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Study on the Economic Insulation Thickness of the Buried Hot Oil Pipelines Based on Environment Factors

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Abstract: It is important to determine the insulation thickness in the design of the buried hot oil pipelines. The economic thickness of the insulation layer not only meets the needs of the project but also maximizes the investment and environmental benefits. However, as a significant evaluation, the environmental factors haven't been considered in the previous study. Considering this factor, the mathematical model of economic insulation thickness of the buried hot oil pipelines is built in this paper, which is solved by the golden section method while considering the costs of investment, operation, environment, the time value of money. The environmental cost is determined according to the pollutant discharge calculated through relating heat loss of the pipelines to the air emission while building the model. The results primarily showed that the most saving fuel is natural gas, followed by LPG, fuel oil, and coal. The fuel consumption for identical insulation thickness is in the order: coal, fuel oil, LPG, and natural gas. When taking the environmental costs into account, the thicker the economic insulation layer is, the higher cost it will be. Meanwhile, the more pollutant discharge, the thicker the economic insulation layer will be.

Keywords: Buried hot oil pipelines; economic insulation thickness; environment influence; mathematical model

1 Introduction

With the acceleration of population, urbanization, and improvement in standards of living, energy consumption has also increased dramatically [1]. According to the BP statistical review of world energy 2019, China, the US and India together accounted for more than two-thirds of the global increase in energy demand [2]. Fig. 1 shows the development of these energy resources from 1993 to 2018. With limited resources and increasing environmental pollution, it is crucial to improve energy efficiency and reduce pollution [3].

For easy-to-condense, high-viscosity, and waxy crude oil, the most commonly adopted method is heating transportation [4]. The most optimal way to ensure pipeline safety is to increase the heat transfer and reducing the heat loss through insulation application [5]. As a result, the insulation reduces not only the heat loss of the pipelines but also the fuel consumption, which achieves the goal of energy-saving and
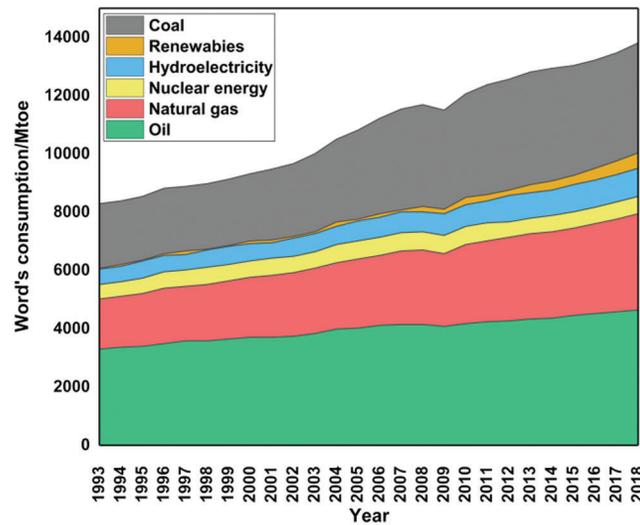
Figure 1: Consumption statistics of major energy resources (BP, 2019)

emission reduction [6]. As the insulation thickness increases, the heat loss of the pipeline decreases; however, the material and construction cost also increases, thus resulting in an 'economic thickness' [7].

With regard to the economic thickness, many studies focus on its impact on building insulation due to the large potential of energy conservation. On the other hand, only a few researchers in China studied the economic insulation of buried hot oil pipeline. Wu et al. [8] designed the thermal pipeline and its insulation layer under the condition of convective heat transfer in the tube. Finally, he worked out the annual net income equation and the calculation formula of optimal pipe diameter and thickness of the insulation layer. Wang [9] proposed that pipelines in high-temperature sections should be covered with thicker insulation. As the temperature along the line decreases, the thickness of the insulation layer should be gradually reduced. For the section where the heat transfer coefficient of soil is abundant, the insulation layer thickness should be appropriately increased. Liu et al. [10] set the annual total work cost as the optimization goal and built a mathematical model for the optimization thickness of the buried hot oil pipelines. Dong [11] established a new mathematical model for calculating the thickness of the economic insulation of the buried hot oil pipelines by calculating the sum of the final cost of the investment, power consumption, and heat consumption. The model comprehensively takes into account the influencing factors such as oil properties, pipeline buried depth, and the time value of funds. Obviously, there are few studies on hot oil pipeline insulation considering environmental factors.

To the best of the authors' knowledge, to date there is no printed information about the effect of insulation thickness on the environment for buried hot oil pipelines. However, as the important equipment in the oilfield, the furnace consumes a large amount of fossil fuel and produces serious pollution when heating the crude oil. As is shown in the survey, the emission of the heating furnace in Huabei oilfield has exceeded the standard, especially the nitrogen oxide, sulfide, and dust [12]. This paper aims to establish a mathematical model of economic insulation thickness of the buried hot oil pipelines which considers the environmental factors and analyzes the influence of various factors on the insulation thickness.

2 The Mathematical Model for Economic Insulation Thickness

The insulation of the buried oil pipelines consists of a steel pipe, polyurethane foam insulation layer and polyethylene waterproof protective layer as shown in Fig. 2 [13]. It is a part of a pipeline that is buried deep
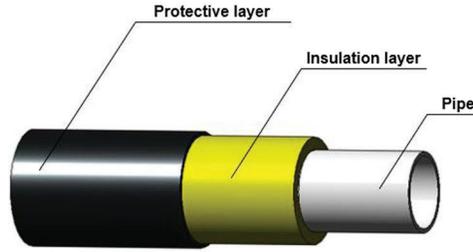
Figure 2: The insulation structure of the buried hot oil pipeline

underground. After being heated and centrifuged, the crude oil is transported to various places at a certain temperature and pressure.

The total cost of the buried hot oil pipeline insulation project covers investment cost, operation cost, and environmental cost. In the designing process of the insulation, three costs should be considered. The objective function and constraint conditions are shown as follows [10]:

$$\min w = w_{1n} + w_{2n} + w_{3n} \tag{1}$$

$$s.t. \begin{cases} \delta > 0 \\ P_Z > P_N \\ T_Z > T_N + 3 \end{cases} \tag{2}$$

where w is the final value of the total investment cost of the insulation project (yuan), w_{1n}, w_{2n}, w_{3n} represent the final value of the investment cost (yuan), the operation cost (yuan), and the environmental cost (yuan), respectively. And δ is the thickness of the insulation (m), P_Z is the endpoint pressure (Pa), P_N is the endpoint minimum pressure (Pa), T_Z is the crude oil inlet temperature (°C), T_N is the condensation point of the crude oil (°C).

The methods used to calculate the cost of the investment, operation, and environment will be introduced respectively as follows.

2.1 The Investment Cost
The investment cost w_1 of the buried hot oil pipeline can generally be calculated by

$$w_1 = w_{1,1} + w_{1,2} + w_{1,3} \tag{3}$$

where $w_{1,1}$, $w_{1,2}$, $w_{1,3}$ are the insulation layer cost (yuan), the protective layer cost (yuan), the construction cost (yuan) respectively. And they can be calculated by

$$w_{1,1} = \frac{\pi}{4}\left[(D + 2\delta)^2 - D^2\right]L\alpha_1 \tag{4}$$

$$w_{1,2} = \pi(D + 2\delta)L\alpha_2 \tag{5}$$

$$w_{1,3} = \beta\left(w_{1,1} + w_{1,2}\right) \tag{6}$$

where D is the outside diameter of the pipe (m), L is the pipeline length (m), α_1 is the price of insulation material (yuan/m^3), α_2 is the price of protective layer material (yuan/m^2), β is the construction cost coefficient, taken as 0.2 [14].

Because the investment cost of the insulation project is a one-time expenditure, regardless of the construction period of the insulation project, the investment cost w_1 is converted to the end of the project life, and the final value w_{1n} is [15]

$$w_{1n} = w_1 \times (1 + i)^n \tag{7}$$

where i is the interest rate, n is the lifetime of insulation (year).

2.2 The Operation Cost

When the pipeline insulation project is officially put into operation, the main expenditure is the operation cost which covers the heat cost $w_{2,1}$ and the power cost $w_{2,2}$:

$$w_2 = w_{2,1} + w_{2,2} \tag{8}$$

2.2.1 The Heat Cost

The heat cost refers to the cost of heat waste caused by the heat loss of the pipeline during the operation of the crude oil pipeline. The calculation formula is as follows:

$$w_{2,1} = \frac{GC(T_R - T_Z)\tau}{\eta_s} \times \alpha_3 \tag{9}$$

where G is the mass flow rate of crude oil (kg/s), C is the specific heat capacity of crude oil (J/(kg·°C)), T_R is the outlet temperature of crude oil and T_Z is the inlet temperature of crude oil (°C), τ is the annual operating time of the pipeline (s), α_3 is the heating price (yuan/J), η_s is the efficiency of the furnace, taken as 80% [16].

In the designing process of the crude oil pipeline, to resolve the congelation of buried waxy crude-oil pipelines and difficulty in restarting, the inlet oil temperature is required to stay at least 3 to 5°C above the freezing point [17], and the outlet temperature of crude oil can be calculated from the Sukhov Formula, as is shown in Eq. (11):

$$T_Z = T_N + 3 \tag{10}$$

$$T_R = T_0 + (T_Z - T_0)e^{\frac{KD\pi}{GC}L} \tag{11}$$

where T_0 is the ambient temperature (°C) and T_N is the condensation point of the crude oil (°C).

Regardless of the heat resistance inside of the pipe and the heat resistance of the pipe wall, the heat transfer coefficient can be calculated by Eq. (12) [11],

$$K = \frac{1}{\pi D} \times \frac{1}{\frac{1}{2\pi\lambda}\ln\frac{D+2\delta}{D} + \frac{1}{\psi\pi(D+2\delta)}} \tag{12}$$

where λ is the soil heat conductivity (W/(m·°C)), ψ is the exothermic coefficient of the outer surface of the pipe to the soil environment outside the pipe, which can be calculated using

$$\psi = \frac{2\lambda_e}{(D + 2\delta)\ln\left[\frac{2h}{D+2\delta} + \sqrt{\left(\frac{2h}{D+2\delta}\right)^2 - 1}\right]} \tag{13}$$

where λ_e is the Heat conductivity of insulation (W/(m·°C)), h is the buried depth of the pipe centerline (m).

2.2.2 The Power Cost

The power cost refers to the cost caused by overcoming the friction of the pipelines, and the motor consumes the energy consumed by the centrifugal pump. It can be calculated as follows:

$$w_{2,2} = \frac{\Delta p G \tau \times 10^{-3}}{3600 \rho \eta_p} \times \alpha_4 \tag{14}$$

where $w_{2,2}$ is the annual power cost of the pipeline (yuan), Δ_p is the pressure drop of the pipeline (m), ρ is the density of the crude oil (kg/m^3), η_p is the pump efficiency, taken as 75% [18], α_4 is the electricity price (yuan/(kw·h)).

Because the crude oil is generally in the hydraulically smooth zones during the transportation process, the Eq. (15) shows that the pressure drop loss of the conveying pipeline is [19]

$$\Delta p = 0.0246 \rho g \frac{\left(\frac{G}{\rho}\right)^{1.75} v^{0.025}}{d^{4.75}} L \tag{15}$$

where g is the acceleration of gravity, which is 9.8 (m/s^2), d is the inner diameter of the pipe (m).

The dynamic viscosity of crude oil is the viscosity at the average temperature. T_{AV} is the average temperature of oil (°C). T_{AV} is defined by

$$T_{AV} = \frac{1}{3}(T_R + 2T_Z) \tag{16}$$

The viscosity calculation is based on the general formula for calculating the viscosity of crude oil in China [11], as shown in Eq. (17):

$$v = b_0 e^{-b_1 T_{AV}} \tag{17}$$

where b_0, b_1 are the viscosity coefficients of crude oil.

Since the operation cost is a perennial expenditure, taking the time value into account, the final value of operation cost is given by [15]

$$w_{2n} = w_2 \times \frac{(1+i)^n - 1}{i} \tag{18}$$

2.3 The Environment Cost

Nitrogen oxides, sulfides, and dust generated by oil field heating furnaces can cause serious soot-type air pollution [20]. Therefore, the environmental costs of exhaust gas emissions must be considered in the design of the insulation.

The annual heat loss of the pipeline during the operation can be written as [21]

$$Q = K\pi D(T_{AV} - T_0)L\tau \tag{19}$$

The annual fuel loss of the pipeline due to heat loss is defined by

$$B = \frac{Q}{H_u \eta_f} \tag{20}$$

where Q is the annual heat loss of the pipeline (J), B is the annual fuel loss of the pipeline (kg), H_u is the lower heating values of the fuel (J/kg), η_f is the fuel combustion efficiency (%).

Insulation design can reduce heat loss in pipelines and fuel consumption. Also, environmental effects are decreased by insulation. The chemical equation for complete combustion of fuel is expressed by [22]

$$C_cH_hO_oN_nS_s + O_{min}(O_2 + 3.78N_2) \rightarrow cCO_2 + (h/2)H_2O + sSO_2 + n_1N_2 \tag{21}$$
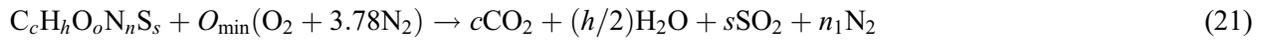
According to the atoms balance, the emissions from annual fuel loss can be calculated in Eqs. (22)–(26).

$$O_{min} = c + h/4 + s - o/2 \tag{22}$$

$$n_1 = n/2 + 3.78O_{min} \tag{23}$$

$$M_{CO_2} = \frac{44c}{M}B \tag{24}$$

$$M_{SO_2} = \frac{64s}{M}B \tag{25}$$

$$M = 12c + h + 16o + 14n + 32s \tag{26}$$

where c, h, o, n, s are the number of C, H, O, N, S in the fuel respectively. And M_{CO2}, M_{SO2} is the mass of CO_2, SO_2 produced by fuel combustion (kg), M is the weight of molecule for fuel.

Tab. 1 shows some properties of the fuels.

Table 1: Lower heating values (Hu) and chemical formulas of fuels and efficiencies of heating systems [23]

Fuels	H_u	η	Chemical formulas
Coal	29.260×10^6	65%	$C_{7.078}H_{5.149}O_{0.517}S_{0.01}N_{0.086}$
Natural gas	49.264×10^6	93%	$C_{1.05}H_4O_{0.034}N_{0.022}$
Fuel-oil	41.278×10^6	80%	$C_{7.3125}H_{10.407}O_{0.04}S_{0.026}N_{0.02}$
LPG	46.398×10^6	92%	$C_{3.7}H_{4.1}$

The collection of sewage charges in China can be worked out through employing the pollution equivalent as given by [24].

$$\text{Pollution equivalent} = \frac{\text{Pollution emissions } (kg)}{\text{Pollution equivalent value } (kg)} \tag{27}$$

and the equivalent value of CO_2 and SO_2 as shown in Tab. 2 [25].

Since the sewage discharge cost w_3 requires annual fixed expenditure, taking the time value of funds into account, the formula for calculating the final value of environmental expenses is shown in Eq. (29).

Table 2: Air pollutant equivalent value

Pollution	Pollution equivalent value
CO_2	20
SO_2	0.95

$$w_3 = (\Delta_{CO_2} + \Delta_{SO_2})\alpha_5 \tag{28}$$

$$w_{3n} = w_3 \times \frac{(1+i)^n - 1}{i} \tag{29}$$

where w_3 is the annual sewage discharge cost (yuan), Δ_{Co_2}, Δ_{SO_2} are the equivalent of CO_2, SO_2, respectively. And α_5 is the emission price (yuan/equivalent).

3 The Method to Solve the Model

As it is difficult to work out the model, the golden section method is adopted. The golden section method is a basic one-dimensional search algorithm of the optimization algorithm, which is essentially a method to solve the extreme value of the single valley function. The algorithm idea is to gradually narrow the search interval through iteration until the length of the interval where the minimum point is located meets the requirement of the given accuracy [26]. The steps of the golden section method are:

(1) Given $a < b$, $\varepsilon > 0$.

(2) Calculated $\delta_1 = a + 0.382(b - a)$, $\delta_2 = a + b - \delta_1$.

(3) Calculated $w_1 = w(\delta_1)$, $w_2 = w(\delta_2)$.

(4) If $w_1 > w_2$, $a = \delta_1$, or $b - a < \varepsilon$ to (5); Or $w_1 = w_2$, $\delta_1 = \delta_2$, $\delta_2 = a + 0.618(b - a)$, $w_2 = w(\delta_2)$, to (4);

Or $b = \delta_2$, if $b - a < \varepsilon$ to (5); Or $w_2 = w_1$, $\delta_2 = \delta_1$, $\delta_1 = a + 0.382(b - a)$, $w_1 = w(\delta_1)$, to (4).

(5) $\delta^* = \dfrac{a + b}{2}$.

where a, b are the upper and lower limits respectively. And ε is the accuracy of the calculation.

Finally, the minimum insulation thickness can be found. The calculation process is shown in Fig. 3.

4 Results and Discussion

Taking a project as an example, the design of insulation thickness is carried out. The details of the project are shown in Tab. 3.

The effect of insulation thickness on the final values over the lifetime of 15 years is shown in Fig. 4. It can be found that the operation cost and environmental cost decreases with insulation thickness increases. This shows that when the insulation thickness increases, the heat loss of the oil flow decreases and there is less influence on the heat dissipation. On the other hand, the investment cost increases with the increase of the insulation thickness, because the consumption of insulation materials and protective materials increases. However, the total cost of insulation engineering shows that decreasing occurs first and then comes increasing. The minimum point is called as the economic insulation thickness. As shown in Fig. 4, when the insulation thickness is 79.54 mm, the total cost is 29901.31×10^5 yuan, which is the economic thickness of insulation. It also can be observed that the percentage of the investment cost and the environmental cost are small compared with the operation cost.

Fig. 5 shows the relationship between the final value and the insulation thickness regardless of the environmental factors. Compared with Fig. 4, the economic thickness is smaller. The economic thickness is 68.79 mm, and the total cost is 29852.61×10^5 yuan.

The effect of environmental factors on the economic insulation thickness is shown in Tab. 4. When considering environmental factors, the economic thickness of insulation increases by 10.75 mm, with the total cost increases by 48.7×10^5 yuan. Mainly because the environmental cost is increased by 46.34×10^5 yuan, accounting for 0.155% of the total cost. However, the outlet and average temperature of crude oil are reduced, which makes the consumption of fuel reduces, and the environmental dividend cannot be ignored.
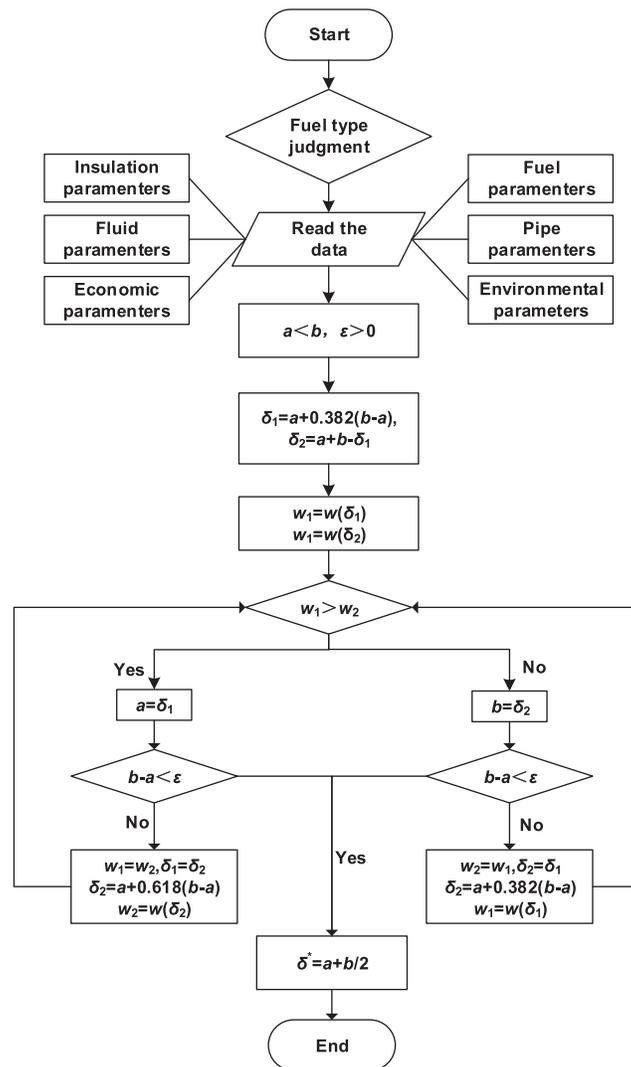
Figure 3: The flowchart of mathematical model

Fig. 6 shows the effect of insulation thickness on oil temperature. It is seen that when the inlet temperature of the oil is constant, the outlet and average temperature are reduced. It is obvious to see the outlet temperature drop, the maximum drop is 17.37%. This is because the heat transfer coefficient decreases with the increase of the insulation thickness and the heat loss is also reduced.

The effect of pipeline diameters and throughput on the economic insulation thickness is shown in Tab. 5. It can be seen from the table that the economic thickness calculated by considering environmental factors is greater than the economic insulation thickness calculated without considering environmental factors. As the pipeline diameter decreases or the throughput increases, the calculation error of the economic insulation thickness increases. This is because as the pipe diameter decreases or the throughput increases, the fuel consumption is increasing, which makes the environmental factors obvious.

Fig. 7 shows the effect of insulation thickness on fuel consumption. It can be found that the increase in insulation thickness not only reduces heat loss but also saves a lot of fuel consumption. The fuel consumption varies from 129.044 to 5537.554 t/a depending on the fuel types used in the oil field, where coal consumption is the largest, followed by fuel-oil, LPG, and natural gas.

Table 3: Parameters and their values used in calculation

Type	Parameters/Technical characteristics	Values
Fluid	Mass flow of oil (G)	300×10^4 t/y
	Density of oil (ρ)	850 kg/m^3
	Condensation point of oil (T_N)	35°C
	heat capacity of crude oil (C)	2340 J/(kg·°C)
Pipe	Pipe size	$\varphi 325 \times 7$
	Pipe length (L)	20 km
	Buried depth (h)	1.2 m
Environmental	Soil heat conductivity (λ)	1.4 W/(m·°C)
	Ambient temperature (T_0)	−10°C
	Annual operating time (τ)	350 d
Insulation	Heat conductivity of insulation (λ_e)	0.035 W/(m·°C)
	Insulation material price (α_1)	980 yuan/m^3
	protective material price (α_2)	20 yuan/m^2
	Life time of pipeline (n)	15 y
Economic	Interest rate (i)	0.1
	electricity price (α_4)	0.75 yuan/(kw·h)
	Heating price (α_3)	26 yuan/GJ
	Emission price (α_5)	1.2 yuan/equivalent
Fuel	See Tab. 1	
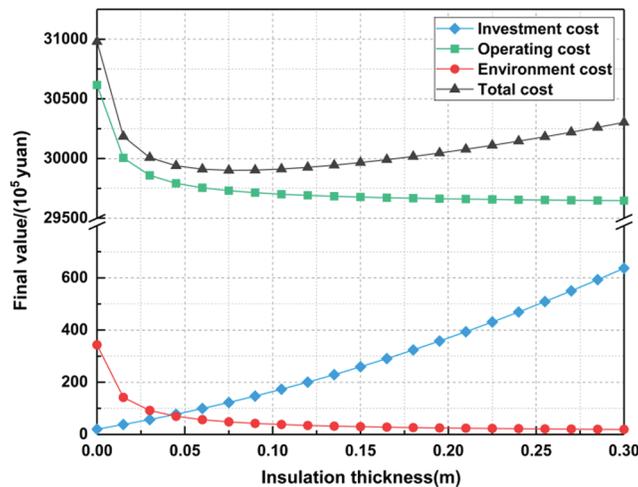
Figure 4: The effect of insulation thickness on final values by using coal

Fig. 8 shows the final value of costs of different fuels (Investment (a), operation (b), environment (c), total (d)). It is seen that when natural gas is selected as the fuel for the oil field, the final operation cost is higher but the economic insulation thickness is the least. Therefore, heat loss is great, and the heating
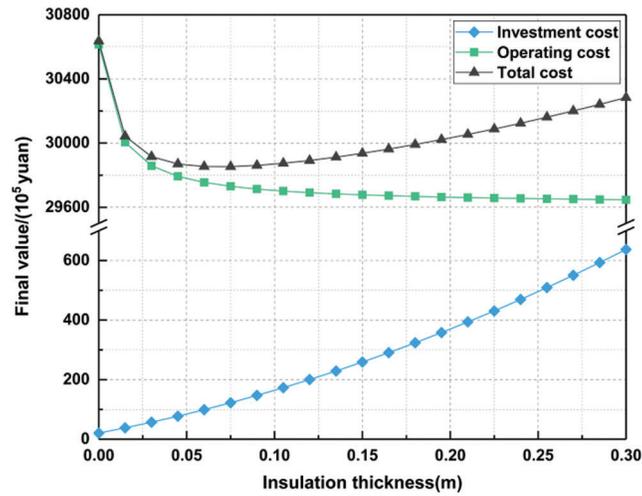
Figure 5: The effect of insulation thickness on final values without the environmental factors by using coal

Table 4: The effect of environmental factors on the economic insulation thickness

Parameters	Values	
	Consider environmental factors	Ignore environmental factors
The economic thickness	79.54 mm	68.79 mm
The investment cost	129.81×10^5 yuan	112.75×10^5 yuan
The operation cost	29725.15×10^5 yuan	29739.86×10^5 yuan
The environment cost	46.34×10^5 yuan	///
The total cost	29901.31×10^5 yuan	29852.61×10^5 yuan
Outlet temperature	40.04°C	40.26°C
Average temperature	38.68°C	38.75°C
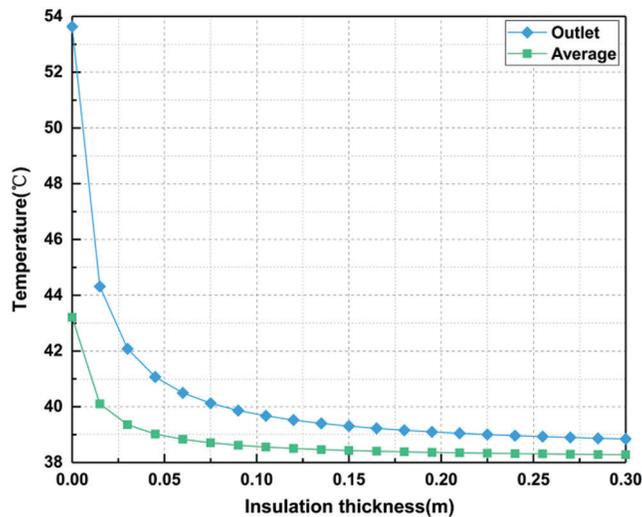
Figure 6: Effect of insulation thickness on the oil temperature

Table 5: The effect of pipeline diameters and throughput on the economic insulation thickness

Pipeline diameter	Consider environmental factors			Ignore environmental factors			Difference of the two results		
	250×10^4 t/y	300×10^4 t/y	350×10^4 t/y	250×10^4 t/y	300×10^4 t/y	350×10^4 t/y	250×10^4 t/y	300×10^4 t/y	350×10^4 t/y
200 mm	56.12 mm	50.10 mm	43.18 mm	40.63 mm	31.28 mm	17.62 mm	27.60 %	37.56 %	59.19 %
300 mm	79.52 mm	78.63 mm	77.81 mm	68.87 mm	67.85 mm	66.90 mm	13.39 %	13.71 %	14.02 %
400 mm	84.52 mm	84.00 mm	83.57 mm	73.67 mm	73.09 mm	72.62 mm	12.84 %	12.99 %	13.10 %
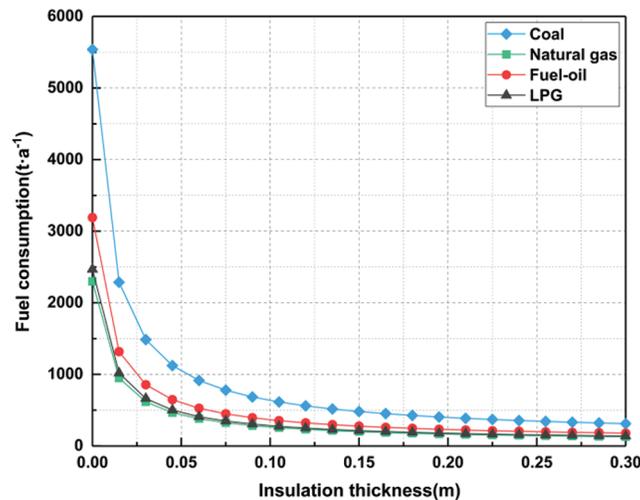
Figure 7: Effect of insulation thickness on the fuel consumption

cost is much higher. However, as a clean energy source, the final environment cost of natural gas is 16.71×10^5 yuan, which is much lower than other fuels. At the same time, the smaller insulation thickness reduces the final value of the investment cost. Therefore, the final value of the total cost of natural gas is the lowest, which is 29869.64×10^5 yuan, followed by LPG, fuel oil, and coal. Compared with traditional fuel coal the natural gas can save 31.67×10^5 yuan.

The annual CO_2 emissions versus insulation thickness for different fuel types are shown in Fig. 9. Here, it is seen that the CO_2 emission decreases with an increase in insulation thickness. The CO_2 emission rates of fuels vary between 398.318 and 17266.260 kg/year for various fuel types. Among them, coal has the largest CO_2 emission rate, followed by fuel-oil, LPG, and natural gas.

Fig. 10 shows the effect on annual SO_2 emission by insulation thickness at various fuel types. To reduce energy consumption and air pollution, thermal insulation is employed. There are no SO_2 emission rates due to the lack of sulfur in chemical formulas of natural gas and LPG fuels. When the insulation thickness is the same, the SO_2 emission rates of the fuel-oil is greater than that of coal.

The effect of pollutant discharge cost on the economic insulation thickness is shown in Tab. 6. It appears that as the pollutant discharge increase, the economic insulation thickness also increases. When the pollutant discharge is fixed, the natural gas has the smallest economic insulation thickness, followed by LPG fuel-oil and coal.
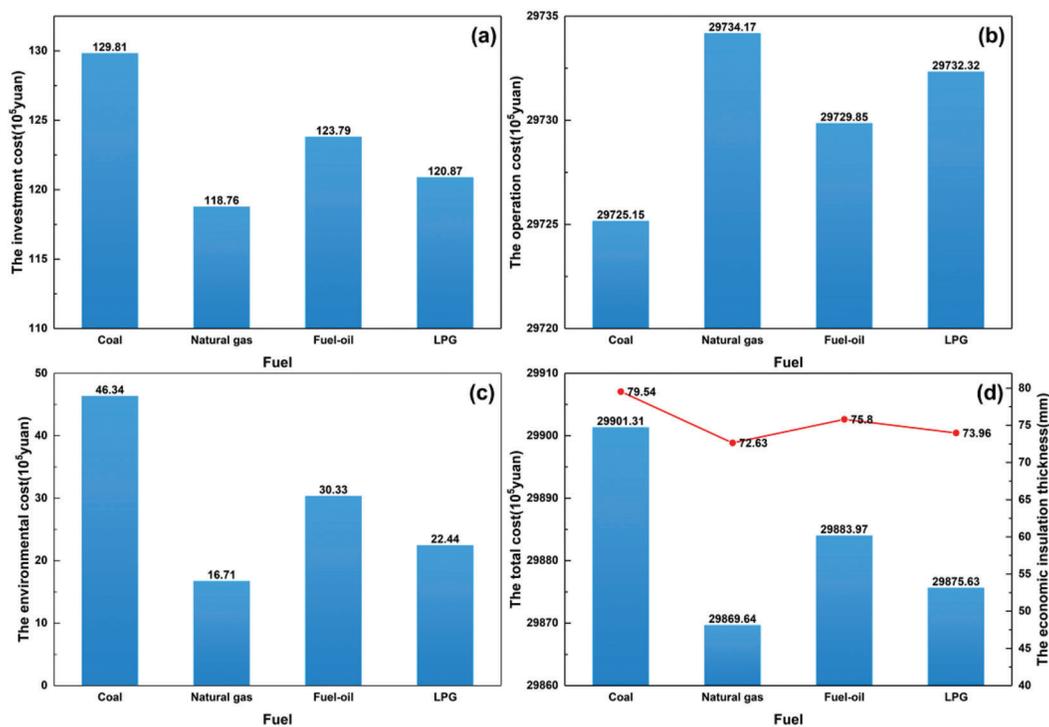
Figure 8: The final value of costs of different fuels (Investment (a), operation (b), environment (c), total (d))
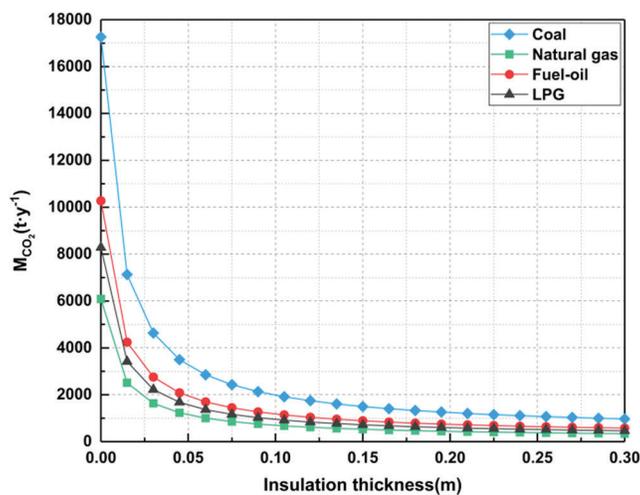
Figure 9: The annual CO_2 emissions *vs.* insulation thickness for different fuel types
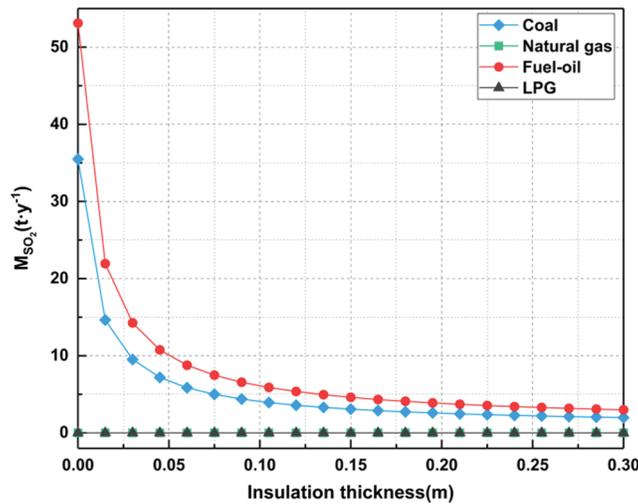
Figure 10: The annual SO_2 emissions *vs.* insulation thickness for different fuel types

Table 6: The effect of pollutant discharge cost on the economic insulation thickness

Fuel	The economic insulation thickness				
	1.2 yuan/ equivalent	1.4 yuan/ equivalent	1.6 yuan/ equivalent	1.8 yuan/ equivalent	2.0 yuan/ equivalent
Coal	79.54 mm	81.16 mm	82.75 mm	84.30 mm	85.51 mm
Natural gas	72.63 mm	73.25 mm	73.86 mm	74.47 mm	75.07 mm
Fuel-oil	75.80 mm	76.89 mm	77.97 mm	79.03 mm	80.07 mm
LPG	73.96 mm	74.79 mm	75.60 mm	76.40 mm	77.19 mm

5 Conclusions

In this study, the mathematical model of the insulation thickness of the buried hot oil pipelines was built, considering the investment cost, operation cost, environmental cost, and the time value of money. The golden section method was adopted to work out the mathematical model. In doing the calculations, coal, natural gas, fuel oil, and LPG were taken as the fuel source and the effect of the insulation thickness was analyzed in terms of three kinds of costs, the temperature of oil, fuel consumption and emission pollutions. The conclusions obtained by the study are listed below:

a) The insulation thickness of the buried hot oil pipeline is affected by the investment cost, operation cost, and environmental cost. When designing the insulation, three kinds of expenses should be considered at the same time, and the operation cost accounts for the largest proportion in the insulation project.

b) If the environmental cost is not taken into account, the thickness of the insulation layer will become smaller, and the total cost of the insulation project will also be reduced. However, the heat loss of pipeline and fuel consumption will increase, bringing serious air pollution.

c) Compared with coal, fuel oil, and LPG, when natural gas is selected as the fuel for oilfield, the economic thickness of insulation is the smallest. Not only the less thick insulation layer can reduce the cost, but the natural gas, as a clean fuel, can also greatly reduce the environmental cost, thereby reducing the total cost of the insulation project.

d) Pressed by the national policy for environmental protection, the cost of processing CO, CO_2, SO_2, and other pollutants will continue to increase. It is foreseeable that the thickness of the insulation will be greater and greater in the future, to reduce environment cost and improve the overall income of the enterprise.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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