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Importance of Increased Knowledge on Reliability of District Heating Pipes

Tymofii Tereshchenko*, Natasa Nord

Norwegian University of Science and Technology (NTNU), Department of Energy and Process Engineering, Kolbjørn Hejes vei 1d, NO-7491 Trondheim, Norway

Abstract

District heating (DH) is a service that satisfies customers' demands in the areas of heating, hot water preparation and the supply of heat to ventilation systems. Three generations of DH distribution technology are already in operation; the next generation of low temperature district heating (LTDH) will soon be upon us. However, without a reliable distribution system, it is quite difficult to utilize the concept of LTDH and remain competitive in the energy market. For that reason, this paper provides a comprehensive review of pipe reliability issues associated with DH systems. In this regard, discussions have been concentrated on factors leading to pipe degradation processes. Three groups of factors, namely physical, environmental and operational, were identified and examined. Allowable heat losses in the DH network and the creation of a pipe failure database were also discussed. The information collected in this paper leads to a better understanding of pipe degradation mechanisms and can be used as a tool for pipe failure prevention.

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Keywords: District heating; distribution system; pipe reliability; pipe accidents.

1. Introduction

District heating (DH) is an energy service based on moving heat from available heat sources directly to customers for immediate use [1]. This service is flexible and allows renewable energy sources to be utilized as a primary energy input. In turn, this leads to decreasing CO_2 emissions and energy savings. Currently three generations of DH distribution technology are in use. The research society is moving towards the fourth generation of low temperature

* Corresponding author. Tel.: +47-92-55-33-22; fax: +47-73-59-38-60.
E-mail address: tymofii.tereshchenko@ntnu.no

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district heating (LTDH) [1]. The development of LTDH is impossible without a reliable distribution system. It is well known that a DH system is rarely developed from a scratch and huge DH networks are a result of extension and merging. Therefore, it is highly desirable that old DH pipes provide reliable operation and do not influence heat distribution through unpredicted failures.

In order to stay competitive in the energy market, DH should provide a reliable heat supply to customers throughout the year. In reality, this is not an easy task. Different malfunctions and accidents associated with the operation of a DH system and the distribution of heat lead to a decrease in the security of supply. The possibility of losing the heat supply is particularly dangerous during the winter season in countries with extremely low outdoor temperatures.

Accidents in the DH networks are inevitable and can occur for various reasons: wear and tear, equipment failures, pipeline breaks and so on [2]. Accidents lead to financial and capital losses, incurred by the repair and restoration of the network. Failures reduce the reliability of the network due to lowering of the pressure or due to interruption of the DH supply, which ultimately leads to customers' dissatisfaction. Sensitive customers, such as industrial centres, governmental buildings and hospitals, are most likely to be affected [3]. One serious problem in DH supply is deterioration of the distribution network; this can occur for different reasons. Pipe deterioration can lead to pipe breaks and leaks, which may result in a reduction in the water-carrying capacity of pipes and lead to substantial repair costs [4]. Pipe breaks incur large direct and indirect economic and social costs, such as water and energy loss, repair costs, traffic delays, and factory production loss due to inadequate DH service interruptions. Unfortunately, it is difficult to locate breaks in the pipe network because most parts of the pipes are buried underground and inaccessible [5]. Component failures in flow networks lead to disappearance of flow capacity, and the expected level of the throughput flow may not be guaranteed. As a result, the quality of service received from the network can be seriously affected [6].

With their further development, it is important to provide high reliability and availability of DH systems for existing and future customers. Piping failures can be prevented through reliability measures and these are subject to improvement.

Nomenclature

HL	heat losses
PL	length of DH pipelines
Q_h	heat production in the DH system
$Q_{h,f}$	heat production affected by pipe failures
Q_{loss}	heat losses in the DH system
ΔQ	decrease in heat delivery due to pipe failures
$\Delta Q_{h,f}$	relative deviation in the heat delivery due to pipe failures
a	model coefficient
b	model coefficient
f	pipe failure factor

2. Factors affecting pipe reliability

In their work, various researchers have tried to identify the main causes leading to pipe deterioration [7-9]. Al-Barqawi and Zayed [10] classified three groups of factors resulting in pipe degradation; these are presented in Table 1.

Table 1. Factors leading to water system deterioration.

Physical factors	Environmental factors	Operational factors
Pipe age and material	Pipe bedding	Internal water pressure
Pipe wall thickness	Trench backfill	Leakage
Pipe vintage	Soil type	Water quality
Pipe diameter	Groundwater	Flow velocity
Type of joints	Climate	Backflow potential
Thrust restraint	Pipe location	Operational and maintenance practices
Pipe lining and coating	Disturbances	
Dissimilar metals	Stray electrical currents	
Pipe installation	Seismic activity	
Pipe manufacture		

Many of the factors listed in Table 1 are not readily measurable or quantifiable. Physical mechanisms that lead to pipe breakage are often very complex. Moreover, the quantitative relationships between these factors and pipe failure are often not completely understood [11, 12]. The most commonly assumed factors for a DH distribution network are described below.

2.1. Age and installation period

DH technology was first put forward in the middle of the nineteenth century in the US and in the early twentieth century in Europe. The differing launching periods for DH systems in Europe indicate that the pipes used in the systems can have been installed in different periods. In France, for example, first generation DH systems with steam as a carrier are still in use. It has been found that the construction period can affect pipe durability [13]. Different types of pipes are used and sometimes older pipes have less tendency to fail than their younger counterparts. Further, only several pipes can remain under the ground after four repairs, since pipe records are unable to provide accurate ages of pipes [14]. When the age of piping exceeds 30 years, the frequency of damage increases, and the technical conditions of the pipeline become the main reason for the formation of defects [15].

2.2. Corrosion

Corrosion is the main reason for pipe replacements [16] and structural deterioration [17]. As indicated in [15], the failures of pipelines due to corrosion mechanisms constitute 30 – 40% of all damage to these pipelines. Metal pipe corrosion pitting is a continuous and variable process. Under certain environmental conditions, metal pipes can become corroded based on the properties of the pipe, soil, liquid properties and stray electric currents [18]. Corrosion deterioration mechanisms can be divided into two types: internal and external. Internal corrosion is caused by different characteristics of transported water. Poor water quality can cause internal corrosion of the pipelines and substations and may block and weaken the functioning of the controlling and metering devices in the entire DH system [19]. Different level of water pH-value, oxygen content or bacteria can be the reasons for this process. Meanwhile, external corrosion occurs with pipes sensitive to soil composition, moisture and aeration. These can be described as aggressive environmental conditions. Corrosion occurs at apparently random locations on a pipe [20], weakening it by decreasing the material’s thickness and by creating stress concentrations [21]. However, not all pipes used in DH are exposed to corrosion. For example, flexible pipes [1] made of polymer material such as PolyEthylene (PE) are corrosion resistant. Nevertheless, they are sensitive to the high temperatures used in DH systems. Therefore, manufacturers normally limit the maximum supply temperatures in order to extend the pipe’s service life.

If the service pipe fails, the escaping hot water may cause extensive damage to the surrounding area. Repairs will then include replacing part of the service pipe, resulting in an interruption to service, which will leave end users without a hot water supply. Aside from the inconvenience caused to end users, the repair costs will be high. This is especially so in the case of larger diameter pipes [22].

2.3. Diameter

The failures associated with pipe diameters can be explained by the thickness of pipes. Small pipes have lower wall thickness, resulting in reduced pipe strength. The high probability of pipe breakage was found in network of small pipes [23]. In the study related to damage caused by earthquakes [21], pipe diameter was identified as an influence on the number of breaks and failures in pipelines. Pipes with small diameters experienced more damage than those with large diameters. The influence of pipe diameter determines the total area from which a failure point may occur. The pipe may be thought of as being developed from a simple plate of area πDL [24]. Smaller pipe sizes, of lesser safety significance, have much higher failure rates [25].

2.4. Pipe length

The dependency of failure probability on pipe length was also acknowledged [24]. The failure probability increases directly in proportion to length; for example, a 1.0 m length of pipe bears a 10-times greater failure probability than a 0.1 m pipe. This assumption was based on uniform distribution of weak spots along the pipe. The number of weak spots such as bends, junctions, welds, flaws increases proportionally with the increase in pipe length.

2.5. Pipe material

It is no surprise that pipe service life is dependent on the pipe material used for hot water distribution. Study of the historical development of DH systems in the world indicates that the use of different types of distribution pipes was due to different materials being available during certain time periods. DH distribution technology can be classified in three generations [1]; the first generation of DH technology used steam as a carrier; while the second and third generations employed water as a carrier to deliver heat. Nowadays, the temperature level in DH networks has decreased; however, systems based on first generation principles are still in operation. Therefore, it is possible to distinguish different pipe types used in DH systems. The traditional metal for pipes is steel. Pre-insulated rigid steel pipes have the largest share in DH systems and a number of publications are devoted to this type of pipe [26, 27]. New developments in the DH field have introduced pre-insulated rigid polymer pipes and pre-insulated flexible PE pipes with a life span of more than 30 years [28]. At the same time, copper pipes are also in use in customer substations [29].

2.6. Dissimilar metals

In general, dissimilar metals could be employed when DH systems of different ages are connected. Welded dissimilar metal joints can have a remarkable effect on the plant’s availability and safety and lead to leakages and pipe cracking [30]. Dissimilar metal joints can be installed in pipes with large diameters. The study devoted to the safety of nuclear plants found that the probability of cracked welding occurring is rather high [31].

2.7. Seasonal variation

Accidents mainly occur during the winter in DH systems. The main reason is that the largest heat demand associated with DH occurs at this time of the year, while extreme outdoor temperatures weaken the pipes, particularly if they are exposed to the cold without adequate insulation.

2.8. Soil conditions

Soil conditions affect eternal corrosion rates and play an important role in pipe degradation [32]. The rate of corrosion is affected by the properties of the soil, in particular its pH content, redox potential, existence of sulphides, water resistance table [33], and by the soil type: clay, sand or peat soil [34]. This is relevant for the DH pipes of the third generation of distribution technology [1], which are buried in the ground.

2.9. Previous failures

The number of previous failures is a significant factor in predicting future failures [35]. Pipes in the same location often have the same age and materials and are laid with the same construction and joining methods. Pipes in the same location are also likely to be exposed to the same external and internal corrosion conditions [32].

2.10. Nearby excavation

Nearby excavation, together with seismic activities, affects pipe integrity. A detailed description of these processes was provided in [36, 37]. Contact during excavation usually occurs when an individual piece of operational excavating equipment breaks the pipe. It was found that the risk due to corrosion is significantly less than the risk due to third-party intervention [7, 34]; research work carried out in the UK showed that third party activities have a high probability of causing pipe failure [38].

2.11. Pressure

The pressure change due to the breakage depends on the ratio of flow rate through the pipe versus flow rate through the break. If the losses of water are very small, compared with the mainstream through the pipe, then pressure fluctuations due to the break would be negligible [39]. The possibilities of pipe ruptures due to high pressure in the water distribution networks, together with the hammer effect, were acknowledged in [40]. The analysis found a high risk of pipe damage that leads to water supply interruptions. The analysis on the DH network found that, under some conditions, pressure peak could exceed the value used in hydraulic tests, but the possibility of pipe damage still remained high [41]. The pressure head in the distribution network has a direct influence on the frequency of pipe failure [42]. Further, water hammering due to an immediate change in velocity of the carrier in DH systems directly affects joints [1, 7]. This situation can occur when distribution pumps are tend to be open rapidly against closing of valves located on pump outages or when predefined valve opening time is ignored [1]. The researchers in [43] identified the possibility of pipe ruptures depending on operational pressure in a DH network. According to results, the rupture probability increases linearly up to a pipe thickness of 3 mm. The plastic deformation will occur from thicknesses of 3 mm to 1 mm. In the case of thickness being less than 1 mm, the rupture probability increases rapidly.

2.12. Land use

Traffic areas, residential areas and commercial areas are used as a substitute for external loads on pipe [32]. The stresses occurring in DH pipes are complex and originate from a number of sources, including soil loading, ground surface loading (due to traffic) and as a result of temperature changes. The pipe failure occurs either when the stress level exceeds the nominal pipe material strength or when a critical defect develops and leads to degraded pipe strength [20].

2.13. Temperature levels

Improper temperature levels used in DH systems can cause mechanical stresses and thermal strain in distribution pipes. When a carrier pipe is made of steel, which is always the case with rigid pipes, normal operation temperatures are too low to cause any significant creep deformation. However, when carrier pipes are made of polymeric material, as they sometimes are in flexible pipes, creep and thermal expansion are the major issues [1]. Thus, when designing and installing a buried pipeline, which is both pressure- and temperature loaded, one should pay special attention to the extreme temperature variations and hence to the stresses and movements that the pipeline will have to withstand [44]. The joints are highly affected by mechanical stresses due to the large temperature differences whenever the distribution network is in operation or shut off [45]. Temperature fatigue, occurring due to high temperature levels in the DH system, results in high failure probabilities [46, 47]. Moreover, different pipe manufacturers limit the maximum supply temperature used in DH systems to 120 °C.

2.14. Welding

According to the study [48] performed by EuroHeat & Power, the largest number of failures in polymeric DH pipes occur in joints. One of the reasons is bad welding procedure. The annual frequency of failure due to the joints of the outer tube is the highest, compared to damage caused by medium tube joints and damages found by the leakage detection system [45].

3. Discussion

As can be seen, there are many different factors affecting DH pipe reliability. In order to remain competitive in the market and provide a reliable service to customers, the reliability issues should be carefully analyzed. For this reason, it would be wise to collect relevant information about accidents associated with DH distribution system. A comprehensive database must include information that allows pipe failure accidents to be predicted by analytical and statistical methods. Therefore, a good database should include three categories of information. firstly, it should contain information about the pipes at the time of their installation: installation year, type of pipes and materials, diameters, lengths of pipe sections and number of joints. Secondly, data should be included on the operational regimes of the DH system, e.g. temperature and pressure levels, pH-value of heat carrier, and number of water replacements during the year. The last part should include type of failure, date and place, and maintenance measures.

According to Statistics of Norway [49], the heat losses in DH pipes corresponds to 14% on the national level. This can be seen from Fig. 1 and Fig. 2.

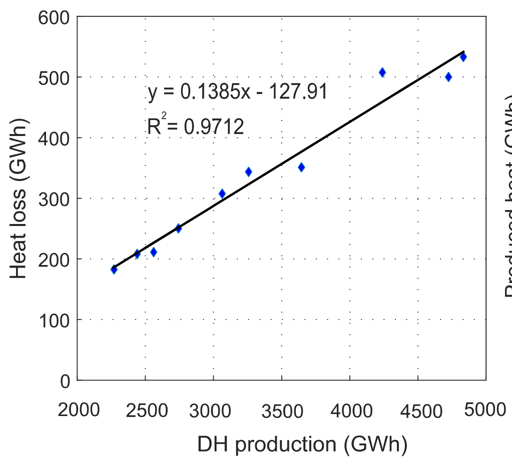

Fig. 1. Dependence of heat production versus heat losses.

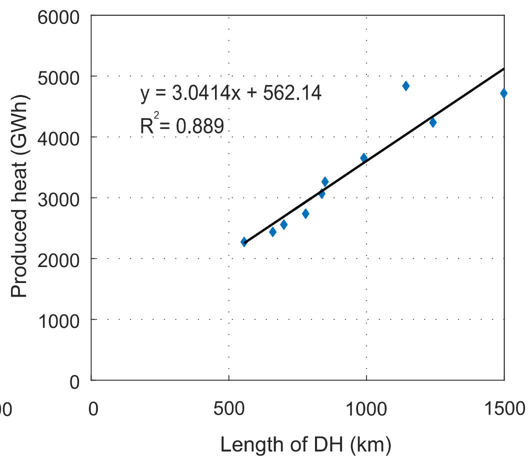

Fig. 2. Dependence of DH pipe length versus heat production.

The presented statistical data may be used to assess the allowed percentage of failures in the DH distribution system. In order to answer this question, let us examine Fig. 1 and Fig. 2. From Fig. 1 it can be seen that the heat losses during the delivery of DH services can be expressed as:

$$HL = 0.14 \cdot Q_h - 127 \quad (1)$$

where HL is heat loss and Q_h is DH heat production. At the same time, the production of heat depending on the length of DH pipelines can be found from Fig. 2 and expressed as:

$$Q_h = 3.0414 \cdot PL + 562.14 \tag{2}$$

This equation shows how much heat can be delivered to the customers, taking into consideration the length of the distribution network. Hence, a and b can be introduced as general model coefficients. Finally, it would be of interest to introduce a pipe failure factor, which has a direct influence on heat delivery.

$$Q_{h,f} = a \cdot PL \cdot (1 - f) + b \tag{3}$$

where $Q_{h,f}$ is heat production affected by pipe failures and f is a pipe failure factor. The decrease in heat delivery due to pipe failures can be estimated as:

$$\Delta Q_h = Q_h - Q_{h,f} \tag{4}$$

The relative deviation in the heat delivery due to pipe failures, can be found as:

$$\Delta Q_{h,f} = \frac{\Delta Q_h \cdot 100\%}{Q_{h,f}} \tag{5}$$

Fig. 3 shows the dependence of the pipe failure factor and the heat percentage of undelivered heat where the length of the distribution system is a parameter.

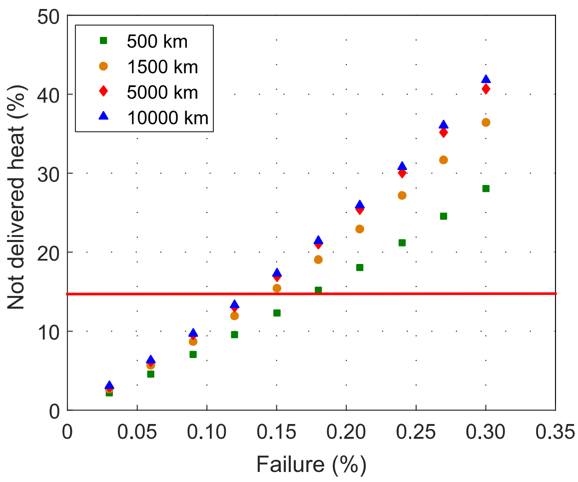

Fig. 3. Percentage of pipe failures versus relative deviation in heat delivery.

Finally, the percentage of pipe failures allowed in the DH system should be lower than the heat losses in the DH system, because if the amount of undelivered heat is too high, the transmission cost can decrease the competitiveness of the DH system:

$$\Delta Q_{h,f} \leq Q_{loss} \tag{6}$$

As it can be seen from Fig. 3, with the increase of the pipe failure factor, the undelivered heat increases. This is especially important for large DH systems, as is shown for 5000 km and 10000 km of DH pipe length. Based on this observation, it can be concluded that the percentage of failure should be less than 10% in order to maintain the decrease in heat delivery due to failures at a lower rate than the heat losses and thus prevent a decrease in the competitiveness of the DH system. That allows reliable heat delivery and security of supply to be provided.

4. Conclusions

A review of factors affecting DH pipe reliability has been carried out. The information collected in this paper leads to better understanding of pipe degradation mechanisms and can be used as a tool for pipe failure analysis. In addition, for proper operation of DH systems, it is desirable to collect the maintenance information about pipe accidents. A good database can provide an immediate start for the analysis of distribution system, help in pipe model creation based on statistical data, lead to accident prevention and increase the security of supply.

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