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Integrated assessment of failure probability of the district heating network

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ABSTRACT

The aim of the research presented in this paper is the assessment of failure probability of the district heating network piping. The applied methodology for assessment of failure probability of the piping network energy systems includes three types of analyses: probabilistic mathematical, deterministic thermal-hydraulic and integrated deterministic–probabilistic structural integrity analyses. The analysis of Kaunas (Lithuania) district heating (DH) network was performed. First of all, the statistical analysis was performed and the piping with the highest failure rate was determined. The thermal-hydraulic analysis was performed and loads for deterministic–probabilistic structural analysis were calculated for the selected part of DH network. The integrated deterministic–probabilistic structural integrity analysis was performed in two steps—general structural integrity evaluation and probabilistic analysis of chosen piping part. Finally, the probabilistic mathematical method was applied for the integrated assessment of failure probability of the DH network piping. This method takes into consideration statistical information about Kaunas DH piping failure data, system structure, and pipe failure probability received by integrated deterministic–probabilistic structural integrity analysis.

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1. Introduction

District heating (DH) networks provide and distribute heat, generated in thermal power plants or other heating sources, for heating of buildings and industry sites, water heating and technological needs. DH network includes three main parts: (1) water heating source, (2) heating supply and distribution piping, (3) consumer systems, which use the heat [1]. The consequences of loss of heating accidents are especially dangerous during the winter season in countries with harsh winters (e.g. in 2006 in Lithuania, Telšiai, an accident at $-26.5\ ^{\circ}$C in the DH network led to the loss of heat supply for thousands of people for almost a week).

In bigger cities of Lithuania and other Baltic countries the DH networks were designed and installed more than 50 years ago. The degradation mechanisms and phenomena influence the ageing behaviour of piping. The bigger part of piping and its components (valves, muffs, connections, etc.) are near at the end of their lifetime. The failures of main piping during hydraulic testing and normal operation also show decrease of reliability of piping.

The analysis of performed works in the field of the failure probability (or opposite characteristic—reliability) assessment of piping network showed that reviewed works in most cases present the investigations of the specific separate phenomena important for reliability of piping network. There are research works devoted for assessment of piping network reliability based on statistical data [2–4], failure data analysis of piping integrated with hydraulics [5–7]. There is available also an interesting research study, which proposes a rapid reliability estimation method for node-pair connectivity analysis of lifeline networks with its application example to interconnected power and water networks under seismic hazards [8]. Other studies investigate piping degradation mechanisms [9–11] or present structural integrity analysis, which is performed using analytical formulas [12–14] or finite element method [15]. However, there are not available systematic evaluation methods or single technology related to real DH network piping operation reliability and risk factor evaluation, which in systematic way takes into account the statistical failure data, thermal-hydraulic loading, corrosion-mechanical damage, aging effects and other factors important for the reliability of pipeline networks. The originality of this paper is that the assessment of failure probability of the piping network of energy systems covers three types of analyses: probabilistic mathematical; deterministic thermal-hydraulic and integrated

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deterministic–probabilistic structural integrity analyses. It should also be noted that the integrated deterministic–probabilistic analysis takes into account degradation mechanisms, aging effects to mechanical properties of steel of networks piping.

The methodology for the assessment of reliability of piping networks, presented in our previous work [1], was taken into account in this paper. Our previous paper includes a pilot study, however, the scope of that study in [1] was limited to the identification of the most vulnerable pipe section on general statistical failure data, evaluation of the mechanical fracture of the selected pipeline and estimation the consequence of this failure to consumers of the network. However, the integrated deterministic–probabilistic pipe rupture analysis, which is part of methodology described in paper [1], was not performed and its influence on the piping failure probability was not taken into account.

In this paper, first of all, the statistical analysis of DH network failure data was performed and the part (section) of this network with the highest failure rate was identified. Using deterministic thermal-hydraulic and structural integrity analysis methods the main parameters and stresses were estimated in the selected part of DH network during normal operation conditions and during dangerous transients. The rupture probability of analyzed part of DH network is obtained in the integrated deterministic–probabilistic analysis. Finally, the failure probability (per 1 km per year) function of this part of DH network was determined taking into account calculated rupture probability and statistic failure data of network operation. The assessment of failure of probability is based on the application of Bayesian method. Bayesian method is a widely used method; it has been applied in reliability analysis of technical systems [16,17] and software [18,19], artificial intelligence [20], expert system, modelling Bayesian networks [21], etc. The estimated failure probability is the main parameter characterizing reliability of district heating network. In the future steps of system reliability and risk analysis other important parameters will be identified (piping life time, mean time to repair, system average interruption duration index, system average interruption frequency index) and evaluated in the prediction of DH network lifetime. The reliability analysis is planned for different piping network (e.g. DH, gas supply) and analysis results will be used for the weakest network node identification, accident prevention, the optimal solution evaluation if there is an accident, and other applications.

2. Object of the study

The failure probability analysis presented in this paper was performed for Kaunas city DH network. Kaunas city is the second biggest city in Lithuania, and it has a district heating network in operation for 50 years already. The layout of current Kaunas DH network is presented in Fig. 1. The figure shows only main piping, while there are many smaller pipes, which branch from the main piping to connect each consumer to the system. Only the main piping was taken into account in the failure probability analysis. It is an important part of the system, which is used to supply heat to many industrial, public and individual customers.

3. Statistic analysis of district heating network failure data

Kaunas DH network contains huge amounts of piping. Only the main piping with nominal diameter DN/300 mm is about 165 km in length. In order to perform reliability analysis of DH network, including evaluation of structural integrity of piping, it is necessary to prepare numerical models of all 165 km length piping. Initial statistical failure analysis of DH network was done in order to identify the section of network with the maximum failure rate.

The following data were collected for the statistical failure analysis of DH network:

- general information about piping: diameters of pipes, material, piping laying technique, length, operating time;
- information about failures of piping: identification of piping rupture place, diameter of pipe, piping laying technique, groundwater levels, causes of the failures repair time.

Collected data includes information about Kaunas DH network in 2009–2012 period. Kaunas DH network is one of the most complicated and oldest one in Lithuania, this network fully represents other networks installed in bigger cities of Lithuanian.

Statistical analysis of failure data is performed for separate parts of DH network (pipelines between the embranchment places). The failure rate (per 1 km per year) was calculated for each part. The part of network with the highest failure rate was selected for the detail analysis.

The selected part of DH network is installed in the center of Kaunas (Fig. 1. piping marked). This selected part is also very important for the hydraulic specifics of the network, because it is located at a significantly lower elevation (−40 m). A throttle valve is needed to reduce pressure in the supply line in this area and pumps are needed to pump the water up the hill via the return line. If the throttle valve fails (this scenario was analyzed in the thermal-hydraulic analysis), the pressure may increase significantly in this part. Moreover, this is a city center, where the heating is needed not only for flats and houses of citizens, but also for the major public and city objects located in this district.

This part (with the highest failure rate) was analyzed in more details performing thermal-hydraulic analysis and integrated deterministic–probabilistic structural integrity analysis.

4. Thermal-hydraulic analysis

In this study, thermal-hydraulic analysis of the DH network is needed to identify thermal-hydraulic parameters (pressure, temperature, etc.) at the selected network location. The structural integrity analysis is then performed taking into account the results of thermal-hydraulic analysis.

Thermal-hydraulic analysis can be divided into two parts—static and dynamic. The results of static analysis are non-time dependent, stationary thermal-hydraulic parameters in some specific network location with the given network configuration and boundary conditions. While dynamic analysis allows to calculate transients in case of an accident and the results are time dependent. The dynamic analysis allows to investigate various accident scenarios, where the pressure may exceed safety limits for a short period of time and cause failure of piping integrity. Both types of analyses were performed and are summarized in this work.

4.1. Static thermal-hydraulic analysis

In the first step, a static thermal-hydraulic analysis must be performed. A dedicated software "TERMIS" was used for this purpose. The entire model of Kaunas DH network was created using "TERMIS" and is presented in Fig. 2. Development of the model was based on the information about the length, diameter, roughness and elevation change of pipe sections in the network as well as the information about pump stations, heat sources and heat consumers.

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