Method of improvement of operational and technical conditions of a large cooling water system

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Abstract. Increasing the energy efficiency of industrial installations is one of the European Union's priorities for achieving energy policy goals. These goals can be achieved, among others, by applying the appropriate methodology for modernization of cooling water distribution pipelines and improving their operation. Water distribution in cooling systems of large industrial installations is associated with significant hydraulic losses due to large flows and spatial spread of these systems. The losses are unavoidable and have a decisive impact on the energy consumption for pumping. Thanks to optimal design solutions, implementation of the repair program and proper operation of cooling water transmission pipelines, it is possible to significantly reduce hydraulic losses and water leakage. This will translate into reduced energy consumption for pumping and, as a result, improved energy efficiency. Abovementioned goals can be achieved by replacing or renovating pipelines. This paper deals with determination of a method and schedule of modernization of cooling water piping systems on the basis of a case study – a large industrial plant. Firstly, evaluation of the existing condition is carried out. Data on flow rate and cooling water pressure in the system are collected and analyzed. A graphical and numerical database of the cooling water system is made, which maps the system in terms of system geometry (lengths, pipe diameters, ordinates) and flow and pressure streams. The hydraulic losses of the cooling water system are simulated. The results of simulation calculations of pressure losses in water distribution system are presented in the form of maps of water pressure distribution in pipelines. Calculations for the pipeline network are performed in the current state for two hydraulic load cases: maximum and average. An assessment of the failure rate is made on the basis of information about the place, time, cause and type of damage. Wall thickness of pipelines in selected locations is measured and samples are taken from pipes in places of failure. The reasons for water pipeline failures are diagnosed. On the basis of pre-modernization simulation, information on failure rate and forecasts of future water demand are obtained, it is proposed which pipeline sections and in what order should be modernized. Depending on the technical condition, pipeline diameter and location in the field, pipe replacement or renovation is recommended. For pipes to be replaced, new diameters, adjusted to the forecasted demand are calculated. For pipes qualified for renovation, different site hardened liners or full wall pipes are recommended depending on pipe condition. Renovation methods, despite the reduction of the internal cross-section, provide similar or lower hydraulic resistance values. After selecting the variants of modernization of distribution pipelines, hydraulic simulations are carried out in the post-modernization condition, taking into account the future demand for cooling water. The presented method can be applied to cooling water systems as well as other industrial water piping systems.
1. Introduction

In 2012, the European Union adopted a key directive of the European Parliament and of the Council, which creates a viable basis for achieving the objectives of the EU policy on energy strategy, i.e. Directive of the European Parliament and of the Council 2012/27/EU of 25.10.2012 on energy efficiency. This Directive, which creates a common framework to reduce 20% of primary energy consumption in the EU, identifies the means to achieve significant improvements in energy efficiency.

In order to be able to implement energy-efficient and ecological operation of large cooling water distribution systems in industrial plants, the operation of pump units should be carried out with high efficiency, and hydraulic losses of cooling water distribution system should be reduced to a minimum. To achieve these goals, often a thorough modernization of the system is necessary. The costs of modernization and the requirement to maintain production continuity often preclude simultaneous modernization of the entire system. Hence the need to develop an appropriate methodology for modernizing existing cooling water systems is high, including the rehabilitation of cooling water distribution pipelines. This paper deals with determination of a method and schedule of modernization of cooling water piping systems on the basis of a case study – a large industrial plant.

2. Methodology

In this section methodology for improvement of operational and technical conditions of a large cooling water system is presented. Firstly, system has to be described. This is necessary to have good understanding of the way it operates. Next step is to collect operational data and assess the condition of the system. On the basis of the assessment methods for improvement can be elaborated and their outcome simulated.

2.1. Data collection

At this stage description of the cooling water system is done. A close cooperation with cooling water system operator is necessary because as accurate as possible technical documentation and operational data have to be obtained. In many cases data for old systems are outdated or not complete. They can be often supplemented with help of personal communication or results from on-site inspections.

2.1.1. Description of cooling water piping system.

Data on spatial structure of the pipeline system should allow one to record the system’s layout in form of graphical-numerical data base in which each section has its characteristics assigned. Such data should include:

- pipe lengths, diameters and elevation
- age and material of pipes
- location of fittings (valves, hydrants etc.)

2.1.2. Operational data.

Operational data include parameters recorded on regular basis in the cooling water distribution system. They consist of flow and pressure measured at pump stations, consumers and other characteristic points in the system. In most cases such data are available in digital form. The data can be presented on graphs (e.g. systematic or chronological) to visualize and better understand modes of operation. Such data should include a period of few years, to enable to observe trends or anomalies. P&I Diagrams are also helpful since industrial installation’s structures are usually complicated.

Water quality and failure data are of great importance. The later should include location, time and local conditions for particular failure. In addition to digital data or reports, observations and opinions of staff are of great importance and can lead to better understanding acquired data.

2.1.3. On-site inspections and tests of selected pipeline sections.

There are few goals of on-site inspections. It can be visual inspection, leading to better understanding of both operation and problems of the system. It is often a chance for conversation with staff operating the system and hearing their
opinions first hand. Other goal is acquisition of additional data by performing measurements of flow or pressure in characteristic points as well as taking samples (eg. for determination of pipe wall thickness).

2.2. Evaluation of pipelines condition

Since cooling water distribution systems are mostly pipelines laid underground it is difficult to directly assess their condition. Therefore it is proposed to base the evaluation on analysis of failures in the system. In such approach data covering period of few years is required. Proposed methodology of pipeline failure assessment should consist of following stages [1]:

- Analysis of structure types: functional, material, age and product range
- Analysis of operational conditions and issues
- Quantitative and qualitative failure analysis
- Evaluation, analysis and assessment of unit failure rate of pipelines
- Assessment of pipeline failure and conclusions.

2.2.1. Analysis of modes and causes of pipeline failures.

To be able to address problems in cooling water distribution system, causes of pipeline failures and extent of damage should be assessed. In general pipeline elements can be divided into pipes and fittings. For pipes, three modes of failures can be defined: uniform, local and joint failures. Fittings can be divided by type, e.g. valve, hydrant, water meter.

The next step is to identify what led to these failures. Causes in pipelines are usually corrosion, leakage, joint failure and other damages. In case of fittings it can be corrosion, natural wear, cracks, leakage, excessive sediments, etc. Samples taken from pipes that failed are of great help. They are often collected by operators of systems or can be obtained during on-site inspection and are the basis for assessment of pipe wall thickness. Wall thickness proofs pipeline resistance and is therefore a significant parameter taken into account when choosing renewal technology [2].

2.2.2. Analysis of pipeline unit failure rate.

For failure assessment unit failure rate \( \lambda \) can be used [1]. For pipe elements:

\[
\lambda_L = \frac{n}{L \cdot \Delta t}, \text{ failure/(km \cdot year)},
\]

where:
- \( \Delta t \) – time interval
- \( n \) – number of failures in the time interval \( \Delta t \)
- \( L \) – length of the pipeline in the time interval \( \Delta t \), km.

For fittings:

\[
\lambda_Z = \frac{n}{N \cdot \Delta t}, \text{ failure/(unit \cdot year)},
\]

where:
- \( \Delta t \) – time interval
- \( n \) – number of valves/hydrants damaged in the time interval \( \Delta t \)
- \( N \) – number of valves damaged in the time interval \( \Delta t \), unit.

It can be assumed that the parameter is constant in the given period of time, in this case for 1 year (number of failures/(km\*year)). There are no standards for acceptable pipeline failure rate for cooling water distribution pipelines. However existing standards for large water supply systems can be adopted. For pipelines with diameter \( \geq \) DN300 the value of 0,1 failure/(km\*year) can be adopted. For the
pipelines with diameter <DN300 the value of -0.3 failure/(km*year) is advised. If failure rate is below abovementioned values, the system is considered reliable [3].

On the basis of unit failure rate analysis it is possible to find areas with highest failure risk. In these locations samples should be taken for pipe wall thickness assessment.

2.3. Implementation of graphical-numerical database
Graphical-numerical database reflects technical characteristics of pipelines and their layout in the field. It is composed of two major parts:
- graphical part, containing the pipe network topology. The primary source of information is the map with presented image of pipe network,
- numeric portion that contains descriptive information of the individual components of the WDS. A numerical database contains the following data:
  - the pipe sections: nominal diameter, inside diameter, the inner pipe surface roughness, length,
  - interchanges (characteristic points of pipe network, place the connection pipe together): the value of the elevation of the terrain
  - Pumping Stations: the value of the outlet water pressure from Pumping Stations, head of the pumps system
  - water consumption points: the value of the flow rate of water.

2.4. Simulation of hydraulic losses in current state
The analysis of the pressure losses of water in pipeline systems is based on calculation of water flow in pipes. Calculations are performed with the use of the graphical-numerical database, described in previous section.

Simulation calculation of pressure losses should be made for water demand conditions prevailing during the year. Hydraulic Model of pipe network needs be calibrated in order to validate the results of a calculation. Measurements of the pressure of the water flow in chosen points of the pipe network are made.

2.5. Program and the schedule for the improvement of the condition of water pipelines

2.5.1. Selection of rehabilitation technology and the scope of renovation. Taking into account pipeline characteristics, operational data, data on failures, pipe wall thickness assessment, forecasts on demand and cost, different rehabilitation methods can be applied:
- replacement, applied in a situation, when a pipeline lost its structural strength within its entire length or on particular sections. It involves installing a new pipeline by using either traditional (trenching) or trenchless methods. This method is also applied for small diameter pipes, regardless their diameter. New pipe diameters should match current demand.
- renovation, with composed liners that protect the pipeline against corrosion and incrustation. In addition the liner provides better hydraulic conditions, and some degree of structure reinforcement.
- reconstruction, where the applied „liner” (often a pipe placed inside the old pipeline), independently or together with the structure of the pipeline being renewed, enables the achievement of required structural parameters.

2.5.2. Recommendations for rehabilitation schedule. Due to the extent of works and necessity to maintain production in plant rehabilitation works have to be carried out in stages. A general
recommendation is to carry out the works gradually, starting with the ones with larger diameters (with the water flow direction from the source to the use points). The reason are bigger consequences of large diameter pipe failure. Pipes of smaller diameters should be rehabilitated in the next step. The renewal phasing process should also include the distinguished parts of pipeline network with higher unreliability and parts of the networks with reduced wall thickness. Such pipelines should be prioritized.

2.6. Simulation of hydraulic losses after rehabilitation
After technology of rehabilitation is chosen hydraulic performance of the system after rehabilitation has to be evaluated.

To take full advantage of pipeline rehabilitation, it should be carried out simultaneously with modernization of pumping stations. In this case simulation of losses should also take into account required pump heads.

3. Case study

3.1. System description
The industrial plant was built in the early 1940’s. Due to the nature of production, which requires continuous water supply for cooling of processes, the water distribution system was expanded but not thoroughly modernized. Today elements from every decade can be found in the cooling water distribution system.

The system is in bad condition. Pipelines are made of steel and therefore main problems are corrosion and scaling of pipes and fittings. Hydraulic losses are high and there is a significant leakage. This condition not only results in low energy efficiency but also threatens the continuity of cooling water supply to processes. Total length of pipelines is over 30 km and maximum diameter is DN1200. Due to the big scope and high investment, repair program has to be developed which will include schedule and methodology of works.

The Cooling system is of open recirculating type and is supplied from two pumping stations operating simultaneously. Cooled “cooling water” with temperature approx. 11-24 °C is pumped from Pumping Stations to consumers. After it absorbs heat it returns as heated “cooling water” with temperature of 17-36 °C.

Natural or mechanical draft cooling towers are collaborating with Pumping Stations, in which the return water cools down and can be supplied to consumers again. In each Pumping Station two sets of pumps are installed to pump cooled/heated water. Pumps on the supply side ensure flow to consumers and pumps on return side maintain sufficient pressure for cooling system (cooling towers).

Results presented in following sections are based on data provided by the operator of the cooling water distribution system (5 year period) and data acquired during on-site inspections.

3.2. Pipeline failure assessment

3.2.1. Modes and causes of pipeline failures. To address problems in cooling water distribution system, causes of pipeline failures and extent of damage were assessed. In the figure 1 shares of failure causes in water distribution system are presented.
3.2.2. *Assessment of operating issues*. Influence of the ground-watery environment and infiltrating precipitation water, insufficient and inefficient anti-corrosive pipe insulation and age of pipes result in damages of the insulation layer. There is a significant proportion of pitting corrosion on the external surface of the pipeline walls. Internal corrosion is largely due to chlorine compounds oxidation products present in the fresh and cooling water. The dominance of pressure pipeline failures can be checked in the documentation of pipeline failures. Damage of fittings results from natural wear of elements during long-term exploitation [4].

3.2.3. *Spatial distribution of pipeline failures*. Visualization of the location of failures allows to capture areas with high density of failures in water distribution systems. Parameter values of failure rate were calculated for these areas. Pipeline with failure rate above critical value is considered unreliable. The value was assumed 0,1 failure/(km*year) for pipelines with diameter ≥ DN300 and 0,3 failure/(km*year) for pipelines with smaller diameters. Spatial distribution of failures is presented in figure 2.

High failure of cooling water distribution system is caused mainly by pipes. Influence of fittings (mainly valves) is very insignificant.

3.2.4. *Assessment of results of pipeline wall thickness measurements*. The results of on-site inspections are inter alia observations and conclusions made during visual inspection of the facility and during conversations with technical personnel, and pictures

The degree of the corrosion varies, but in most cases does not indicate total wear of pipeline sections. Nevertheless, in certain places there are thorough corrosion pits that occur on sections with the length range from a few to a dozen centimeters.

The wall thickness proofs the pipeline resistance and is therefore a significant parameter taken into account when choosing renewal technology. Samples of pipes were taken during repairs and on-site inspections. In the table 1 an example of results of pipe wall thickness assessment are shown [5].
3.3. Simulation of hydraulic losses in current state

Pipe network is built with the pipe nominal diameter from DN50 to DN1200 with an overall length of about 32 km. Cooling Water Distribution System data base consists of 1194 records. Unfortunately, they do not contain consumption values at the endpoints. They were not registered by the operator of the system. The values of the flow of water in the water consumption points (end points of the network) were assumed proportional to the cross-section of consumer connections.

Simulation calculation of pressure losses were made for water flow prevailing during the year (average) and maximum flow. Hydraulic Model of pipe network was calibrated in order to validate the results of calculation. Additional measurements of pressure and water flow in chosen locations were done.

![Figure 2. The location of failures and a failure rate in the cooling water distribution system](image)

### Table 1. Comparison of measured and calculated pipeline wall thickness

| DN [mm] | Calculated thickness [mm] | Measured thickness [mm] | Location of measurement | Condition |
|---------|---------------------------|-------------------------|-------------------------|-----------|
| 1000    | 8,8                       | 8,2 – 8,3               | ST. 3610                | N         |
| 1000    | 8,8                       | 5,2                     | ST. 3612                | N         |
| 800     | 7,1                       | 4,6 – 5,2               | Ul. A/5                 | N         |
| 800     | 7,1                       | 8,2                     | St. 3423                | Y         |
3.3.1. Results of simulation. Maps of water pressure distribution in the pipelines are presented in figure 3. Calculations were performed for average flow. Current state is presented on the left side of figure 3. Simulation shows, that water pressure in the cooling water system is in 240 kPa to 350 kPa. The velocity of water in most pipelines is less than 0,6 m/s, indicating large reserves – the system was designed for higher flow rates. For the majority of piping unit pressure losses are below 30 Pa/m. There is, however, a group of pipelines with large hydraulic resistance in excess of 100 Pa/m.

3.4. Scope and technology of pipeline rehabilitation
Depending on pipeline characteristics, operational data, data on failures, forecasts on demand and cost, different rehabilitation technologies were chosen for pipelines in the cooling water distribution system.

Pipeline sections with smaller diameters (e.g. branches to the main pipeline of diameter ≤ DN100) used as connections to buildings, can be replaced by traditional method of trenching, especially when the density of underground utilities around these pipelines is usually large.

For pipeline sections maintaining structural strength (e.g. the wall thickness is correct or reduced slightly) the renovation technology with site hardened liner is advised. The technology is already well known and proofed for renewal of municipal water supply system.

For pipeline sections with structural strength lost in particular places (spots) (e.g. the wall thickness is incorrect) the renovation (or reconstruction) technology with liner reinforcing pipeline structure, e.g. Phoenix Double Jacket- Blue Line method is advised.

For longer pipeline sections with structural strength lost (e.g. the wall thickness is incorrect) - the technology of reconstruction with the method of inserting a full wall pipe securing required pipeline strength level is advised.

3.5. Recommended rehabilitation schedule
Schedule of renewal of cooling water pipelines was divided in two stages (IIa and IIb carried out in parallel) [6]:

- Stage I - approx. 2 years duration
  - DN1200 – DN600 pipelines
  - pipelines with highest density of failure
  - trenchless renovation or reconstruction

- Stage IIa – approx. 1 – 1.5 year duration
  - DN500 – DN150 pipelines
  - trenchless renovation or reconstruction

- Stage IIb – approx. 4,5 month duration
  - DN50 - DN100 pipelines
  - Replacement through excavation
  - Diameters adapted to current demand

3.6. Simulation of hydraulic losses after rehabilitation
For pipeline sections to be renovated it was assumed that internal diameter of pipe remains the same after renovation because it is required to clean pipes internally of deposits prior to application of a sleeve. For internal roughness of pipe value of 1mm was assumed. Calculations were performed for average and maximum hydraulic load taking into account forecast of future demand for cooling water and proposed changes in heads of new pumps.
3.6.1. Results of simulation. The objective of rehabilitation is not only improvement of system’s condition and reliability but also optimization of diameters. Calculations were performed for predicted average flow. General increase in pressure after rehabilitation is visible due to higher predicted demand. Maps of water pressure distribution in the pipelines are presented in figure 3. Values for current and rehabilitated state are compared.

![Figure 3. Map of water pressure distribution pipelines. Current state on the left, state after rehabilitation on the right](image)

4. Conclusions
In the paper consistent methodology for rehabilitation of underground cooling water distribution systems was produced. Required actions were presented in steps, on an example of a large existing cooling water network.

- Description of the system was made. It included acquisition of necessary data required for analysis of structure and operation of a large cooling water distribution system.

- Operational data were analyzed and methodology for assessment of system condition was introduced. Causes and modes of failure were examined. The focus was on underground systems, in which condition of pipelines cannot be assessed directly. Analysis using unit failure rate, indicating areas with low reliability was presented.

- Graphical-numerical database was presented. Hydraulic Simulation for current flow in the system was carried out. Such calculation helps to find areas in the system where capacity is too low or reserve exists. Such tool makes it possible to obtain flow and pressure for locations in the system where measuring equipment is not installed.
On the basis of hydraulic conditions, distribution and modes of failures program for rehabilitation was elaborated. Methodology of rehabilitation technology selection was presented, including trenchless and traditional techniques.

Rehabilitation schedule was proposed. Suggested rehabilitation solutions were assessed. Hydraulic simulation after rehabilitation, taking into account predicted demand was performed.

This methodology can be used as a guide in planning rehabilitation of large cooling water distribution systems. It can also be a guideline in case of other underground piping networks, particularly helpful in case of systems in bad condition, where predicted investment is high and execution of works in stages is required.

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