International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

ORIGINAL ARTICLE

Thermo-economic analysis and optimization of thermal insulations

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Article Information

Received: 05 April 2021
Revised: 21 April 2021
Accepted: 09 May 2021
Available online: 16 May 2021

Keywords:

Thermal analysis;
Thermodynamic performances;
HFO refrigerants;
Ultra low GWP refrigerants

Abstract

Energy is fundamental to meet many human needs, including lighting, cooking, heating and traveling. The swiftly growing world population, escalating energy demands and industrialization of countries have resulted in high energy costs and environmental problems; therefore, studies that focus on cutting unnecessary costs have been gaining prominence. Energy consumption can be generally examined in four major sectors, namely industry, building, transportation and agriculture. In almost all countries, energy consumption in buildings constitutes a substantial part of total energy consumption.
In this paper, mathematical modeling of thermal insulation has been carried to find the effect of various parameters such as payback period, rate of interest, heat transfer co-efficient and temperature differences in the cost of insulation, cost of heat losses and the total cost for a cylindrical surfaces and flat surfaces, it was observed that cellular plastic gives better properties of insulation than other materials.

1. Introduction

The energy consumption is distributed among four main sector: industrial, building (residential/ commercial), transportation and agricultural areas.
The building sector is the highest energy consumer area. Energy consumption rate is gradually increase due to urbanization, industrial growth and population growth. Population growth means contracting more buildings, which increases energy expenditure.
The heat losses in buildings generally occur through external walls, ceiling, floor, windows and air infiltration. Insulations are very important in industrial applications & domestic use because it reduces heat losses to atmosphere or heat gain in cooling applications for conserving energy in terms of money saving by reducing burden on energy resources & environment. Heat loss through the building envelope can be controlled by computing optimum insulation thickness [1]

2. Thermo-economic optimization of thermal insulations

The popular use of insulation is governed by economic considerations in terms of critical economic thickness. The method to find economic thickness of insulation have progressed significantly. Many researchers have laid down different methods of tackling thickness of insulation. Subhash Mishra, et.al [1]. carried out techno-economic analysis using Degree-Day method for determining optimum insulation thickness for the different wall types; because brick, concrete and stone etc. are used in building construction in India. Also compared two as insulation materials (i.e. and) and found optimum insulation thickness varies between 0.052m in extruded polystyrene and 0.074m in expanded polystyrene and energy saving varies between Rs. 2560/m^2 and 5510 Rs/m^2, depending on cost of fuel Mishra [2,3] has studied the effect of insulating materials on solar cooker thermal performance experimentally and calculated economic thickness theoretically by modifying running and inertial cost equations.

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https://doi.org/10.36037/IJREI.2021.5303

Khawaja [4] determined the optimum thickness of insulation for some insulating materials used in order to reduced rate of heat flow to the buildings in hot countries. Important factor that effects the optimum thickness of insulation is the solar radiation energy flowing into the house. Dombayci [5] investigated the environment impact of optimum insulation thickness. In the calculations, coal was used as the fuel source and the Expanded Polystyrene(EPS) as the insulation material M.Mc Chesney [6] has calculated heat losses and developed thermal models which can be used for determining thickness of insulation. They have not considered if economic factors are not known so that heat losses considered without the fact that actual variable market conditions. Sofrata and Salmeen [7] developed a consistent and more general mathematical model for optimum insulation thickness. He also introduced a program flow chart to select the best insulation thickness. In this study, the life-cycle cost analysis (LCCA) is used to calculate the costs of heating over the life time. Turki and Zaki [8] investigated the effect of insulation and energy storing layers upon the cooling load. A mathematical model to study the thermal response of multilayer building components is presented.

Bolatturk [9] calculated the optimum insulation thicknesses, energy savings and payback periods. The annual heating and cooling requirements of building in different climates zones were obtained by means of the heating degree-days concept. Durmayaz et al. [10] estimated the heating energy requirement in building based on degree-hours method on human comfort level and determined economic thickness of local fire-clay for heat retention at optimum expense on heating and material.

In this paper, simple economic analysis has been carried out for five insulating materials such as cellular plastic, pearlite, corrugated asbestos, polyurethane rubber, styro-foam and rock-wool with the objective in terms of most economic thickness.

The various costs of insulations have been computed using explicit expressions & effect of various parameters i.e. thickness, heat transfer coefficients, temperature difference, payback period, interest rate for cylindrical geometry of pipes on the costs have been explained.

2.1 Analysis of Thermal Insulation

Considering flat surfaces, the heat losses per square meter per year is given by the following expression.

$$Q = (T_1-T_a) *Y / ((L/K) +R) \text{ watt/year} \quad (1)$$

Where T_1 = Temperature of surface without insulation (^{0}C),
T_a=Ambient Temperature (^{0}C),
L=Thickness of insulation(m),
K = Thermal conductivity of insulation material(W/mK),
R=Thermal resistance of outer surface of insulation (m^2 K/W),
h_0=Heat Transfer coefficient of outer surface of insulation (W/m^2 K),
Y=Hours of operation per year

Assuming M is the cost of heat losses (rupees per million watts), Therefore, the cost of heat losses per year per meter is expressed by the following equation:

$$m=Q*M/1000000 \text{ (Rs)} \quad (2)$$

Substituting equation (1) in equation (2) one gets following equation.

$$m=(T_1-T_a) \,\&\, Y*M / (1000000) (R+(L/K)) \text{ (Rs)} \quad (3)$$

The cost of insulation can be expressed as

$$n=100B*L+C \quad (4)$$

Where,

C=Installation Cost which is fixed (in Rs) and
B=Cost of installed insulation per square m per cm length of insulation per year.

The cost of insulation can be given by adding equation (3) and equation (4) respectively i.e.: therefore, total cost of insulation is given below

$$C_t=m+n \quad (5)$$

Total cost of insulation is

$$C_t = (T_1-T_a) *Y*M/ (1000000) (R+(L/K)) +100*B*L+ C \quad (6)$$

Now assumin*g*

$$A=y*(T1-Ta) *M/1000000 \quad (7)$$

Therefore, the total cost of insulation can be expressed as

$$C_t=A*K/(L+(K*R)) + 100*B*L + C \quad (8)$$

To get optimum (minimum) value of thermal insulation in above expression (8), one can differentiate equation (8) with respect to thickness of insulation for flat surface. then

$$dCt/dL = 0 \quad (9)$$

Solving equation (9), one can get following expression:

$$dC_t/dL = AK/((L+RK) (L+RK)) + 100B = 0 \quad (10)$$

Simplifying equation (10) one gets, following equation.

$$AK=100B((L+RK) (L+RK) \quad (11)$$

Now rearranging equation (9), one can get quadratic equation in terms of L as follows

$$L^2=2LRK+R^2K^2K-AK/100B = 0 \quad (12)$$

Solving equation (12), the economic thickness of insulation for flat surface becomes

$$L = (AK)^{1/2} / (100B)^{1/2} - RK \quad (13)$$

Similarly, heat losses per meter length of insulating cylinder can be expressed as

$$Q= 2*3.14(T_1-T_a)/((1/K) *(\ln (r_2/r_1)) +(1/h_0r_2)) \text{ Watt/m} \quad (14)$$

Where r_1=Radius of inner surface of insulation (m), r_2=radius of outer surface of insulation (m).
The cost of heat losses per year per meter can be expressed by the following

$$m=[2*3.14(T_1-T_a)/((1/K) *(\ln(r_2/r_1)) + (1/h_0r^2))] *Y*M/10^6(\text{Rs/yr}) \quad (15)$$

Where

$$R=1/h_0 \quad (16)$$

Substituting the value of R from equation (16) in equation (15) one gets running cost of insulation as

$$m= 2*3.14(r_2*A*K)/(r_2\ln(r_2/r_1) + RK) \quad (17)$$

Where

$$A= y*(T_1-T_a) *(M/1000000) \quad (18)$$

The cost of insulation per liner metre per year can be expressed as (n)

$$n=2*3.14*(r_2^2-r_1r_2) *B +C \text{ and } m=2*3.14*r_2*1] (r_2-r_1) *B + C \quad (19)$$

Therefore, total cost per metre per year can be expressed as

$$C_t = 2*3.14*AK/((r_2 \ln(r_2/r_1) +RK)+ 2*3.14(r_2^2-r_1r_2)*B+C \quad (20)$$

To get optimum value of r_2, we differentiate eq. 20) with respect to r_2 because inner diameter of a cylinder is constant. Differentiating equation (20) one gets following expression:

$$dC_t/dr_2=[2*3.14*(r_2\ln(r_2/r_1) +RK) AK-r_2AK(1+\ln(r_2/r_1))] /(r_2\ln(r_2/r_1) +RK)^2+ 2*3.14* B (2r_2-r_1) = 0 \quad (21)$$

Rearranging equation (21), one gets following expression:

$$[(2*3.14*(r_2 \ln(r_2/r_1) +RK) AK))/B] - [(r_2AK(1+\ln(r_2/r_1)))/B] + (2r_2-r_1) *(r_2\ln(r_2/r_1)) + RK)^2 = 0 \quad (22)$$

Solving equation (22) and rearranging, one can get following transcendial equation for thermal insulation. which was solved by trial and error method.

$$(r_2 \ln(r_2/r_1) +RK) *(2r_2-(r_1/r_2)-RK)^{1/2} =(Y(T_1T_a) BMK / 1000000)^{1/2} \quad (23)$$

The economic thickness of insulation is obtained by $(r_{2\ opt} - r_1)$

3. Result and Discussion

Insulations are very important in industrial applications & domestic use because it reduces heat losses to atmosphere or heat gain in cryogenic applications for conserving Energy in terms of money saving by reducing burden on energy resources & environment. The popular use of insulation is governed by economic considerations in terms of critical economic thickness. The various costs of insulations have been computed using explicit expressions & effect of various parameters i.e. thickness, heat transfer coefficients, temperature difference, payback period, interest rate for cylindrical geometry of pipes on the costs. In this paper, simple economic analysis has been carried out for six insulating materials such as cellular plastic, pearlite, corrugated asbestos, polyurethane rubber, styro-foam and rock-wool with the objective in terms of most economic thickness shown in table-1 have been computed. The other input variables numerical value is given in table-2. In this paper by considering following six insulating materials such as

Table 1: Thermal conductivity of insulating materials

Thermal conductivity Insulation Material	Unit	Value
Cellular plastic	W/m°C	0.031
Perlite	W/m°C	0.06
Corrugated Asbestos	W/m°C	0.1
Polyurethane rubber	W/m°C	0.15
Polystyrene Styrofoam	W/m°C	0.263
Rock Wool	W/m°C	0.4

Table 2: Input variables used in techno-economic optimization

Other Input variables	Unit	Value
Length of pipe	L	1.0
Temperature of inner surface	°C	172
Ambient temperature	°C	20
Heat transfer Coefficient	W/m^2 °C	10.32
Cost of insulation	(Rs/m^2),	5540
Payback period	Years	5
cost of heat generation	Rs/KJ.	0.001437

The total cost of insulations with rate of interest has been computed and presented in the table-3 respectively.
It was observed that increasing the rate of interest, the total cost of insulation decreases significantly.
For all insulating materials increasing heat transfer coefficient, the cost also increases. Similarly, payback period also increases with the total cost.
Similarly, by decreasing temperature differences, the total cost of insulation also decreases significantly for an insulating materials. The thickness of insulation increases, the total cost of insulation decreases, and optimum value of thickness of insulation has been obtained. It was observed that the most efficient and economic material comes to be cellular plastic of 0.031(W/m°C) thermal conductivity. for increasing the thermal conductivity, the total cost also increases as same value of temperature difference. For increase in payback period, the total cost also increases linearly. Increase in the heat transfer co-efficient the total cost of insulation first increases rapidly and stabiles for higher value of heat transfer co-efficient.

Table 3: Optimum economic thickness of various thermal insulations with optimum cost

Insulating Materials	Thermal Conductivity	Economic thickness (m)	Total cost (Rs.)
Cellular Plastics	0.031	0.060	16949.56
Pearlite	0.06	0.095	2330.85
Corrugated Asbestos	0.1	0.120	3252.6
Polyurethane Rubber	0.015	0.145	4261.48
Styrofoam	0.263	0.19	6177.9
Rockwool	0.4	0.25	7958.93

4. Conclusions and Recommendation

The thermal analysis was done for the materials for 6 different insulation materials for a given pipe internal radius of 0.05m and numerical computation was carried out to find out most economics materials. The following conclusions have been drawn:

- The most efficient economic material comes out to be cellular plastic.
- With increase in thermal conductivity the cost of insulation decreases and cost of heat losses increases and hence total cost also increases.
- Increases in interest rate leads to increases in total cost.
- for increase in heat transfer co-efficient, the total cost first increases rapidly and stabilizes for higher values of heat transfer co-efficient.
- For increases in temperature differences the total cost increase linearly.
- For increase in thermal conductivity the total cost also increases for same value of temperature differences.
- For increase in payback period the total cost of insulation also increases linearly

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Cite this article as: R.S. Mishra, Thermo-economic analysis and optimization of thermal insulations, International journal of research in engineering and innovation (IJREI), vol 5, issue 3 (2020), 150-153. *https://doi.org/10.36037/IJREI.2021.5303*