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Thermo-Economic Assessment on Insulation Conditions of the Buried Heating Pipeline for District Heating

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ABSTRACT

Insulation performance and buried depth of heating pipelines are the vital factors affecting the energy loss of directly buried heating pipelines. This study considers the thermo-economic assessment of insulation of directly buried heating pipelines for district heating. The optimal insulation thickness, energy-saving effect, and payback period of district heating pipelines with five nominal pipe diameters, four fuel types, four kinds of insulation materials, and four buried depths are calculated. A numerical code is developed based on Life Cycle Cost Analysis and is validated via comparing with results in the open literature. Three representative cities of Xi'an, Shenyang, and Harbin subjected to three different climatic zones in China are explored. The highest values of optimum insulation thickness are 176, 153, and 121 mm in Harbin, Shenyang, and Xi'an, respectively, which are reached using oil as fuel, rock wool as insulation material, nominal pipe diameter 500 mm, and buried depth 1 m. A sensitivity analysis is performed to indicate how much the optimum insulation thickness and payback period are sensitive to the changes of insulation, fuel, and buried depth. The results show that insulation and fuel have a greater influence on the optimum insulation and payback period than the buried depth.

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Introduction

For the time being, increasing energy demand and environmental awareness worldwide have made it imperative to improve energy efficiency. Severe environmental problems, e.g., fog and haze, sulfur dioxides, and desertification, are mainly due to the excessive utilization of fossil fuels [1–3]. To mitigate these environmental hazards, renewable energy, including biomass, solar, tide, and wind energy, should be considerably involved in the traditional energy supply system [4]; Due to the limited energy and environmental pollution arising from the use of fuels, to improve the energy efficiency of energy utilization or transport process has become compulsory. The economical design of heating pipe insulation plays a decisive role in the heat loss of the district heating system. The increase of insulation thickness can reduce air pollution and reduce energy consumption. Nevertheless, it is neither practical nor economical to attain zero heat losses by increasing insulation thickness. It is necessary that a balance of the initial investment and energy saving achieved should be established, which indicates that the optimum insulation thickness must be found [2]. Therefore, selecting the insulation thickness of heating pipes will be one of the most efficient energy-saving approaches in the district heating system.

Insulating materials to reduce heat losses have been used in practice over the years. The investigation emphasizes that heat preservation is a requirement of energy saving. However, most of the existing research focused on the optimal insulation thickness of buildings [4–6], refrigeration fields, and cold storage [7–10].

Some researchers have studied the optimum insulation thickness for cylindrical pipelines based on heat loads. Zaki and Al-Turki [11] reviewed the optimum thickness for a system of pipelines insulated by different composite materials. Kalyon and Sahin [12] used the control theory method and the most rapid descent method to study the optimal insulation thickness of the pipeline due to convective heat transfer. Sahin [13] investigated the optimal insulation thickness of circular pipes under external thermal radiation heat

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Nomenclature

A	surface area of pipe (m^2)
C_F	annual energy cost (\$/kg, \$/ m^3 or \$/kW·h)
$C_{\text{total-F}}$	energy cost (\$)
C_{ins}	cost of insulation material per unit volume (\$/m^3)
$C_{\text{total-ins}}$	insulation cost (\$)
C_t	total cost (\$)
D_k	diameter of outmost layer (m)
D_e	characteristic length (m)
D_1	ratio of down payment to initial investment (%)
d	market discount rate (%)
E_W	annual energy requirement for heating losses (J)
HDD	heating degree days (°C·days)
H_u	lower heating value of fuel (J/kg, J/m^3 or J/kW·h)
H	distance from pipeline central axis to ground surface (m)
H_z	distance from pipeline upper surface to ground surface (m)
h	convection heat transfer coefficients (W/m^2·°C)
h_t	convective heat transfer coefficient of the soil surface (W/m^2·°C)
i	inflation rate (%)
L	length of pipe (m)
LCCA	annual heating degree-hours (°C-days) Life Cycle Cost Analysis
MAE	mean absolute error analysis
M_s	ratio of miscellaneous expenses to initial investment in first year (%)
m_F	annual fuel consumption for heating losses (kg)
N	lifetime (years)
OIT	optimum insulation thickness (mm)
P_1	present worth factor
P_2	ratio of life cycle expenditure
PP	payback period (years)
Q_A	annual heat losses (kW·h/m^2)
Q_P	heat losses occurred from pipe (kW·h/m^2)
R_p	total inner resistance of pipe (°C/W)
R_v	ratio of resale price at the end of analysis period to initial investment
$R_{\text{p,ins}}$	inner resistance of insulated pipe (°C/W)
$R_{\text{p,un-ins}}$	internal resistance of un-insulated pipe (°C/W)
r_0	inner radius of pipe (m)
r_1	outer radius of pipe (m)
r_2	outer radius of insulation layer (m)
r_3	outer radius of protective layer (m)
r_3'	outer radius of protective layer of non-insulation pipe (m)
r_3''	outer radius of protective layer of insulation pipe (m)
S	net energy cost savings over life cycle (\$)
T	temperature (°C)
U	total heat transfer coefficient (W/m^2·°C)
V	volume of insulating material used in insulated pipe (m^3)

Greek symbols

η_s	efficiency of the heating system
λ	thermal conductivity of soil (W/m·°C)
λ_1	thermal conductivity of pipe (W/m·°C)
λ_2	thermal conductivity of protective layer (W/m·°C)
λ_f	thermal conductivity of thermal media (W/m·°C)
λ_t	thermal conductivity of soil (W/m·°C)
ΔU	difference between the overall heat transfer coefficients of non-insulated and insulated pipelines (W/m^2·°C)

Subscripts

b	base
f	hot fluid
F	fuel
i	inside surface
ins	insulated pipe
o	outside surface
sa	sol-air
t	soil
un-ins	un-insulated pipe

transfer. It was found that under radiation heat transfer, the insulation thickness with a linear decrease of the minimum slope was the best. However, in the case of radiative heat transfer, uniformly distributed insulation did not provide the best results. Their further study [14] analyzed the critical insulation radius of a circular tube under radiation and convection heat transfer. The results show that there may be a required adiabatic thickness, which maximizes the heat transfer between the fluid and the radiation environment.

There is little research on improving central heating pipelines' thermal insulation performance, and most of them concentrated on aerial laying without different climatic zones. The thermo-economic analysis of optimal insulation thickness of pipes applied to central heating pipelines has been done by Keçebaş et al. [15] in the city of Afyonkarahisar/Turkey, only using rock wool as insulation material. In the research, an optimization model was established according to Life Cycle Cost Analysis (LCCA) using the P_1-P_2 method. Başoğul and Keçebaş [16] investigated the energy, economic and environmental assessments of thermal insulation in the central heating system. According to the heating loads in Afyonkarahisar/Turkey, the optimal adiabatic layer thickness, energy-saving, and CO_2, CO, and SO_2 emissions of pipe diameter and fuel type were calculated. Kayfeci [17] investigated the optimal insulation thickness, energy-saving, annual cost, and payback period of Isparta/Turkey heating system for different pipe diameters and insulation materials using the LCCA method and chose natural gas as the fuel. Başoğul et al. [18] used two different methods (Life Cycle Assessment and Life Cycle Cost) to analyze the optimal insulation thickness in pipes, which were used to determine the optimal insulation thickness for the reduced environmental impact of pipe insulation.

Keçebas [19] used a new method that combines exergy analysis and life cycle assessment to calculate the optimal insulation thickness, net savings, total energetic environmental impact, and payback period for the pipeline. Ertürk [20] investigated the effects of insulation thickness on the life cycle cost of steel pipes with different diameters. The optimization and sensitivity analysis were performed using heating degree days and life cycle cost procedures. Açı kkalp and Kandemir [21] determined the optimal insulation thickness of pipes in the Marmara region of Turkey using the combined economic and environmental methods. Rock wool and glass wool were chosen as insulation materials. All of the above research on central heating pipeline systems' insulation economy was based on aerial laying. However, in most central heating regions, such as China and Europe, directly buried installation is the most common method of installing central heating pipes. Therefore, it is obligatory to research the optimal insulation thickness of the buried pipeline. Meanwhile, fossil fuel is the main energy source used in district heating piping systems in most district heating regions such as China and Europe. With the environmental problem becoming more and more stern, more environment-friendly energy sources, such as geothermal, solar energy, and so on, are needed. So, research on these different fuels is essential. An economic model, life cycle cost analysis, is the effective method to determine the optimum insulation thickness, which considers the climatic conditions, wall structure, insulation types, fuel cost, and other economic parameters [22]. Moreover, the energy cost savings and payback periods are also non-negligible during the process of determining the optimum insulation thickness [23].

Heat loss and heating medium temperature change of buried heating pipeline for district heating are significantly affected by climatic conditions, insulation and buried depth of heating pipelines. However, the above-mentioned research on the thermal-economic analysis of direct buried heating pipelines has not simultaneously considered the effects of climatic conditions, fuel/heat source types, insulation materials, and buried depth. In particular, the research on the effect of buried depth on the direct buried heating pipelines is lacking in the literature. Based on the past research, the major goal of the present study is to achieve the optimum insulation thickness of the buried heating pipeline under different climate zones and installing parameters. According to the LCCA method, MATLAB software is used to calculate the optimum heating pipeline insulation thickness, total cost savings, and payback period. Meanwhile, the effects of fuel types, insulation materials, pipeline diameters, and buried depth are investigated for different climatic zones in China.

Description of the physical and mathematical model

Based on the *design code of the district heating network* [24], the composite structure of steel tube, insulating layer, and external protective layer are usually applied to the district heating pipelines. The insulating layer is used to reduce the energy losses. The external protective layer plays a role in waterproofing and increasing the pipeline network's steadiness. The high-density polyethylene outer sheath tube or fiber reinforced polymer outer protective tube is commonly used indirectly buried laying pipelines. The unit length of the heating pipeline considered in this paper is exhibited in Figure 1. The heat loss and temperature change of hot fluid are affected by the insulation material, soil, ambient, and pipeline properties. The constant fluid temperature and thermodynamic properties were assumed throughout the research process. Besides, under steady-state flow volume control conditions, it is also assumed that the hot fluid in the heating system has a constant velocity [17].

In a central heating pipeline, the heat loss of the pipeline can be determined as follows:

$$Q_{\mathrm{P}} = UA(T_{\mathrm{f}} - T_{\mathrm{o}}) = UA\Delta T \tag{1}$$

where U is the overall heat transfer coefficient of the pipeline; A is the surface area of the pipeline; T_{o} is the ambient temperature; T_{f} is the average design temperature of thermal fluid.

In this study, the annual heating degree days method considers changes in ambient air temperature per hour. The annual heat loss can be calculated as

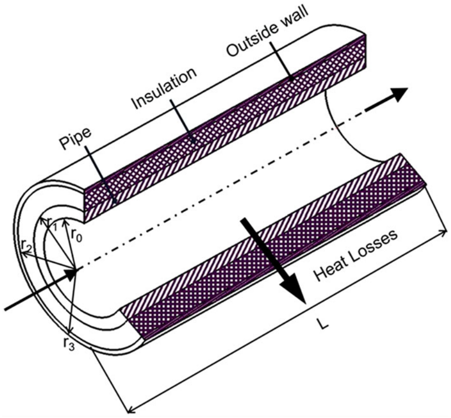


Figure 1. The diagram of unit length heating pipeline.

follows:

$$Q_A = 86400\ (HDD)\ U \tag{2}$$

where *HDD* is the annual heating days which is calculated by [21]

$$\text{HDD} = (1\ \text{year})\sum_{1}^{365}(T_b - T_{sa})^{+} \tag{3}$$

where T_b is the base temperature; T_{sa} is the average daily sol-air temperature. The sign "+" above the parenthesis means that only a positive value is calculated; that is, the temperature difference is set at zero as $T_{sa} > T_b$.

The total heat transfer resistance (R_p) of any pipe is equivalent to the sum of the convective and conductive heat transfer resistance of all layers, which is given as

$$R_p = \frac{1}{h_i A_i} + \frac{ln\left(\frac{r_1}{r_0}\right)}{2\pi L\lambda_1} + \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi L\lambda_2} + \dots \frac{ln\left(\frac{r_n}{r_{n-1}}\right)}{2\pi L\lambda_n} + \frac{1}{h_o A_o} \tag{4}$$

where λ_1, λ_2, etc. are the thermal conductivities of layers of pipelines; r_0, r_1, etc. are the radiuses of the pipeline; A_i is the internal surface area of the pipe; while A_o is the external surface area of the utmost pipe; h_i is the convective heat transfer coefficient of the inner surfaces of the pipe; h_o is the convective heat transfer coefficient of the outer surfaces of the pipe.

For directly buried pipelines, the thermal resistance of soil should not be neglected. However, the traditional thermal resistance formula is not applicable due to its special performance. The soil thermal resistance can be calculated by [25]

$$R_t = \frac{1}{2\pi\lambda_t}\ln\left(\frac{2H}{D_k} + \sqrt{\left(\frac{2H}{D_k}\right)^2 - 1}\right) \tag{5}$$

$$H = H_z + \frac{D_k}{2} + \frac{\lambda_t}{h_t} \tag{6}$$

where H is the distance from the pipeline central axis to the ground surface; H_z is the distance from the pipeline upper surface to the ground surface, which is usually defined as buried depth; λ_t is the thermal conductivity of the soil; D_k is the diameter of the outmost layer of pipelines; h_t is the convective heat transfer coefficient of the soil surface for directly buried laying, which usually can be taken as $12 - 15\ \text{W/(m}^2\cdot\text{K)}$ [25].

In this research, the total thermal resistance of un-insulated pipe is

$$R_{p,\ un-ins} = \frac{1}{h_i A_i} + \frac{ln\left(\frac{r_1}{r_0}\right)}{2\pi L\lambda_1} + \frac{ln\left(\frac{r_3'}{r_1}\right)}{2\pi L\lambda_2} + R_t \tag{7}$$

The total thermal resistance of insulated pipeline is as follows:

$$R_{p,\ ins} = \frac{1}{h_i A_i} + \frac{ln\left(\frac{r_1}{r_0}\right)}{2\pi L\lambda_1} + \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi L\lambda_{ins}} + \frac{ln\left(\frac{r_3''}{r_2}\right)}{2\pi L\lambda_2} + R_t \tag{8}$$

where λ_{ins}, λ_1, and λ_2 are the thermal conductivity of insulation material, pipeline, and protective layer, respectively. The convective heat transfer coefficient of the inner surfaces of the pipe, h_i, can be determined by Dittus–Boelter correlation:

$$h_i = 0.023Re^{0.8}Pr^{0.3}\left(\frac{\lambda_f}{D_e}\right) \tag{9}$$
$$(\text{Pr} = 0.7 - 160;\ \text{Re} > 10^4)$$

The difference between the overall heat transfer coefficients of non-insulated and insulated pipelines can be written as

$$\Delta U = U_{un-ins} - U_{ins} = \frac{1}{R_{p,\ un-ins}} - \frac{1}{R_{p,\ ins}} \tag{10}$$

The annual energy requirement for heating losses in the pipeline can be calculated by dividing annual heat loss by the efficiency of the heating system (η_s).

$$E_w = \frac{86400(HDD)U}{\eta_s} \tag{11}$$

and the annual fuel consumption for heating losses is

$$m_F = \frac{86400(HDD)U}{H_u\eta_s} \tag{12}$$

where H_u is lower heating value of the fuel depending on the fuel type. The annual total energy cost for

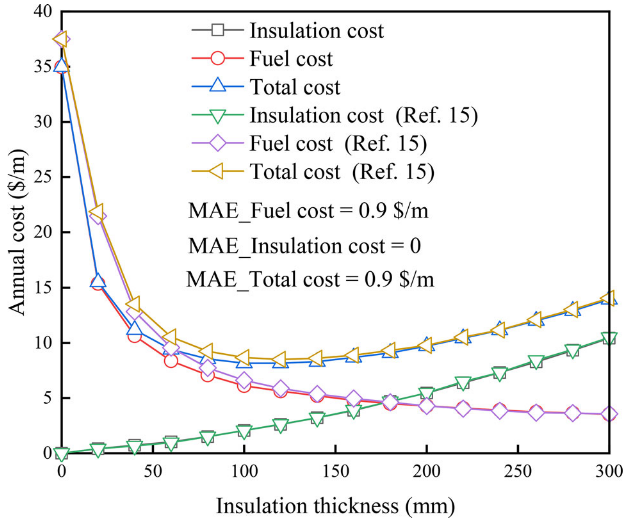


Figure 2. Comparison of the calculation results with the Keçebaş et al. [15].

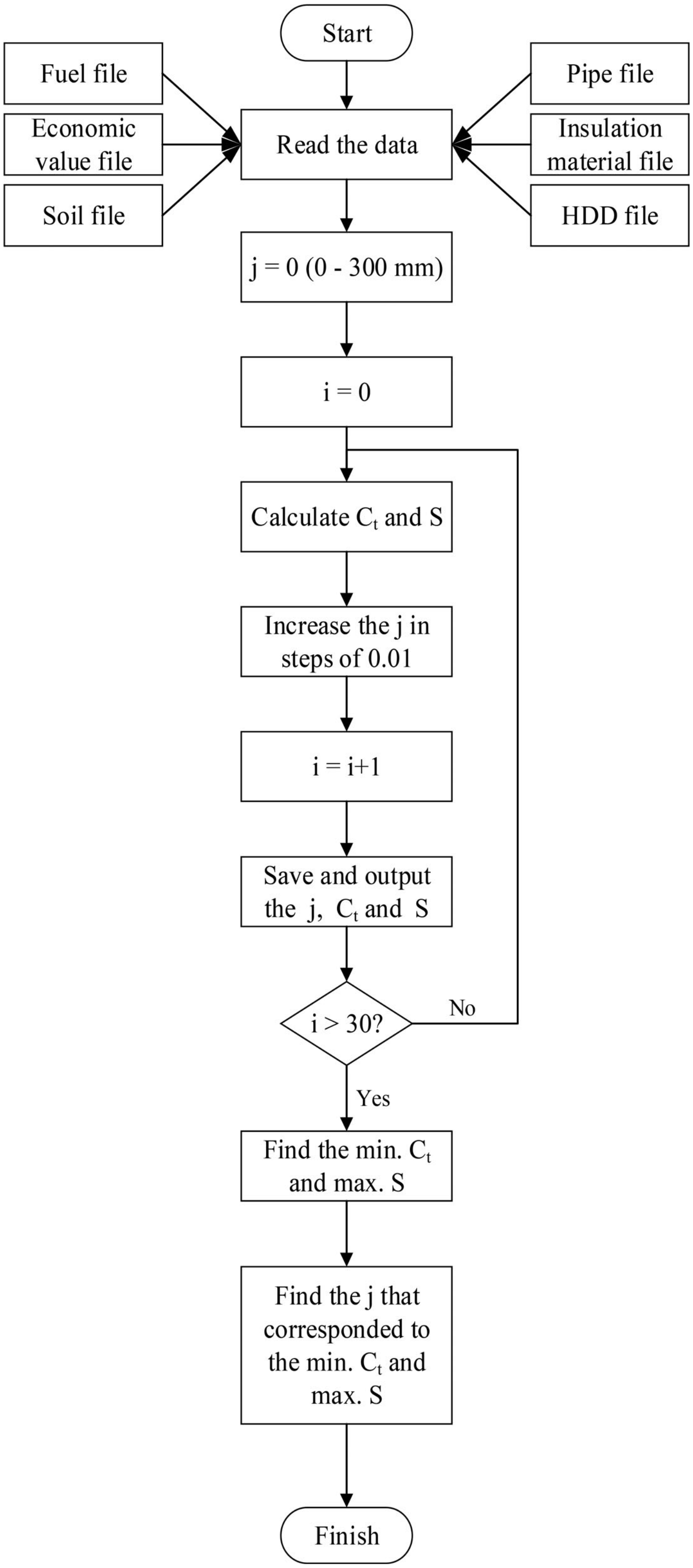


Figure 3. The flowchart of optimization procedure.

heating losses is given by

$$C_{\text{total}-\text{F}} = \frac{86400(HDD)\ U \cdot C_{\text{F}}}{H_{\text{u}}\eta_{\text{s}}} \tag{13}$$

where C_{F} is fuel cost depending on the fuel type.

The total cost of insulation depending on the insulation material price can be calculated as

$$C_{\text{total}-\text{ins}} = C_{\text{ins}}V \tag{14}$$

where C_{ins} is the cost of insulation material per unit volume and $V = \frac{\pi}{4}(r_2 - r_1)L$ is the volume of insulation material.

The total cost over a lifetime for ten years is obtained by multiplying the annual cost by a present worth factor P_1 as follows [26]:

$$P_1 = \frac{1}{d-i}\left[1 - \left(\frac{1+i}{1+d}\right)^N\right] \quad i \neq d \tag{15}$$

$$P_1 = \frac{N}{1+i} \quad i = d \tag{16}$$

where P_1 is concerned with the market discount rate d (currency value), inflation rate i (energy cost), and economic analysis cycle N (or technical life of application insulation). P_2 is the ratio of life cycle expenditure to initial investment due to additional capital input, which can be determined as follows [26]:

$$P_2 = D_1 + (1 - D_1)P_1 + M_s P_1 - \frac{R_v}{(1+d)^N} \tag{17}$$

where D_1 is the ratio of the first payment to the initial investment; M_s is the ratio of the first-year miscellaneous expenses (maintenance, insurance, and other miscellaneous expenses) to the initial investment; R_v is the ratio of resale value to initial investment by the end of the life cycle. If there is no supererogatory capital input other than the initial investment, P_2 can be considered as 1 [27].

The total cost can be determined by the following formula:

$$C_t = P_1 C_{\text{total}-\text{F}} + P_2 C_{\text{total}-\text{ins}} \tag{18}$$

The net total cost savings over the life cycle, S, can be expressed as

$$S = \frac{86400 P_1\ (HDD)\ \Delta\text{U} \cdot \text{C}_\text{F}}{H_\text{u} \eta_\text{s}} - P_2 C_{\text{ins}} V \tag{19}$$

Using MATLAB technical computing software, the optimal insulation thickness can be achieved by minimizing Eq. (19).

Validation

MATLAB was employed to calculate the optimal insulation thickness of the heating pipeline. The validity of the calculation process was verified by comparing the calculated annual cost (including insulation cost, fuel cost, and total cost) with the results of Kecebas et al. [15] under the same conditions, as shown in Figure 2. From the mean absolute error analysis (MAE) of fuel cost, insulation cost and total cost, it can be learned that the results agree well with the data from Ref. [15].

Results and discussion

The climatic zone of China is divided into five zones: severe cold zone (it can be divided into severe cold zone A and B in detail), cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and mild zone. However, district heating is usually used in severe cold zone A, severe cold zone B, and cold zone. In the present research, Harbin, Shenyang, and Xi'an are chosen to the typical cities presenting the three different climatic zones. So, the calculation results of representative cities can be eligibly applied to design the optimal insulation thickness of the corresponding climatic zone.

This research calculates the optimal insulation thicknesses of the three typical cities subjected to three different climatic zones. The MATLAB flowchart of the optimization procedure is illustrated in Figure 3.

The parameters involved in the calculation are presented in Ref. [28] and Tables 1–3 [15–17,25,29–31]. The corresponding energy-saving and payback periods have been obtained using the LCCA method. The effects of fuel types, insulation materials, pipeline diameters, and buried depths on the energy and economic performance of the central heating system are discussed, and the optimal insulation thicknesses were obtained.

Table 1. Thermal conductivity and price values of insulation materials.

Insulation materials	Thermal conductivity (W/m·°C) [17,25]	Price (\$/m^3) [15,29]
Rock wool	0.04	95
Fiberglass	0.033	350
Aluminum silicate	0.044	214.44
Calcium silicate	0.056	145.52

Table 2. Properties of fuels used in the calculation.

Fuel types	Price [16]	$H\mu$ [16]	η_s [30]
Coal	0.3926 (\$/kg)	29.26×10^6 (\$/kg)	68%
Oil	1.3202 (\$/kg)	41.278×10^6 (\$/kg)	88%
Natural gas	0.5022 (\$/m^3)	34.485×10^6 (\$/m^3)	90%
Geothermal [31]	0.3044 (\$/m^3)	80.928×10^6 (\$/m^3)	38%

Table 3. Other parameters and their values used in the calculation.

Parameters	Values
λ_1	44 W/m·°C
λ_f	0.686 W/m·°C
λ_t	1 W/m·°C [25]
h_t	15 W/ m^2·°C [25]
i	4%
d	5%
N	10 years [25]

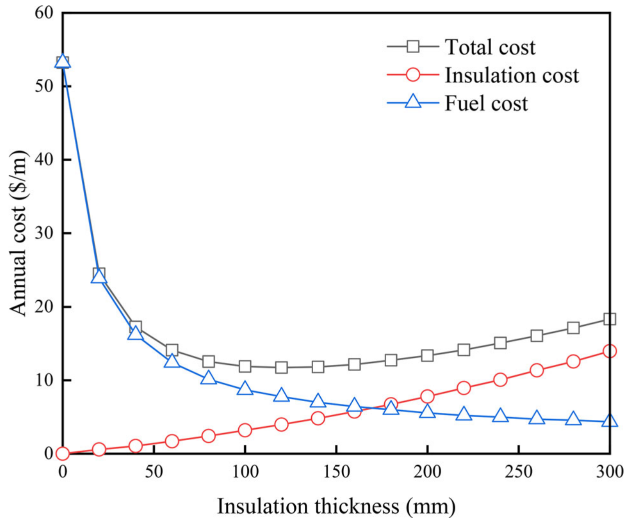
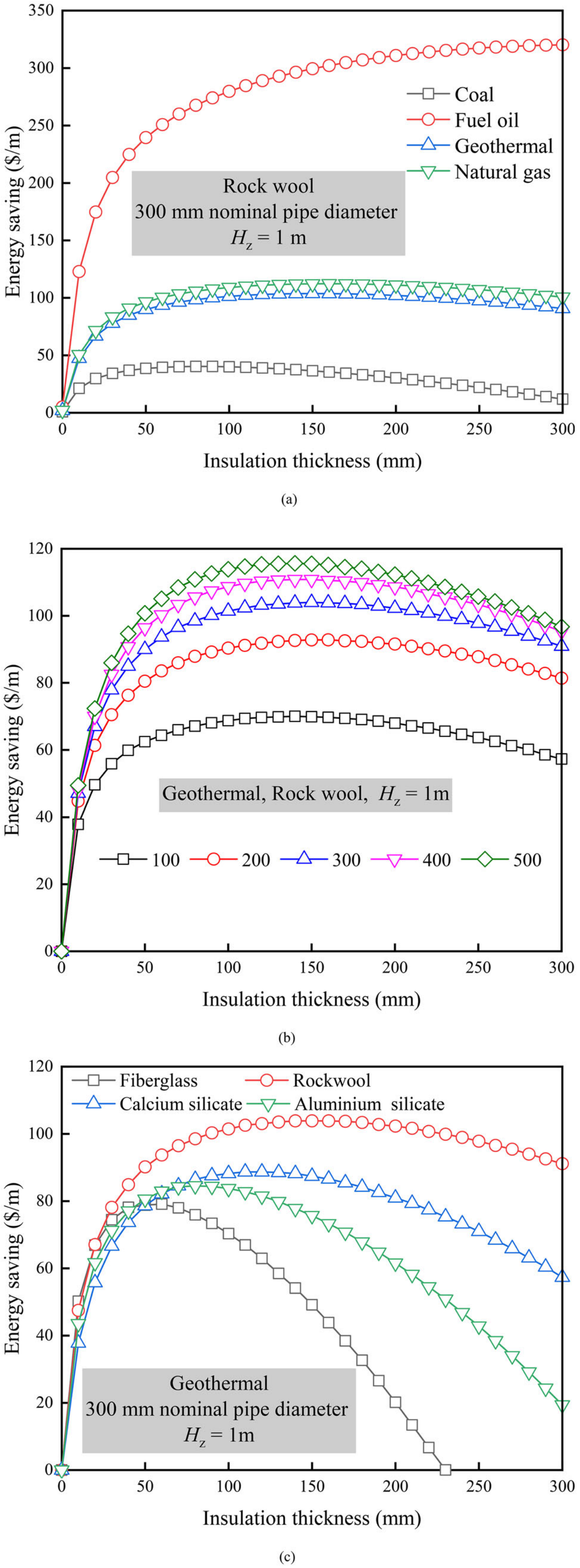


Figure 4. The annual cost vs. insulation thickness.

The effect of insulation thickness on annual cost and energy saving

Figure 4 shows that the effect of the insulation thickness on the annual cost for Harbin with the pipeline diameter of 300 mm, buried depth 1 m, and coal as fuel. It indicates that the fuel cost decreases and the insulation cost increase with increasing insulation thickness. However, the total costs, including fuel and insulation material, decrease initially and then increase gradually with increasing the insulation thickness. The insulation thickness that minimizes the total cost is called the optimal insulation thickness. Xi'an and Shenyang have the same trends as Harbin, while their corresponding annual total cost is smaller than Harbin's with the same condition.

The energy-saving over the lifetime versus insulation thickness for different fuel types, pipeline diameters, and insulation materials for Harbin is illustrated in Figure 5. It indicates that, with the insulation thickness increasing, the energy-saving increases initially and then decreases gradually. If the insulation thickness is greater than the critical value, there will be negative savings and no longer be economical. It can be found from Figure 5(a) that the energy-saving cost of oil as fuel is significantly higher than that of other fuels used; the saving value of oil as fuel is about 9 times than coal used as fuel. Figure 5(b) indicates that the relationship between energy-saving and insulation thickness for several pipeline diameters over the life cycle. The maximum energy saving is 500 mm nominal pipe diameter, followed by 400, 300, 200, and 100 mm. However, as the insulation thickness keeps increasing, the energy-saving of 500 mm nominal pipe



(a)

(b)

(c)

Figure 5. Energy saving over the lifetime vs. insulation thickness for various (a) fuels (b) nominal pipe diameters (c) insulation materials.

diameter reduces more quickly than others. Because the larger the pipe diameter, the higher the investment cost. Figure 5(c) shows that the largest energy saving of different insulation materials is reached at different insulation thicknesses, and the critical points are various. Therefore, the energy savings are very different as the various fuel types, pipeline diameters, and insulating materials are used. So, it is necessary to study the effect of different parameters on the optimum insulation thickness separately.

The effect of fuel types on the optimal insulation thickness

The varieties of the optimal insulation thicknesses with the pipeline diameter for Harbin are illustrated in Figure 6. The results show that the optimal insulation thickness increases with the increase of nominal pipe diameter. That is because the larger the pipeline diameter, the larger the heating transfer area. For the coal as fuel, optimal insulation thicknesses are 116, 114, 111, 105 and 93 mm for 500, 400, 300, 200 and 100 mm nominal pipe diameter respectively. From the point of different fuel types, the largest optimal insulation thickness is obtained when oil is used as fuel, then the order is followed by the natural gas, coal, and geothermal energy. The price of the four fuel types from high to low is ordered by oil, natural gas, coal, and geothermal energy. The lower the fuel price, the smaller the optimum insulation thickness. In general, the optimum insulation thickness for Harbin is the largest, and that is the smallest for Xi’an among the three cities, as shown in Table 4. The largest optimal insulation thicknesses are 176, 153, and 121 mm, which are obtained from 500 mm nominal pipe diameter and oil as fuel in Harbin, Shenyang, and Xi’an, respectively. The smallest values are 85, 75, and 60 mm, obtained from 100 mm nominal pipe diameter and geothermal as fuel, respectively.

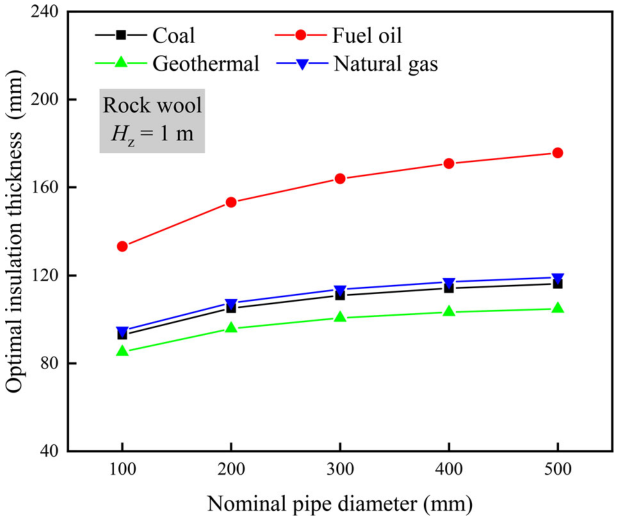


Figure 6. Optimal insulation thickness vs. nominal pipe diameter for various fuel types.

Figure 7 shows the effect of the nominal pipe diameter and the fuel type on the energy-saving corresponding to the optimum insulation thickness indicated in Figure 6. It can be observed that the larger the pipeline diameter, the more energy saving. Energy savings for the coal as fuel are 187.5, 176.6, 163.3, 143.3, and 107.3 \$/m for 500, 400, 300, 200, and 100 mm nominal pipe diameter in Harbin, respectively. The energy-saving corresponding to their optimum insulation thicknesses of Harbin is the largest, followed the order by Shenyang and Xi’an as indicated in Table 5. It shows that applying the optimal insulation thickness is more favorable in colder climates. The most energy-saving is obtained by the use of 500 mm nominal pipe diameter and oil as fuel, and their corresponding values are 345.7, 250.1, and 194.7 \$/m in Harbin, Shenyang, and Xi’an. The lowest values are obtained using 100 mm nominal pipe diameter and geothermal as fuel, and the values are 85.5, 62.8, and 36.4 \$/m, respectively.

Table 4. Optimal insulation thickness for different fuel types and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Fuel types	100	200	300	400	500
Optimal insulation thickness (mm)	Xi’an	Coal	66	73	75	76	77
		Fuel oil	96	108	115	118	121
		Natural gas	67	75	77	78	79
		Geothermal	60	66	68	68	68
	Shenyang	Coal	82	92	96	98	100
		Fuel oil	118	135	143	149	153
		Natural gas	83	94	99	101	102
		Geothermal	75	83	87	89	90
	Harbin	Coal	93	105	111	114	116
		Fuel oil	133	153	164	171	176
		Natural gas	95	107	114	117	119
		Geothermal	85	96	101	103	105

Note: Buried depth 1 m, rock wool as insulation material.

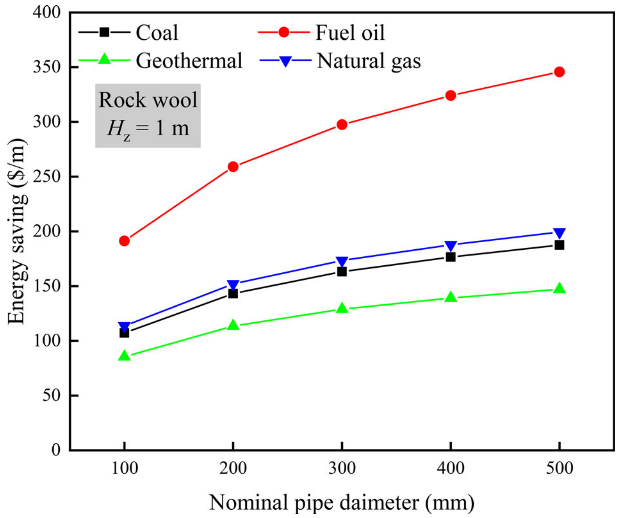


Figure 7. Energy saving vs. nominal pipe diameter for various fuel types.

Table 5. Energy saving for various fuels and nominal pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Fuel types	100	200	300	400	500
Energy saving ($/m)	Xi'an	Coal	45.4	59.4	66.	70.9	74.2
		Fuel oil	112.2	149.3	169.8	183.5	194.7
		Natural gas	48.0	62.9	70.6	75.3	78.9
		Geothermal	36.4	47.2	52.6	55.7	57.9
	Shenyang	Coal	78.9	104.7	118.8	127.9	135.2
		Fuel oil	140.7	189.7	216.9	235.3	250.1
		Natural gas	83.6	111.2	126.2	136.1	143.9
		Geothermal	62.8	82.8	93.5	100.3	105.6
	Harbin	Coal	107.3	143.3	163.3	176.6	187.5
		Fuel oil	191.3	259.0	297.5	324.0	345.7
		Natural gas	113.7	152.0	173.4	187.8	199.5
		Geothermal	85.5	113.6	128.9	139.1	147.2

Note: Buried depth 1 m, rock wool as insulation material.

The payback period versus nominal pipeline diameter for various fuel types in Harbin is illustrated in Figure 8. It is observed that the use of geothermal as fuel reaches the longest payback period, then followed by natural gas, coal, and oil. Table 6 presents the payback period for different fuel types and pipeline diameters subjected to Xi'an, Shenyang, and Harbin. The longest payback periods are 0.97, 1.31, and 1.69 years for 500 mm nominal pipe diameter and geothermal as fuel in Harbin, Shenyang, and Xi'an, respectively. The shortest payback periods are also found to be 0.27, 0.36, and 0.45 years for 100 mm nominal pipe diameter and oil as fuel, respectively.

The effect of insulation materials on the optimum insulation thickness

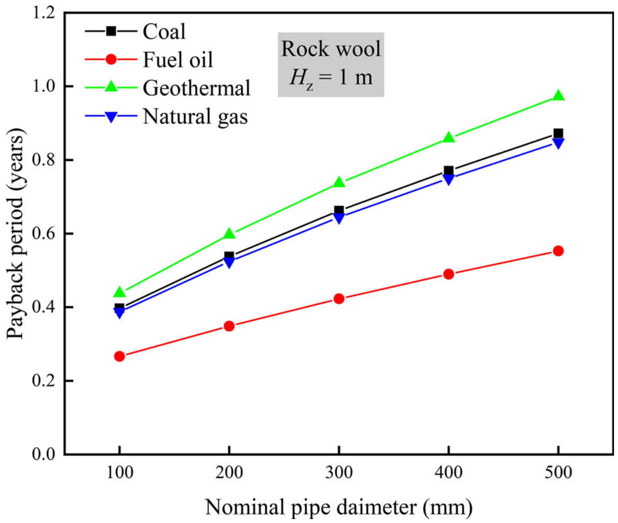


Figure 8. Payback period vs. nominal pipe diameter for various fuel types.

Table 6. Payback period for various fuels and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Fuel types	100	200	300	400	500
Payback period (years)	Xi'an	Coal	0.67	0.93	1.15	1.34	1.52
		Fuel oil	0.45	0.60	0.73	0.85	0.96
		Natural gas	0.66	0.90	1.12	1.30	1.48
		Geothermal	0.74	1.03	1.28	1.49	1.69
	Shenyang	Coal	0.53	0.72	0.89	1.03	1.17
		Fuel oil	0.36	0.47	0.57	0.66	0.74
		Natural gas	0.52	0.70	0.86	1.01	1.14
		Geothermal	0.59	0.80	0.99	1.15	1.31
	Harbin	Coal	0.40	0.54	0.66	0.77	0.87
		Fuel oil	0.27	0.35	0.42	0.49	0.55
		Natural gas	0.39	0.52	0.65	0.75	0.85
		Geothermal	0.44	0.60	0.74	0.86	0.97

Note: Buried depth 1 m, rock wool as insulation material.

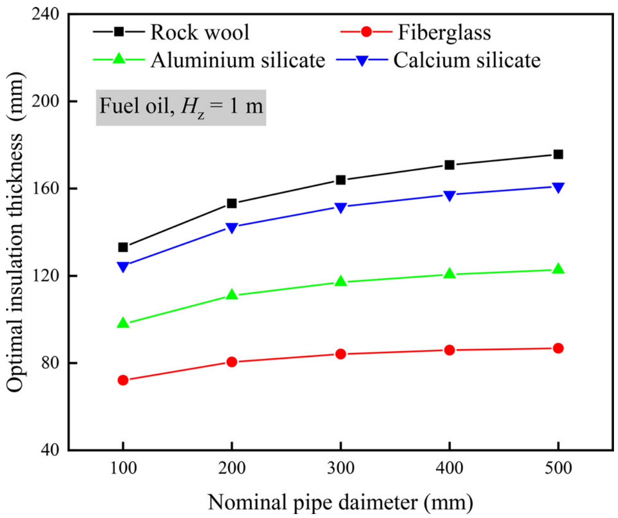


Figure 9. Optimal insulation thickness vs. nominal pipe diameter for various insulation materials.

Figure 9 indicates the effect of nominal pipe diameter on the optimal insulation thickness for different insulation materials in Harbin. It indicates that the largest optimal insulation thickness is achieved by the use of rock wool, then followed by calcium silicate,

Table 7. Optimal insulation thickness for various insulation materials and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Insulation materials	100	200	300	400	500
Optimal insulation thickness (mm)	Xi'an	Rock wool	96	109	115	119	121
		Fiberglass	51	55	57	57	58
		Aluminum silicate	70	77	80	81	82
		Calcium silicate	89	100	105	107	108
	Shenyang	Rock wool	118	135	144	149	153
		Fiberglass	64	70	73	74	74
		Aluminum silicate	86	97	102	104	106
		Calcium silicate	110	125	132	137	139
	Harbin	Rock wool	133	153	164	171	176
		Fiberglass	72	81	84	86	87
		Aluminum silicate	98	111	117	121	123
		Calcium silicate	125	143	152	157	161

Note: Buried depth 1 m, oil as fuel.

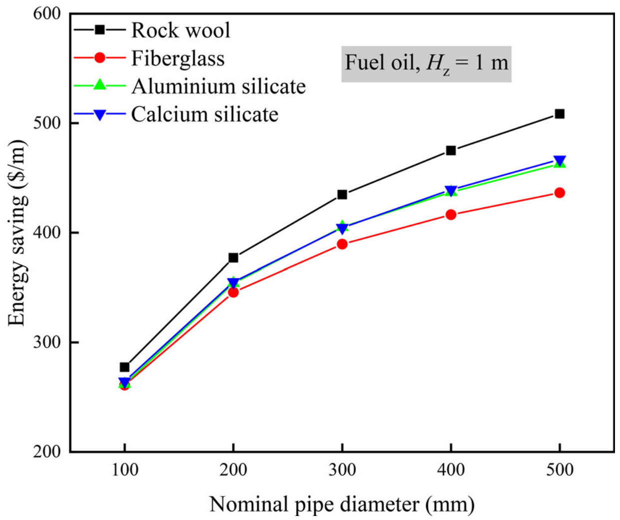


Figure 10. Energy saving vs. nominal pipe diameter for various insulation materials.

aluminum silicate, and fiberglass as insulation material. The thermal conductivities of the four insulation materials from high to low are ordered by rock wool, calcium silicate, aluminum silicate, and fiberglass. The greater the insulation material's thermal conductivity, the thicker the corresponding optimal insulation thickness. In general, the cheaper the insulation material, the greater the thermal conductivity, and then the thicker the optimal insulation thickness. It can be observed from Table 7 that the highest optimal insulation thicknesses are 176, 153, and 121 mm in Harbin, Shenyang, and Xi'an, respectively, which are obtained by use of 500 mm nominal pipe diameter and rock wool as insulation material; the lowest values are 72, 64 and 51 mm which are obtained by use of 100 mm nominal pipe diameter and fiberglass as insulation material respectively.

Figure 10 shows the effect of the nominal pipeline diameter and the insulation material on the energy-saving for Harbin corresponding to the optimal insulation thickness indicated in Figure 9. It can be seen, for all the insulation materials studied, that the larger the pipeline diameter, the more energy saving. Among the four kinds of insulation materials studied, the highest energy saving is reached by the use of rock wool based on the optimal insulation thickness. That is to say, the insulating effect of the rock wool is the best, followed by the calcium silicate, aluminum silicate, and fiberglass. It can be shown from Table 8 that the greatest energy savings are 508.5, 371.5, and 209.9 $/m in Harbin, Shenyang, and Xi'an, respectively, which are obtained by use of 500 mm nominal pipe diameter and rock wool as insulating material. Meanwhile, the smallest are 261.0, 180.4, and 106.7 $/m, respectively, which are obtained by the use of 100 mm nominal pipe diameter and fiberglass as insulation material. The corresponding value is the largest in Harbin, followed by Shenyang and Xi'an.

The payback period versus nominal pipeline diameter for various insulation materials in Harbin is illustrated in Figure 11. It is observed that the longest payback period is achieved by the use of rock wool, then followed by calcium silicate, aluminum silicate and fiberglass as insulation material. Table 9 shows the payback period for various insulation materials and pipeline diameters subjected to Xi'an, Shenyang, and Harbin. The longest payback periods are found to be 2.01, 1.55, and 0.96 years in Harbin, Shenyang, and Xi'an, respectively, for 500 mm nominal pipe diameter and rock wool used as insulating material. The shortest payback periods are also found to be 0.27, 0.36, and 0.21 years for 100 mm nominal pipe diameter and fiberglass used as an insulation material, respectively.

The effect of the buried depth on the optimal insulation thickness

According to the *Handbook of Thermal Engineering* [25], the buried depth is usually from 1.0 to 1.3 m. Figure 12 indicates the optimal insulation thickness versus the buried depth depending on the pipeline

Table 8. Energy saving for different varieties of insulation materials and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Insulation materials	100	200	300	400	500
Energy saving ($/m)	Xi'an	Rock wool	119.2	159.8	182.4	191.5	209.9
		Fiberglass	106.7	140.9	159.5	171.7	182.0
		Calcium silicate	117.8	157.7	179.8	194.6	206.7
		Aluminum silicate	113.2	150.8	171.6	185.5	196.9
	Shenyang	Rock wool	204.9	277.8	319.3	348.0	371.5
		Fiberglass	180.4	237.1	267.2	286.3	301.4
		Calcium silicate	190.4	255.5	290.7	313.6	331.8
		Aluminum silicate	186.1	247.3	280.1	301.3	318.2
	Harbin	Rock wool	277.3	377.1	434.7	475.0	508.5
		Fiberglass	261.0	345.8	389.4	416.4	436.5
		Calcium silicate	264.5	356.2	407.1	439.2	466.8
		Aluminum silicate	262.0	354.1	404.6	437.02	462.8

Note: Buried depth 1 m, oil as fuel.

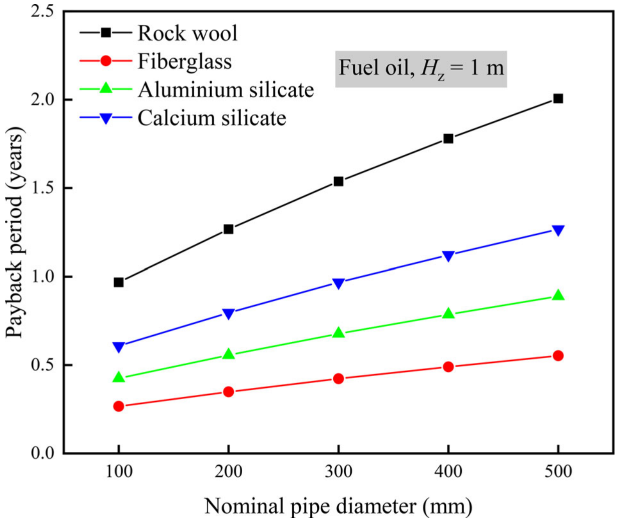


Figure 11. Payback period vs. nominal pipe diameter for various insulation materials.

Table 9. Payback period for various insulation materials and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Insulation materials	100	200	300	400	500
Payback period (years)	Xi'an	Rock wool	0.45	0.60	0.73	0.85	0.96
		Fiberglass	0.21	0.30	0.37	0.44	0.50
		Calcium silicate	0.41	0.54	0.66	0.77	0.87
		Aluminum silicate	0.30	0.41	0.51	0.59	0.67
	Shenyang	Rock wool	0.75	0.98	1.19	1.38	1.55
		Fiberglass	0.36	0.47	0.57	0.66	0.74
		Calcium silicate	0.60	0.86	1.02	1.19	1.35
		Aluminum silicate	0.55	0.74	0.91	1.06	1.19
	Harbin	Rock wool	0.97	1.27	1.54	1.78	2.01
		Fiberglass	0.27	0.35	0.42	0.49	0.55
		Calcium silicate	0.61	0.80	0.97	1.12	1.27
		Aluminum silicate	0.43	0.56	0.68	0.79	0.89

Note: Buried depth 1 m, oil as fuel.

diameter for Harbin. It is observed that the optimal insulation thickness decreases with increasing the buried depth, but the downtrend is very smooth. The reason is that the soil layer on the pipeline prevents heat transfer and can be seen as another insulation layer. The deeper the buried depth, the thicker the soil layer on the pipeline, and then the better the insulating performance. However, the soil thermal conductivity is far less than that of insulating materials, so the influence of soil buried depth on the optimal insulation thickness is very small. Table 10 presents the largest optimal insulation thicknesses of 176, 153, and 119 mm, obtained from 500 mm nominal pipe diameter and buried depth 1 m in Harbin,

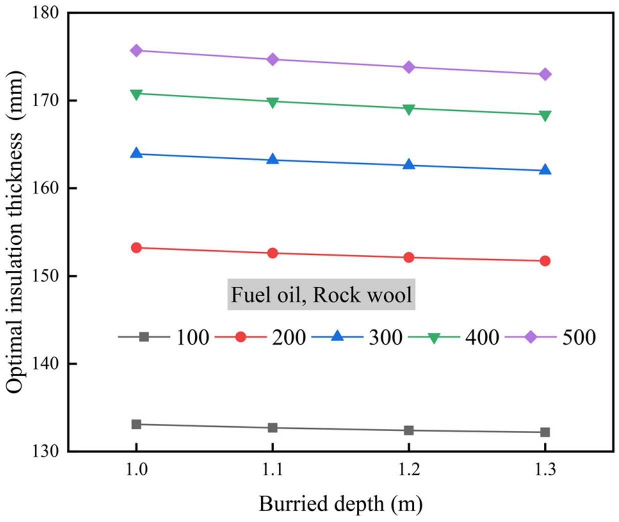


Figure 12. Optimal insulation thickness vs. buried depth.

Table 10. Optimal insulation thickness for various buried depths and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Buried depths (m)	100	200	300	400	500
Optimal insulation thickness (mm)	Xi'an	1.0	95	108	114	118	119
		1.1	95	108	114	117	118
		1.2	95	107	113	116	118
		1.3	94	106	112	116	117
	Shenyang	1.0	118	135	143	149	153
		1.1	117	134	143	148	152
		1.2	117	134	142	147	151
		1.3	116	133	142	147	150
	Harbin	1.0	133	153	164	171	176
		1.1	132	153	163	170	175
		1.2	132	152	163	169	174
		1.3	131	151	162	168	173

Note: Oil as fuel, rock wool as insulation material.

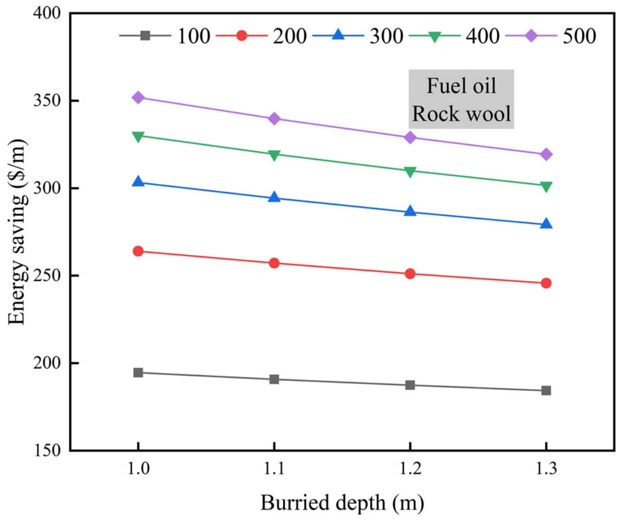


Figure 13. Energy saving vs. buried depth.

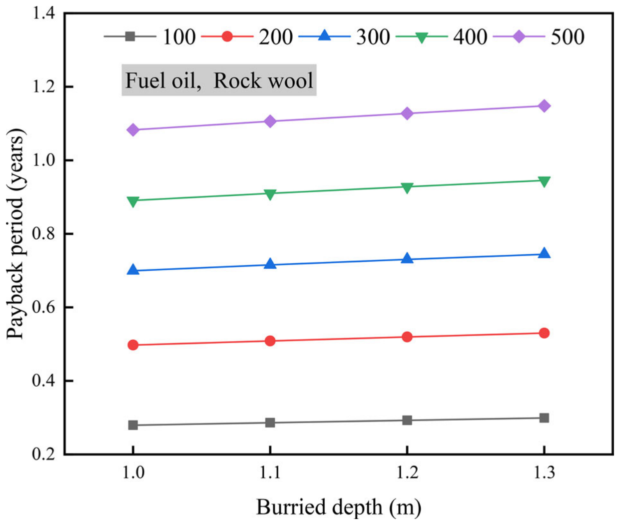


Figure 14. Payback period vs. buried depth.

Shenyang, and Xi'an, respectively. The corresponding smallest values are 131, 116, and 94 mm, which are obtained from 100 mm nominal pipe diameter and buried depth 1.3 m, respectively.

Figures 13 and 14 show the effect of the buried depth on the energy-saving and payback period corresponding to the optimal insulation thickness indicated in Figure 12. It suggests that, with the increase of the

Table 11. Energy saving for various buried depths and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Buried depths (m)	100	200	300	400	500
Energy saving ($/m)	Xi'an	1.0	114.8	152.0	172.1	185.4	196.0
		1.1	111.2	145.7	163.9	175.7	184.8
		1.2	108.2	140.4	157.1	167.6	175.7
		1.3	105.6	136.0	151.3	160.8	168.0
	Shenyang	1.0	140.7	189.7	216.9	235.3	250.1
		1.1	138.0	184.7	210.4	227.6	241.3
		1.2	135.5	180.4	204.7	220.7	233.4
		1.3	133.3	176.4	199.5	214.6	226.5
	Harbin	1.0	194.5	264.0	303.2	330.1	351.8
		1.1	190.8	257.2	294.3	319.4	339.7
		1.2	187.4	251.1	286.3	310.0	329.0
		1.3	184.3	245.7	279.2	301.5	319.4

Note: Oil as fuel, rock wool as insulation material.

Table 12. Payback period for various buried depths and pipe diameters.

			Nominal pipe diameters (mm)				
	Cities	Buried depths (m)	100	200	300	400	500
Payback period (years)	Xi'an	1.0	0.30	0.54	0.77	0.98	1.19
		1.1	0.31	0.56	0.80	1.02	1.23
		1.2	0.32	0.58	0.83	1.05	1.27
		1.3	0.33	0.60	0.85	1.08	1.31
	Shenyang	1.0	0.32	0.58	0.81	1.04	1.26
		1.1	0.33	0.59	0.83	1.06	1.29
		1.2	0.34	0.60	0.85	1.08	1.31
		1.3	0.34	0.61	0.87	1.10	1.34
	Harbin	1.0	0.28	0.50	0.70	0.89	1.08
		1.1	0.29	0.51	0.72	0.91	1.11
		1.2	0.29	0.52	0.73	0.93	1.13
		1.3	0.30	0.53	0.74	0.95	1.15

Note: Oil as fuel, rock wool as insulation material.

Table 13. Optimal set of parameters for various nominal pipe diameters.

Cities	Nominal diameters (mm)	Fuel types	Insulation types	Buried depths (m)	Insulation thicknesses (mm)
Xi'an	100	Fuel oil	Rock wool	1	95
	200				108
	300				114
	400				118
	500				119
Shenyang	100	Fuel oil	Rock wool	1	118
	200				135
	300				144
	400				149
	500				153
Harbin	100	Fuel oil	Rock wool	1	133
	200				153
	300				164
	400				171
	500				176

buried depth, the corresponding energy-saving decreases, and the payback period increases. The reason is that the deeper buried depth leads to the thinner optimum insulation thickness, which decreases the insulating performance. So, the energy-saving decreases, which causes the payback period to increase. Table 11 presents the energy saving for different buried depths subjected to Xi'an, Shenyang, and Harbin. The most energy-saving is obtained by use of 500 mm nominal pipe diameter and buried depth 1 m, and their corresponding values are 351.8, 250.1, and 196.0 $/m in Harbin, Shenyang, and Xi'an. The lowest values are obtained using 100 mm nominal pipe diameter and buried depth 1.3 m, and the values are 184.3, 133.3, and 105.6 $/m, respectively. Table 12 presents the payback period for different buried depths subjected to Xi'an, Shenyang, and Harbin. The longest payback periods are found to be 1.15, 1.34, and 1.31 years in Harbin, Shenyang, and Xi'an, respectively, for 500 mm nominal pipe diameter and buried depth 1.3 m. The shortest payback periods are also found to be 0.30, 0.32, and 0.28 years for 100 mm nominal pipe diameter and buried depth 1 m, respectively.

Sensitivity analysis

In order to indicate how much the optimum insulation thickness and payback period are sensitive to the changes of insulation (conductivity and price), fuel (lower heating value and price), and buried depth, a sensitivity analysis is performed. An optimal set of thickness, depth, material, and fuel is obtained based on the calculation of different pipe diameters for each city indicated in Table 13. In this way, every optimal set of thickness, depth, material, and fuel is obtained based on the calculation of different pipe diameters for each city is considered and its parameters used in the calculation are assumed as the base conditions. Then, it should be investigated how much the optimum insulation thickness and payback period change with ±10% variation in insulation (conductivity and price), fuel (lower heating value and price), and buried depth. The sensitivity of optimum insulation thickness (OIT) and the payback period (PP) can be calculated as follows:

$$\text{Sensitivity of } OIT(\%) = \left[\frac{OIT_{\text{after changes}} - OIT_{\text{base condition}}}{OIT_{\text{base condition}}}\right] \times 100 \tag{20}$$

$$\text{Sensitivity of } PP(\%) = \left[\frac{PP_{\text{after changes}} - PP_{\text{base condition}}}{PP_{\text{base condition}}}\right] \times 100 \tag{21}$$

The results of sensitivity analysis of optimum insulation thickness and payback period change are shown in Tables 14 and 15. Table 14 shows that reducing the price of insulation and lower heating value improve *OIT*; while their effect is more than buried depth. However, with increasing the conductivity of insulation and the price of fuel, *OIT* improved. Consequently, the result of sensitivity analysis has shown that the quota of buried depth is inferior to the other parameters. The effect of the insulation price and conductivity, the fuel price, and lower heat values on optimum insulation thickness are considerable, while their effects are much greater than the buried depth. Table 15 shows that the PP can be improved by reducing the fuel price. However, with increasing the price and conductivity of insulation, the lower heating value of fuel, and buried depth, *PP* improved. Consequently, the insulation price and fuel lower heating value have greater effects on *PP*; while the insulation conductivity and buried depth had fewer effects on *PP*.

Table 14. Sensitivity analysis of optimum insulation thickness (%).

				Nominal pipe diameters (mm)				
Cities	Parameters		Changes (%)	100	200	300	400	500
Xi'an	Insulation	Conductivity	+10	3.23	3.21	3.30	3.29	3.23
			−10	−3.54	−3.58	−3.57	−3.54	−3.64
		Price	+10	−3.95	−4.22	−4.35	−4.47	−4.67
			−10	4.46	4.78	5.04	5.23	5.30
	Fuel	Lower heating value	+10	−3.95	−4.22	−4.35	−4.47	−4.64
			−10	4.48	4.78	5.04	5.23	5.30
		Price	+10	4.16	4.32	4.52	4.73	4.80
			−10	−4.37	−4.68	−4.78	−4.98	−5.13
	Buried depth		+10	−0.21	−0.28	−0.26	−0.34	−0.41
			−10	0.21	0.18	0.35	0.42	0.41
Shenyang	Insulation	Conductivity	+10	3.22	3.26	3.41	3.348	3.39
			−10	−3.56	−3.63	−3.61	−3.61	−3.66
		Price	+10	−3.90	−4.07	−4.17	−4.28	−4.44
			−10	4.41	4.66	4.86	4.95	5.09
	Fuel	Lower heating value	+10	−3.90	−4.07	−4.17	−4.28	−4.44
			−10	4.41	4.66	4.86	4.95	5.09
		Price	+10	3.98	4.22	4.38	4.49	4.57
			−10	−4.32	−4.52	−4.59	−4.15	−4.90
	Buried depth		+10	−0.17	−0.22	−0.21	−0.27	−0.33
			−10	0.17	0.22	0.28	0.34	0.39
Harbin	Insulation	Conductivity	+10	3.23	3.33	3.36	3.40	3.42
			−10	−3.61	−3.53	−3.66	−3.69	−3.70
		Price	+10	−3.83	−3.98	−4.09	−4.27	−4.33
			−10	4.36	4.57	4.76	4.86	4.95
	Fuel	Lower heating value	+10	−3.83	−3.98	−4.09	−4.27	−4.33
			−10	4.36	4.57	4.76	4.86	4.95
		Price	+10	3.98	4.11	4.27	4.33	4.50
			−10	−4.28	−4.44	−4.52	−4.68	−4.78
	Buried depth		+10	−0.15	−0.20	−0.18	−0.29	−0.29
			−10	0.15	0.20	0.24	0.29	0.34

Table 15. Sensitivity analysis of payback period (%).

				Nominal pipe diameters (mm)				
Cities	Parameters		Changes (%)	100	200	300	400	500
Xi'an	Insulation	Conductivity	+10	1.16	1.20	1.53	1.39	1.51
			−10	−1.14	−1.19	−1.30	−1.39	−1.45
		Price	+10	10.03	10.03	10.03	10.04	10.09
			−10	−10.01	−10.02	−10.04	−10.04	−10.02
	Fuel	Lower heating value	+10	10.03	10.03	10.03	10.04	10.09
			−10	−10.01	−10.02	−10.04	−10.04	−10.02
		Price	+10	−9.10	−9.11	−9.13	−9.13	−9.10
			−10	11.15	11.15	11.15	11.16	11.20
	Buried depth		+10	1.86	2.45	2.79	3.03	3.26
			10	−1.99	−2.63	−3.01	−3.25	−3.42
Shenyang	Insulation	Conductivity	+10	1.01	1.03	1.08	1.16	1.23
			−10	−1.01	−1.01	−1.09	−1.14	−1.21
		Price	+10	10.06	10.04	10.01	10.03	10.04
			−10	−10.03	−10.02	−10.03	−10.02	−10.02
	Fuel	Lower heating value	+10	10.02	10.04	10.01	10.03	10.04
			−10	−10.02	−10.02	−10.03	−10.02	−10.02
		Price	+10	−9.10	−9.10	−9.11	−9.12	−9.12
			−10	11.15	11.15	11.14	11.16	11.16
	Buried depth		+10	1.85	2.44	2.77	3.00	3.20
			−10	−1.99	−2.61	−2.98	−3.21	−3.40
Harbin	Insulation	Conductivity	+10	1.01	1.00	1.09	1.06	1.21
			−10	−1.01	−1.03	−1.06	−1.14	−1.23
		Price	+10	10.02	10.01	10.02	10.02	10.02
			−10	−10.02	−10.01	−10.00	−10.02	−10.02
	Fuel	Lower heating value	+10	10.03	10.01	10.02	10.02	10.02
			−10	−10.02	−10.01	−10.00	−10.02	−10.02
		Price	+10	−9.12	−9.10	−9.10	−9.11	−9.12
			−10	11.11	11.13	11.13	11.13	11.13
	Buried depth		+10	1.84	2.44	2.77	3.00	3.18
			−10	−1.99	−2.61	−2.95	−3.21	−3.40

The sensitivity analysis technique has been applied for three cities to observe the effect of insulation, fuel, and buried depth on the *OIT* and *PP*. It was found that the same trend was observed. In other words, insulation and fuel have a greater influence on the optimum insulation and payback period than the buried depth for all climate zones studied.

Conclusions

Based on the economic analysis of central heating pipeline insulation, the optimal insulation thickness, energy-saving, and payback period of district heating pipelines with directly buried laying are investigated for three cities representing three typical climatic zones for the first time. The results indicate that the optimal insulation thickness is directly related to the fuel types, insulation materials, pipeline diameters, buried depths, and climatic conditions.

The optimal insulation thickness for Harbin is the largest, followed by Shenyang and Xi'an. With increasing the buried depth, the optimal insulation thickness decreases slowly. The optimal insulation thickness for different insulation materials from high to low is ordered by rock wool, calcium silicate, aluminum silicate, and fiberglass, and that for different fuels is oil, natural gas, coal, and geothermal energy. However, the order of the optimal insulation thickness corresponding to different pipeline diameters from high to low is 500, 400, 300, 200, and 100 mm.

A sensitivity analysis is performed to indicate that insulation and fuel have a greater influence on the optimum insulation and payback period than the buried depth.

Therefore, this research will provide effective guidance for the insulation design, analysis, and application of directly buried heating pipelines. The results not only adapt to the district heating pipelines in China, but also adapt to other country or regions owning district heating pipelines such as some countries in Europe.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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