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Assessing the Thermal Performance of District Heating Twin Pipes with Vacuum Insulation Panels

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Abstract

In Sweden, around 10% of the energy supplied to the district heating networks are lost through heat losses from the distribution pipes. In cylindrical geometries it is preferable to improve the insulation as close to the center as possible. This has resulted in a hybrid insulation district heating pipe concept with a combination of vacuum insulation panels at the center, held in place by polyurethane foam. In the twin pipe concept, the vacuum insulation panel cover the supply pipe. This creates a complex temperature profile over the section and measured results on single pipes might not be applicable. Therefore, there is a need for a method to evaluate the improvement of hybrid insulation twin pipes in the laboratory. This paper presents a method where two guarded hot pipe apparatuses is used, one heating rod for each pipe, to measure the heat losses from hybrid pipes and compare to a conventional polyurethane pipe. The measurements indicate an improvement in thermal performance by 12%-18% for the total losses and by 29% -39% for the supply pipe losses.

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Keywords: Vacuum insulation panels, hybrid insulation, district heating pipes, thermal performance, super insulation.

1. Introduction

Collected energy statistics in Sweden [1] show that for 2013, 10 % of the energy supplied to the district heating network was lost in heat distribution. This is mainly due to the heat transfer from the distribution pipes. Within the research project 'Värmegles' (Sparse Heating), Fröling [2] concludes that the thermal performance of the district heating pipes is very important for the environmental performance of sparse district heating network.

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New district heating pipes today commonly uses polyurethane foam to insulate the district heating pipes. With cyclopentane and carbon dioxide as blowing agents, the thermal conductivity of the polyurethane pipe insulation at 50°C ranges from 22 mW/(m·K) to 27 mW/(m·K) depending on production method and pipe producer [3–6].

The heat loss from a district heating pipe can be reduced by adding insulation thickness to the pipe. For a cylindrical geometry, the effect of the insulation decreases with distance from the center of the cylinder. This gives incentives to exchange the thermal insulation close to the pipe to a better performing insulation, rather than adding insulation on the outside of the pipe.

Vacuum insulation panels consist of porous insulation which has been evacuated to decrease the thermal conductivity through the pore gas. The evacuated material reaches a minimum room temperature thermal conductivity between 2.5 mW/(m·K) and 7 mW/(m·K) depending on the material [7]. For building sector applications, a long life time performance is prioritized. This has led to the common use of nano-porous materials, such as fumed silica, as core material with a minimum thermal conductivity around 4.5 mW/(m·K) [7,8], less than a fourth of the thermal conductivity of polyurethane foam.

This also has led to a concept of a hybrid insulation district heating pipe where the innermost part of the polyurethane foam has been exchanged by a vacuum insulation panel, shown in Fig. 1.

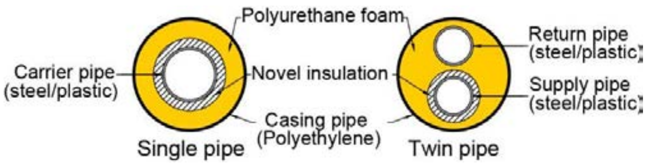

Fig. 1: District heating pipe cross sections describing the concept for hybrid insulation. A single pipe to the left and a twin pipe to the right. The novel insulation surrounds the supply pipe in the twin pipe configuration.

The hybrid insulation district heating pipes have been evaluated through the projects 'Högpresterande fjärrvärmerör' [9,10] (High performance district heating pipes) and 'Hybridisolerade fjärrvärmerör' [11,12] (Hybrid insulation district heating pipes). The projects have been separated into four parallel research paths: thermal performance measurements with guarded hot pipe, finite element simulations of hybrid pipes in field and laboratory, field measurements on pipes connected to active district heating networks and high temperature performance measurements in laboratory.

Meaurements with guarded hot pipe have shown an improvement of more than 30% when 10 mm of vacuum insulation panel is added to a single pipe with a steel pipe diameter of 114.3 mm and a casing pipe diameter 225 mm [9]. In Sweden, twin pipes are common for district heating pipes, where the return pipe is placed above the supply pipe within the same surrounding insulation. The temperature field in a twin pipe differs a lot from the temperature field in a single pipe. When a vacuum insulation panel is added to the supply pipe, the symmetry of the pipe is reduced further, making the measurements on single pipes even less representative of the twin pipe performance. Therefore, it is of interest to develop a method to measure the thermal performance of twin pipe in the laboratory.

1.1. Scope

This paper presents the development of a method to assess the thermal performance of twin pipes in the laboratory, with a focus on the comparison between conventional pipes and district heating pipes with vacuum insulation panels incorporated in the insulation. The method has been used to make some first estimations of the performance of a set of hybrid insulation district heating pipes with varying vacuum insulation panel set-ups.

1.2. Method

Measurements of the thermal performance of pipes have been done with a modified guarded hot pipe apparatus. The measurements are based on the standard for thermal conductivity measurements on polyurethane in SS-EN 253:2009 [13]. Conductances have been calculated according to the network analysis presented by Hagentoft [14].

2. Guarded Hot Pipe measurements on twin pipes

The measurement equipment was created for standardized thermal conductivity measurements on single pipes according to Appendix F of SS-EN 253:2009 [13]. In the standard measurement, one heating rod is inserted into the media pipe of a single pipe and the temperature at the steel pipe surface and at the casing surface is measured at 4 positions longitudinally and circumferentially equally distributed. For the twin pipe case, two apparatuses were used, with 2 heating rods, 4 temperature measurements in each pipe and 8 temperature measurement points around the surface as presented in Fig. 2.

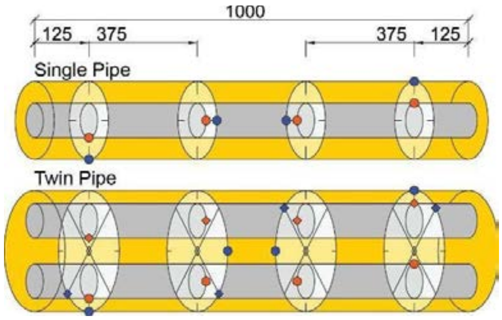

Fig. 2. Thermocouple placement for the guarded hot pipe measurements. Description of the measurements on a single pipe on top and the measurements for a twin pipe measurement below.

In the standard measurement, the thermal conductivity at 50°C is sought after. Therefore, the heat losses are measured at an average temperature around 50°C. For the twin pipe measurements, relative heat flow measurements were done instead.

In previous simulations within the project, the boundary temperatures of the supply pipe, the return pipe and the ambient air have been chosen to 85°C, 55°C and 5°C respectively. The laboratory measurements were limited to the laboratory air temperature at 22.5°C and the maximum temperature of the heating rods at 80°C. The measurement temperatures were chosen to be linearly proportional to the temperature differences in the simulation case, giving a supply pipe, return pipe and ambient temperature of 80°C, 58°C and 22.5°C.

It was also of interest to separate the magnitude of the heat flow from the supply pipe from the flow out from the return pipe. This was done by setting the same temperature in each pipe. Since the thermal conductivity and thus the heat losses depend on temperature, measurements were done both for 58°C in each pipe and 80°C in each pipe.

The measurement regime for each pipe is shown in Table 1.

Table 1. The three measurement cases.

Measurement	T_{supply} [°C]	T_{return} [°C]	$T_{ambient}$ [°C]
1.Symmetrical @ 58°C	58 ± 0.5	58 ± 0.5	22.5 ± 0.5
2.Proportional	80 ± 0.5	58 ± 0.5	22.5 ± 0.5
3.Symmetrical @ 80°C	80 ± 0.5	80 ± 0.5	22.5 ± 0.5

Due to the surface resistance between the casing pipe surface temperature and the room air temperature, the temperature at the casing surface will be higher than the room temperature. The temperature will also vary with the circumference of the pipe since the distance between the heated steel pipes and the casing pipe varies. The consequence of this variation has to be analyzed.

The measurements were performed for four samples with varying set-ups of vacuum insulation panels and one reference sample with only polyurethane foam insulation. The outer diameter of the steel carrier pipes were 89.9 mm and the pipes were positioned at 25 mm distance from each other. The outer diameter of the casing pipe was 315 mm with a thickness of around 4 mm. All vacuum panels were 1 m long and the pipes were cut to 1060 mm to avoid cutting through the panels.

The main difference between the different samples was the overlap of the vacuum insulation panel, but one sample also had a thicker vacuum insulation panel. The samples are presented in Fig. 3.

Sample nr	1.	2.	3.	4.	5.
Thickness	0 mm	10 mm	10 mm	10 mm	15 mm
Overlap	0 mm	0 mm	60 mm	100 mm	60 mm

Fig. 3. The five measured samples with the thickness and the overlap of the vacuum insulation panels presented.

3. Conductance model

A temperature independent conductance model was also tested, to see if the heat flows could be described as constant heat flow terms between each temperature boundary, as presented in Fig. 4. The relation between the conductances and the heat flows is described by Equation (1):

$$Q = K \cdot \Delta T \tag{1}$$

where Q is the heat flow (W), K is the thermal conductance (W/K) and ΔT is the temperature difference between the temperature nodes (°C).

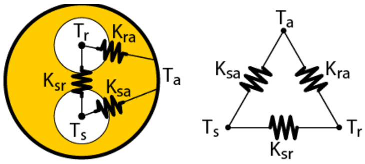

Fig. 4. Description of the conductance model.

The main simplifications in using conductances is that the conductances are temperature dependent, because the thermal conductivity of the insulation is temperature dependent, and that the boundary temperature T_a has a varying temperature.

For the case when T_s and T_r in Fig. 4 are equal, no heat is transferred between these pipes. For that case, the heat power supplied to one of the pipes can be used, together with the boundary temperatures, to calculate the conductance between that pipe and the ambient boundary, T_a.

4. Results

The heating power needed to reach the prescribed temperatures are presented in Fig. 5. As expected, the heating in the supply pipe decreases with extra insulation. One consequence is that the return pipe comes in a colder surrounding, increasing the heat loss from the return pipe. This means that the heat losses from the return pipe increases. Nevertheless, the total heat loss is also decreasing with vacuum insulation panels and with increasing overlap.

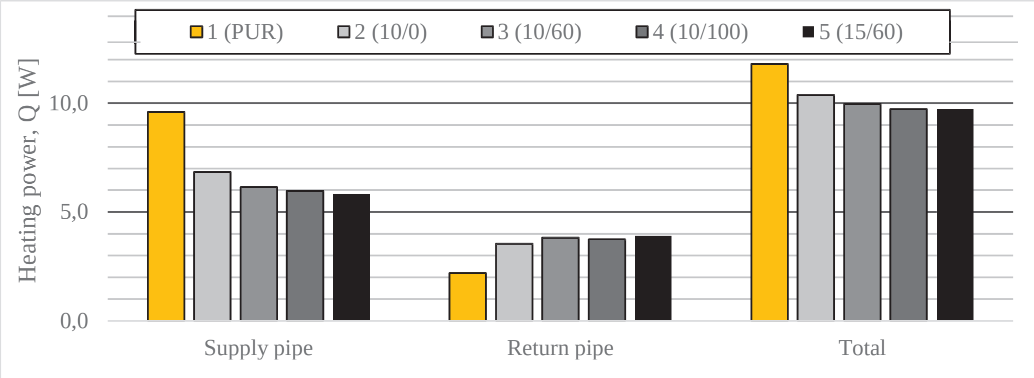

Fig. 5. Heating demand for the supply pipe, the return pipe and the total energy demand for the proportional boundary temperatures. The samples are listed as: Sample number (Vacuum insulation panel thickness [mm]/ Overlap length [mm]).

Samples 2-5 have been compared to sample 1 (the reference pipe with only polyurethane insulation). For the total losses, the improvement is between 12% and 17%. The largest contribution to the improvement comes from the supply pipe losses which are decreased by 29% and 39%. Conventionally, the total losses are considered when characterizing district heating pipes. But this also depends on the method of heat production. If the return temperature is lower, the heat production could be more effective, why decreasing the losses from the supply pipe is of higher importance.

Table 2. Total heat loss from the proportional measurements and calculated by the conductances achieved from the symmetrical temperature measurements.

Sample nr	Q [W]	$Q_{@58°C}$ [W]	$Q/Q_{@58°C}$ -1 [%]	Q_{avg} [W]	Q/Q_{avg} -1 [%]	$Q_{@80°C}$ [W]	$Q_{tot}/Q_{@80°C}$ -1 [%]	$Q_{@80°C}/Q_{@58°C}$ -1 [%]
1.	11,80	11,17	6%	11,62	2%	12,07	-2%	8%
2.	10,39	9,81	6%	10,26	1%	10,70	-3%	9%
3.	9,97	9,75	2%	10,03	-1%	10,32	-3%	6%
4.	9,73	9,53	2%	9,83	-1%	10,13	-4%	6%
5.	9,74	9,58	2%	9,81	-1%	10,04	-3%	5%

The results from the conductance calculations are shown in Table 2. The measured total heat loss for the proportional case is compared to the heat loss calculated from the conductances measured at 58°C, at 80°C and for the average between them. The conductances have been multiplied with the boundary temperatures from the proportional case, meaning 58±0.5°C in the return pipe, 80±0.5°C in the supply pipe and an ambient temperature of 22.5±0.5°C.

The result indicate how well the conductance model can be used to represent the thermal performance of the pipes. By separating the boundary temperatures from the conductances, as in Equation (1), the performance could be estimated for any boundaries. Table 2 show that the variation in the estimated heat losses varies with up to 9% dependent on the temperature at which the conductances were measured. Consistently, the higher temperature gave larger conductances, which was expected.

The average gives the best fit, reasonably because the temperature in both pipes will influence the conductances. The low conductances and the high conductances form limits between which the true conductance will lie as long as the boundary temperatures are within these limits. This creates a maximum deviation in the heat flow between 5% and 9%.

It might be possible to improve the conductance model by introducing some temperature dependence.

5. Conclusions

This paper presents the results from guarded hot pipe measurements on hybrid insulation twin pipes with vacuum insulation panels and polyurethane foam insulation. With a vacuum insulation panel, the total heat loss from the pipe is reduced. For the tested dimensions, two steel pipes with a 114.3 mm diameter, a casing pipe with a 315 mm diameter and 10-15 mm vacuum insulation panel, the total heat loss was reduced by 12%-17%. The whole variation of 5 percentage units can be seen in the change from 0 mm to 100 mm in overlap length. The increment of thickness from 10 mm to 15 mm gave an improvement of 2 percentage units. It should be considered that there only were one sample for each set-up.

The improvement is resulting from a reduction in the supply pipe losses between 29% and 39%. Some of the improvement is lost because the return pipe losses increase. This happens because the temperature around the return pipe decreases when the supply pipe has better insulation.

For the conductances there were a variation in the calculated total heat losses of up to 9% between the high temperature and the low temperature. This deviation is the limit for any pipe temperatures between 58°C and 80°C and a ambient temperature at 22.5°C. The measured heat flow could be predicted by the average conductances with an error of less than 3%.

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