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STATUS ASSESSMENT, AGEING, LIFETIME PREDICTION AND ASSET MANAGEMENT OF DISTRICT HEATING PIPES

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ABSTRACT

Today District Heating (DH) utilities have to work on status assessments and lifetime predictions while many pipes in the DH systems are close to the expected service lifetime according to the design criteria. Consequently, they have to think about suitable maintenance strategies. Additionally, they must also work on the transformation of their DH systems towards the increased use of renewable energy sources.

Because the ageing of DH pipes consists of several different processes the results of available lifetime prediction models show a large variation, so that reliable predictions require many researchers working on this topic. Therefore, researchers started an international research collaboration platform under the supervision of IEA DHC, where the experience of international researchers and research results from national research projects are being compiled and consolidated. The overall goals of the annex task shared 6 “Status assessment, ageing, lifetime prediction and asset management of district heating pipes” are to improve existing methodology of accelerated ageing, lifetime prediction, status assessment and asset management of district heating pipeline systems to provide district heating companies with valuable knowledge on how to treat their pipe network optimally. Besides the tasks to improve the knowledge of ageing processes and lifetime prediction, there is a need to revise the current standards to gain more realistic results. Asset management tools based on this enable utilities to develop targeted strategies for decarbonizing district heating systems in addition to predictive maintenance. The TS 6 project as well as the scientific approach are presented in this contribution.

***Keywords:* District Heating pipes; ageing; asset management.**

1. INTRODUCTION

In the planning of heating networks, the pipe systems are designed in accordance with the relevant standards, depending on the stresses acting on them. The material properties of the pipelines of a heating network deteriorate over time due to ageing processes taking place during service. To ensure the security of supply in district heating systems, asset management simulations are used to develop suitable maintenance strategies based on statistical ageing models. Besides that, material based ageing models are used to predict the service life of DH pipes based on acting loads in situ. These material ageing models are described in the relevant standards for each type of pipe. Regarding pre-insulated bonded pipes status assessment, accelerated ageing and lifetime predictions of buried pipes are described in EN 253 [1], EN 448[2] and EN 13941 [3]. The findings of Swedish and German research have led to the complete deletion of the previous relation of lifetime at operative temperature and time of accelerated ageing tests of DH pipes in the European Standard [1]. A verified replacement of this testing method is currently not available.

A reliable asset management simulation of DH networks is a strong tool to meet the requirements of high security of supply. When the average age of existing DH networks is increasing, the asset management is becoming more important to ensure the security of supply. Besides that, as described in Reference [4] on the example of a case study in Germany, the remaining service life of DH pipes is important to develop a suitable transformation strategy to fulfil the climate goals in existing DH systems. To improve the existing methods and models for asset management of DH pipes, further investigations in status assessment and ageing mechanisms of DH pipes are needed. Based on the results of these investigations, models for lifetime predictions must be improved as well as to be evaluated through further testing in the field. The future perspective of the

DH system and the piping technologies used, need to be considered for managing the assets from a system-oriented point of view. The TS 6 project is collecting relevant findings and results from researchers to address the described approach. The overall goal of the project is to identify holistic and innovative approaches to improve ageing methodology and calculations for lifetime predictions of DH pipes. To manage the requirements on the pathway to improve the security, economic and sustainability of DH systems the findings of the TS 6 project needs to be migrated in the relevant standards, so that DH operators can use them. project needs to be migrated in the relevant standards, so that DH operators can use them.

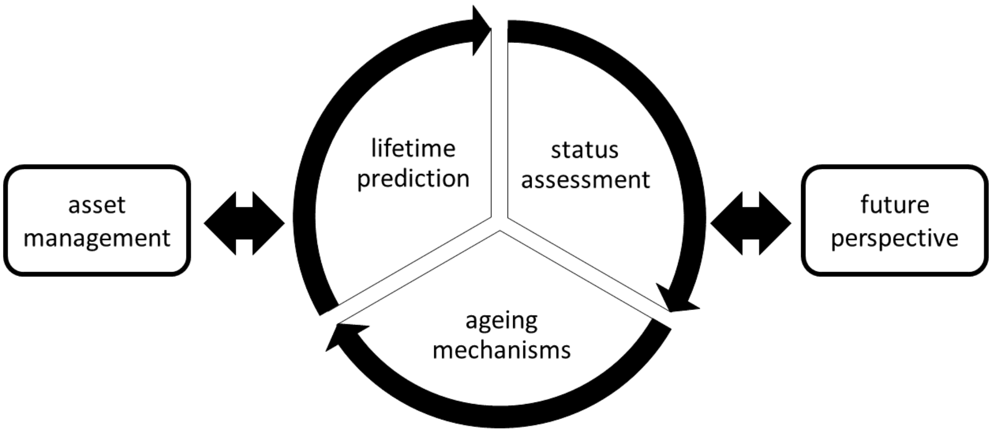

Figure 1. Approach of the TS 6 project to improve asset management in DH based on the needs of DH operators, source: AGFW.

Based on the approach described, the TS 6 project is divided into five work packages. The different work packages as well as the current results are presented in the following paragraphs.

2. STATUS ASSESSMENT OF DH PIPES - SUBTASK A

The status of a DH-pipeline depends on the local load spectrum and the involved material of the system. This includes the pipe materials and the bedding situation in the trench (e.g., presence of groundwater). The overall objectives of Subtask A are to improve the knowledge concerning the status of DH networks in participating countries, status assessment methods and failure modes of DH networks.

To achieve these goals, there is a need to investigate which types of pipe failures occur in the district heating networks and their frequency. Therefore, network owners have to improve their existing data set and statistics. Failure registers should include a categorization of the failures related to reason of the failure installation, operation, design, or site conditions. Besides that, it is recommended to identify the causes behind the failures and if they are age related.

Identified available technologies for status assessment based on different approaches to evaluate status of the pipes are summarized as follows:

- Surveillance system for leakage detection: Measuring the electrical conductivity between alarm wires and service pipes indicating water leakage by increased conductivity due to humidity in the DH pipe.
- Thermographic check: By airplanes or drones, to show under defined weather conditions the increase of heat losses of existing DH pipes. An increased heat conductivity is used to make ageing processes visible.
- Visual inspection: Visual condition assessment by experts in freely accessible pipelines as well as camera inspections in non-accessible district heating culvert systems
- Material testing in the lab: Test removed pieces of buried pipes from the field to the lab according to [1], chemical and physic-chemical test methods (thermogravimetry, infra-red spectroscopy, Raman spectroscopy, dynamic mechanical analysis, etc.)
- Investigation and evaluation of the status for the pipe in the field: using the Pipeopsy method (use the RISE (SP) Plug Method in the field, examine the plug in the laboratory and restore of the pipe) [5] or on-site testing of axial shear strength with mobile test rig [6].

- Evaluation of measurement data: Analysis of operational as well as conditional data of the pipes via measurement equipment using simulation models and material ageing models (e. g., fatigue analysis according to [3]).

Figure 2 shows three different ways of determining the actual adhesion strength of a pipe by measuring of shear strength. From the left to the right image in Figure 2, the amount of interference on the pipe decreases as the specimen is removed. Similarly, the cost of removing the specimen decreases. In Subtask A of the TS 6 project, it is planned to present scientific results and practical experience of the different methods for condition assessment in a comparative manner.

Figure 2. Different methods to measure the adhesion between steel pipe, PUR and PE-casing: In the laboratory (left picture, source FFI Hannover) and the field (middle, source: IMA Dresden) and (right picture, source: RISE)

3. AGEING OF DH PIPES - SUBTASK B

The ageing of a DH pipeline depends on the pipe system and the materials themselves, the operational load spectrum, and the local boundary conditions. The scope of the project includes pre-insulated pipes, concrete duct DH systems and alternative pipe materials. Ageing processes of the materials used based on single ageing mechanisms are well known. For example, if steel is used as the service pipe material, corrosion is a mechanism that affects the service life. Besides that, damage accumulations in the area of low cycles fatigue are used to estimate the ageing of the service pipe based on thermal stresses [3]. Until the amendment of EN 253 in 2018, the axial shear strength due to artificial or operational thermal ageing was an essential criterion for ensuring the quality, describing the actual status and predicting the remaining service life of pre-insulated DH pipes. Evidence that the change in axial strength occurs in three phases - thermal ageing, plateau, thermo-oxidative ageing - has led to the deletion of the Continuous Operating Temperature Test in EN 253. For the degradation of the PUR foam thermal ageing and thermal oxidative ageing are well known [7, 8, 9, 10, 12].

As different ageing mechanisms (e.g., chemical, thermal, mechanical) sometimes occur simultaneously in different materials (e.g., steel, PUR foam and PE coating) as a result of operational stresses on the pipelines, the results of tests of the actual condition and service life predictions with simulation models can differ. Therefore, the overall objective of Subtask B is to improve knowledge on ageing processes taking place in real applications under operational load conditions. Here, the main question is, when are pipes obsolete? Besides that, the crucial and dominated ageing mechanisms especially for each material in pipe design and generally for status assessment and life-time prediction of DH pipe needs to be elucidated. Another important topic is to define reliable accelerated ageing test methods for different materials and pipes systems considering elevated temperature and mechanical load, etc. Especially for the PUR-foam of pre-insulated DH pipes, there are current findings gained in national research projects available that needs to be discussed and harmonized in the TS 6 project [6, 7, 8, 9, 10, 13, 14].

4. LIFETIME PREDICTION MODELS - SUBTASK C

Prediction of service life for materials expected to perform reliably for many decades, is a challenge. Lifetime prediction of a district heating system has to consider different time dependent phenomena. The deterioration of individual properties can mostly be explained, but this does not describe the performance of the design. A wide range of mechanisms for the degradation of polymer-based materials, metals and concrete includes thermal degradation, mechanical degradation, oxidation, chemical attack, creep, and fatigue. Some of them are already considered in the design process of the DH pipes, f. e. the fatigue of the steel pipe caused by temperature changes of the DH system [3].

To allow extrapolation of short-time data to predict long-term performance, an appropriate mathematical model must be applied through which the short-term values obtained at elevated temperatures and/or higher stresses can be recalculated to conditions in service. Methodologies that make a combined approach possible are needed. Considering the diverse range of piping systems utilized in DH networks, including post-insulated steel pipes in concrete ducts and buried pre-insulated bonded pipes, it is essential to examine each system individually when making predictions regarding their lifespan.

Pre-insulated bonded pipes are nowadays the most used system of piping in DH systems and the most used model to predict lifetime of a product is the so-called Arrhenius approach which is based on assumption that an overall degradation process has a rate of deterioration proportional to $\exp(-E_a/RT)$ where E_a is the activation energy, R is the gas constant and T is the absolute temperature. Data is produced under accelerated aging conditions to estimate the value of E_a. This value of E_a is then assumed to be constant in the entire temperature range below the level of accelerated temperature, allowing extrapolation to predict lifetime at a lower service temperature.

There are two crucial requirements for a relevant accelerated ageing test:

1. degradation processes are speeded up without being changed.
2. all factors which might contribute to degradation in the intended end-use environment are considered in the ageing test.

In a previous investigation degradation of DH pipes at different temperatures (130 – 170 °C) were studied. The outcome of the study was that results from accelerated aging at temperatures ≥150 °C follow a different trend than from temperatures below 150 °C [9]. The key conclusion was that one degradation process is dominant over a temperature regime ≥150 °C and another one is dominant below 150 °C. Consequently, accelerated tests at temperatures ≥150 °C cannot be used for the prediction of lifetime at service temperatures because they do not follow the Arrhenius relationship. However, through optimization techniques, the networks are able to maintain a temperature equivalent to a constant value that remains below 90°C [19]. During operating conditions, DH pipes undergo significant temperature variations due to variations in customer demands, soil-pipe interaction, and weather conditions. The temperature fluctuations lead to expansion and contraction of the steel service pipe, which give rise to alternating axial shear stress due to the restrain of the pipe by the surrounding soil. Because a relevant accelerated ageing test must include all factors which might affect the rate of degradation, significance of a repetitive axial shear stress on the rate of thermal degradation of DH pipes were investigated. The main conclusion from this study was that the mechanically stressed pipes degrade significantly more rapidly than non-loaded pipes aged at the same temperature [18]. Other research results show that the mechanical load has a minor influence on the ageing behaviour of PUR foam and thus on the service life of the district heating pipes [10, 12]. The exchange and discussion of these previous research results is necessary in order to compare the results of the laboratory tests with the actual loads in the field and the resulting ageing effects.

Furthermore, the FTIR analyses of the aged samples provided a strong indication that the effect of combined mechanical and thermal ageing was not due to fatigue but due to a faster chemical degradation of the PUR foam. These results in total suggest that a combine mechanical and thermal exposure should be adopted in accelerated ageing tests to avoid overestimation of the lifetime of DH pipes and to reproduce better the ageing characteristics of mechanically stressed DH pipes, especially those intended for use in the fourth-generation district heating networks. This in turn means that there is a need to develop another calculation model that considers the effect of both temperature and repetitive axial shear stresses.

For prediction of service life of different materials and components, associated input data and different models are also needed. The overall objective of Subtask C is to elaborate appropriate mathematical models that can allow extrapolation of short-time data to predict long-term performance of DH pipes. To achieve this goal existing as well as improved models for ageing processes must be compiled. Of course, the prediction models must be evaluated by studying the results of simulations and the results of the status assessment of naturally aged pipes.

5. ASSET MANAGEMNT (AM) - SUBTASK D

According to the Institute of Asset Management, there are six areas in an AM framework: Strategy & Planning, Asset Management Decision Making, Lifecycle Delivery, Asset Information, Organization & People, Risk & Review [15].

An asset management strategy combining re-active and proactive views based on the importance or the risk of assets, is recommended. Supply reliability and economic restrictions should be considered as well. In order to improve asset management strategies a better documentation of network operational conditions is needed. If historical operational data is not available new approaches like artificial intelligence can be used to enable load history in asset management [16]. Besides that, there is a need to build up reliable failure statistics that can be used for risk-based inspections methods.

Current software programs support asset strategy simulations considering ageing models and a risk-based assessment of single assets. For getting an improved asset management procedure an intelligent status assessment is necessary. The existing wire technology or an implemented (light-)fibre technology could be used to determine changes arising from ageing processes aside from leakage detection. The intelligent use of such a (already existing) surveillance technology might push the asset management to a much higher level. In any case "big data" statistics also improve the Asset Management. Using hydraulic models will help to assess supply reliability (overall and for each customer) based on condition (status assessment, ageing behavior) and also to improve risk assessment of the system and support decisions about maintenance activities.

As shown in Figure 1, the improvement of asset management is a closed loop approach running status assessment test in the field, improving ageing models as well as accelerated ageing test in the laboratory and the validation of the lifetime prediction models based on improved mathematical models to describe ageing processes in DH pipes. So, the overall objective of Subtask D is to establish an AM framework for the other four subtasks in TS 6 project, enabling effective and sustainable AM decisions in short- and long-term.

The work areas in this subtask cover a comprehensive description of asset management processes/activities and their relationships/interfaces including a state-of-the-art review on data requirements, available technologies/tools, inputs, and outputs. Existing examples from the DH sector should be given, but also experiences from other infrastructure sectors.

Furthermore, a KPI (key performance indicators) system should be established in order to evaluate DH pipe systems related to technical, economic and ecological aspects. The focus should be here on KPIs related to status assessment, ageing and lifetime prediction as well as rehabilitation related indicators.

Since ecological aspects become more and more important, the carbon footprint over the lifetime of DH pipes should be assessed to support rehabilitation and/or re-investment decisions of network operators.

Another important aspect in DH pipe network operation and asset management is the knowledge about current and future supply reliability for various supply scenarios. The influence of decentralized renewable energy sources on network operations should be investigated.

The findings of the other subtasks will improve asset management. New or further developed methodologies will be implemented in the existing asset simulation tool KANEW 3S. A practical demonstration with data from various network operators will show these benefits.

6. FUTURE PERSPECTIVE OF DH PIPES - SUBTASK E

For future heating networks, the reduction of the operating temperatures will determine the developments. Design technology and DH pipe systems will change with new requirements and different load spectra of future DH-systems. New materials, joining methods and backfilling will be used, which lead in combination with different loads to different ageing phenomena, changes in lifetime and the subsequent predictions and asset management.

It can be assumed that the reduction of the operating temperature will have a positive effect on the service life of existing pipelines. Similarly, the changes in operating temperature will have a similar effect on the future pipe materials to be used [17].

How the transformation process of the heating networks to a larger number of decentralized and fluctuating renewable energies will affect the life span of existing pipelines cannot be estimated at present. Further investigations are necessary to avoid endangering existing networks as the backbone of the heat supply and as a component of a successful decarbonization of the district heating systems. The work in subtask E will contribute to these requirements.

Regarding the status assessment, ageing and lifetime prediction, the development of the digitalization of the district heating system is expected to have further positive effects. The availability of real time data will allow an improved and precise life cycle assessment. Currently, the possibilities and the degree of digitalization of future heating networks are difficult to estimate. However, it can be assumed that existing networks without digital elements will continue to be operated and will require greater attention from the perspective of remaining service life estimation. In a more digitalized DH system, the heat and temperature losses along the pipes could be used for status assessment.

The transferability of the gained experience from the 3rd gen DH networks will be one central key point to make future networks more secure, more reliable, and easy to maintain. Therefore, a knowledge transform framework will be advantageous to be planned for future developments.

Another very important but also central point in the context of futures perspectives is circular economy. It is a future research area, and it is important to determinate the quality of different recycled material which has potential to use in DH system.

The subtask E will contribute to this future research area by collecting the available findings as well as to prepare key performance indicators for the implementation in asset management simulation tools.

7. CONCLUDING REMARKS

District heating can contribute to improve the environment. To this end, there is a need to assess the status of the district heating networks, predict service lifetime, and develop methods for asset management of the networks including maintenance. There is also need to have improved product standards for the district heating network components to manufacture optimal components with the current knowledge. The present networks must be improved by selective replacement of obsolete parts, since replacing entire networks would be too costly in economic and environmental aspects. When building new or expanding existing networks, it is essential that optimal components are used. Hence, the lifetime and the environmental impact from manufacturing are essential.

The IEA DHC TS 6 Project have been created to improve the methodology of asset management of district heating networks. The main objectives of the project are

- Collection of research results available
- Harmonize latest results and make proposals for the improvement of related standards/recommendations
- Make research results available for DH utilities
- Identify and close knowledge gabs
- Involve the international DH community (researchers, experts, municipalities, etc.).

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