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An analytical method for calculating the thermal conductivity of a twin pipe in district heating system

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KEYWORDS: *Twin heating pipe, Heat Conductivity, Experimental Measurements, analytical Solution*

SUMMARY:
In this paper a simple analytical method is introduced for calculating the overall thermal conductivity of a twin pipe in district heating network. The method is developed based on calculating the conductive and convective heat transfer around the casing pipe in different perimetral sections. Temperature inside the supply and return pipes and also over the heating pipe is measured on different points. These data are imported to a computer program which was written to calculate the heat loss and the total conductivity of the heating pipe. The method has shown good agreement with measurements and it is simple and quick enough in calculating the thermal conductivity of asymmetric- geometries and their temperature distribution. The method is capable to make calculations for more complicated geometries, such as heating pipes with heterogeneous insulating materials.

1. Introduction

District heating systems are widely used in Sweden, mainly for residential and commercial space/water heating. The common medium for the distribution is water. Heat is distributed through underground networks of insulated pipes which consist of supply and return pipes. The higher the temperature difference between supply and return, the higher the efficiency of the delivered energy. .

By improvements in insulating buildings in Sweden there is less heating demand which results in lower temperature difference between the supply and the return pipes. As a consequence heat losses from the pre-insulated pipes to the surrounding environment apportion larger percentage of heat losses of the district heating network. Having the vision of energy plus buildings, smart grids and smart energy networks between buildings, motivates to make pipes better insulated and more efficient, i.e. more complex and more efficient designs such as twin pipes insulted with new materials such as vacuum insulated panels. Effectiveness of new designs and the efficiency of heating pipes are usually assessed by the combination of measurements and numerical simulations, which can be expensive and time consuming. More complex designs, geometries and materials, increase the complexity of the measurements and calculations. Therefore having easier methods for measuring/calculating the thermal performance of heating pipes is desired.

A simple analytical method for calculating the overall thermal conductivity of a twin pipe is presented in this paper. The experimental setup which was used to measure the temperature profile of the twin pipe and surrounding air is described briefly. The measured temperatures were used to calculate the thermal conductivity analytically.

2. The experiment

2.1 The experimental setup

Experiments were performed using a "guarded hot pipe" (more information available in (Berge 2013) and (ISO 8497:1994)) based on the standard for twin pipe assembly of steel service and return pipes, polyurethane thermal insulation and outer casing of polyethylene (15698-1:2009). A schematic figure of the twin pipe, casing and two steel pipes inside the casing, and the installed thermocouples is shown in FIG 1. One of the twin pipes is to supply heat (the pipe ion the bottom - red colour) and the other one contains the return flow (the pipe on top - blue colour). One heat rod was placed inside both of the supply and return pipes to simulate the warm fluid inside pipes. The electrical current in the heat rods were set to get a constant heat power depending on the desired temperature. Thermocouples were placed over the casing, 16 positions, and inside the steel pipes, 4 positions in each pipe – not visible in the figure – to measure temperature at different points. Temperature of the heat rods and the ambient air were also measured. The measured data were collected by two software programs. All the programs and thermocouples were calibrated before running the experiment to make sure about the accuracy of the collected data.

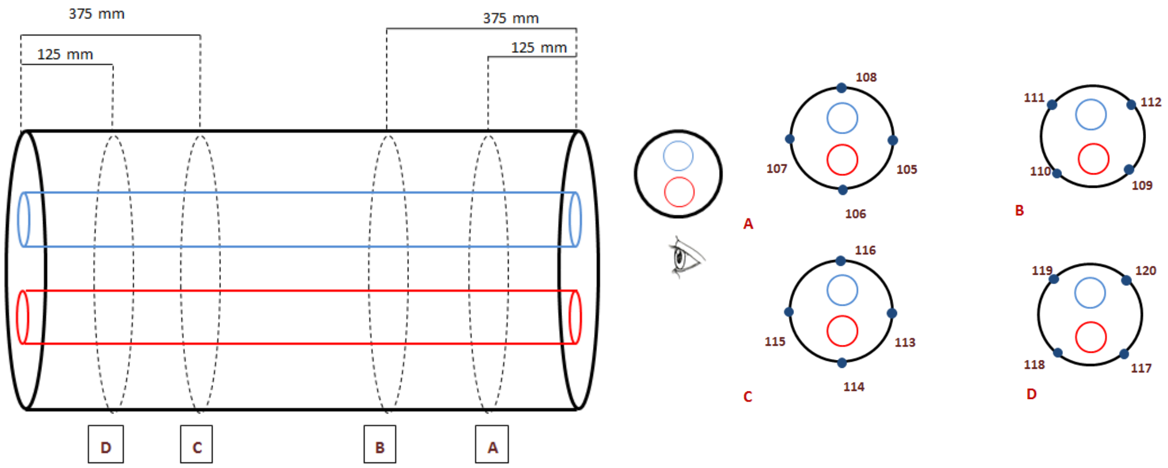

*FIG 1. Position of thermocouples on the casing pipe for the **vertical position** of the twin pipe. The red pipe (bottom) represents the supply pipe and the blue pipe (top) represents the return pipe.*

2.2 Measurements

Measurements were done in four different steps:

1. Horizontal: Supply flow of 78°C – Return flow of 78°C (supply and return pipes lay side by side)
2. Vertical: Supply flow of 78°C – Return flow of 78°C
3. Vertical: Supply flow of 70°C – Return flow of 50°C
4. Vertical: Supply flow of 80°C – Return flow of 40°C

Measurements were performed for two positions of the twin heat pipe; horizontal and vertical (as FIG 1). The aim was investigating the effects of rotating the twin pipe on the temperature distribution over the casing, since it affects the convective heat flow pattern around the casing. All the heat from the twin pipe transfers to the ambient air through natural convection, which the pattern of the air flow and its thermal properties can be influenced by the temperature profile on the casing and its variations. Comparing horizontal and vertical positioning (steps 1 and 2) helps to investigate the importance of positioning and the consequent difference in flow patterns on the temperature profile over the casing pipe. Main differences of the temperature profile are shown in FIG 2; the maximum difference caused by rotating the casing is for point **A** which its temperature increases for 2.6% when the casing turns to the vertical position. Since the actual position of the twin pipe is vertical most of the measurements were performed for this position. Although for the real case the surrounding environment is soil and very different from air, but this sensitivity test enables to estimate the maximum divergence in results caused by positioning and the consequent difference in natural convection around the casing.

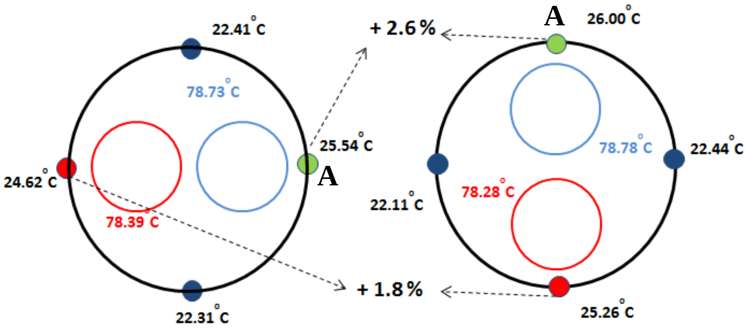

FIG 2. Differences in the temperature distribution on the casing caused by rotating the casing of the twin heat pipe.

3. The analytical method for calculating the thermal conductivity

An analytical method was developed to calculate the overall thermal conductivity of the twin pipe. The method is based on calculating the conductive and convective heat transfer around the heating pipe in different perimetral sections when steady state condition is achieved.

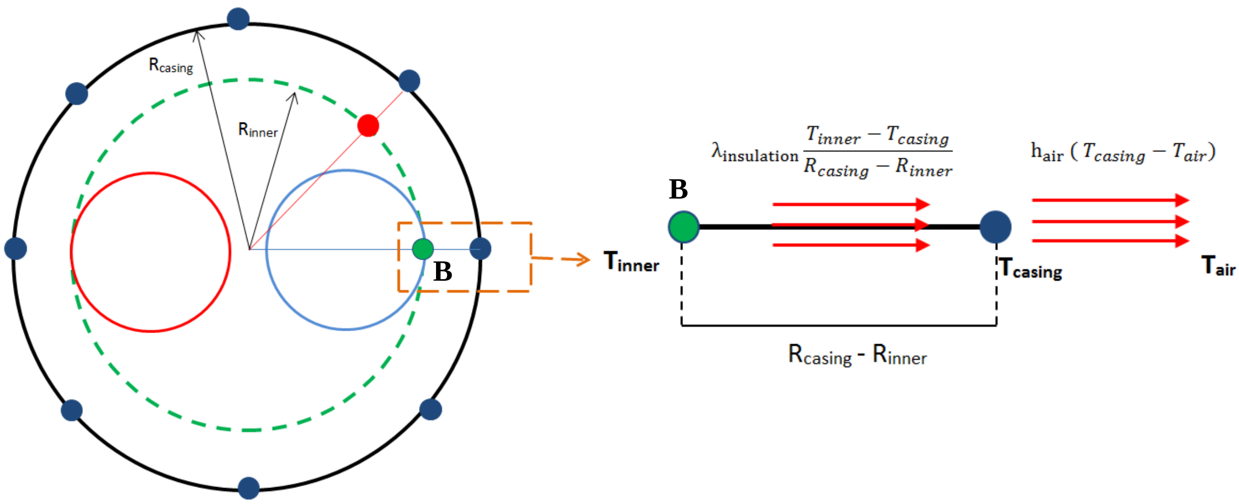

FIG 3. Left: Cross section of the twin heating pipe with an imaginary circle (green dashed circle) tangent to the steel pipe on the right side. Temperature of 8 points on the casing and one point on the steel pipe (**B**) *are known. Right: An infinite narrow section of the heating pipe; through conduction heat transfers from the imaginary circle to the casing where loses heat to the surrounding air through convection.*

Imagine a circle tangent to one of the steel pipes as shown in FIG 3. The amount of heat which passes through the imaginary dashed circle is equal to the heat which transfers to the surrounding air through the casing (the thermal capacity of the insulation and the casing is neglected, moreover measurements were done for steady-state condition). Assuming an infinite narrow section, the amount of conductive heat transfer from the imaginary circle, point **B** in FIG 3, is equal to the amount of convective heat transfer from the blue point on the casing to the air.

$$\lambda_{\text{insulation}} \frac{T_{inner}-T_{casing}}{R_{casing}-R_{inner}} = \text{h}_{\text{air}} \left(T_{casing} - T_{air}\right) \quad (1)$$

Where $\lambda_{\text{insulation}}$ thermal conductivity of the insulation [W/m/K]

h_{air} convective heat transfer coefficient of air [W/m^2/K]

R_{casing} radius of the casing [m]

R_{inner} radius of the imaginary inner circle [m]

T_{air} temperature of the surrounding air [K]

T_{casing} temperature on the casing at the considered point [K]

T_{inner} temperature on the imaginary circle at the considered point [K]

T_{casing} is known for the 8 measured points on the casing and T_{inner} is known for the point on the steel pipe, point **B** on FIG 3. Since the geometry is not perfect the imaginary circle is not tangent to the other steel pipe and consequently temperature is assumed unknown for the imaginary circle located on the other steel pipe. The aim is finding the temperature profile of the imaginary circle based on equation (1). Three parameters are unknown in the equation; $\lambda_{\text{insulation}}$, T_{inner} and h_{air} .

The thermal conductivity of the insulation can be defined as a function of its temperature (Berge 2013):

$$\lambda_{\text{insulation}} = 26 + 0.1(T - 50) \quad (2)$$

Where the unit for conductivity in the equation is [mW/m/K].

Coefficient of the convective heat transfer for air, h_{air}, can be calculated in two ways:

1. By knowing T_{inner} for point **B** and using equation(2), h_{air} is calculated for that section of the casing. Afterwards the same h_{air} is used for all the other points around the casing.
2. The amount of heat which is generated inside the twin pipe is known. All the heat transfers to the surrounding air according to the following equation:

   $$Q = h_{air}\, A_{casing}\, (T_{casing} - T_{air}) \quad (3)$$

   Where T_{casing} is the average temperature of the measured points over the casing and A_{casing} is the surface area of the casing for a unit length. Using equation (3) it is possible to find an average h_{air} which can be used in the calculations.

Using the above mentioned equations and assumptions, T_{inner} is calculated for 8 points on the imaginary circle corresponding to the 8 measured points on the casing. The resulted temperature profile for the insulation inside the casing, located on the imaginary circle, helps to calculate the heat conductivity according to equation (2). Temperature values which are used in equation (2) are the average temperature of the casing and the imaginary circle:

$$T_{insulation,i} = (T_{inner,i} + T_{casing,i})/2 \quad (4)$$

i=1, 2,…,8

A Matlab program was written which reads the measured values out of experiments and calculates heat losses and the thermal conductivities based on the developed method.

4. Results and the calculated thermal conductivity

Measured and calculated temperature profiles for the four steps of the measurements are presented here. Thermal conductivity is calculated according to the previous section for 8 sections around the twin pipe. An average thermal conductivity is calculated as the mean value of the thermal conductivities at 8 points. The average thermal conductivity can be interpreted as the overall conductivity of the whole setup since it is based on the calculation of the amount of heat flow from the twin heating pipe to the surrounding air. The following figures show the distribution of temperature and the thermal conductivity around the twin heating pipe. Tables compare the calculated thermal conductivities, calculated based on the two methods for calculating h_{air}.

4.1 Horizontal – Supply flow of 78°C – Return flow of 78°C

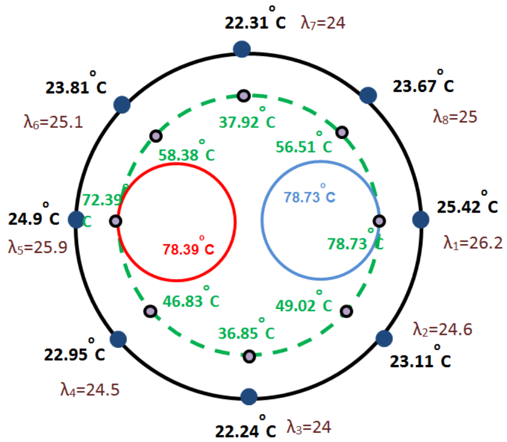

FIG 4. Temperature distribution over the casing and the imaginary circle (dashed green line). The calculated heat conductivity is shown at each section in mW/m/K.

TABLE 1. The calculated thermal conductivities for the twin district heating pipe at 8 points and the average value. Values are compared for the two methods of calculating the convective heat transfer coefficient of air.

	Temperature			$\lambda_{isulation}$ (or λ_{setup}) [mW/m/K]	
	T_{casing}	T_{inner}	T_{mean}	h_{air} was calculated for point **B**	h_{air} was calculated as a mean
1	25.42	78.73	52.075	26.2	25.8
2	23.11	49.02	36.065	24.6	24.4
3	22.24	36.85	29.545	24	23.8
4	22.95	46.83	34.89	24.5	24.3
5	24.9	72.39	48.645	25.9	25.5
6	23.81	58.38	41.095	25.1	24.8
7	22.31	37.92	30.115	24	23.9
8	23.67	56.51	40.09	25	24.8
Mean			39.07	24.9	24.7

4.2 Vertical – Supply flow of 78°C – Return flow of 78°C

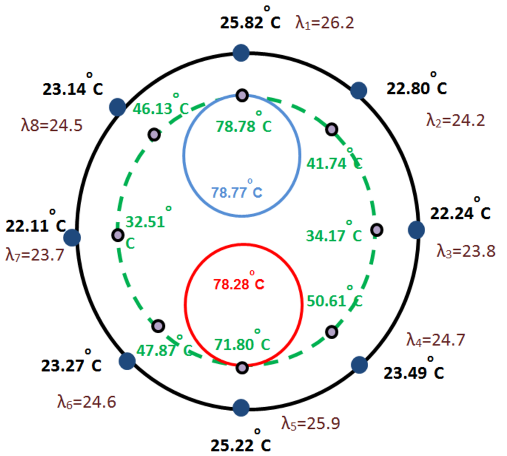

FIG 5. Temperature distribution over the casing and the imaginary circle (dashed green line). The calculated heat conductivity is shown at each section in mW/m/K.

TABLE 2. The calculated thermal conductivities for the twin district heating pipe at 8 points and the average value. Values are compared for the two methods of calculating the convective heat transfer coefficient of air.

	Temperature			$\lambda_{isulation}$ (or λ_{setup}) [mW/m/K]	
	T_{casing}	T_{inner}	T_{mean}	h_{air} was calculated for point **B**	h_{air} was calculated as a mean
1	25.82	78.78	52.3	26.2	26.1
2	22.8	41.74	32.27	24.2	24.2
3	22.24	34.17	28.205	23.8	23.8
4	23.49	50.61	37.05	24.7	24.7
5	25.22	71.8	48.51	25.9	25.8
6	23.27	47.87	35.57	24.6	24.5
7	22.11	32.51	27.31	23.7	23.7
8	23.14	46.13	34.635	24.5	24.4
Mean			36.98	24.7	24.7

4.3 Vertical – Supply flow of 70°C – Return flow of 50°C

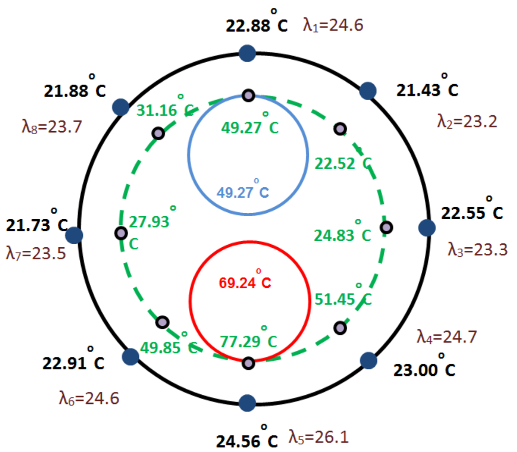

FIG 6. Temperature distribution over the casing and the imaginary circle (dashed green line). The calculated heat conductivity is shown at each section in mW/m/K.

In this case the calculated temperature for the imaginary inner circle is overestimated since it is higher than the temperature of the supply pipe (steel pipe on the bottom). Calculations were performed again by assuming temperature of the supply pipe as known, instead of the return pipe. There was almost no difference in the calculated conductivity; hence the overestimation of the calculation method could be neglected.

TABLE 3. The calculated thermal conductivities for the twin district heating pipe at 8 points and the average value. Values are compared for the two methods of calculating the convective heat transfer coefficient of air.

	Temperature			$\lambda_{isulation}$ (or λ_{setup}) [mW/m/K]	
	T_{casing}	T_{inner}	T_{mean}	h_{air} was calculated for point **B**	h_{air} was calculated as a mean
1	22.88	49.27	36.075	24.6	24.4
2	21.43	22.52	21.975	23.2	23.2
3	22.55	24.83	23.69	23.3	23.3
4	23	51.54	37.27	24.7	24.5
5	24.56	77.29	50.925	26.1	25.7
6	22.91	49.85	36.38	24.6	24.4
7	21.73	27.93	24.83	23.5	23.4
8	21.88	31.16	26.52	23.7	23.6
Mean			32.21	24.2	24.1

4.4 Vertical – Supply flow of 80°C – Return flow of 40°C

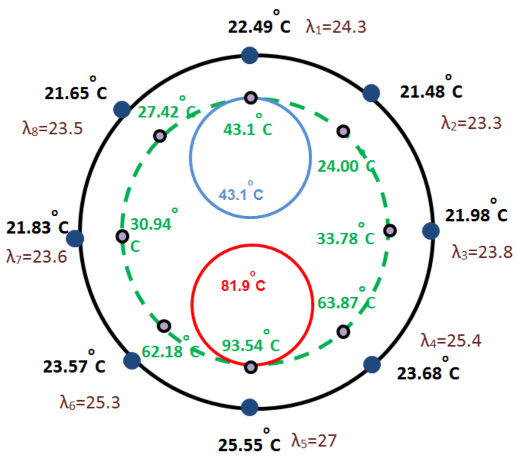

FIG 7. Temperature distribution over the casing and the imaginary circle (dashed green line). The calculated heat conductivity is shown at each section in mW/m/K.

TABLE 4. The calculated thermal conductivities for the twin district heating pipe at 8 points and the average value. Values are compared for the two methods of calculating the convective heat transfer coefficient of air.

	Temperature			$\lambda_{isulation}$ (or λ_{setup}) [mW/m/K]	
	T_{casing}	T_{inner}	T_{mean}	h_{air} was calculated for point **B**	h_{air} was calculated as a mean
1	22.49	43.1	32.795	24.3	24
2	21.48	24	22.74	23.3	23.2
3	21.98	33.78	27.88	23.8	23.6
4	23.68	63.87	43.775	25.4	24.8
5	25.55	93.54	59.545	27	26.1
6	23.57	62.18	42.875	25.3	24.8
7	21.83	30.94	26.385	23.6	23.5
8	21.65	27.42	24.535	23.5	23.4
Mean			35.07	24.5	24.2

5. Discussion and conclusion

According to the results, the two methods for calculating of the convective heat transfer coefficient of air do not affect the calculated thermal conductivity of the setup considerably. The maximum difference between the overall thermal conductivities is around 1.2% for the fourth case. For this case the maximum difference for $\lambda_{isulation}$ at a point happens at point 5 (see

TABLE 4) on the bottom of the heating pipe; 3.5% difference. Therefore it is possible to conclude that both methods for estimating h_{air} are valid. However using more accurate techniques to calculate h_{air} may give better results, although it will increase the complexity of the calculations and measurements.

The maximum difference between the calculated overall thermal conductivities is around 3.3% between the first case, 24.9 [mW/m/K] in TABLE 1 for the mean temperature of 39.07^{o}C, and the third case, 24.1 [mW/m/K] in TABLE 3 for the mean temperature of 32.21^{o}C. This maximum difference is induced by different positioning of the casing and also different temperatures. These two cases show the maximum differences in both positioning and temperature among the four cases, , which induces the maximum difference in the air flow around the casing and its thermal properties. This results in the maximum difference between the calculated $\lambda_{isulation}$.

Although there are differences between the calculated thermal conductivities, there are small enough to have a good estimate for the overall thermal conductivity of the twin heating pipe. The proposed method for calculating the thermal conductivity of the twin district heating pipe is simple and quick. Moreover it is not very dependent on the geometry inside the casing, for example it might be possible to use the same technique for estimating the conductivity of a twin pipe insulated partly by vacuum insulation panels. However more experiments and calculations will be performed in future.

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