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Thermo-economic analysis of Insulation thickness for district cooling piping system

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Abstract—*The selection of insulation thickness for chilled water piping in District Cooling systems has a significant impact on energy consumption and overall cost. Inadequate thermal insulation can result in heat loss, leading to higher energy consumption and operating costs. Conversely, excessive insulation can result in excess material and installation expenses, rendering it unprofitable. Hence, determining the optimal insulation thickness that balances these factors is crucial. This study proposes an optimization approach to determine the economical insulation thickness for a chilled water piping system. The objective function minimizes the life cycle cost of the insulation, incorporating the cost of insulation materials and energy consumption. The study found that when using PIR(Polyisocyanurate) material for insulation in District Cooling applications, the most effective thickness range is between 0.050 and 0.090 m. Within this range, energy savings can vary significantly, and creates scope for potential savings. The presented optimization approach can support designers and engineers in making informed decisions regarding insulation thickness, leading to substantial cost savings and energy efficiency improvements.*

Keywords: *District Cooling System, Insulation Thickness, Heat loss, Energy Cost, Insulation Cost*

1. INTRODUCTION

The rising demand for energy consumption, coupled with the limited availability of fossil fuels and electricity, has become a major concern globally[1]. With a 3% yearly growth rate, India's energy demand is predicted to increase more than any other country this decade[2]. The building sector stands as a significant driver of overall energy consumption. In particular, the District Cooling systems used for air conditioning are responsible for a significant amount of energy consumption. As a result, there is a need to optimize these systems to reduce energy consumption. District cooling systems offer a potential solution to this problem. These centralized systems provide cooling to multiple buildings and have the potential to be more energy-efficient than traditional HVAC systems. However, the effectiveness of these systems depends on several factors, including the insulation thickness used in the system. In this technical study explores the economic benefits of using insulation with varying thicknesses in district cooling systems. Present analysis focuses to determine economical insulation thickness and associated cost savings, The aim to proposed analysis is to provide insights into the potential for optimizing insulation thickness for chilled water piping system of Using DCS, the building sector will use less energy. Study will be based on a combination of literature review and numerical solutions. The study will also take into account a number of other factors, like the thermal conductivity of insulation materials, to confirm the analysis's relevance and accuracy. Overall, Study will highlight the importance of using efficient and optimized district cooling systems in reducing energy consumption and environmental impacts in the building sector. It will also provide guidance on the selection of insulation thickness to reach the desired level of energy efficiency and cost savings, insulation thickness.

Insulation plays a crucial role in achieving optimal insulation thickness in chilled water systems. This study's goal is to identify the most economical insulation thickness for chilled water piping systems, considering factors such as thermal conductivity, inside water temperature, and outside air temperature. Through a comprehensive methodology, combining literature review and Mathematical Modeling, the study provides practical guidance for selecting the appropriate insulation thickness to enhance energy efficiency and cost savings. By employing LCC analysis and utilizing tools like EES, the

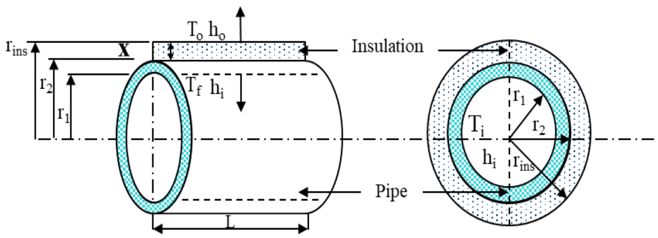

Figure 1 A Graphic Representation of Insulated Pipe

OIT for various insulation materials is identified, highlighting potential economic. Ensuring adequate insulation thickness can minimize energy losses and optimize the overall performance of chilled water systems

2. LITERATURE REVIEW

The use of thermo-economic approaches to optimize the thickness of the insulation of HVAC and water piping systems is the main topic of the aforementioned literature study. The most effective and economical design parameters are found using thermo-economic approaches, which analyses both economic and thermodynamic factors. The optimization method in this context takes into account things like heat losses, insulation expenses, and overall costs.

(Daşdemir et al., 2017) research examined the most effective economic thickness For HVAC systems, taking into consideration different pipe materials. The study showed optimal thickness of insulation depends on the pipe material used, with thicker insulation being necessary for some materials to achieve ES. For example, the optimal insulation thickness for copper pipes is 0.75 inches, while for steel pipes, it is 1.5 inches. Increasing the insulation thickness beyond a certain point was found to have a diminishing effect on ES. The study also revealed that using more expensive insulation materials with longer lifetimes can be more cost-effective over time. and for potential ES ranged from 5% to 20% depending on the insulation thickness and material used.

(Soponpongpipat et al., 2010) research was conducted for a study on the TEA analysis of the optimum double-layer insulation for air conditioning ducts and it aims to determine the optimal insulation thickness for ducts in terms of energy efficiency and cost-effectiveness. The study found that the optimal thickness for single-layer insulation was 25 mm, while for double-layer insulation, it was 20 mm for the inner layer and 10 mm for the outer layer. The study also discovered that the optimal thickness for the insulation material was 15 mm, with thicker materials not resulting in significant additional ES. Using the optimal thickness of insulation for the ducts resulted in ES of 27.31 kWh/m^2/year and a PP of 2.2 years, making it a highly cost-effective solution. The study's findings can aid in designing more efficient air conditioning systems with optimized insulation thicknesses.

(Söylemez & Ünsal, 1999) study on the thickness of insulation for refrigeration applications aimed to establish the OTI for refrigeration systems, taking into account energy efficiency and economic factors. According to the study, the optimum insulation thickness for steel pipes was 25 mm and 19 mm for copper pipes. The study also discovered that the most cost-effective insulation material was polyurethane foam, which resulted in a PP of 1.1 years. The potential ES from using the ideal thickness for insulation could range between 10 and 30%, depending on the pipe material and insulation thickness used. The study's findings can aid in designing more energy-efficient and cost-effective refrigeration systems with optimized insulation thicknesses.

(Ali Keçebas et al., 2011) conducted research to identify the optimal insulation thickness for district heating piping systems in the Turkish city of Afyonkarahisar. An optimization model based on LCC analysis using the P_1-P_2 approach was employed in the study and considered rock wool as the insulating material with hot water flowing through pipes ranging from 50-200 mm nominal sizes. According to the study, depending on the pipe size and fuel type used, the ideal insulating thickness, ES, and payback time vary. The fuel-oil fuel type produced the maximum ES at 250 mm nominal pipe size, whereas geothermal energy produced the lowest value at 50 mm nominal pipe size. The study suggests that geothermal energy is the most cost-effective and eco-friendly option, followed by natural gas. energy is the most cost-effective and eco-friendly option, followed by natural gas.

The aforementioned literature provides insight into the OIT and ES calculations for piping in both residential and commercial. The researchers had conducted using an LCC analysis to calculate the OIT for piping and heat transfer coefficient for ambient air, taking into consideration various Energy sources include coal, fuel oil, LPG, natural gas, and electricity, as well as insulating materials like fiberglass, rock wool, and Aero flex. However, regarding the chilled water piping, there is no written proof available for economical insulation. The study delves into the technical aspects of the subject matter, providing an in-depth analysis of the insulation materials used in cooling system.

3. MATHEMATICAL MODELING

A LCC analysis is a useful tool for determining the economic feasibility of utilizing thermal insulation in new energy technology projects[4]. When applied to chilled water piping systems, the analysis shows that reducing heat gain from the surroundings can result in net ES that justify the initial investment in insulation over the system's expected lifetime. The LCC analysis considers factors such as inflation, interest rates, and the cost of electricity and insulation to determine the OTI for the piping system.

The research considers following assumptions:

Steady-state conditions

a constant length of the piping, as well as a uniform cross-sectional area.

Constant temperatures for the supply and return water and constant velocities for the supply water and ambient air.

The analysis does not take into account radiation heat transfer or pressure drop through the piping.

In DCS system, the heat gain trough pipe is estimated as

$$Q°_{in} = \frac{(T_i - T_o)}{R} \quad (1)$$

The variables $Q°_{in}$, T_o, T_i ,and R in the equation represent heat gain, supply chilled water temperature, ambient air temperature and the total sum of thermal resistance offered by an un-insulated pipeline. Figure 2 The total thermal resistance for both uninsulated pipe and insulated pipe can be calculated using this equation.

$$\frac{1}{R_{un-ins}} = \frac{1}{A_i h_i} + \frac{ln\left(\frac{r_1}{r_2}\right)}{2\pi L_p k_p} + \frac{1}{A_o h_o} \quad (2)$$

$$\frac{1}{R_{un-ins}} = \frac{1}{A_i . h_i} + \frac{ln\left(\frac{r_1}{r_2}\right)}{2\pi . L_p . k_p} + \frac{ln\left(\frac{r_0}{r_2}\right)}{2\pi . L_p . k_{ins}} + \frac{1}{A_o . h_o} \quad (3)$$

variable r_1, r_2, r_0 represents the inner radius, outer radius and insulation radius of the pipes with and without insulation. R shows the thermal resistance that is provided by the supply water, pipe, insulation material, and ambient air. A_i and A_o are the both the pipe's internal and external surfaces area, respectively, and h_i and h_o indicate the supply air's convective heat transfer coefficient and ambient air acting on the interior and exterior surfaces of the pipe. k_{pipe} and k_{ins} denote the thermal conductivity of the pipe and insulation material. The values of h_i and h_o are calculated using appropriate formulas based on the dimensions and characteristics of the pipe.

$$h_i = \frac{0.023 Re^{0.8} Pr^{0.4} k_{water}}{D_h} \quad (4)$$

$$h_o = 11.58 . \left(\frac{1}{D_h}\right)^{0.2} . \left\{\left(\frac{1}{T_i + T_o}\right)\right\}^{0.181} . (T_s - T_o)^{0.266} . (1 + 2.86 . V_o)^{0.5} \quad (5)$$

The formula below may be analyzed to measure the Reynolds number (Re), where Pr is the Prandtl number, k_{water} is the supply water's thermal conductivity, D_h is the pipe's hydraulic diameter, which (being four times the pipe's cross-sectional area), T_s is the Pipe's surface temperature, and V_o and T_o are the ambient air velocity and temperature, respectively.

$$R_e = \frac{V_{SA} . D_h}{v_{SA}} \quad (6)$$

V_{SA} and ϑ_{SA} indicate the supply water's velocity and kinematic viscosity.

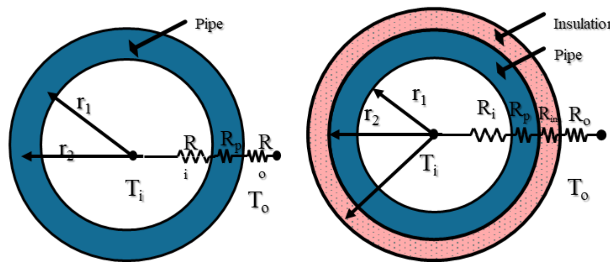

Figure 2 Cross Sectional Area of uninsulated and Insulated Pipe

The cooling loss through the pipe can be expressed using an appropriate formula based on the dimensions, materials, and other characteristics of the system.

$$\dot{Q}_{Save} = (T_o - T_i) . \left(\frac{1}{R_{un-ins}} - \frac{1}{R_{ins}}\right) \quad (7)$$

The calculation for annual energy cost (CE) is:

$$C_E = \dot{m}_F . C_F \quad (8)$$

Here, C_F represents the fuel cost, and m_F is the annual fuel consumption. The value of m_F can be calculated using appropriate formulas based on the characteristics and usage of the system.

$$\dot{m}_F = \frac{\dot{Q} . N}{Hv . COP} \quad (9)$$

The variable $\dot{Q}$ shows the energy loss as a result of heat gain by an uninsulated pipe, N represents the operating hours (which is assumed to be 3000 hours). Hv and COP represent the energy source's lower heating value and the coefficient of performance, respectively.

The initial investment cost can be calculated using appropriate formulas based on the size, material, and other characteristics of the system.

$$C_I = u_{ins} . C_{ins} \quad \textbf{(10)}$$

To assess the insulation economy, it is important to calculate the percentage of the initial investment that is made up of operating costs (P2) and life cycle energy costs (P1). These ratios depend on the system's lifespan (LT), rate of interest (assumed to be 5%), and rate of inflation (assumed to be 7%).

The life cycle energy cost (P1) and operating expenditures (P2) can be calculated using the following formulas:

$$P_1(LT, x, y) = \sum_{j=1}^{LT} \frac{(1+x)^{j-1}}{(1+y)^j} \quad \textbf{(11)}$$

$$P_1(LT, x, y) = \begin{cases} \frac{1}{y-x}\left[1-\left(\frac{1+x}{1+y}\right)^{LT}\right] & if\ x \neq y \\ \frac{LT}{1+x} & if\ x = y \end{cases} \quad \textbf{(12)}$$

$$P_2 = 1 + P_1 MR - SV(1+y)^{LT} \quad \textbf{(13)}$$

The ratio of maintenance to initial investment (MTR) and the salvage value to initial investment ratio (SV) are assumed to be equal to zero, and therefore P_2 is equal to 1. Based on the values of P_1 and P_2, the total life cycle cost of the pipe system can be calculated.

$$C_T = C_E P_1 + C_I P_2 \quad \textbf{(14)}$$

The ES over the expected lifespan of the DCS can also be estimated using appropriate formulas based on the system's energy efficiency and other important considerations.

$$ES = \frac{\dot{Q}_{save} C_F N P_1}{HV\ COP} + C_I P_2 \quad \textbf{(15)}$$

4. RESULT AND DISCUSSION

In order to assess the economical insulation of the system, Study will consider the following values:

Inside Radius(r_1):	447 mm
Outside Radius (r_2):	457 mm
Thermal Conductivity (k_{pipe}):	23.7 W/mK
Outside air temperature (T_o):	303 K
Supply water temperature (T_i):	278 K
Lower Heating Value (H_V):	3.5 MJ/kWh
Cost (C_f):	9.5 ₹/kWh
COP:	5.5
PIR conductivity(k_{pir}):	0.023 W/mK
EPS conductivity(k_{eps}):	0.031 W/mK
XPS conductivity(k_{xps}):	0.036 W/mK

Figure 3 depicts the influence of insulation thickness on annual costs for different insulation materials, revealing a decline in heat loss costs with the implementation of insulation. Interestingly, the costs associated with insulation itself increase. Moreover, while the annual cost initially decreases, it reaches a minimum point before beginning to rise again. This minimum point is referred to as the optimum insulation thickness.

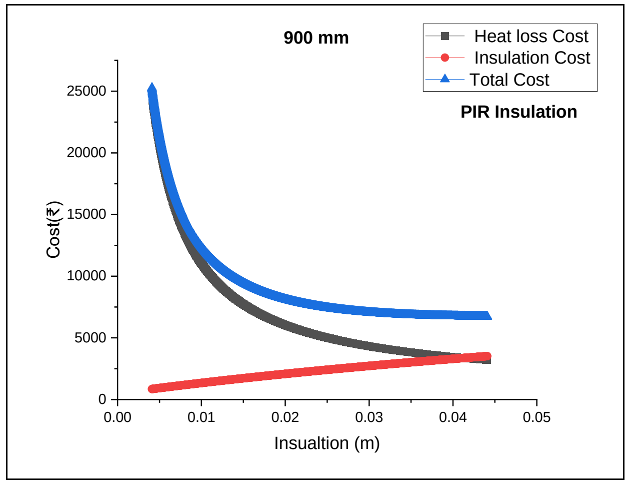

Figure 3 Life Cycle Cost using PIR

The investigation of insulation thickness for various materials revealed significant findings in terms of both economical insulation thickness and energy-saving potential. For PIR material, the analysis determined an optimal insulation thickness of 68 mm, which provides the most cost-effective solution. This insulation thickness not only minimizes heat loss but also maximizes ES.

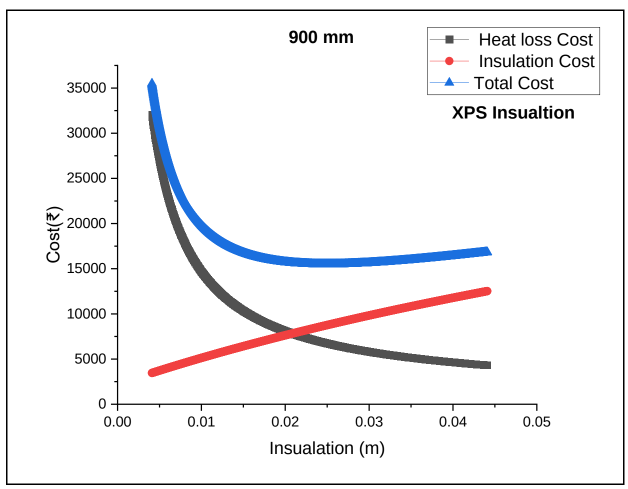

Figure 4 Life Cycle Cost using XPS

Similarly, in **Figure 4**, for XPS material, the study identified an economical insulation thickness of 28.36 mm, which offers the most favorable balance between insulation cost and energy-saving benefits. Implementing this thickness provides an efficient solution for reducing heat loss and achieving significant ES.

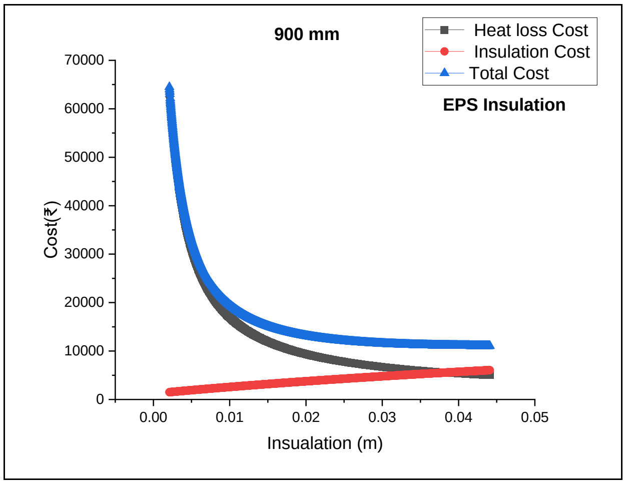

Figure 5 Life Cycle Cost using EPS

Figure 5, In the case of EPS material, the analysis revealed that an insulation thickness of 40.95 mm is the economically optimum choice. This thickness not only delivers effective insulation properties but also leads to substantial ES.

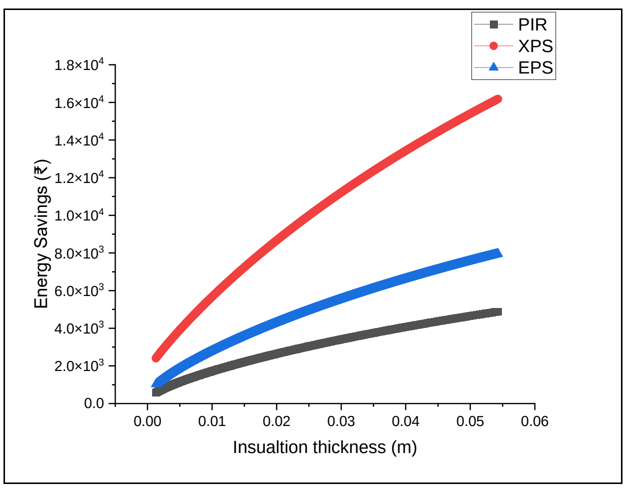

Figure 6 Energy Savings vs insulation for Pipe considering different insulation

The change in ES in given **Figure 6** as can be seen, the greatest ES for Pipe is obtained by XPS insulation. The EPS and PIR come behind it. For 900 mm pipe using EPS, XPS, and PIR has shown that ES over the system's expected lifespan. This thickness was determined to be the optimal economic insulation thickness for the district cooling system under consideration and more specific terms, when utilizing a 50 mm thickness of insulation, the energy-saving potential is determined to be ₹4659/ meter for a PIR insulation system, ₹ 7585/ meter for EPS insulation, and ₹15400/ meter for XPR insulation.

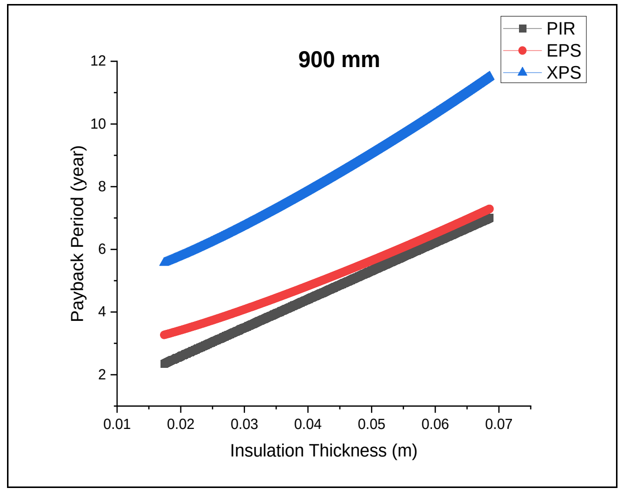

Figure 7 Payment Payback for different Insulation material

A comprehensive assessment of PP was conducted for PIR, EPS, and XPS materials. The PP represents the time required to recover the initial investment through energy cost savings. The PP curves according to insulation thickness for different insulation are illustrated in **Figure 7** indicates that as the insulation thickness increases, the PP lengthens. Comparatively, PIR material stands out with a relatively shorter PP of 5.3 years. This shorter PP can be attributed to the superior insulation performance and cost-effectiveness of PIR insulation.

In contrast, EPS material exhibits a slightly longer PP of 5.6 years, while XPS material demonstrates the longest PP of 9.08 years. The longer PP for EPS and XPS insulation can be attributed to factors such as their insulation efficiency and associated cost.

5. CONCLUSION

The economic insulation thickness for district cooling systems must strike a balance between ES and insulation costs. This paper presented a comprehensive approach for determining the optimal insulation thickness, considering the specific characteristics and requirements of the system. The results of the analysis revealed in **Figure 3, Figure 4, Figure 5,** a clear trade-off between ES and insulation costs. As the insulation thickness increased, the cost of heat transfer losses decreased, resulting in higher ES. However, the cost of insulation materials and installation also increased with thicker insulation. A specific insulation thickness was identified as the point 68 mm, 28.36 mm, 40.95 mm for PIR, XPS and EPS insulation for 900 mm pipe.

In summary, all three insulation materials, PIR, EPS, and XPS, exhibited distinct energy-saving advantages. Properly selecting and implementing the recommended insulation thickness for each material can result in substantial reductions in heat loss and significant ES.

In conclusion, the analysis of **Figure 7** indicates that increasing insulation thickness leads to longer PP. PIR material offers the shortest PP of 5.3 years, followed by EPS with 5.6 years, and XPS with 9.08 years. These variations are influenced by factors such as insulation performance, cost-effectiveness, and efficiency. When choosing insulation materials, it is crucial to consider these factors to determine the most suitable option based on specific needs and preferences.

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Abbreviations

PIR	Polyisocyanurate
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
HVAC	Heating, Ventilation and Air Conditioning
LCC	Life Cycle Cost
TEA	Thermo Economical analysis
OTI	Optimum Thickness of insulation
PP	Payback period
ES	Energy Saving

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