Thermal Fatigue in Piping Tees- Cost Effective Methods for Assessment

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ABSTRACT

The paper discusses the various thermohydraulic phenomena that have been encountered in such piping tees, both for steady state and transient operation. High cycle fatigue and low cycle fatigue issues are addressed. The phenomena are put into perspective with respect to their uncertainties for their description. Then, a method is presented, which combines the procedures of analysis of the pressure vessel code approach and the piping code approach. This method allows to tune the analysis effort for each fatigue stress contributor to its reasonable degree of detail in the analysis, and thereby attain a favorable cost/benefit ratio for the fatigue analysis. Also, a method is presented to assess high cycle fatigue due to turbulent mixing zones in the vicinity of tees.

INTRODUCTION

Thermal fatigue in tee junctions of piping is basically covered by standard piping codes like ASME Section III Subsection NB-3600, and can formally be applied readily. However, experience has shown that such tees can be subjected to various complicated loadings like stratification in adjacent piping or turbulent mixing zones, which are not addressed by these codes. The procedure for a rigorous three-dimensional pressure vessel analysis according to ASME Section III Subsection NB-3200 has been applied, taking into account various complicated thermohydraulic boundary conditions, but this can be very time-consuming and therefore costly, with a questionable cost/benefit ratio due to the uncertainties in these thermohydraulic assumptions that underlie the procedure. It is therefore desirable to have methods at hand which provide a physically reasonable approach without being overly conservative. This paper describes such methods that have been applied in practice.

THERMOHYDRAULIC PHENOMENA

The classical thermohydraulic phenomena considered in piping codes are plug-flow type transient conditions that act as thermal shocks and create thermal gradients across the pressure boundary walls in a piping tee. Structural discontinuities can be considered by differences in mean wall temperatures between adjacent parts (e.g. $T_a - T_b$).

However, in actual operation of piping, very complicated thermal loadings have been measured, for example in spray lines of PWR pressurizers (ref. 1). Fig. 1 shows the instrumentation of a piping tee with thermocouples.
As an example, we show here the temperature recordings for a typical event for these thermocouple locations in Fig. 2:

![Temperature recordings in tee region](image)

It can be seen clearly that the temperatures show markedly different courses, despite the fact that they are all very close to the tee junction. The interpretation of these trends and relative differences among the thermocouples is a very difficult task, to have reliable thermal loadings for a thermal low cycle fatigue analysis. This is especially true, because these wall outside temperatures first have to be converted to wall inside and fluid temperatures, in order to be interpreted by thermohydraulic models of fluid behavior.

The thermohydraulic behavior is governed by fluid flow in all adjacent pipes of the tee. Such phenomena are phase transitions water/steam, presence of non-condensable gases and
stratified flow in the pipes. Moreover, the fluid flow is different at different times during the operational cycle of the plant, which again complicates the situation.

Another thermohydraulic phenomenon which can cause fatigue, can be significant during steady-state operation. If two flows of water join at the tee with different temperatures, turbulent mixing zones after the junction can be close to a piping wall downstream. This might lead to high cycle fatigue due to passing of hot and cold fluid eddies at relatively high frequencies and consequentially also cycle numbers. The frequencies are usually so high that the turbulent temperature fluctuations cannot be measured on the outside surface of the pipe wall.

Damages due to such a fatigue mechanism have been encountered in the past, not only in piping. However, here again, the establishment of a thermohydraulic model is difficult, and there is a need for an adequate numerical approach to describe the situation.

A METHOD FOR ASSESSMENT OF LOW CYCLE FATIGUE AT TEES WITH COMPLICATED THERMAL LOADINGS

There is a need for a method to calculate the fatigue usage in the tee by:

a. having enough conservatism to bound the uncertainties in the thermohydraulic phenomena.

b. thereby avoid unjustified costs for extensive fluid and structural modeling by computer programs like CFD and FE.

c. reducing conservatism for loading parts that can be assessed more accurately with reasonable cost impact and more certainty.

The method to attain above goals and proposed here is based on the combination of the two structural analysis codes in the ASME Section III, Subsection NB (NB-3200, Pressure Vessel Code, and NB-3600, Piping Code). This method is decomposing the relevant fatigue stress ranges into contributions according to the Piping code with the following terms:

1. Pressure term
2. Thermally induced pipe moment term
3. $\Delta T_1$, the linear through-wall gradient term
4. $\Delta T_2$, the non-linear through-wall gradient term
5. $(T_a - T_b)$, the term relating different mean temperatures at locations along the wall

Fig. 3 FE-Model of a Tee with stresses due to branch moment, including stratification
The 5 individual contributions are assessed in the following way:

- The pressure and moment terms 1 and 2 are computed by 3D finite elements, in line with a pressure vessel analysis approach. Figure 3 gives an example of such a stress calculation for a moment loading. The pressure term is readily computed. The moments are taken from flexibility analyses of the whole piping, which include thermal stratification according to measurements or theoretical considerations. The term for pressure and the two terms for moments (branch and run pipe moment) are superimposed on a finite element basis. This procedure attains the above goal c, by reducing unnecessary conservatism due to piping stress concentration factors and by not superimposing maximum stresses irrespective of their location in the tee.

- The thermal terms 3, 4 and 5 are calculated by a special “1½D” thermal calculation (D = dimension in space), that attains the goals a and b above, in line with the piping code approach. This calculation is done with a special purpose computer program which considers through-wall gradients by accurate 1D heat conduction analysis. This yields the terms 3 and 4 for each location in the tee. The further “½D” is attained by the fact, that these 1D calculations are done in pairs of locations, and the difference of the mean temperatures are used for the term 5 (T_a - T_b).

These special purpose programs allow consideration of the signs and the actual times in the superposition of the 3 terms, so that only the maximum stresses (maximum in time) due to the three terms combined are considered. A time shift for the start of transients at neighboring locations (see e.g. Fig. 1) is used in the program, so that realistic terms 5 are resulting. This typical time shift has to be defined by measurements and/or thermohydraulic considerations. Moreover, differences in wall thicknesses within the tee can be considered, so that the mean temperatures also reflect these influences.

This procedure has the advantage that unnecessary combination of the time-independent maxima of the individual terms does not have to be considered. Besides, there is no need to know the “exact” fluid flow behavior, because the pairs of calculations are done between all neighboring locations, thereby bounding the possible structural constraints for the thermal strains.

- The above two procedures are finally combined to form the total stress range for the calculation of the fatigue usage factors.

The special penalty factor K_c, which may be of importance, is calculated by forming the secondary stress range in a very similar way in parallel by the above procedure. The only difference is that terms 1 and 2 are formed by linearization of the stresses through the wall at various locations in the FE model, and that terms 3 and 4 are not considered.

With this procedure, it is possible to attain the 3 goals stated above. It is advisable that the thermal boundary conditions that enter the calculations, are derived from measurements or from considerations of similar conditions in similar geometries.

A METHOD TO COMPUTE THE HIGH CYCLE FATIGUE USAGE IN TURBULENT MIXING ZONES AFTER TEES

If two fluids of different temperatures meet at a tee junction, a turbulent mixing zone near a downstream wall can be formed, leading to rapid temperature fluctuations in the metal surface. If this situation is present for a substantial time duration during steady-state operation, high cycle fatigue damage can be induced and cracks may develop.

For this situation, the numerical method outlined in the following has been applied to assess this type of damage.
• The thermal loading in the mixing zone is defined as a spectrum of temperature differences rather than a distinct value, because the turbulent mixing has a stochastic nature and can be interpreted as a mixture of temperature ranges and frequencies. High temperature differences have low frequencies, and lower ones occur more often, and have therefore higher frequencies. This spectrum can be taken from measurements in turbulent mixing zones for other applications, but has to be scaled to the actual fluid velocity encountered near the interesting location. The spectrum is defined as composed of stepwise discrete classes of temperature differences and corresponding frequencies, or periods, respectively.

• The spectrum of the fluid temperature fluctuations is converted to a spectrum of metal temperature fluctuations by the following formulas for a sinusoidal function:

\[
\Delta T_x = \frac{\Delta T \cdot e^{-\zeta}}{\sqrt{1 + 2 \cdot \beta + 2 \cdot \beta^2}}
\]

whereby:

\[
\zeta = x \cdot \sqrt{\frac{\pi}{(a \cdot t_0)}}
\]

\[
\beta = \frac{\lambda}{\alpha} \cdot \sqrt{\frac{\pi}{(a \cdot t_0)}}
\]

\(\Delta T_x\) = Temperature range in the wall at depth \(x\) (\(x=0\) for surface)

\(\Delta T\) = Temperature-range of the fluid for this spectrum class

\(a\) = Diffusivity (\(= \lambda/c_p/p\))

\(t_0\) = Period of sinusoidal temperature fluctuation for this spectrum class

\(\lambda\) = Heat conductivity

\(\alpha\) = Film coefficient

• The fatigue usage factors for each class in a time interval \(\Delta t\) during the steady-state operation is computed by dividing the number of fluctuations in this class by the number of allowable cycles based on the stress range due \(\Delta T_x\) and using a fatigue curve extending into the high cycle range (\(>10^6\) cycles) for the wall material. The overall fatigue usage factor in the time interval \(\Delta t\) is computed by summing the values over all classes of the spectrum.

• The final usage factor is integrated over the whole time interval of interest for all time increments \(\Delta t\). If the fluid temperature difference \(\Delta T\) is a constant over time, the integration of course is a simple multiplication by the time ratio \(t/\Delta t\).

This method yields a usage factor for high cycle fatigue which can be combined by a corresponding usage factor for the low cycle fatigue contribution.
CONCLUSIONS

- Two methods have been presented to assess thermal fatigue in piping tees.
- A method to assess the low cycle fatigue for complicated thermal loadings with moderate cost impact has been shown. The method uses a tuned accuracy approach, thereby using more exact stress determinations where it is reasonable, in order to reduce conservatism, and using bounding stress determinations for the thermal loadings with contain more uncertainty.
- A second method addresses the possible damages due to high cycle fatigue. A thermal loading spectrum approach gives an indication whether high cycle fatigue due to a mixing zone can be a problem or can be excluded from further consideration. The method can also be used to assess measures necessary to improve the mode of operation during steady-state conditions.
- Actual cases have been encountered and treated, where these methods led to the proof of acceptable fatigue situations.

REFERENCES