Experimental Investigation of Optimum Insulation Thickness for Air Conditioning Duct

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Abdul Shakoor Shaikh[1], Prof. Dr. Hassan Ali Khan Durrani[2], Awais Junejo[3], Dileep Kumar[4]

[1]*Postgraduate Student – Energy Systems, MUET SZAB Campus Khairpur*
[2,3,4]*Department of Mechanical Engineering, MUET SZAB Campus, Khairpur*

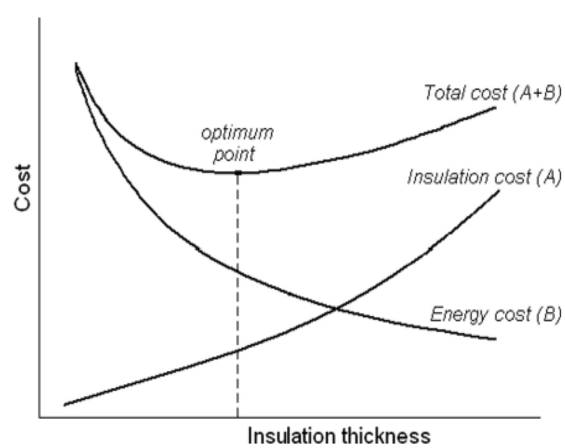
Abstract: Owing to growing industrialization and consequent upward change in the lifestyle, people are moving away from traditional ways of living and fastly adopting a city lifestyle, paving the way forward for construction of more and more buildings. The increased number of building in cities accounts for an ever increasing demand for energy. Buildings all over the world, consume around 40% of the energy generated by all the available resources. When it comes to meeting the cooling and heating needs of the dwellings in large skyscrapers, buildings in particular are notorious for devouring the lion's share of the electricity supplied by the grid. Efforts in this regard are being made to reduce the net energy consumption by buildings and this area of study concerning management of energy in buildings has been one of the most attractive topics for researchers all around the world, specially the 1st world countries, where the number of tall structures is relatively higher than those in rest of the other countries. The intricate and costly piping configurations of HVAC system, industrial and chemical process plant are the main source of transporting heat energy. Therefore, considerable amount of energy is wasted in pipelines due to improper use of thermal insulation material and thickness. The use of thermal insulation in HVAC system is considered as energy conservation measure, as it not only reduces energy consumption but also abates polluting products. One of the most effective tools in achieving this objective is using properly designed insulation with a careful deliberation over optimizing its thickness in a cost-effective, environmentally-friendly and energy-saving perspective. In this research, focus has been put over experimental investigation of the optimal thickness of thermal insulation over ducts and pipes of varying diameters, and its effect on maintaining thermally comfortable atmosphere or change in temperature inside a building / conduit. At the end of experimental and mathematical studies of the Optimum insulation thickness, it was concluded that net cost of energy for the air-conditioning system was calculated to be 15.53 % whereas Conditioned Space Parameters were reduced from 24℃ to 21℃.

Keywords: *Insulation Thickness, HVAC, Buildings Energy Management, Air-conditioning Duct*

1. Introduction

All over the world, particularly in buildings, the HVAC systems have been employing the thermal insulation mechanisms in order to prevent the loss or gain of heat responsible for decreasing the efficiency of the Air Conditioning systems. The concept of Optimum Economic Thermal Insulation involves the capital cost of the insulation mechanisms in addition to the amount of money saved over the life of the project under consideration. There are a variety of studies carried out on different systems of thermal insulation for various applications such as tanks, pipelines buildings and ducts. Most of the publications concerning the enhancement of insulation efficiency consider the types of structures like flat surfaces, walls of the building etc. However work on insulation over ducts specifically has been quite less in the studies conducted so far in spite of the fact that the analysis of insulation mechanism in buildings has been very vast. The economic insulation thickness for HVAC ducts is a function of different parameters like climatic conditions, insulation properties and cost, energy type and cost and efficiency of the heating or air-conditioning system [1-2]

As per most of the analysis done on insulation thickness, the calculations relied on the radiative and convective heat transfer from the duct or pipe and other factors like the costs of the material used for insulation, performance characteristics of the heating systems, and economic parameters like lifetime and present inflation rates etc. The heat transfer usually taking place in the ducts is commonly the main input desired to understand the required insulation thickness. The heat transfer occurs through conduction, convection and natural radiation. Most studies considered only convective and radiative heat transfer mechanisms whereas various other publications considered both the mechanisms [3].



Source: Omer Kaynakli *, "Economic thermal insulation thickness for pipes and ducts: A review study", Renewable and Sustainable Energy Reviews30(2014)184–194

Figure .1 Optimum Thermal Insulation Thickness

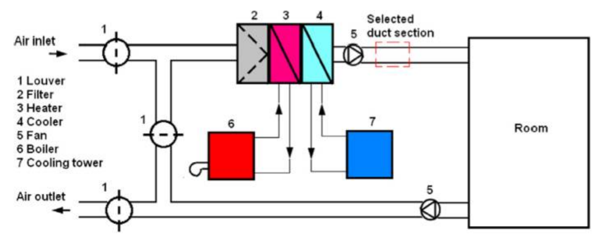
Corresponding author Email address*: engr.ashakoor@gmail.com*

In this paper, experimental approach is adopted to evaluate the changes in the psychometric characteristics of the air being supplied in the system. After examining the economic analysis methods used to obtain an economic insulation thickness, a simple and practical application for determining the optimum insulation thickness for pipes was conducted.

In order to reduce the consumption of energy and its cost, apart from the reduction in the transfer of heat from the surroundings, effort was made to optimize the thickness of the insulation material (glass wool in this case) used. The main reason for doing so was to minimize the overall expenditure over, which includes the cost of insulation, the cost of its installation and maintenance along with the expenses borne due to the losses in energy by convective heat transfer in the duct from outside[5]. The principles of heat transfer and the information related to the cost are employed to characterize the overall cost function to be reduced. The economic insulation thickness for a duct encompasses large number of parameters, like length and cross-sectional area the duct, conductivities of the duct and the insulation material, operating and surrounding temperatures, heat transfer coefficients inside and outside of the duct, economic parameters and the timings for which the unit is being operated annually. The optimum economic insulation thickness is often accepted as a value the accounts for the minimum total life cycle cost as described in the Figure 1 [Comments on point # 5, 6 & 7 by Dr. Aftab]. With the increase in the insulation thickness on the duct, the cost of energy required for transmission of cooling loads decreases. The data related to the cooling transmission loads is used as the input value for an economic model to examine the changes in the cost of the insulation in addition to the present value of energy utilization over the life of the system. On the other hand, the cost of insulation rises if the amount of material used in insulation increases [6-8]. Contrary to the flat surfaces, the change in the amount of insulation used on a pipe versus the insulation thickness is not a straight line, but in fact, the increase is parabolic.

2.Literature Review

The sole purpose of HVAC system is to maintain and control the zone parameters i.e. temperature, relative humidity, odor, noise to an acceptable and desirable level for occupants and requirements of manufacturing processing plants (Pharmaceutical, food, beverage, textile companies etc.). It is intended to provide cooling in hot climate and heating in cold climate. The required cooling and heating is achieved with following equipment i.e. chiller, boiler, cooling tower, hot and cold water system and air distribution system. In air distribution systems following psychometric processes occur i.e. simple heating and cooling, heating with humidification and cooling with dehumidification [1-5], cleanliness and purification and attenuation of noise level. In addition to that it distributes the chilled/hot air to zone through ducting i.e. supply, return, fresh and exhaust air duct. The chilled air is delivered from air conditioning unit/ air handling unit to the different zones with supply air duct and registers. As air pass through different zones it gets warm by absorbing heat from the zone. This warm air is than circulated back towards air handling unit with return air duct. The fraction of warm air pro part to fresh air is exhausted into the surrounding with exhaust air duct. HVAC's duct is typically located inside and outside the building. Usually, plant room is located inside the building. Therefore, most the HVAC's ducts are installed inside the building. The ambient temperature of plant room is lower than outside the building. HVAC's ducts installed outside the building are subjected to harsh environment whereas those located inside the building are also subject to considerable temperature. There is temperature difference exist between the conditioned air inside the duct and its immediate surroundings[9-11]. This temperature difference increases the cooling/heating loss from the duct because heat transfer is directly related with temperature difference in contrast heat transfer decreases with thermal insulation, thickness of insulation and duct material and lowering the value of thermal conductivity. The cooling/heating loss to/from the duct enlarges the energy bill of the building to home owner and also causes peak load to the utilities. Therefore, in order to decreases heat transfer to/from the duct, the thermal insulation should be one of the most important tools to avert heat loss from the duct. Moreover, thermal insulation also prevents condensation of water vapor at external surface of the duct .



Source: Abdullah Yildiza,n, Mustafa Ali Ersöz b, "The effect of wind speed on the economical optimum insulation thickness for HVAC duct applications" Renewable and Sustainable Energy Reviews 55(2016)1289–1300

Figure 2. Schematic View of Basic HVAC System

Mostly engineering investigations consider thermal insulation material and thickness as a key factor from energy, economic and environmental point of views. The economic insulation thickness concept is basically based on the initial investment of thermal insulation used in HVAC system and energy saving achieved by using thermal insulation over the expected life time of HVAC system. In order to decrease heat loss to the surrounding, insulation thickness should be optimized by minimizing the energy and insulation cost occurred on HVAC system. The economic insulation thickness for a pipe and duct is a function of design, operating and economic parameters[13]. The parameters needed to determine optimum insulation thickness are pipe or duct size, cost, thermal conductivity of the duct and insulation material, operating and ambient temperatures, convective heat transfer coefficient inside and outside the duct, inflation and interest rate, type of the fuel, efficiency of the system and annual operating hours. In most of the studies, the degree-time concept is one of the simplest methods used to determine the cooling/heating energy requirement of a building under constant operating and environmental condition.

Zaki and Al-Turki performed thermo-economic analysis to estimate the optimum insulation thickness for pipelines (0.1-0.273m) of an oil industry using rock wool and calcium silicate as insulation material. In this analysis working fluid was superheated steam, furfural, crude oil and 300-distillate were used and outside convective heat transfer coefficient was constant. The analysis considers initial investment on insulation and energy saving achieved over an expected lifetime of piping.

Li and Chow determined optimum insulation thickness on tubes (0.02-0.2m) to protect pipe from cold freezing using thermo-economic optimization analysis. They analyzed the effect of ambient air and design parameters on optimum insulation thickness for tube. It was investigated that insulation thickness decreases as thermal conductivity and insulation cost increase, while insulation thickness increases as outside surface temperature of the insulation decreases.

Soponpong pipat et al. estimated the optimum insulation thickness for HVAC's duct using thermo-economic analysis. In this analysis galvanized steel duct (0.5m) with glass wool and rubber as insulation material were chosen. The variation of optimum insulation thickness, energy savings and payback period for duct with convective heat transfer co-efficient was investigated. It was estimated that variation of convective heat transfer coefficient doesn't affect optimum insulation thickness but energy saving increases with heat transfer coefficient.

Yildiz and Ersöz estimated the effects of wind speed on optimum insulation thickness, energy savings and payback period for HVAC duct installed outside the building in Usak, Turkey using P1-P2 method. Four fuel types and two insulating material were used in this analysis. Under above analysis following results were obtained i.e. optimum insulation thickness was between 12.85-23.91cm, energy savings 79.36-98.45% and payback period was 0.0053-0.0925 years (~ 2 days – 33.76 days) for fiberglass, while in case of rock-wool optimum insulation thickness was varying between 11.87-22.21 cm, energy savings 76.63-98.26% and payback periods 0.0061 and 0.1115 years. It was concluded that type of fuel has significant effects on optimum insulation thickness, energy saving and payback periods for HVAC duct. Additionally, wind speed of 7m/s produced maximum energy savings for LPG whereas minimum energy saving were estimated with wind speed of 0.2m/s in case of NG [14].

From available literature, the number of studies founds that significant research has been conducted to determine optimum insulation thickness for building because there is large potential of energy savings. Moreover, significant research is also conducted on pipelines and cylindrical heat exchangers in industries, refineries, HVAC system and power plant. However, it is seen that there are few studies conducted on HVAC's duct. Consequently, less attention is given to the environmental impacts of energy loss through HVAC's duct and piping. And, most of the studies conducted to investigate the environmental impacts of building insulation are:

Dombaycı estimated the environmental impacts of optimum thermal insulation on external wall of the building in Denizli, Turkey. In this analysis coal was as a fuel and expanded polystyrene as the insulation material were used. It was estimated that optimum insulation thickness reduces the fuel consumption by 46% and the CO2 and SO2 emission reduced by 41%.

Yildiz et al. estimated that optimum insulation thickness on the external wall of the building in the city of Ankara, Turkey reduced CO2 emission by 30% for glass wool insulation material.

Uçar and Balo estimated that optimum insulation thickness on the external wall of the building in the city of Elazıg, Turkey reduced CO2 and SO2 emission by 82% using coal as a fuel.

The mathematical studies carried out on the effect of Duct Insulation by Natasha (2014) and Dileep (2016) have been calculated to be 14% and 16% respectively. On the analysis of various research works carried out in the field, it was observed that all the studies and made on the basis of mathematical modelling and simulation based results. A significant and reliable test of such results was remaining to be conducted on experimental basis. Therefore, a thorough observation of the psychometric changes taking place due to variation in different parameters was important.

3. Design & Operating Parameters

The duct used in this experiment was of Galvanized steel and the insulation with dimensions mentioned as follows;

1	Duct Material	Galvanized Steel
2	Thickness of duct	0.0075 m
3	Side of the Duct	0.3048 m
4	Duct Area of Cross-Section	0.0929 m^2
5	Perimeter of Duct	4 x 0.3048
6	Length of Duct	4.86768 m
7	Thermal Conductivity of duct	60 w/m.K

Table. 1 Design Parameters of the duct

1	Insulation Material	Fiberglass with self-adhesive aluminum foil and reinforcement tape
2	Thickness of Insulation	2 in = 0.0508 m
3	Density of Insulation	24 kg/m3
4	Size of Insulation	6.096 m

Table. 2 Thermal Insulation Properties

Surrounding Atmosphere	
Pressure at the system inlet	101 kPa
Dry Bulb Temperature	32 ^{O}C
Wet Bulb Temperature	26 ^{O}C

Conditions at Duct Inlet	
Dry Bulb Temperature	17.3 ^{O}C
Wet Bulb Temperature	16.8 ^{O}C
Conditions at Duct Outlet	
Velocity of air	1.5 m/s
Dry Bulb Temperature	23.3 ^{O}C
Wet Bulb Temperature	18.8 ^{O}C

Table. 3 Operating Parameters of Bare Duct

Surrounding Atmosphere	
Pressure at the system inlet	101 kPa
Dry Bulb Temperature	33 ^{O}C
Wet Bulb Temperature	22 ^{O}C
Conditions at Duct Inlet	
Dry Bulb Temperature	20.3 ^{O}C
Wet Bulb Temperature	18.3 ^{O}C
Conditions at Duct Outlet	
Velocity of air	1.5 m/s
Dry Bulb Temperature	20.3 ^{O}C
Wet Bulb Temperature	18.6 ^{O}C

Table. 4 Operating Parameters of Insulated Duct

The expected outcome of this setup was to achieve reliable results on the effect of insulation over the air conditioning duct on the basis of experimental data obtained at various times of the day i-e morning, evening and night time and see if a significant reduction in fuel cost is achieved.

4. Mathematical Models

Heat Transfer Calculation:

The Figure. 4 illustrates the side view of the duct whereas Figure 5 show the area of cross sectional area of the duct in the form of hydraulic diameter and resistance to heat transfer of bare or insulated duct. The quantity of heat flowing into the duct can be obtained with the help of following equation:

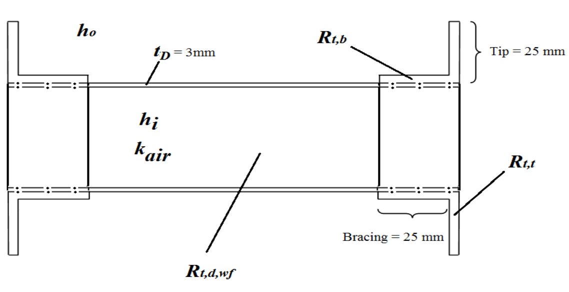


Figure. 3 Side view of duct showing Resistances at various regions

$$Q_{bare\ duct} = \frac{\Delta T}{R_{total,bare\ duct}}$$

Where ΔT is the difference of temperature between inside and outside the duct and can obtained by:

$$\Delta T = T_{o,mean} - T_{i,mean}$$

The total Thermal Resistance in case of un-insulated or bare duct ($R_{T,bd}$) is given as;

$$\frac{1}{R_{T,bd}} = \frac{1}{R_{t,d,wf}} + \frac{1}{R_{t,b}} + \frac{1}{R_{t,t}}$$

Where is t $R_{t,d,wf,i}$ represents total Resistance of insulated duct without flange, $R_{t,b,i}$ represents total thermal resistance of insulated bracing and $R_{t,t,i}$ represents total thermal resistance at the insulated tip region.

The total heat losses in the bare duct and insulated duct are calculated respectively with the help of following formulae;

$$Q_{bd} = \frac{T_{di} - T_s}{R_{T,bd}}$$

$$Q_{id} = \frac{T_{di} - T_s}{R_{T,id}}$$

Where Td_1 is the temperature of air flowing inside the duct and Ts represents temperature of the surrounding atmosphere.

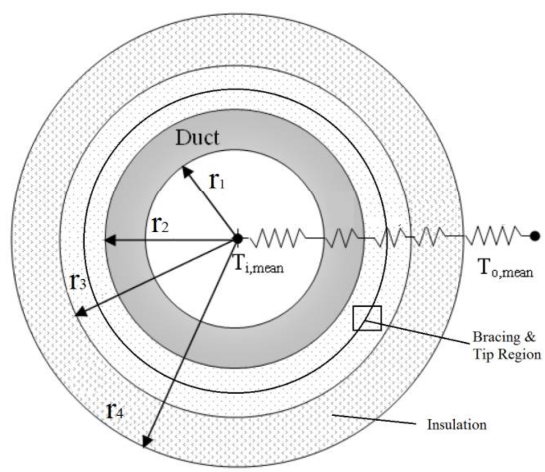


Figure 1. The heat resistance in case of duct, bracing, insulation & the air inside and outside the duct

5. Results and Discussion

The experiment performed was aimed at finding out the most optimum thickness of the insulation used for the HVAC Duct. The information pertaining to the experiment is already given in the design and operating parameters section. The experiment was performed at the Mechanical Engineering department at MUET SZAB Campus Khairpur while the Mathematical Modeling was performed on Engineering Equation Solver (EES) program. A comparison of energy losses in both the setups is given as;

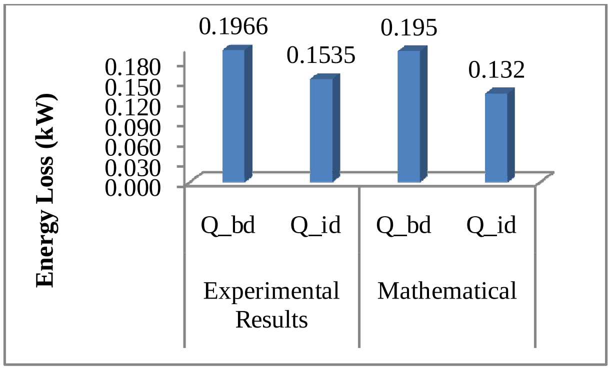


Figure.5 Comparison between Experimental & Mathematical Results for Energy Losses

Where

Q_bd = Energy losses in case of bare duct
Q_id = Energy Losses in case insulated duct

The results of heat loss in insulated and un-insulated duct are presented in the graph whereas a comparison of the previous studies carried out on the similar subject is presented as follows;

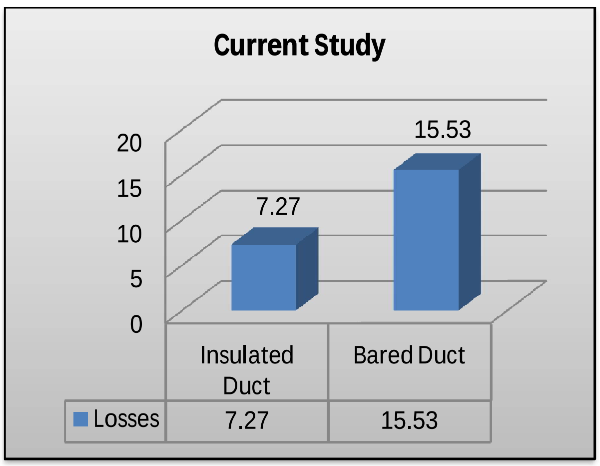


Figure. 6 Current Study

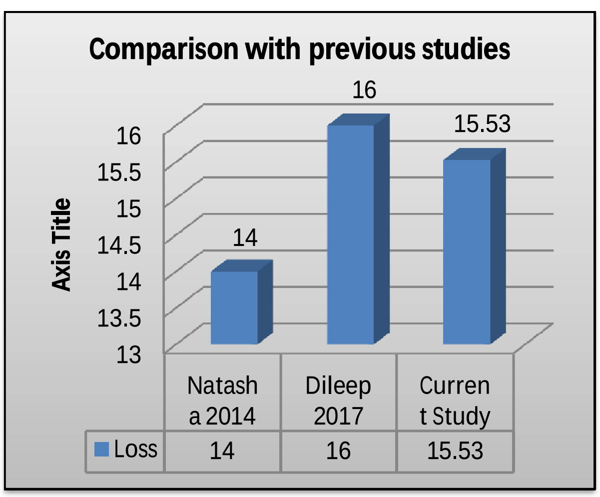


Figure. 7 Comparison with previous studies

6. Conclusion

At the end of experimental and mathematical studies of the Optimum insulation thickness, it was concluded that net cost of energy for the air-conditioning system was calculated to be 15.53 % as compared to the previous studies by Natasha (2014) and Dileep 2016, whereas Conditioned Space Parameters (temperature in this case) were reduced from 24℃ to 21℃. This ultimately decreased the overall expenditures of the air conditioning unit and therefore as a result, the size of the Air conditioned system was reduced.

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About Authors

Engr. Abdul Shakoor Shaikh has done his B.E from Mehran University of Engineering & Technology Jamshoro and is currently pursuing his Masters in Energy Systems Engineering from Mehran University SZAB Campus Khairpur Mirs. He is currently working as Lecturer at the Benazir Bhutto Shaheed University of Technology & Skill Development and Chairperson, Department of Petroleum & Chemical Engineering Technology. He has keen interest in the field of alternative and renewable energy sources and has therefore intends to divert most of his efforts in research and development in the field Energy Engineering.

Prof. Dr. Hassan Ali Khan Durrani has done his Bachelors, Masters and PhD from Mehran University of Engineering & Technology. Having vast experience in the field of Mechanical Engineering, both in academia and industry, he started benefitting his students with his knowledge and expertise. Currently he is working as Professor and Chairman at the Department of Mechanical Engineering at Mehran University SZAB Campus Khairpur Mirs. Prof. Durrani is a highly motivational personality and has many national and international publications to his credit.

Engr. Awais Junejo has obtained his Bachelors and Masters in Mechanical Engineering from Mehran University of Engineering & Technology. He is currently working as Lecturer at Mehran University SZAB Campus Khairpur Mirs. His research interests are mostly focused in harvesting the alternative sources of energy in Pakistan through various creative and innovative techniques.

Engr. Dileep Kumar has done his Bachelors and Masters of Engineering from Mehran University of Engineering & Technology, Jamshoro. He is currently working as Lab Engineer and is on study leave for PhD. His main research interests include Building Energy, Energy Efficiency Enhancement, HVAC. Mr. Dileep is a highly research oriented person and has many national and international publications to his credit.