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Research Article

Energy-efficient Thermal Insulation Material for District Heating Pipelines

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Abstract

In recent years, Mongolia has experienced a shortage of district heating sources and networks, primarily due to intensive construction, including apartment buildings. With urbanization and economic growth, new buildings are being built at a rapid pace, requiring connections to the district heating (DH) system. Recent data shows that the annual growth rate of heat consumption has increased by approximately 3 to 5 percent compared to previous periods. As a result, one of the key tasks for our energy sector is to implement a cost-saving policy to reduce heat losses in the distribution network. Additionally, around 30 percent of Ulaanbaatar's heating networks are outdated and cannot be swiftly replaced due to economic and time constraints. This paper focuses on experimental studies of heat losses within district heating (DH) systems' pipe networks. In these heat networks, various thermal insulating materials are used. Over time, the insulation around the pipelines deteriorates, and due to wear and environmental factors, it fails to meet technical requirements, leading to a significant increase in heat loss beyond calculated values. Effectively implementing energy efficiency in a district heating system requires a comprehensive understanding of the energy performance of the pipe networks, which can be achieved through energy audit techniques. Using a drone equipped with a thermal camera, we assessed pipeline heat loss and damage in real-time and dynamic conditions. Additionally, we compared different pipeline insulation materials and conducted feasibility studies on utilizing high-density pre-insulated polyurethane foam insulation boards. Our proposal indicates that the heat loss from the insulation panels will be 1.7 times lower than the reference value, resulting in a 30% energy saving, as confirmed by both technical and economic calculations.

Keywords

High-density Polyurethane Foam, Thermal Insulation, District Heating Pipe, Energy Efficiency

1. Introduction

Over the past two decades, the population of Mongolia’s capital, Ulaanbaatar (UB), has grown exponentially, primarily due to rapid rural-to-urban migration. With urbanization and economic growth, new buildings are being built at a rapid pace, requiring connections to the district heating (DH) system. The DH system has a total connected load of 3373,7 Gcal/h in 2024. By the end of 2023, the demand from consumers connected to Ulaanbaatar city's district heating

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system exceeded the installed capacity by 33%, highlighting a significant inadequacy in the system's reliability and capacity to meet heating needs [1].

The city of Ulaanbaatar records the lowest average temperature of all national capitals. It goes through intense continental weather characterized by long and cold winters but with short summers, in January temperatures can be as low as -40 ℃.

Energy saving in thermal energy transportation is one of the most important problems in reducing energy consumption. Heat losses through the insulation of pipelines in heating networks can be significant, therefore, there is potential for energy savings.

According to the research, more than 30 percent of the district heating system pipelines are overdue in their lifetime, and approximately 170 km of pipeline networks need to be replaced [2]. Therefore, one of the urgent goals of our energy industry is to reduce heat loss in the distribution network.

The practical implementation of energy efficiency in district heating requires knowledge of the energy performance of pipe networks through energy audit techniques. The application of infrared thermography in energy is widely used, since, through such a non-invasive investigation, and the correct interpretation of infrared images, it is possible to highlight inefficiencies in heating systems and related facilities. With the help of a drone equipped with a thermal camera, pipeline heat loss was determined in real-time dynamic mode.

In heat networks, various thermal insulating materials are used. During the long period of use, the insulation of the pipeline wears out, and due to damage and natural effects, it does not meet the technical requirements, and the heat loss significantly increases from the calculated value. Losses in the transportation of heat-carrying bodies are important factors for heat tariffs [3]. Therefore, the main purpose of this study is to determine the heat loss caused by the insulation of the pipeline, identify the cause, and improve the quality requirements of the heat insulation used in the future.

There are many research materials made by scientists on the heat loss of pipelines of district heating systems and ways to solve it [4-9]. Completely replacing and renewing all the old heat pipelines in UB city at once is not feasible due to economic and time constraints. Therefore, we have explored the possibility of using pre-insulated panels (high-density polyurethane foam insulation) by manufacturing them in our country. The problem of determining the amount of heat loss due to network water leakage was not considered in the framework of the research work.

2. Materials and Methods

The environmental impact can be decreased by reducing heat losses in the district heating pipes during heat distribution to customers. One of the several methods for determining the heat loss of pipeline insulation is the method of calculation by the thermal resistance of the network [10, 11]. For this purpose, it is possible to improve the calculation accuracy by taking samples from the insulation parts of the pipeline and analyzing them in laboratory conditions by determining the coefficient of thermal conductivity and making corrections.

However, the actual state of thermal insulation of the pipeline is rarely the same due to the wide variety of operating conditions. In some places, there may be an error in the calculation depending on the factor that the heat insulation is thinned, hollowed out, bare, made of poor quality heat insulation, the insulation layer has fallen off, etc. Therefore, long-term studies and measurements are required to bring the calculations closer to reality.

The following problems arise from uncertainty in the magnitude of heat losses in the heat network. These include:

(1) It is not possible to calculate the heat loss and accurately adjust the water consumption in the adjustment of the heating pipeline hydraulic mode.

(2) Due to the uncertainty of the heat loss of each section of the pipeline, it is impossible to determine which section should be replaced or repaired first.

(3) It is impossible to accurately calculate the heat loss by calculating the heat sold and purchased between the thermal power plant and the heat network.

The thermal insulation design should maintain the normalized level of heat loss of equipment and pipelines, the required parameters of the heat and cold transfer body, and the conditions for the temperature of the outer surface to be safe for the human body during its use [12-14].

An important component in heat loss is thermal transfer, from the heat carrier to the environment, which leads to a drop in temperature within the heat carrier flowing along the pipe, directly affecting the outer surface temperature of the thermal insulation.

Heat loss (Eq. (1)) from an insulated pipe under the annual average operating conditions of the heat network is determined by the following formulas.

$$\Delta Q = \frac{\tau - t_o}{\sum \beta} \cdot l \cdot \beta \qquad (1)$$

Where: β – the local heat loss factor is a term used to describe the heat losses created by fittings, compensators, and supports. For pipes with a diameter of 150 mm or greater, the value is $\beta = 1,15$; l – the length of the pipe of each dimension in the DH network, m; τ – the fluid temperature inside the pipe, ℃; to – the ambient air temperature, ℃.

Although there are methods used to calculate thermal resistance and heat loss for certain lengths of DH networks, e.g., Wang et al. research [15], they are not applicable for a long-term assessment of an entire DH network. For above-ground insulation, it is recommended to use a method that accounts for various factors (weather, supply temperature, state of insulation, and moisture content, etc.). The overall heat loss assessment technique is defined as the ratio of heat flux to thermal resistance (Eq. (2)). The thermal resistance of the network is calculated using the following equation:

$$\sum R = R_{int} + R_{ins} + R_{ext} \tag{2}$$

Where: R_{int} – the internal heat transfer resistance; R_{ins} – the insulation resistance; R_{ext} – the external heat transfer resistance, $m^2 \cdot ℃ /W$.

The thermal transfer resistance on the exterior surface of the last layer is at ambient air temperature. Provided that the temperature at the surface of the insulation is known, the specific loss (Eq. (3)) of heat can be determined with the aid of the ratio:

$$q_l = \frac{\tau - t_o}{\sum R} = \frac{\tau - t_o}{\frac{1}{2\pi\lambda_{ins}}\ln\frac{d_{ins.o}}{d_o} + \frac{1}{2\pi\lambda_{p.c}}\ln\frac{d_{p.c.o}}{d_{ins.o}} + \frac{1}{\pi d_{p.c.o}\alpha_o}} \tag{3}$$

Where: $d_o, d_{ins.o}, d_{p.c.o}$ – outer diameters of pipe; outer diameters of pipe include the insulation layer; outer diameters of pipes, including insulation and protective coat layer; $\lambda_{ins}, \lambda_{p.c}$ – thermal conductivity of thermal insulation and protective coat layer, $W/(m°C)$.

The approximation made by neglecting the resistance on the interior surface and the resistance of the pipe's wall is much reduced in the case of insulated pipes, then in uninsulated ones, because in the case of insulated pipes, the thermal resistance of the insulation represents about 85% from the total resistance, and the rest of 15% belongs to the resistance at superficial heat transfer on the exterior surface.

The heat transfer coefficient through convection and radiation (Eq. (4)) in the case of exterior pipes is determined by the following formulas.

$$\alpha = 11.6 + 7\sqrt{w} \tag{4}$$

Where: w – the speed of the wind, m/s.

If the environmental air is in motion, then the convection coefficient is mainly influenced by the speed of the air.

3. Results and Discussions

In heat networks, various insulating materials are used. Mineral wool, based on rock wool, has become widespread in heating networks due to its thermal performance and ability to withstand high temperatures. However, the characteristics of rock wool deteriorate with time.

In the framework of this experimental research, the 800 mm diameter pipeline of the centralized heat supply system of UB city, insulated with mineral wool, mesh, and asbestos cement, was selected. The heat loss test was carried out with a MAVIC 2 drone with a thermal imaging system. The heat loss of the pipeline with a total length of 2500m was determined by the thermal resistance method by measuring the surface temperature distribution by recording with a thermal camera from a height of 10-20 meters. The specifications of the equipment utilized for the measurement are listed in Table 1.

Table 1. Specifications of a drone MAVIC 2.

Sensor	Uncooled VoxMicrobolometer
Focal length	Approx.9mm 35mm format equivalent: Approx.38mm
Sensor Resolution	640x512@30Hz
Accuracy of thermal temperature	Measurement:±2°C or ±2%, whichever is greater
Scene Range	-40°C to 150°C (High Gain) -40°C to 550°C (Low Gain)
Spectral Band	8-14 µm
Photo Format	R-JPEG
Metering Method	Spot Meter, Area Measurement

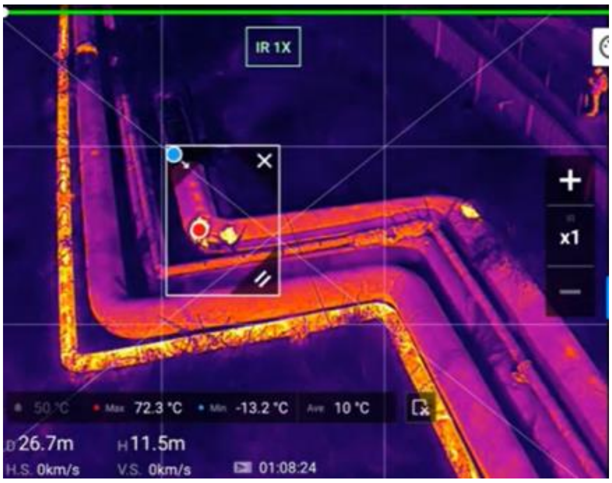

Figure 1. Infrared detection using a drone, the placement of heat energy loss.

Figure 2. Infrared detection of damaged areas of thermal insulation.

Figures 1 and 2 illustrate pipeline surface temperature distribution maps, while Figure 3 presents an actual image and the measurement progress of selected heat pipelines. The test was conducted in the winter of 2023, in November, December, and January.

A comparison of the physical properties of mineral wool and high-density polyurethane foam is shown in Table 2.

Table 2. *Physical properties of mineral wool and high-density polyurethane foam.*

Specifications	PUR	Mineral wool
Thermal conductivity, W/(m°C).	0.019-0.040	0.052-0.058
Insulation thickness, mm	35-70	120-220
Service temperature, °C	-150...+150	-150...+350
Actual heat loss	1.7 times less than the norm	Characteristics of mineral wool deteriorate with time
Techno-economic analysis	30% energy savings	

The 800 mm diameter pipeline is wrapped with mineral wool, covered with iron mesh, and covered with asbestos cement mortar.

As illustrated in Figure 3, the pipe's sections from the analyzed areas of the pipeline are represented.

Figure 3. *Section of pipe from the analyzed area.*

Figure 4. *Image of a pipeline with a high-density polyurethane foam insulation.*

During the measurements with the thermal imaging camera, the insulation of most parts was broken, the insulation gap was opened, and the repaired part was no longer insulated. The heat loss of the pipeline is 0.7 Gcal/h, and the temperature drop of the heat-carrying body at the end user is 8.4%.

The following aspects are put forward as a result of determining the actual heat loss of pipelines, which is one of the main indicators of the efficiency of thermal energy transportation, and evaluating the heat loss in the operating conditions, ways to reduce network heat loss, and the appropriate option of insulation materials should meet standard requirements. It includes:

Provide the thermal conductivity coefficient to the laboratory for analysis and verify compliance with the MNS 3442: 2002 standard (Mongolian Standard);

Verify compliance with MNS ISO 29469: 2010 standard for deformation;

And an urgent need to replace unrenovated lines with insulation that meets quality requirements and creates energy savings should be mentioned.

The insulation material production has started in a trial manner in our country (Figure 4), according to the quality standard requirements. The thermal technical test parameters of the material were accredited by the Mongolian National Authority for Accreditation (MNAS). Optimizing the initial investment of insulation materials is important, so to choose the right option, it is necessary to consider it from many angles.

The heat loss of the old mineral wool asbestos insulation was 4 times higher than the standard value due to the heat loss and the temperature difference between the start and endpoints. Therefore, the most suitable replacement insulation for the conditions of our country is a high-density pre-insulated polyurethane foam insulation board. The heat loss of the surface of the plate is 1.7 times less than the standard norm.

4. Conclusions

Energy saving in thermal energy transportation is one of the most important problems in reducing energy consumption. The practical implementation of energy efficiency of district heating requires knowledge of the energy performance of pipe networks through energy audit techniques. With the help of a drone, MAVIC 2 is equipped with a thermal camera, and pipeline heat loss and damage were determined in real-time dynamic mode. Also, pipeline insulation materials were compared, and feasibility studies of using high-density pre-insulated polyurethane foam insulation boards were conducted.

Production of insulation materials has commenced in our country on a trial basis to meet quality standard requirements. The thermal performance parameters of the material have been accredited by the Mongolian National Authority for Accreditation. The actual heat loss of the insulation panels proposed will be 1.7 times lower than the standard, resulting in a 30% energy savings. This claim is supported by both technical and economic calculations.

Abbreviations

DH	District Heating
MNAC	Mongolian National Authority for Accreditation
MNS	Mongolian Standard
UB	Ulaanbaatar

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Author Contributions

Tserendolgor Dugargaramjav: Conceptualization, Writing – review & editing, Supervision

Chantsaldulam Erdenechuluun: Conceptualization, Writing – original draft

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Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

Tserendolgor Dugargaramjav: Efficiency of heat exchangers, heat and mass transfer, and energy auditing in the energy sector.

Chantsaldulam Erdenechuluun: Heat distribution sector.