Optimization of the Geometric Parameters of the Thermal Insulation of the Heating System by Using Multi-Pipe Circular Thermal Insulation

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Abstract – The publication presents a design solution for circular multi-pipe thermal insulation and an example of an existing heating installation consisting of six individual heating pipes in the building of the Bialystok University of Technology. In the paper, the arrangement of six heating system pipes in circular thermal insulation was designed in such a way that one heating pipe is centrally located in the circular thermal insulation, the other five heating pipes are located at the vertices of a regular pentagon inside the circular thermal insulation. Heat loss calculations were made using the Boundary Elements Method (BEM) with the actual boundary conditions in the room where the existing heating installation is located. Additionally, the ecological effect was determined in the form of reduction of pollutants emitted into the atmosphere resulting from heat losses for the developed multi-pipe thermal insulation. The calculation results showed a significant reduction in heat losses as a result of the use of multi-pipe thermal insulation in relation to the existing single heating installation. The use of multi-pipe insulation undoubtedly follows the trend of energy-saving heat transport and is an alternative to the commonly used single pipes.

Keywords – Heat losses; heat transport; multi-tube thermal insulation; pre-insulated pipes

Nomenclature

d	diameter of the heating pipe	m
D	diameter of thermal insulation for a single pipe	m
D'	diameter of multi-pipe thermal insulation for variant A	m
D''	diameter of multi-pipe thermal insulation for variant B	m
ΔE_m	reduction of pollutants emission	kg/year
E	annual energy resulting from heat loss	GJ
E_f	the emission factor of pollutants into the atmosphere	g/GJ
h	heat transfer coefficient	W/m ² /K
k	thermal conductivity	W/m/K
L	pipe length	m
q	unit heat flux	W/m
q'	heat flux density	W/m ²

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T	temperature	°C
w	the distance between the pipes in variants A and B and the distance between the pipe and the external wall of thermal insulation for variant A	m
w'	distance between the pipe and the external wall of thermal insulation for variant B	m
x, y	Cartesian coordinates	m
<i>Subscripts</i>		
A	variant A	
amb	ambient	
B	variant B	
i	pipe number	
j	variant designation (A or B)	
R	return pipe	
S	supply pipe	

1. INTRODUCTION

For years improvements possible to apply in heating and domestic hot water networks have been analysed to provide higher energy efficiency of systems and achieve a reduction in pollutants emission.

Some researchers analysed new solutions or methodologies for estimation of heat generation and distribution. Volkova *et al.* [1] proposed to supply buildings from new cogeneration plants using renewable energy sources and heat pump technologies. Vigants *et al.* [2] studied energy usage in DHS in dependence on flow and temperature conditions in networks. Stennikov *et al.* [3] showed results of optimization of heat supply radius for DHS in a town in Russia. Ruseljuk *et al.* [4] studied legal, climate and economic factors to highlight weak points in DHS in Estonia and Serbia networks. Authors noted the need of government support, through regulations and financial aids, that could increase efficiency of solutions. Pourbozorgi Langroudi *et al.* [5] reviewed different methods of predictive maintenance and the compatibility to apply on a DH network. Al-Barqawi and Zayed [6] classified three main groups of factors influencing DHN efficiency changes in time as: physical factors connected with pipes (like age material, diameter, isolation etc.) environmental factors (for example climate, solid type, pipes location) and operation parameters (like fluid quality, flow velocity etc.).

Designing a new heat source for a building or modernizing an existing heat source involves determining the heat demand for central heating purposes and the heat demand for hot water heating, taking into account losses in heat transport. By reducing heat losses in heat transport through pipes, the power of the heat source can be reduced, which translates into the reduction of pollutants emitted to the atmosphere from the heat source and the operating costs of the heat source.

The improvement of thermal insulation of heat transporting pipes can be related to both external heating networks and heating systems inside the building. The amount of heat losses depends on the climate in which the heating network is located [7], [8] and the operating parameters of the heating networks, such as the temperature of the heating medium [9]–[12].

Modifications aimed at improving the thermal insulation of heating pipes usually consist in the use of new insulation materials with a lower thermal conductivity coefficient or a change in the geometry of the thermal insulation cross-section. Changing the geometry of the thermal

insulation may consist in: adding an additional layer of thermal insulation (so-called heating pipes with thermal insulation in the 'plus' version [13]), using new shapes in cross-sections of thermal insulation [12], [14], [15] and locating many pipes in a common thermal insulation [14], [16].

According to the 'A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy', improving the energy efficiency of heating systems is a priority policy task for the European Union. In the Directive of the European Parliament and of the Council (EU) of December 11, 2018, it was stated that: *'Improving energy efficiency throughout the full energy chain, including energy generation, transmission, distribution and end-use, will benefit the environment, improve air quality and public health, reduce greenhouse gas emissions...'* [17]. One of the ways to improve the energy efficiency of the energy sector in line with the Directive [17] is the modernization of heat transport pipes.

The aim of this study is to propose a solution for circular multi-pipe thermal insulation in which six heating installation pipes are located. The concept of multi-pipe thermal insulation was made on the basis of the existing heating installation in the underground part of the building of the Faculty of Civil Engineering and Environmental Sciences of the Bialystok University of Technology. In order to compare the heat losses of the multi-pipe thermal insulation with the existing heating pipes, numerical calculations were performed using the Boundary Elements Method (BEM). It should be noted here that in practice the number of pipes in a common thermal insulation is usually limited to two pipes [13].

2. THE CONCEPT OF MULTI-PIPE CIRCULAR INSULATION ON THE BASIS OF THE EXISTING HEATING INSTALLATION

For the transport of heat in heating systems, single heating pipes with round thermal insulations are most often used (Fig. 1).

Fig. 1. The analysed heating system in the building of the Bialystok University of Technology, consisting of six single heating pipes.

Fig. 2. Longitudinal connections of a typical thermal insulation of a single conductor, which may cause linear thermal bridges: a) Cross-section of the thermal insulation; b) View of the longitudinal connection of the thermal insulation.

The main advantage of circular thermal insulation on single heating pipes is the simplicity of installation. The disadvantages of thermal insulation of circular individual pipes are high consumption of thermal insulation material around the heating pipe and thermal bridges that may appear, which result from the method of thermal insulation installation after the heating installation is completed. The simplest installation of thermal insulation on a heating pipe made is to apply thermal insulation through an indentation along the thermal insulation Fig. 2(a) and 2(b). After applying thermal insulation to the pipe, the longitudinal indentation is usually sealed with plastic tape. This type of connection of the edges of the thermal insulation can cause a longitudinal thermal bridge. Thermal bridges generate additional heat losses in heating pipes.

The solution to the problem of linear thermal bridges in heating systems can be prefabricated heating pipe systems in pre-insulated technology. Additionally, by using multi-tube thermal insulation, the amount of insulation material can be reduced compared to circular thermal insulation used in single heating pipes. The publication presents the technical solution of round multi-pipe thermal insulation as an alternative to six thermal insulation of single pipes of a heating system. The geometry of the presented circular multi-pipe thermal insulation is designed in such a way that one of the supply pipes is placed centrally in a regular pentagon, while the other five pipes are placed at the vertices of a regular pentagon. The distances between heating pipes in multi-pipe thermal insulation were adopted, similarly to standard twin pipe pipes, and for the presented example the distance is equal to 20 mm. Two variants were adopted due to the distances between the piping and the external wall of thermal insulation: in the first standard solution, the distance between the pipe and the external surface of the thermal insulation was assumed to be equal to the distance between the pipe $w = 20$ mm (version A, Fig. 3(b)), in the second case (version B, Fig. 3(c)), the distance between the pipes and the outer wall of the thermal insulation was assumed to be equal to the thickness of the thermal insulation of a single heating pipe $w' = (D-d)/2$, Fig. 3(a) and 3(c). Table 1 presents the main features of the geometry of single pipes and multi-pipe insulation in A and B versions. The total thermal insulation area in the cross-section of the multi-pipe thermal insulation in variants A and B is respectively lower by 37.6 % and 20.1 % compared to the thermal insulation surface area of six single pipes.

Fig. 3. Geometry and boundary conditions (S-supply pipe, R-return pipe): a) Six single pipes of the heating system; b) Multi-pipe thermal insulation (variant A), where 'w' is the distance between the pipes and the distance between the pipe and the external wall of thermal insulation; c) Multi-pipe thermal insulation (variant B), where w is the distance between the pipes and w' is the distance between the pipe and the external wall of thermal insulation.

TABLE 1. GEOMETRY OF THE ANALYSED VARIANTS OF THERMAL INSULATION

Description of the thermal insulation variant	Heat pipe diameters d	Minimum distance between pipes w^*	The minimum thickness of the thermal insulation between the pipe and the external wall of the thermal insulation w, w'^*	Thermal insulation diameter D, D', D''	Thermal insulation field	Percentage change in the area of thermal insulation in relation to single pipes
–	m	m	m	m	m ²	%
six single pipes	0.04830	0.02000	0.03085	0.11000	0.04603	–
multi-pipe thermal insulation, version A	0.04830	0.02000	0.03085	0.22490	0.02873	37.6
multi-pipe thermal insulation, version B	0.04830	0.02000	0.02000	0.24660	0.03677	20.1

*Note: Fig. 3(b) and 3(c)

3. METHODOLOGY OF DETERMINING HEAT LOSSES THROUGH MULTI-PIPE THERMAL INSULATION

The following chapter presents the methodology for determining heat losses through single pipes and multi-pipe thermal insulation. In order to determine the heat losses in single pipes, the theoretical solution of thermal conductivity in circular pipes was used:

$$q_{Sia} = \frac{(T_s - T_{amb})\pi}{\left(\frac{1}{2k} \ln\left(\frac{D_i}{d_i}\right) + \frac{1}{hD_i}\right)} [W/m], \quad (1)$$

$$q_{Ria} = \frac{(T_R - T_{amb})\pi}{\left(\frac{1}{2k} \ln\left(\frac{D_i}{d_i}\right) + \frac{1}{hD_i}\right)} [\text{W/m}], \quad (2)$$

where

- q_{Sia}, q_{RSia} Heat losses through the supply and return conduit, respectively;
- D_i Diameter of the thermal insulation;
- d_i Diameter of the heat pipe;
- h Heat transfer coefficient of 25 W/m²/K;
- k Thermal conductivity coefficient of the thermal insulation;
- T_S, T_R Temperature of the heating medium of the supply and return heating pipe, respectively;
- T_{amb} Ambient temperature and i is the number of the pipe.

The total heat losses through six single pipes were determined according to the formula Fig. 3:

$$q_a = q_{S1a} + q_{S2a} + q_{S3a} + q_{R1a} + q_{R2a} + q_{R3a} [\text{W/m}]. \quad (3)$$

Determination of heat losses in multi-pipe insulation was performed using the Boundary Element Method. For this purpose, the differential equation of thermal conductivity in the cross-sectional area of multi-pipe insulation was solved:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0, \quad q_x = -k \frac{\partial T}{\partial x}, \quad q_y = -k \frac{\partial T}{\partial y}, \quad (4)$$

where x and y are Cartesian coordinates in the cross-sectional area of multi-pipe thermal insulation.

Robin's condition was adopted for the calculations:

$$q' = -k \frac{\partial T}{\partial n} = h(T - T_{amb}) [\text{W/m}^2]. \quad (5)$$

Unit heat losses for multi-pipe thermal insulation were determined from the heat flux balance (Fig. 3(b) and 3(c)):

$$q_b = q_{S1b} + q_{S2b} + q_{S3b} + q_{R1b} - q_{R4b} + q_{R2b} - q_{R5b} + q_{R3b} - q_{R6b} [\text{W/m}], \quad (6)$$

where the negative heat fluxes mean the heat transferred from the supply pipe S to the return pipe R (Fig. 3(b), 3(c)).

The Boundary Element Method is used in many thermal and flow problems [18], [19]. Details of the BEM algorithm are presented in the literature [20]. For the simulation, a *Fortran* program was written. The verification of the Boundary Element Method is presented in the following works [15]. For the numerical BEM simulations, the boundary of a cross-section of 3000 elements was adopted.

4. RESULTS AND DISCUSSION

Fig. 4 shows a diagram of unit heat losses in the ambient temperature range from 0 to 20 °C for six single pipes determined from the analytical Eq. (1) and unit heat losses of multi-pipe thermal insulation determined by the BEM method. Average heat losses turned out to be 57 % and 67 % lower, respectively for variants A and B, compared to single thermal insulations. Multi-tube thermal insulation is characterized by a significant reduction in heat loss compared to single ducts. In the works [14], [21], the use of twin pipes allowed to reduce heat losses by

about 32 % to 50 % compared to single pipes, depending on the thickness of the insulation. It should be noted that there are various versions of the standard insulation and the so-called 'plus' [13] with a thickened layer of thermal insulation. In the case of triple pre-insulated pipes, heat losses are approximately 42 % to 55 % [14], [16] lower than in the case of single pre-insulated pipes. It can be seen that the more pipes are located in a common multi-pipe insulation, the greater the reduction of heat losses in relation to single heating pipes.

Fig. 4. Unit heat losses in the ambient temperature T in six single heating pipes and in two variants of multi-pipe thermal insulation (cases A and B).

Fig. 5(a) and 5(b) show the temperature and heat flux density fields, respectively, for variants A and B of multi-pipe thermal insulation for an ambient temperature of 8 °C. In the case of variant A, significant values of the heat flux density between the supply pipes and the external walls of thermal insulation can be noticed, which can be eliminated by adding an additional thermal insulation field in the cross-sectional area (option B), i.e. increasing the diameter of the multi-pipe circular insulation.

The heat source in the building of the Bialystok University of Technology is powered by a coal-fired CHP plant. It should be noted here that the actual heat source, in line with the trends of climate neutrality, should be replaced by a renewable energy source. Reducing heat losses in the internal heating system allows to reduce the heat demand for the entire building, and thus reduces the emission of pollutants into the atmosphere. Table 2 shows the reduction of pollutants emitted to the atmosphere by the use of multi-pipe thermal insulation in relation to single pipes. The following pollutants emitted into the atmosphere were assumed for the calculations [22], [23]: nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulphur oxides (SO_x), total suspended particles (TSP), particulate matter (PM₁₀ and PM_{2.5}), carbon dioxide (CO₂) and methane (CH₄).

The reduction of pollutants (ΔE_m) emitted into the atmosphere resulting from heat losses by the application of variants A and B in relation to single pipes on the tested section of the installation was determined according to the following formula:

$$\Delta E_m = (E_a - E_{b(j)}) \cdot E_f \text{ [kg/year]}, \quad (7)$$

where

- E_f Pollutant emission coefficient according to [20, 21];
 E_a Annual energy for heat loss in the existing six single heating pipes;
 $E_{b(j)}$ Annual energy for heat loss in multi-pipe thermal insulation in variants A and B, ($j = A$ or $j = B$).

Fig. 5. Temperature field in the cross-section of multi-pipe thermal insulation for variant A (a) and variant B (c) and the distribution of flux density in the cross-section of multi-pipe thermal insulation for variant A (b) and variant B (d).

The annual energy for heat loss $E_{a,b(A),b(B)}$ is determined as the product of the pipe length, time and unit heat losses.

Table 2 shows the calculation results of the annual emission of pollutants resulting from heat losses for six single pipes $E_a E_f$ and multi-pipe thermal insulation in variants A $E_{b(A)} E_f$ and B $E_{b(B)} E_f$, for an assumed length of 40 m, and an ambient temperature of 8° C during the heating season (255 days). Additionally, the study determined the unit reduction of pollutants per meter of installation length $\Delta E_{a-b(A)}/L$, $\Delta E_{a-b(B)}/L$, so that other scientists and engineers could refer to the obtained results and compare their results. Pollutants emitted to the atmosphere from heat losses in the tested heating installation turned out to be on average about two and three times smaller for variants A and B, respectively, compared to single heating pipes.

TABLE 2. ANNUAL EMISSIONS OF POLLUTANTS DUE TO HEAT LOSSES DETERMINED FOR VARIANTS OF SIX SINGLE PIPES AND MULTI-PIPE THERMAL INSULATION IN VARIANTS A AND B

Pollutant	E_f , g/GJ	$E_a E_f$, kg/year	Case A			Case B		
			$E_{b(A)} E_f$, kg/year	$\Delta E_{m(A)}$, kg/year	$\Delta E_{m(A)/L}$, kg/year/m	$E_{b(B)} E_f$, kg/year	$\Delta E_{m(B)}$, kg/year	$\Delta E_{m(B)/L}$, kg/year/m
NO _x	209.0	11.616	5.0	6.6	0.166	3.807	7.8	0.195
CO	8.7	0.484	0.207	0.276	0.007	0.158	0.3	0.008
NM VOC	1.0	0.056	0.024	0.032	0.001	0.018	0.0	0.001
SO _x	820	45.6	19.5	26.1	0.65	14.9	30.6	0.766
TSP	11.4	0.634	0.271	0.362	0.009	0.208	0.4	0.011
PM ₁₀	7.7	0.428	0.183	0.245	0.006	0.140	0.3	0.007
PM _{2.5}	3.4	0.189	0.081	0.108	0.003	0.062	0.1	0.003
CO ₂	98 300	5463.5	2340.0	3123.5	78	1790.5	3673.1	91.827
CH ₄	1	0.056	0.024	0.032	0.001	0.018	0.0	0.001

5. CONCLUSIONS

The obtained calculation results indicate the energy-saving role of multi-pipe thermal insulation in heat transport. Inserting six heating pipes in common thermal insulation contributes to the reduction of heat losses, and thus to the reduction of pollutants emitted into the atmosphere resulting from heat losses. The location of many heating pipes in a common thermal insulation also reduces the material consumption of thermal insulation in multi-pipe insulations as compared to single pipes. It should be noted here that each action towards energy-efficient heat transport leads to the improvement of the quality of the environment and reduction of the operating costs of the heat source.

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