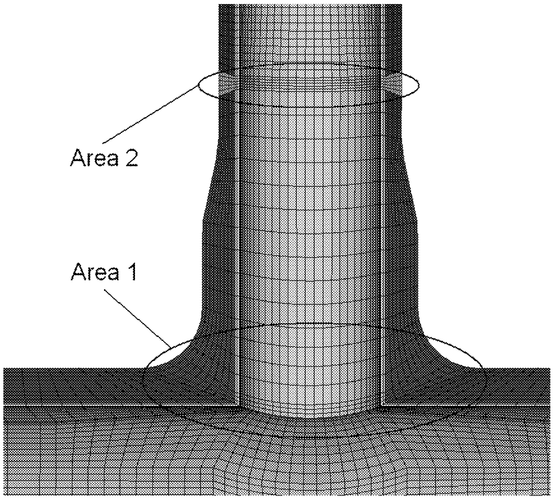

Fig.6: The most loaded areas

Temperature [°C]	50	100	150	200	250	300
Area 1	—	0.0001	0.0004	0.0023	0.0102	0.0258
Area 2	—	—	0.0002	0.0009	0.0037	0.0098

Tab.1: Damage cumulation for particular cases

Damage cumulation was determined for the most loaded areas (see table 1). The conditions were described before. The most loaded area in all cases of streams temperature differences was area 1. Damage cumulation equaled to 2.58 % at the temperature difference equal to 300 °C. This high value appears in the area of austenitic weld deposition, which is a critical place. The difference between damages at maximum and minimum temperature differences is more then of an order. Temperature difference equal to 100 °C can be considered acceptable.

4. Conclusion

The aim of the work was to analyze thermal damage of a pipe connection, where hot and cold streams of different temperatures and speeds are mixed. Attention was paid to assessment of temperature differences influence on pipe damage level and determination of acceptable temperature difference. At the same time the most unsafe areas were identified, analyzed and assessed from fatigue point of view.

Thanks to analyses of several cases describing different temperature differences of mixing streams, the acceptable value was found which is 100 °C. Since the allowed damage level is unknown for a case of medium injection to the pipe, it is necessary to verify the conclusion in industrial application.

The area 1 corresponding to the sharp internal edge turned out to be the most dangerous area. The border area between austenitic and ferritic materials is also a critical one, because nonuniform thermal expansions cause high values of stresses. In the case of temperature difference equal to 300 °C damage cumulation reached the values of 2.6 %. Further on, conditions causing cracks initiation and propagation were discovered in austenitic weld connection (area 2), which is not advisable for safe operation of this type of pipe connection.

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