

Temperature Variations in preinsulated DH pipes - Low Cycle fatigue (1996 N6)

Background

Design of District Heating Pipes with Respect to Temperature

The development in construction principles for preinsulated pipes for district heating is clearly moving towards pre-heated or pre-stressed systems or systems where the cold spring effect is utilised not only in bends and curved lines but also in straight pipes (cold laying and self-induced pre-stressing).

Utilisation of the cold spring effect is not new. Most codes for design of piping systems under pressure assume that the formal yield stress in bends is approximately twice the yield stress for steel. Therefore the real stress range will be +/- the yield stress after the initial self-induced pre-stressing.

When the stress range is larger than twice the yield stress the system is said to be in the low cycle fatigue range. In the low cycle fatigue range the analysis should in principle be done based on the strain range, but in practice the calculations are normally made with a linear elastic model and formal stresses. When evaluating these formal stresses, which can be larger than twice the yield stress, a correction has to be made because in practice the strain will be larger than calculated by the elastic model. This correction can typically be included in the fatigue curve.

The use of pre-heating or pre-stressing does not increase the allowable stress range, but it reduces the forces and displacements in the system.

As this design method is based on low cycle fatigue design the number of load cycles has to be limited, and in codes for pressure piping a figure of 7000 complete load cycles is normally assumed (one full temperature cycle per day in 20 years).

For each °C a straight pipe is heated the axial stress will increase $1.2 \times 2.1 = 2.52 \text{ N/mm}^2/\text{°C}$. The minimum yield stress for mild steel used for preinsulated pipes is typically 235 N/mm^2 . This means that heating more than 93 °C can

give yield over the entire cross section of the pipe.

Accepting yield over the entire cross section is quite new and unique for district heating pipes. Temperature induced axial stresses are low in most other piping systems, and therefore it is not a serious limitation in these systems to have restrictions in the codes not allowing yield over the entire cross section.

However, for preinsulated district heating pipes many designers are beginning to accept the concept of self-induced prestressing combined with very high nominal axial stress ranges. The maximum acceptable stress range depends very much on the predicted number of complete load cycles in the lifetime of the systems, and as the design method is quite progressive the loads should on the other hand be estimated quite conservatively. Also the safety factor of the design will solely be applied on the loads.

The maximum temperatures in a systems is normally known quite well due to the safety equipment on the boilers, although peaks exceeding the maximum design temperature with up to 10 °C may happen e.g. in case of failing controls or sudden increase in combustion in waste incineration.

Another more serious problem is the variation in temperature.

The temperature in the systems will often vary during the operation in order to meet the heating demand, but the unintended variations in temperature are more difficult to estimate, and they are the most serious threat to the lifetime of the systems when speaking of low cycle fatigue.

Intended variations in the systems are typically:

- Planned variations due to normal use of the system.
- Variations at the boilers in order to vary the production.
- Variations in house connection due to e.g. night time set-back or shut-off by the consumer and other variations due to consumer behaviour.

Unintended variations are typically:

1. Cold plugs after start-up or changes in production e.g. in boiler central with cascade coupling.
2. Variation due to sudden changes in the calorific value during combustion of waste.
3. Hunting (pendling) in control equipment.
4. Hot plugs at consumers installations.

The examples show that the trend to conserve energy by more sophisticated control and operation also increases the risk of increased temperature variations.

On the other hand the number of temperature cycles should be limited when utilising prestressing or self -induced prestressing preinsulated piping systems.

Summary

In Denmark, Germany, Korea, The Netherlands and Sweden at 17 district heating sites the supply and return pipes have been fitted with temperature measuring equipment and data loggers.

There are 8 measuring sites at consumers with pipe diameters from 28 to 219 mm and 9 measuring sites at supply stations (production or heat exchanger stations) with pipe diameters from 356 mm to 1219 mm.

At each of these sites the temperature has been logged every minute for a period from 81 to 365 days - more than 5000 days or 7.6 million measurements all together.

For each site the measurements have been sorted by the so-called rainflow method forming a matrix, where the number of cycles are sorted according to range ($\Delta T = 1, 2, 3 \dots 110$ °C) and mean temperature. An overview of the results is given for $\Delta T = 5, 10, 15 \dots 110$ °C.

The matrixes have been analysed using the Palmgren-Miner cumulative damage theory,

and the number of full temperature cycles, N_0 , have been calculated for low cycle fatigue curves with different slope constants, b . In the calculations the measurement period of approximately 1 year have been converted into a 30-year period by simple linear progression.

The effect of different measuring frequencies is discussed together with an evaluation of the results.

For each site the measurements are graphically illustrated with:

1. A graph showing all measurements.
2. The matrix showing the number of temperature cycles in relation to mean temperature.
The number of full temperature cycles corresponding to a 30-year period for slope constants $b = 3, 4$ and 5 for a common reference temperature $\Delta T = 110$ °C and for $\Delta T = T_{\max} - 10$ °C where T_{\max} is the maximum temperature measured at the pipe concerned.
3. A logarithmic graph showing the number of cycles as a function of the temperature range.
4. A graph showing how the different temperature ranges contribute to the cumulative damage.

Conclusion

The following conclusions can be drawn from the project:

1. The curves from the 17 measuring sites are very different.
2. There is a big difference between main lines and house service connections.
3. The largest number of full temperature cycles is at the consumers.
4. At the consumers the largest number of full temperature cycles is always at the return pipe.
5. A consumer on a high temperature system can cause more damage than one on a low

- temperature system.
6. Low temperature systems will other things being equal have smaller cycles than a high temperature systems.
 7. At the production sites there is a tendency that the largest number of full temperature cycles is at the supply pipe.
 8. The number of full temperature cycles depends on b. (b is the slope of the fatigue curve).
 9. The large peaks have the greatest influence (specially for b = 5).
 10. The small peaks have greater influence for b = 3.
 11. A sampling frequency of 1 min. is acceptable.
 12. A measuring period of one year is acceptable in the assessment of the stress from temperature over a 30-year period.

A summary of the calculated number of full temperature cycles is given in the tables below for the reference temperature $\Delta T_{ref} = 110 \text{ }^\circ\text{C}$.

It shall be noticed that the greatest values is at the consumers return pipe and the smallest at the return pipe at the productions sites. The difference is significant.

The largest values of full temperature cycles calculated for b = 3 are within the range specified in the guideline in the Danish Standard for DH pipes, see chapter 3.

These values are for b = 3 :

- 100 - 250 full temperature cycles for large main pipelines
- 250 - 500 full temperature cycles for ordinary distribution pipelines
- 500 - 2500 full temperature cycles for house service connections

For the time being there is therefore no basis for changing these recommendations. The same recommendations are used in a draft European Standard for design and installation of preinsulated bonded pipes for district

Supply			
Maximum	Minimum	Average	Production
b = 3	17	136	365
b = 4	4	42	102
b = 5	1	18	37

Return			
Production	Minimum	Average	Maximum
b = 3	2	7	14
b = 4	0	1	1
b = 5	0	0	1

Supply			
Consumer	Minimum	Average	Maximum
b = 3	7	139	578
b = 4	2	55	308
b = 5	1	31	197

Return			
Consumer	Minimum	Average	Maximum
b = 3	35	429	1050
b = 4	4	111	379
b = 5	1	37	157

Table 1.1: Numbers of full temperature cycles for $\Delta T_{ref} = 110 \text{ }^\circ\text{C}$ and b = 3, 4 and 5.

heating, though the lower limit for house service connection are set at 1000 instead of 500.

Lower figures should only be used, if the designer has a firm knowledge of the temperature history to which the system in question will be subject. Even if such knowledge is available conservatism is advisable, because there might be suspicion that the expectations of the operating personnel are not in accordance with the realities. Furthermore it is important to be aware of systems with irregular operational conditions.

The information on where the largest number of full cycles occur should cause that more attention is paid to details like the fatigue life of branch connections to consumers, especially

the tee where the branch is connected to the main pipe.

The operating personnel should use the results to evaluate the mode of operation and especially the impacts on the DH system from the consumers. Some temperature variations are due to energy saving measures and the systems should of course be designed to withstand these variations. However, many of the temperature curves more than indicate that many of the large temperature variations occur due to inexpedient instrumentation at the consumers, thus causing an unnecessary wear of the system.

Finally, it must be mentioned that although the Palmgren-Miner cumulative damage theory is a generally accepted theory for fatigue analysis there is a strong suspicion that a temperature history with few large temperature cycles is more harmful than a temperature history with many small variations, which give the same number of full temperature cycles.

This is especially true for preinsulated bonded pipes. If for example a change of direction is designed with foam cushions in order to absorb the expansion of e.g. $\Delta T = 110\text{ }^{\circ}\text{C}$, it is more or less evident that the construction detail better can absorb a large number of small temperature variations than a limited number of very big variations.

When the project originally was described it was expected that after processing the temperature measurements would give figures for full temperature cycles, which, without any further consideration, could be used as a design basis when designing bends, tee and

other district heating components in the low cycle fatigue range.

However, even though the project has added considerably to the knowledge of temperature variations it has not given the final answer, but raised a number of new questions.

The most important question is the choice of SN-curve. It is very important that the same SN-curve is used for calculation of the number of full temperature cycles and as limit state for the fatigue analysis, but which curve is most relevant for buried preinsulated pipes, $b = 3, 4$ or 5 ?

The second question is the conversion into full temperature cycles. From many of the temperature spectra it is seen that very many of the temperature cycles must be in the high cycle fatigue range and it might therefore not be correct to convert them into few cycles in the low cycle fatigue range.

A third question is the assumption that the stress differences are proportional to the temperature differences.

These questions can probably be answered by applying the measured temperature histories to elasto-plastic models of buried preinsulated pipes using "real" fatigue curves, and it is among other things the intention to examine these questions in an expected continuation of the project under the IEA District Heating and Cooling Project, Annex V.

The measured and processed data make up close to 450 Mb and will be burned on CD-ROM so that it is available for further studies.