Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 116 (2017) 343–350

Energy Procedia

www.elsevier.com/locate/procedia

The 15th International Symposium on District Heating and Cooling

Identification of Individual District Heating Network Conditions using Equivalent Full Load Cycles

Jooyong Kim[a,]* and Ingo Weidlich[b]

[a]*Korea District Heating Corporation (KDHC), Yangjae-daero 781, Gangnam-gu, Seoul 06340, Korea*
[b]*HafenCity University (HCU), Überseeallee 16, 20457 Hamburg, Germany*

Abstract

Repeated loading in district heating networks is occurring inconstantly. There are small and great load amplitudes in the system. As small load amplitudes are usually observed more frequently than great load amplitudes, their accumulation with respect to great load amplitudes is of common interest. A growing share of renewable energy can be noted in energy markets. Because of this, flexible operation of combined heat and power plants is necessary. For the connected district heating network this means additional temperature amplitudes in the system, causing higher stresses for the network. Repeated loading in the system has to be considered in the fatigue analysis. For a suggested lifetime of a district heating network of 30 years, an estimated number of cycles for the temperature load were accumulated for standardization. Nevertheless a longer lifetime than 30 years for district heating pipes is expected in the district heating sector, which also means higher cyclic loading. Due to individual operation parameters and individual network conditions, the equivalent action cycles are expected to be different at every element in the network. The paper is based on a review on damage accumulation theories that may be used for district heating systems regarding future developments. Some examples are shown for equivalent full load cycles for different locations in district heating networks.

Peer-review under responsibility of the Scientific Committee of The 15th International Symposium on District Heating and Cooling.

Keywords: Load cycles; Damage accumulation theory; Woehler-curve; Ageing theories; Network condition

* Corresponding author. Tel.: +82-2-2040-1255; fax: +82-2-2226-3443.
E-mail address: jykim43@kdhc.co.kr

1876-6102
Peer-review under responsibility of the Scientific Committee of The 15th International Symposium on District Heating and Cooling.
10.1016/j.egypro.2017.05.081

Nomenclature

ΔT_{ref}	reference temperature increment
n_i	load amplitudes
N_i	maximum number of load cycles until failure
χ_i	damaging exponent or material exponent
t_i	times on different temperatures
T_i	fatigue life

1. Introduction

Ageing theories are generally applied in order to predict the failure or failure rates of components and technological systems. These theories correlate the ageing of pipes, joints, bows, branches, etc. with physical parameters, such as the load regime (mechanical, thermal).

These models assume an interaction between the condition of all system components (e.g. media or casing pipe, expansion pads, insulation) and physical loads (mechanical, thermal). Thus, prognosis techniques for the ageing of ductile DH components are widespread. On the other hand, scientific researches on fatigue life of non-ductile system components, such as the insulation or expansion pads, are sparsely given. Resulting, predictions on the residual lifetime of DH systems are still precarious. The focus of prognosis techniques for ageing has been and still is on ductile materials (metals) regarding single components and parts of DH systems. Fortunately, within DH systems, these materials are widely utilized for the medium pipe.

2. Load Spectrum

Since energy markets and infrastructure are important background for the wealth and industry of a society they are influenced by national and global political decisions. For example No. 7 of the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development of the United Nations, set officially into force the 1st January 2016, is “Affordable and clean energy”. Thus worldwide transformation of the energy sector is expected with a growing share of renewable energy. For the connected district heating network this means lower supply temperature for the integration of low exergy heat sources and the reduction of heat losses. On the other hand the balancing of renewable energy with the heating grid by e.g. “Power to Heat” technologies is an option that may lead to additional repeated temperature loading of the system. These reverse acting effects are not well understood today.

Nevertheless repeated loading in today’s district heating systems has to be respected in the fatigue analysis. In 1996 a suggested lifetime for preinsulated bonded district heating pipes was estimated to be 30 years and equivalent full load cycles were derived in [1] according to table 1.

Table 1. Equivalent full load cycles [1].

Pipe Type	Equivalent full load cycles for 30 years
Large Main pipelines	100-250
Ordinary distribution pipelines	250-500
House service connections	500-2500

A longer lifetime than 30 years for district heating pipes is expected in the district heating sector [2], which also means higher cyclic loading. In Europe the experiences from [1] were implemented by the EN13941 standard [3]. However most district heating networks are subjected to historical development and many different types of pipe systems may be found, which provide different ageing behaviour. Thus accurate asset management strategies are difficult to achieve. A survey of the German district heating association AGFW from 2011 came up with estimated lifetime for different pipe systems according to table 2.

Table 2. Estimated lifetime of pipe systems [3].

Pipe system	Minimum expected lifetime	Maximum expected lifetime	Average
Preinsulated bonded pipe	35	70	52.5
Steelcased pipe in pipe	30	80	55
Channel system	48	80	64
Overhead line	50	80	65
Inhouse pipes	50	100	75

Table 2 shows an average expected lifetime for at least preinsulated bonded district heating pipes, which is about 20 years higher than estimated in 1997. This experience was confirmed in other countries in Europe. Because of this current development in the EU-standardization tries to respect this and an increased lifetime of 50 years for preinsulated bonded district heating pipes is discussed, which also means higher cyclic loading. Against this background common equivalent full load cycles for 50 years were introduced according to table 3. The figures are linearly extrapolated.

Table 3. Equivalent full load cycles [4].

Pipe Type	Equivalent full load cycles for 50 years
Large Main pipelines	170-420
Ordinary distribution pipelines	420-840
House service connections	1700-4200

Table 3 and Table 2 refer on a reference temperature increment of T_{ref}=110℃.

Furthermore table 2 and 3 only give a general characteristic for district heating networks. Due to individual operation parameters and individual network conditions the equivalent action cycles are expected to be different at every element in the network. This leads to the evidence that accurate life-cycle-analysis has to be more precise because only rough estimated load spectra are available today. An element based approach, that also respects today operation characteristics should be developed.

3. Incremental Damage

Basing on Woehler-fatigue tests (see Fig. 1), Palmgren-Miner formulated the most commonly utilized “linear” damage accumulation theory. The basic assumption of this theory states, that arbitrarily occurring loads (stresses) with different amplitudes n_i can be combined, consuming a certain percentage of the fatigue life N_i (N_i is the maximum number of load cycles until failure in a constant amplitude test). Thus, failure occurs for

$$\sum n_i / N_i = 1 \tag{1}$$

The very simplified character of this assumption however leads to major deviations of the Palmgren-Miner rule. Thus, defects for $\sum n_i/N_i \approx 0{,}2$ have been reported, whereas some components were in operation for $\sum n_i/N_i \approx 10$. Thus, different refinements on this approach have been formulated.

Against this background, an elongation of the Woehler-curve considering the effects of very low loads on the fatigue of a component are suggested (Fig. 1).

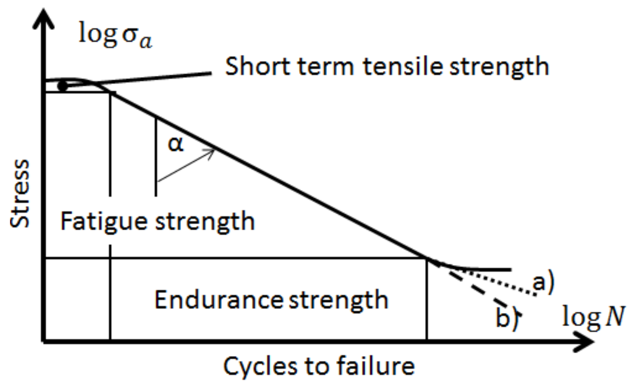


Fig. 1. Woehler-curve of a ductile component;
a) Palmgren-Miner elementary; b) Palmgren-Miner modified

These modifications are basically double linear damage rules:

- “Palmgren-Miner elementary” elongates the curve of the fatigue strength into the domain of endurance strength maintaining its gradient,
- “Palmgren-Miner modified” elongates the curve of the fatigue strength into the domain of endurance strength diminishing its gradient is diminished

Basing on the Palmgren-Miner rule, a number of non-linear damage accumulation theories have been developed, mainly distinguished by the calculation of the damaging exponent or material exponent [5]-[7]. Thus, failure for a ductile component occurs for

$$\sum \left(\frac{n_i}{N_i} \right)^{\chi_i} = 1 \tag{2}$$

For illustration, a two stage damage accumulation shall be described in detail:

- At first, the component is strained with n_1 amplitudes, generating an according stress σ_1. The damage accumulation of this phase is described by $(n_1/N_1)^{\chi_1}$.
- Secondly, the amplitude changes to n_2 amplitudes, generating an according stress σ_2. The damage accumulation of this phase is described by $(n_2/N_2)^{\chi_2}$.
- Finally, failure occurs for $\left(\frac{n_1}{N_1}\right)^{\frac{\chi_1}{\chi_2}} + \left(\frac{n_2}{N_2}\right) = 1.$

Given that results of multi-staged material tests are available, the accuracy of these non-linear models is quite good. However, the accuracy is independent from the order of the experiments performed.

Finally, besides mechanical loads, temperature regimes affect the fatigue of ductile materials and components of DH systems [8]-[10]. An easy approach of considering the superposition of creeping due to temperature regimes and mechanical load is the combination of the Palmgren-Miner and Robinson rule. Instead of mechanical stresses, dwelling times on different temperatures t_i consume a certain percentage of the fatigue life T_i (T_i is the maximum dwelling time at the temperature level until failure). Thus, failure occurs for

$$\sum n_i/N_i + \sum t_i/T_i = 1 \tag{3}$$

Unfortunately, creeping fatigue and mechanical fatigue are interacting. Therefore, defects are occurring for $\sum n_i/N_i + \sum t_i/T_i < 1$.

4. Individual District Heating Network conditions

Hence different approaches are available for the description of the fatigue of district heating pipe systems. Nevertheless calibration of the models is one mayor issue concerning the accuracy of the results. The complex methodologies made the Palmgren-Miner rule winning through the other theoretical approached. Furthermore measuring data from the field must be available.

For the evaluation of Korean conditions temperature data was collected in different locations in the network of Seoul. Figure 2 gives some examples for temperature data.

Temperature data was collected for 12 months in 9 different locations with 1-hour measuring frequency.

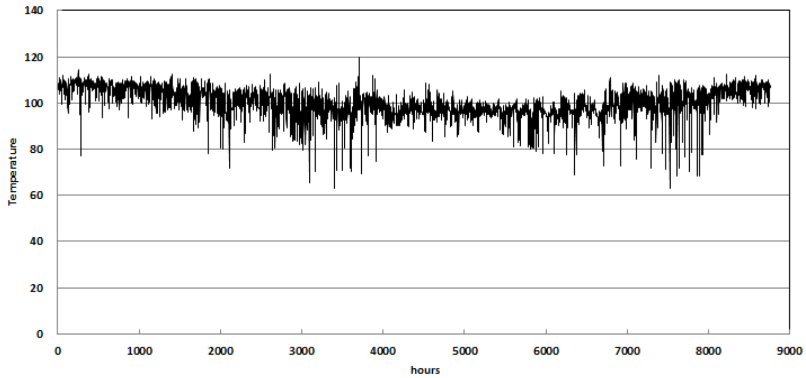
- P01, P02 and P03: Production plant with heat exchanger for CHP, heat-only boilers and/or accumulator tanks. The outside diameter of steel service pipes are 864mm, 864mm and 914mm, respectively.

- B01, B02 and B03: Booster stations. The outside diameter of steel service pipes are 356mm, 610mm and 711mm, respectively.

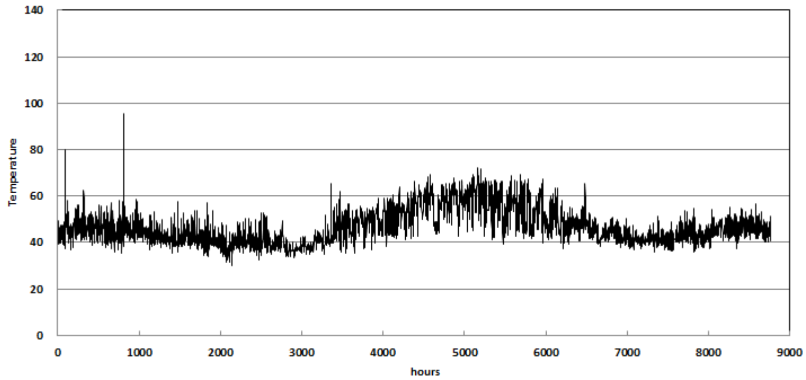
- H01, H02 and H03: House connections. The outside diameter of steel service pipes are 114mm, 114mm and 89mm, respectively.

"S" and "R" after the location number indicate the supply and return pipes for each location.

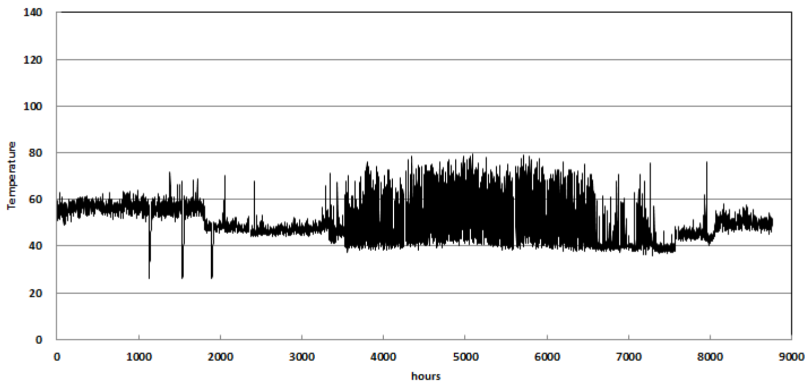
The equivalent full load cycles were determined according to Table 4. The rainflow counting method has been used to calculate the number of cycles with the range increments of 5℃. □Tref=110℃ has been chosen as reference temperature.



(a) P02-S



(b) B03-R



(c) H02-R

Fig. 2. Examples for temperature data in Seoul

Table 4. Equivalent full load cycles in the field.

Location		Equivalent full load cycles for 12 months	Linearly extrapolated for 50 years
Plant	P01-S	0.70	35.21
	P01-R	0.47	23.41
	P02-S	2.10	105.06
	P02-R	0.56	28.02
	P03-S	0.13	6.38
	P03-R	0.23	11.58
Booster Station	B01-S	1.24	61.79
	B01-R	0.83	41.36
	B02-S	0.73	36.55
	B02-R	0.41	20.57
	B03-S	0.78	39.10
	B03-R	1.22	60.78
House connection	H01-S	1.16	58.02
	H01-R	2.02	101.01
	H02-S	0.81	40.37
	H02-R	5.67	283.71
	H03-S	1.12	55.76
	H03-R	1.96	97.85

The determined equivalent full load cycles for boost stations and house connections are very small in comparison with other literature. It is caused by measuring frequency of temperature. In this study, the frequency is 1- hour. Generally the number of full load cycles increases according to decrease of measuring frequency [1].

Small temperature level and high reference temperature also could be a cause of small equivalent full load cycles. In this condition, only small lifetime of the pipe is consumed.

5. Conclusions

The investigation showed that individual district heating conditions may be monitored at different locations in the network, which lead to more precise evidence on the load spectrum to be evaluated for accurate life time assessment. Although the determined data is in the general range of values given in the literature, the investigation showed that general data from literature cannot be recommended for precise life time assessment in district heating grids.

Regarding the needs of DH utilities, for forecasting defects of DH components as well as their residual lifetime are necessary for a tailored asset strategy of these systems. An element based assessment approach that includes data from several locations in a district heating network seems to be very promising for the DH sector. Transition to new energy concepts and operational modes in district heating underlines the demand of assessment strategies, which also respects today and future operation characteristics.

Against this background, the examination of loads occurring in DH systems in situ could give a better understanding on the ageing of components. Furthermore, an integrated concept taking DH components interacting with each other into account seems to be forward-looking as well.

References

[1] P. Randløv, K.E. Hansen, M. Penderos "Temperature Variations in Preinsulated District Heating Pipes, Low Cycle Fatigue", International Energy Agency, IEA District Heating and Cooling, ISBN: 90-72130-97-9, No. 6, 1996

[2] Hoffmann H.-W., Grage T., Röse A., "Remaining useful life of pre-insulated bonded pipes", Euroheat&Power journal, 31. series., volume 3, 2002

[3] AGFW FW 114, "Strategies for maintenance and planning of rehabilitation", AGFW | Energy efficiency association for heat, cold and CHP, 2013

[4] prEN13941, "Design and installation of pre-insulated bonded pipe systems for district heating — Part 1: Design", CEN/TC 107, 2015

[5] Miner, M. A.: "Cumulative damage in fatigue", Journal of Applied Mechanics, 1945.

[6] Bernard Conolly, M.; Bui-Quoc, T.; Biron, A.: "Multilevel strain controlled fatigue on type 304 stainless steel", Transactions of the ASME, 105, 1983.

[7] Hashin, Z.; Laird, C.: "Cumulative damage under two level cycling", Fatigue of Engineering Materials and Structures, 2, 1980.

[8] Lee, Y. S.; Lim, J. S.; Kwon, Y. N.; Moon, Y. H.: "Fatigue characteristics of small radius pipe fabricated by pipe bending with induction local heating", Procedia Engineering 10, 3333–3338, 2011.

[9] Knowles, D. M.: "R5 High Temperature Creep-Fatigue Life Assessment for Austenitic Weldments", 1st International Conference on Structural Integrity, Procedia Engineering 86, 315 – 326, 2014.

[10] Webster, G. A.; Nikbin, K. M.; Chorlton, M. R.; Celard, N. J. C.; Ober, M.: "A comparison of high temperature defect assessment methods", 1998.