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Study the Thermal Analysis of Materials Used in Insulation Pipelines

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دراسة التحليل الحراري للمواد المستخدمة في عزل خطوط الأنابيب

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Abstract:
The goal of the study is to examine and evaluate the various insulating materials utilized in pipelines. The study focused on the tubes used by Libyan Norwegian Fertilizers Company in order to determine how the insulator affected the quantity of heat loss and to determine the most cost-effective form of insulation. The research was conducted using the MATLAB application R2014a, and the data came from the reports utilized by the Libyan-Norwegian enterprise. Additionally, the thermal conductivity of insulating materials was measured using a Lee's disk experiment. According to the findings, rock wool may be the most cost-effective and ideal option for insulation, but it has a drawback in that it is toxic. The study investigates the thermal analysis of insulation pipeline materials and alloys using a Lee's disk experiment to measure various insulation materials (such as rock wool and camel skin) using a MATLAB computer program.

Keywords: MATLAB, pipeline, rock wool, thermal analysis, thermal conductivity.

الملخص
الهدف من الدراسة هو فحص وتقييم المواد العازلة المختلفة المستخدمة في خطوط الأنابيب. وركزت الدراسة على الأنابيب المستخدمة من قبل الشركة الليبية النرويجية للأسمدة من أجل تحديد كيفية تأثير العازل على كمية الفقد الحراري وتحديد أكثر أشكال العزل فعالية من حيث التكلفة. تم إجراء البحث باستخدام برنامج الماتلاب (MATLAB R2014a)، وجاءت البيانات من التقارير المستخدمة من قبل الشركة الليبية النرويجية للأسمدة. بالإضافة إلى ذلك، تم قياس التوصيل الحراري للمواد العازلة باستخدام تجربة قرص لي. ووفقًا للنتائج، قد يكون الصوف الصخري الخيار الأكثر فعالية من حيث التكلفة والأكثر مثالية للعزل، ولكن له عيبًا في كونه مادة سامة. تتناول الدراسة التحليل الحراري لمواد وسبائك أنابيب العزل باستخدام تجربة قرص لي لقياس المواد العازلة المختلفة (مثل الصوف الصخري وجلد الجمل) باستخدام برنامج حاسوبي من برنامج الماتلاب.

الكلمات المفتاحية: الأداء الحراري، الصوف الصخري، الماتلاب، خطوط الأنابيب، التوصيل الحراري.

Introduction

Today's market offers a wide range of insulating solutions that may be used in every temperature and installation scenario. Although there are many products to mention, it is crucial that the researcher has a good understanding of some of the different products available and their applications. The researcher must be able to comprehend the task requirements and know how to construct the insulation correctly. Insulation materials are those that prevent or reduce the various modes of heat transfer—conduction, convection, and radiation—regardless of whether the surrounding environment is hot or cold [1].

Steam pipes are essential components in many industrial processes, as they transport high-temperature steam required for manufacturing, chemical processing, and power generation. These pipes operate under high pressure and temperature to maintain system efficiency, power machinery, and ensure precise thermal control. However, uninsulated or poorly insulated steam pipes suffer from significant heat loss, reduced energy efficiency, safety hazards (such as burns from hot surfaces), and increased risk of condensation-induced corrosion. Proper insulation minimizes thermal energy loss, preserves steam quality, reduces fuel consumption, lowers operational costs, and enhances workplace safety [2].

Steam Pipeline Insulation

In order to convey high-temperature steam for heating, power generation, and other vital functions, steam pipes are crucial parts of many industrial processes. If not adequately insulated, these pipes are vulnerable to corrosion, serious heat loss, and safety risks. Insufficient insulation raises operating expenses, lowers system efficiency, and increases energy consumption. Additionally, because of the high surface temperatures that might result in burns and other injuries, uninsulated steam pipes present a safety concern to employees. Furthermore, the lack of insulation accelerates the development of condensation, which can lead to corrosion and the pipes' eventual collapse.

Moreover, the environmental impact of uninsulated steam pipes in terms of energy loss and greenhouse gas emissions becomes a major issue as enterprises work to meet sustainability targets. Despite these challenges, a large number of industrial facilities continue to use antiquated or inadequate insulation systems, which results in inefficiencies and needless dangers.

This research aims to alleviate these problems by highlighting the importance of steam pipeline insulation. It investigates efficient insulation methods, assesses the most insulation-suited materials, and illustrates the advantages of appropriate insulation in terms of energy savings, safety enhancement, operational effectiveness, and environmental sustainability.

Scope of the Study

The issue of high-superheated steam pipes from a superheater and ending with a high-pressure turbine is investigated. The steam temperature of superheat is crucial in this case. Therefore, any heat lost from the steam pipes is linked to a steam degree of superheat degradation, which raises fuel consumption. In this sense, appropriate insulation choices can minimize heat losses through the insulation of the steam pipes. However, the capital cost rises with increasing insulating thickness.

The study examines the thermal analysis of insulation pipeline materials, alloys, and cost using the MATLAB computer application and the Lee’s disc experiment to evaluate various insulation materials (camel skin fluff and rock wool). Real data from the pipeline currently in place at the Libyan Norwegian Fertilizers Company is used to create a simulation and obtain results in the form of figures, tables, and equations.

Literature Review

A simple method has been developed to estimate the required thermal insulation thickness for flat surfaces, ducts, and pipes. It covers ambient-to-surface temperature differences up to 250°C and insulation temperature drops up to 1000°C. The method calculates insulation thickness up to 250 mm for flat surfaces and estimates it for pipes and ducts with outer diameters up to 2400 mm. It shows excellent agreement with experimental data, with an average absolute deviation of only 3.25%, and is based on fundamental heat transfer principles [3].

Pipe insulation systems are vital for maintaining indoor environmental health. When chilled pipes are inadequately insulated, condensation forms and drips onto surfaces, potentially causing mold growth. The temperature difference between the cold pipe and warm ambient air drives moisture into the insulation, where it condenses upon contact with the pipe surface. Laboratory tests under wet, condensing conditions revealed that moisture ingress—due to cylindrical geometry, split joints, and micro-imperfections in jacketing—systematically increases the thermal conductivity of insulation, thereby reducing its effectiveness [4].

A critical review highlights ongoing controversy regarding differences in thermal conductivity between pipe insulation systems and flat slab configurations. These discrepancies are often linked to variations in testing methodologies. Both steady-state and transient methods have been used, yielding different results under dry conditions. For wet insulation, four sample preparation techniques were identified, each producing significantly different thermal conductivity values. The review concludes that accurate measurement of thermal performance under real-world moisture conditions remains a challenge and calls for standardized protocols [5].

Moisture absorption in mechanical pipe insulation can severely degrade thermal performance and lead to pipeline failure. An optimal insulation strategy must account for moisture absorption rates under various operating conditions and how thermal conductivity changes with moisture content. The same review reiterates that testing methodology greatly influences reported values, emphasizing the need for consistent evaluation approaches [5].

A study conducted in Afyonkarahisar, Turkey, optimized insulation thickness for HVAC pipes made of copper, steel, and plastic using life-cycle cost analysis based on heating degree-days. Results showed that rock wool and

fuel oil provided the greatest energy savings. Insulation priority followed the order: copper > steel > plastic. Optimal thickness ranged from 5–12 cm for copper and 5–16 cm for steel pipes. Plastic pipes showed limited benefit due to their inherently low thermal conductivity [6].
Another study examined the impact of thermal oil leaks on mineral wool insulation in solar thermal systems (e.g., parabolic trough collectors). Oil-saturated mineral wool exhibited higher thermal conductivity than dry material. Tests at 175°C and 250°C with 0%, 33%, and 50% oil saturation confirmed that heat loss increases with oil content, underscoring the importance of leak prevention in high-temperature piping [7].
Thermal contact resistance between pipe and insulation significantly affects heat loss. A simple experimental device using steam condensation and thermocouples was developed to measure this resistance. Calibration with materials of known conductivity (e.g., fiberglass and calcium silicate) enabled accurate determination via electrical analog methods. Introducing small air gaps with spacers altered contact resistance and heat loss. A generalized optimization model was proposed that balances insulation cost against long-term energy loss [8].

Methodology

Hot Insulation Materials

It is recommended that the use of these materials be limited to 90% of the manufacturer's limiting temperatures to safeguard against temperature surges during plant startup. Actual figures may differ between manufacturers and must be confirmed individually.

Hot Insulation

Equipment or pipework operating above 55°C on metallic surfaces and 65°C on non-metallic surfaces should be insulated so that the cold surface temperature does not exceed 55°C. Temperatures of 60°C or higher cause discomfort to personnel, making 55°C a prudent maximum. If fluid may remain static below its freezing point, supplementary heating (e.g., heat tracing) should be considered, especially in small-diameter pipes with intermittent flow.

Selection of Hot Insulation Materials

The objective is to select a material that serves the insulation purpose at the lowest cost. Over-specifying insulation thickness unnecessarily increases the cost of outer protection. In multi-layer systems, the choice of outer cladding (e.g., aluminum with low emissivity) affects surface temperature and heat loss. Mass must also be controlled where constant-load supports are used, and internal duct linings must be non-combustible per BS 476 (Holman, 2010).

Lee's Disc Experiment

As shown in **Figure 1**, Lee's and Charlton's apparatus is made from rock wool. The disc (10 cm diameter, 10 cm outer diameter, 9 cm inner diameter) and steam chamber (6 cm deep) are cast in cast iron with a rough surface. Surface finishing is performed using a lathe machine, followed by grinding for smoothness. Holes are drilled in each cast iron disc to accommodate thermometers for temperature measurement. Steam enters and exits through two holes in the steam chamber. Steam is generated in a galvanized mild steel container, and brass gas welding is used to join components. The entire system is suspended horizontally by three symmetrically placed cords from a cast iron ring to minimize external heat interference.

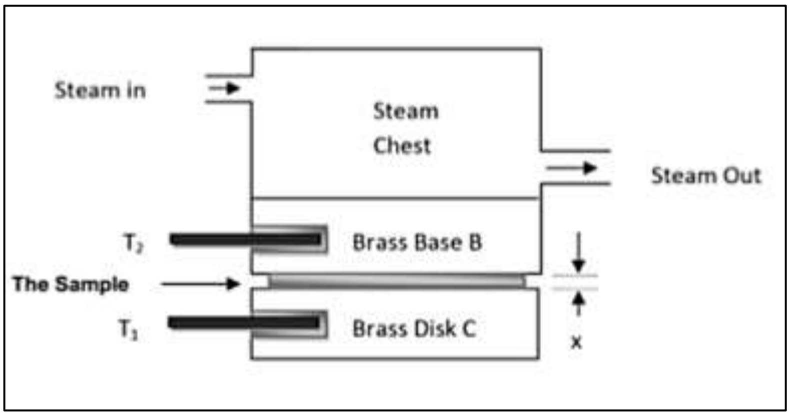

Figure 1 Lee disk Experiment.

Working Method of Lee's Disc Experiment

Thermal conductivity indicates a material's ability to conduct heat. Heat flows from high- to low-energy molecules when a temperature gradient exists. Fourier's law expresses steady-state conductive heat transfer as:

$$q = kA\frac{(T_i - T_o)}{\chi} \quad (1)$$

where is the heat transfer rate (W), is thermal conductivity (W/m·°C), is cross-sectional area (m²), is the $Ti - To$ temperature difference (°C), and is thickness (m). The sample is shaped as a thin disc with large area-to-edge ratio to minimize lateral heat loss and reach steady state quickly. Lee's disc method is suitable for poor conductors.

Conduction Heat Transfer

When a temperature gradient exists in a body, energy transfers from high- to low-temperature regions. The heat flux per unit area is proportional to the temperature gradient:

$$\frac{q_x}{A} \sim \frac{\partial T}{\partial x} \quad (2)$$

When the proportionality constant is inserted,

$$q_x = -KA\frac{\partial T}{\partial x} \quad (3)$$

These energy quantities are given as follows:

$$\text{Energy in left face} = q_x = -KA\frac{\partial T}{\partial x} \quad (4)$$

Thermal Conductivity

Thermal conductivity is defined by equation (2). Experimental measurements can determine material thermal conductivity based on this definition [9].

Convection Heat Transfer

The cooling rate of a hot plate of metal is much faster when it is placed in front of a fan rather than in still air. Convection heat transfer occurs when heat is transferred by convection. The convective heat transfer rate is given by:

$$q = h\,A(T_1 - T_2) \quad \textbf{(5)}$$

Radiation Heat Transfer

This process differs from conduction and convection, which depend on the transfer of energy through a medium.

Heat can also be transferred through regions with perfect vacuums; this case is called electromagnetic radiation.

The discussion is limited to electromagnetic radiation that propagates due to temperature differences [9].

The radiation problem occurs when a large heat-transfer surface at temperature T_1 is enclosed by a much larger surface at temperature T_2. [9]:

$$q = \epsilon_1\,\sigma\,A_1\,(T_1^4 - T_2^4) \quad (6)$$

Steady-State Conduction – One Dimension

Fourier's law of heat conduction is applied to simple one-dimensional systems. Cylindrical and spherical systems are considered one-dimensional when temperature depends only on radial distance and is unaffected by azimuth angle or axial distance [9].

Cylinders

Suppose having a long cylinder with an inside radius of r_i and an outside radius of r_o, as illustrated in Figure (3.4). In this case, we expose the cylinder to a temperature differential $T_i - T_o$ and ask what the heat flow will be. When the length of a cylinder is larger than its diameter, the heat flows only radially, so the only coordinate necessary to specify the system is r. Fourier's law is used once again by inserting the appropriate area relationship. In a cylinder system, the area for heat flow is:

$$A_r = 2\,\pi\,r\,L \tag{7}$$

Fourier's law can be written as

$$q_r = -KA_r\frac{dT}{dr} \tag{8}$$

$$q_r = -2\,\pi\,K\,r\,L\,\frac{dT}{dr} \tag{9}$$

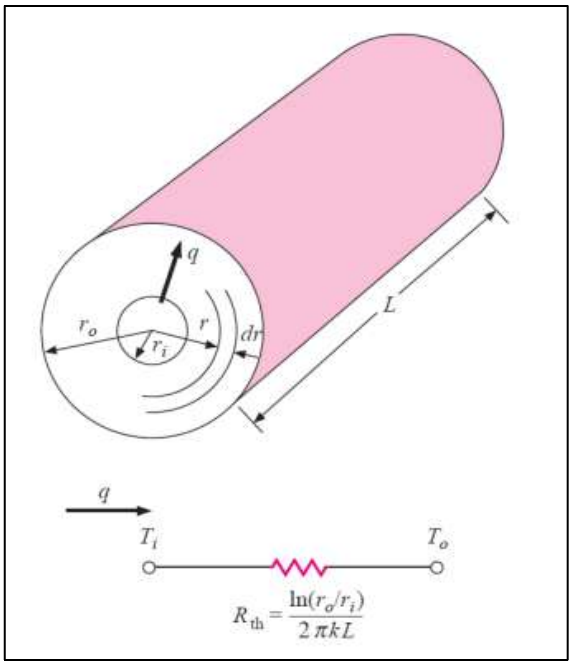

Figure 2 One-dimensional heat flow through a hollow cylinder and electrical analog.

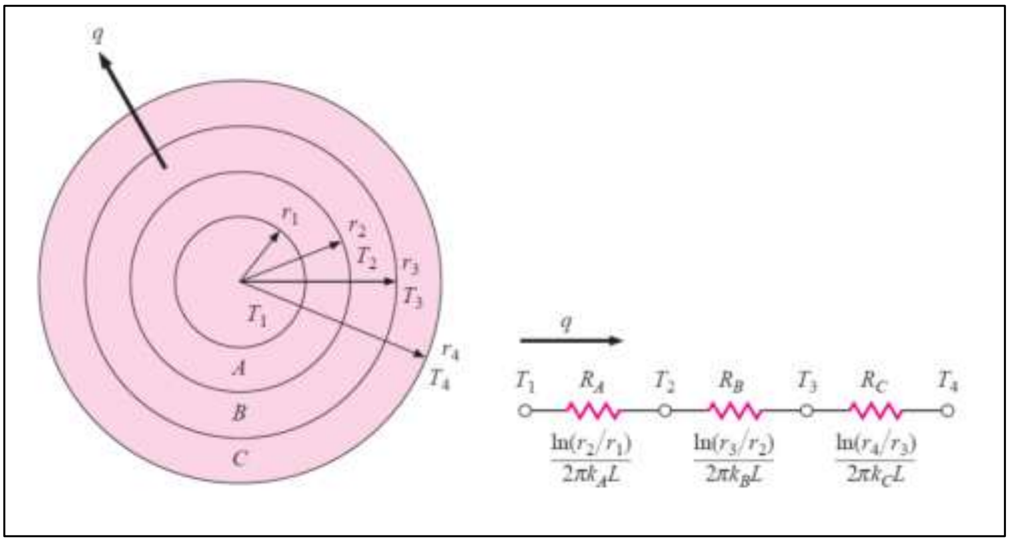

Figure 3 One-dimensional heat flow through multiple cylindrical sections and electrical analog**.**

With boundary conditions

$T=T_I$ at $r = r_i$

$T=T_O$ at $r = r_O$

The solution to Equation (10) is

$$q = \frac{2\,\pi\,k\,L\,(T_I - T_O)}{\ln(r_o/\,r_i)} \qquad (10)$$

and the thermal resistance in this case is

$$R_{th} = \frac{\ln(r_o/\,r_i)}{2\alpha\,k\,L} \qquad (11)$$

A thermal circuit is also shown in **Figure 3** [9].

Insulation Types and Applications

The following table summarizes common insulation materials used in industrial piping systems, along with their temperature ranges, thermal conductivity, density, and typical applications.

Table 1 Insulation types and applications.

N	Type Insulation	Temperature Range,C	Thermalconductivity W/m·C	Density kg/m^3	Application
1	Lindeevacuatedsuperinsulation	-240 – 1100	0.0015–0.72	Variable	Many
2	Urethanefoam	-180 – 150	16–20	25–48	Hot and cold pipes
3	Urethanefoam	-170 – 110	16–20	32	Tanks
4	Cellularglassblocks	-200 – 200	29–108	110 – 150	Tanks and pipes
5	Fiberglassblanketforwrapping	-80 – 290	22–78	10 – 50	Pipe and pipe fittings
6	Fiberglassblankets	-170 – 230	25–86	10 – 50	Tanks and equipment
7	Fiberglasspreformedshapes	-50 – 230	32–55	10 – 50	Piping
8	Elastomericsheets	-40 – 100	36–39	70 – 100	Tanks
9	Fiberglassmats	60 – 370	30–55	10 – 50	Pipe and pipe fittings
10	Elastomericpreformedshapes	-40 – 100	36–39	70 – 100	Pipe and fittings
11	Fiberglasswithvapor	-5 – 70	29–45	10 – 32	Refrigeration lines
12	Fiberglasswithoutvapor	to 250	29–45	24 – 48	Hot piping
13	Fiberglassboards	20- 450	33–52	25 – 100	Boilers, tanks, heat exchangers
14	Cellularglassblocksandboards	20 – 500	29–108	110 – 150	Hot piping
15	Urethanefoamblocksand	100 – 150	16–20	25 – 65	Piping
16	Mineralfiberpreformedshapes	to 650	35–91	125 – 160	Hot piping
17	Mineralfiberblankets	to 750	37–81	125	Hot piping
18	Mineralwoolblocks	450 – 1000	52–130	175 – 290	Hot piping
19	Calciumsilicateblocks,boards	230 – 1000	32–85	100 – 160	Hot piping, boilers, chimney linings
20	Mineralfiberblocks	to 1100	52–130	210	Boilers and tanks

Computational Thermal Analysis Using MATLAB

MATLAB is a programming language developed by MathWorks, originally designed for matrix and linear algebra operations. It supports both interactive sessions and batch execution. In this study, MATLAB R2014a is used to simulate heat transfer scenarios, analyze thermal performance under varying conditions, and validate experimental results through numerical modeling.

Table 2 Types of insulation materials.

	insulation materials	Thermal conductivity ranges	Temperature ranges
Hot insulation materials	Rock mineral wool	0.033 W/m.K	-200°C to 900°C
	Cellulose glass	0.034 to 0.081 W/m.K	- 260°C to 430°C
	Ceramic fibre	0.030 to 0.079 W/m.K	1400°C up to
	Melamine foam	0.034 W/m.K	10°C to 150°C
	Perlite expanded	0.057 W/m.K	-250°C to 1000oC
	Vermiculate	0.066 to 0.083 W/m.K	0°C to 1300oC
Cold insulation materials	Cork	0.038 W/m.K	-180°C to 100oC
	Nitrile rubber expanded	0.033 to 0.044 W/m.K	-40°C to 116°C
	Phenolic foam	0.018 to 0.022 W/m.K	-180°C to 120oC
	Polyethylene foam	0.033 to 0.045W/m.K	-50°C to 105°C
	Polystyrene	0.033 to 0.038 W/m.K	-150°C to 80oC
	Polyurethane foam (PUF)	0.016 to 0.023 W/mK	-180°C to 110°C
	Synthetic rubber expanded	0.038 W/m.K	-50°C to 150°C

Results and discussion

Thermal Performance

Thermal performance characteristics—represented by heat loss under different operating and design conditions such as thermal conductivity, internal temperature, external temperature, and thermal resistance—are obtained using MATLAB R2014a software.

Validation of the Mathematical Model

Thermal analysis and thermal performance prediction are performed for the insulating pipe using the Lee's disc experiment to measure various materials (rock wool and camel skin fluff). The model is validated by comparing calculated thermal conductivity values with standard data from the Libyan Norwegian Fertilizers Company, as shown in Table 3.

Table 4 Validation of Thermal Conductivity Measurements

MATERIAL	CALCULATED(W/M·°C)	STANDARD(W/M·°C)
Rock wool	0.0414	0.033
Rock wool sheets	0.0452	0.033
Fluff (camel skin)	0.0690	0.0690

The Results and Discussions

The relationship between temperature and time for rock wool is shown in **Figure 4**. An inverse relationship is observed: as time increases, temperature decreases, and vice versa.

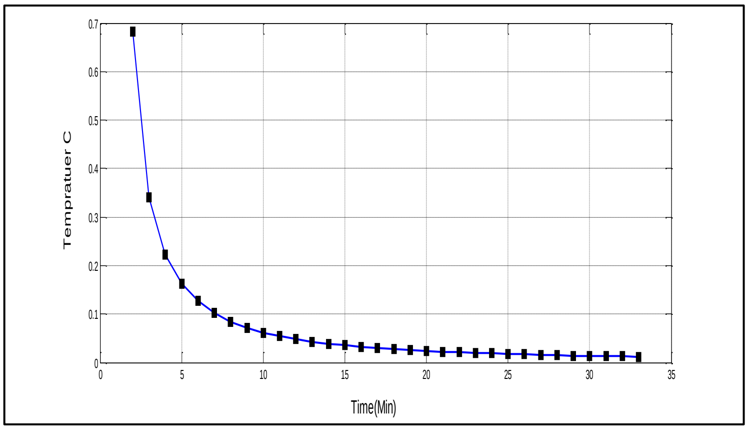

Figure 4 Effect of changing time with temperature (Rock wool)

Similarly, **Figure 5** shows the temperature–time relationship for rock wool sheets, confirming the same inverse trend.

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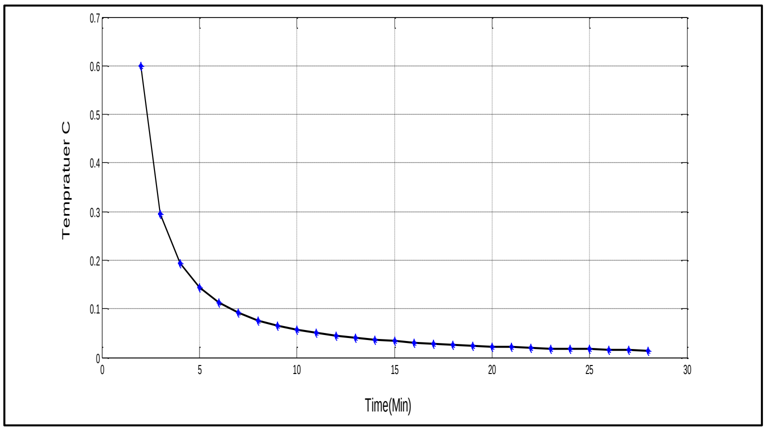

Figure 5 The relationship between temperature and time (Sheet Rock wool)

Figure 6 illustrates the correlation between time and temperature for camel skin fluff, with a measured thermal conductivity of 0.0690 W/m·°C. Again, an inverse relationship is evident.

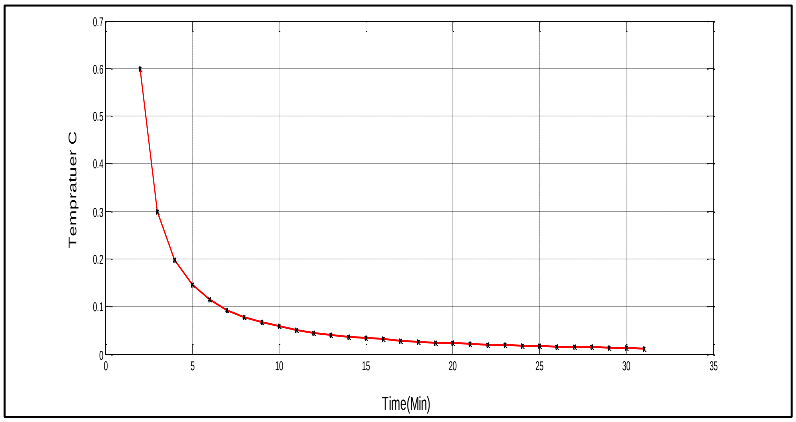

Figure 6 Effect of changing temperature with time (Fluff camel skin)

A direct relationship exists between internal temperature and heat loss, as shown in **Figure 7**: higher internal temperatures lead to greater heat loss.

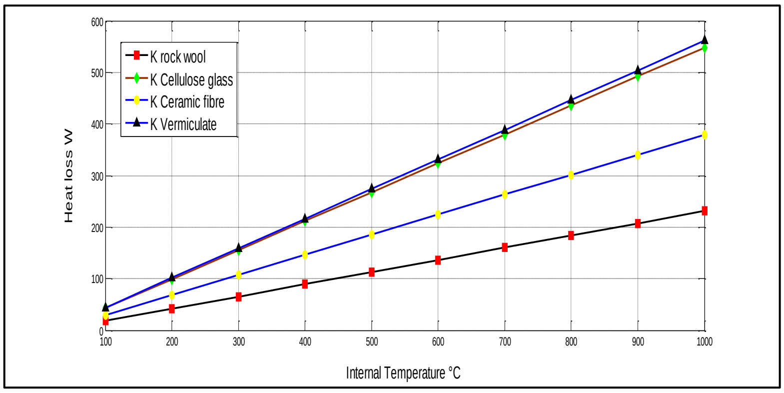

Figure 7 Effect of changing inner temperature with heat loss and thermal conductivity

Figure 8 shows an inverse relationship between external temperature and heat loss across several insulator types. Higher ambient temperatures reduce heat loss. Rock wool consistently exhibits the lowest heat loss among all materials tested.

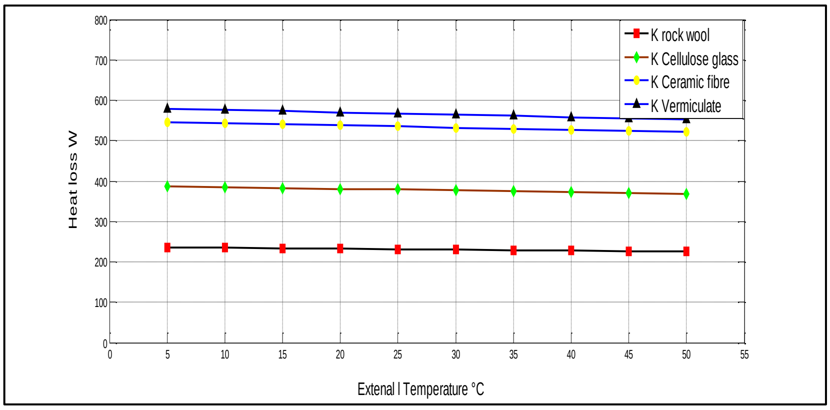

Figure 8 Effect of changing external temperature with heat loss and thermal conductivity materials

Figure 9 demonstrates that increasing the ambient convection heat transfer coefficient from 5 to 25 W/m²·°C raises heat loss from 56 W to 72 W—a 28% increase.

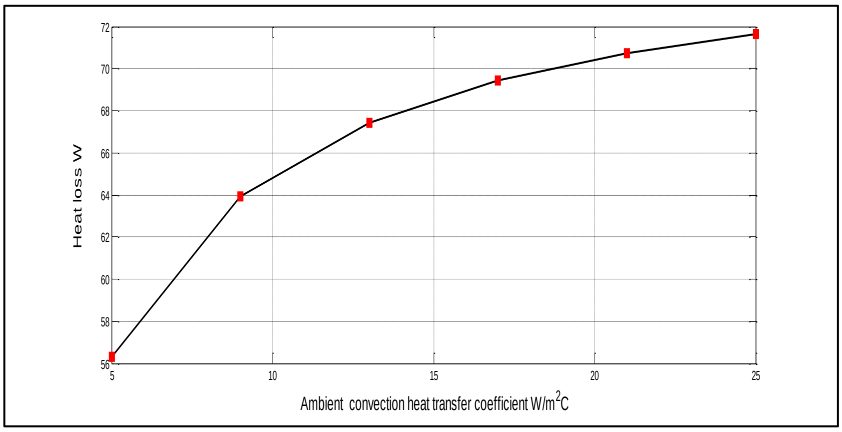

Figure 9 Effect of changing ambient convection heat transfer coefficient with heat loss

Figure 10 depicts the inverse relationship between ambient temperature and heat loss: as external temperature rises from 5°C to 50°C, heat loss decreases from 73 W to 63 W—a 16% reduction.

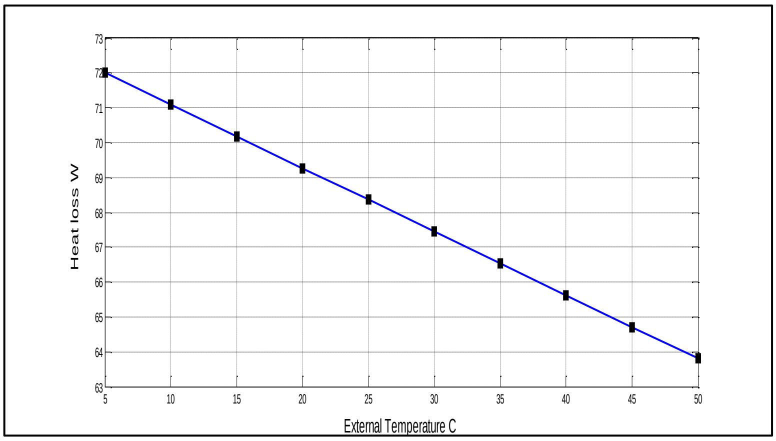

Figure 10 Effect of changing external temperature with heat loss

Figure 11 shows a direct correlation between internal convection heat transfer coefficient and heat loss. As the internal load increases from 0 to 5000 W/m²·°C, heat loss rises from 1300 W to 1600 W—a 23% increase.

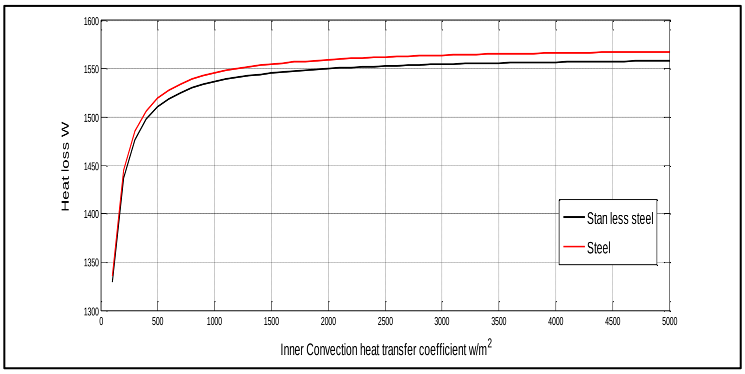

Figure 11 Effect of changing inner convection heat transfer coefficient with heat loss

Figure 12 illustrates the effect of internal temperature on heat loss for uninsulated stainless steel pipes: heat loss increases with rising internal temperature.

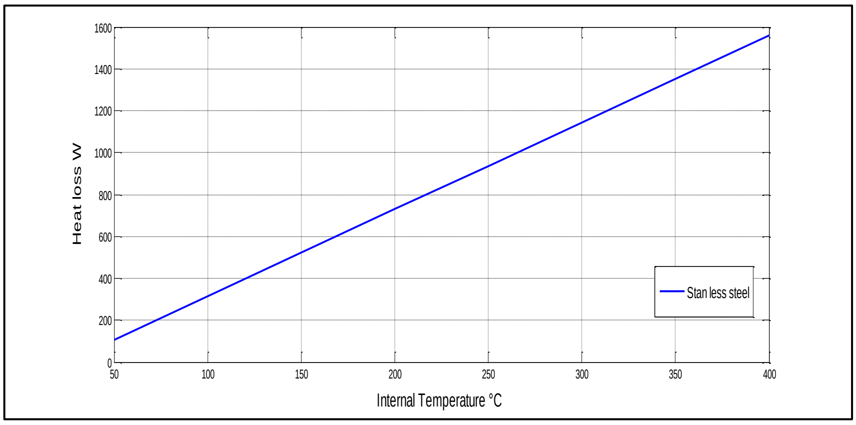

Figure 12 Effect of changing internal temperature with heat loss

Figure 13 reveals an inverse relationship between internal convection coefficient and internal thermal resistance for stainless steel: higher internal load reduces resistance to heat flow.

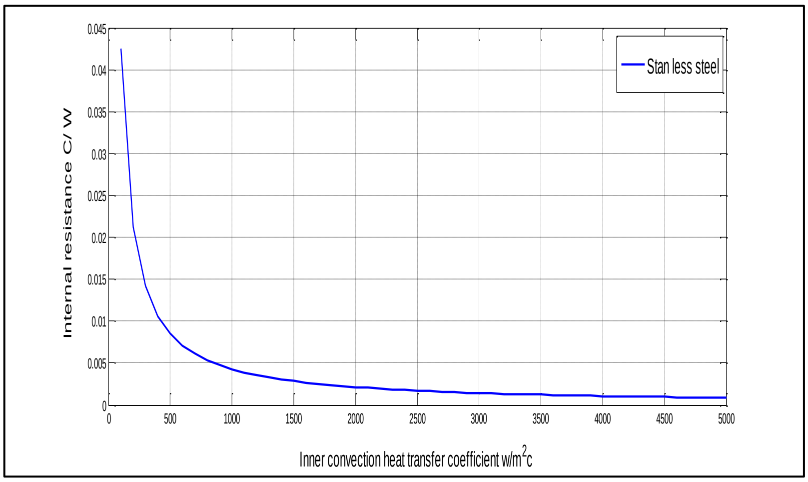

Figure 13 Effect of changing inner convection heat transfer coefficient with internal resistance

Figure 14 compares heat loss in uninsulated carbon steel and stainless steel pipes under varying ambient temperatures. Stainless steel shows lower heat loss due to its lower thermal conductivity. As ambient temperature increases from 5°C to 50°C, heat loss drops by 17% (from 1700 W to 1450 W).

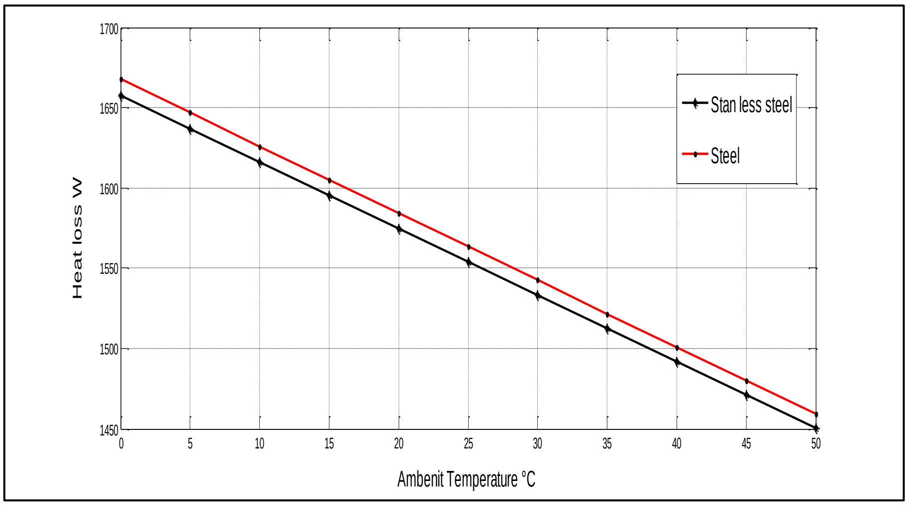

Figure 14 Effect of changing ambient temperature with heat loss

Finally, **Figure 15** compares the cost of hot insulation materials. Rock wool is the most economical option.

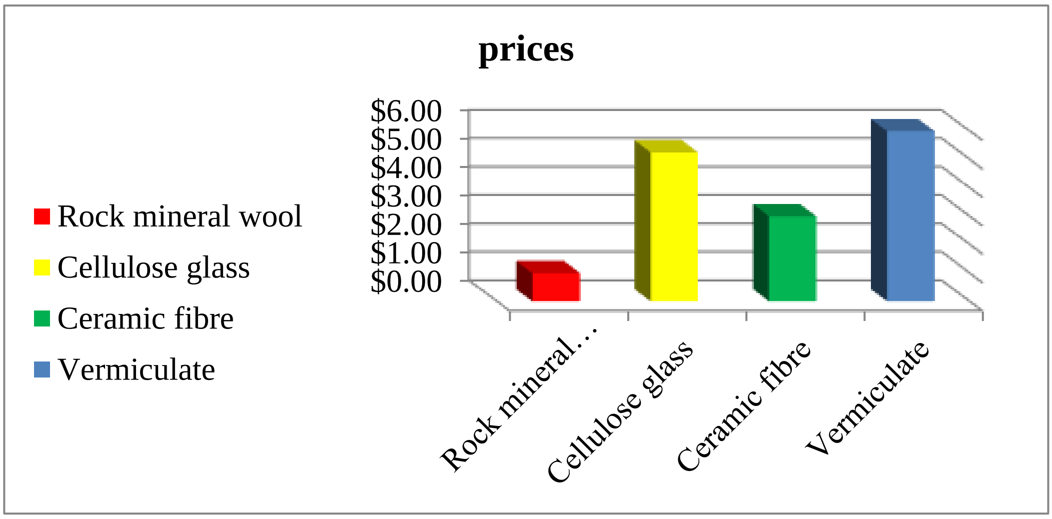

Figure 15 Price of hot insulation materials in dollars

Conclusion

The study included a thermodynamic analysis of the insulating pipe's operating and design parameter effects. Key findings are:

1. Rock wool emerged as the best-performing insulation material in terms of both thermal efficiency and cost.
2. The type of pipe metal significantly affects heat loss; stainless steel exhibits lower loss than carbon steel.
3. The Lee's disc method successfully measured thermal conductivity, including for a novel material—camel skin fluff.
4. Heat loss increases with higher internal fluid temperature.
5. Changes in external (ambient) temperature have a moderate inverse effect on heat loss, but not a dominant one.

6. Increasing the internal convection heat transfer coefficient leads to higher heat loss.

Compliance with ethical standards

Compliance with Ethical Standards

This research was conducted in accordance with the ethical standards of the University of Ajdabiya and the principles of academic integrity. All experimental procedures, data collection, and analysis were performed with full adherence to scientific honesty and transparency.

Disclosure of Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this work. No financial, personal, or professional relationships influenced the design, execution, interpretation, or reporting of this study.

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