# Lifecycle Cost Analysis of An Insulated Duct With An Air Gap

**Dileep Kumar**
Swinburne university of technology https://orcid.org/0000-0001-5139-0174
**Muhammad Haris Khan**
Mehran University of Engineering and Technology
**Muhammad Ali Abro** (muhammad_aliabro@muetkhp.edu.pk)
Mehran University of Engineering and Technology

**Research Article**

**Keywords:** Air Gap, Cost savings, LCC analysis, ducts, Insulation Materials.

**Posted Date:** June 7th, 2021

**DOI:** https://doi.org/10.21203/rs.3.rs-485997/v1



**Version of Record:** A version of this preprint was published at Environmental Science and Pollution Research on October 14th, 2021. See the published version at https://doi.org/10.1007/s11356-021-16839-2.

# Lifecycle Cost Analysis of an Insulated Duct with an Air Gap

**Dileep Kumar[1], Muhammad Haris Khan[2,] and Muhammad Ali Abro[2,*]**

1. Centre for Smart Infrastructure and Digital Construction, Swinburne University of Technology, Hawthorn 3122, VIC, Australia
2. Department of Mechanical Engineering, Mehran University of Engineering and Technology Shaheed Zulfiqar Ali Bhutto Campus, Khairpur Mir's-66020, Pakistan

*(abromdali@gmail.com & +923003246995).

## Abstract

The insulation materials are used to reduce heat loss to/from the ducts with additional investment. This study aims to reduce this additional investment in the duct application by introducing an air gap between insulation and duct surface. It uses Life Cycle Cost (LCC) analysis to determine the economic benefits of the air gap considering four insulation materials for insulating the duct and natural gas as an energy source for chiller operation. The preliminary data regarding design and operating parameters were obtained from a renowned pharmaceutical company. The duct's annual energy loss was estimated for given operation hours in a year using the preliminary data and ambient conditions. The estimated energy loss through the duct is fed in LCC analysis to determine the impact of the air gap on optimum insulation thickness corresponding to the minimum LCC and payback period. The results show that the introduced air gap in an insulated duct lowers the optimum insulation thickness for the duct. As a result, the air gap maximizes the cost savings and minimizes the payback period. The expanded polystyrene is investigated as the most economical with maximum cost savings of USD 508.8-USD $766.8/m/year and a payback period of 1.15-1.17 years for the duct applications. Contrary, the air gap is determined the most effective in terms of cost and emission savings for the ducts insulated with rock wool. In conclusion, an air gap is an economical option for duct applications.

**Keywords:** Air Gap; Cost savings; LCC analysis; ducts; Insulation Materials.

## 1. INTRODUCTION

Buildings are designed to provide a comfortable environment to occupants and the required conditions of manufacturing processes. As a result, they consume around 40% of total energy demand, mainly consumed to meet space heating and cooling demand via heating, ventilation, and air conditioning (HVAC) system (60%) (Perez-Lombard et al. 2011; Shaikh et al. 2014). It is responsible for 36% of greenhouse gas emissions in developed countries (Pe´rez-Lombard et al. 2008 ). In an HVAC system, the significant share of energy lost in the water and air distribution system due to heat gain/loss to/from its immediate surroundings. Therefore, they drop the efficiency and capacity of the HVAC system, which is improved by using the proper insulation material and thickness along with adequate control of air exchange rate. Therefore, the optimization of insulation thickness for the HVAC duct has excellent potential to reduce its energy consumption (Kumar et al. 2018c; Mageshwaran et al. 2018).

The insulation materials are used to decreases heat gain and loss to/from the HVAC distribution systems (pipes and ducts) into the intermediate surrounding. The pipes and ducts are made up of fragile metallic sheets; thereby, they have very high thermal conductivity and meager resistance to heat loss. In addition, the cold water and hot water temperature are shallow, 6-8 °C and 70-90 °C in supply pipelines, followed by 12-14 °C and 36-40 °C in supply air ducts, respectively. This higher than the conditioned space temperature 18 and 26 °C recommended by ASHRAE for the heating and cooling season (ASHRAE 1989). The heat transfer through the ducts installed in outdoor and indoor unconditioned spaces-such as attics, crawl spaces, and garages, causes significant loss of energy due to heat gain and loss into the immediate surroundings. The heat transfer loss accounts for 10%–45% of space cooling and heating demand in a single-family residential building. The heat transfer through the duct is particularly severe in hot climatic regions. In these regions, a significant amount of air conditioning load is needed to maintain the acceptable comfort level, and ducts are subjected to harsh ambient conditions leads to high heat gain. It worsens in peak hours, substantially lowering the duct system efficiencies under the hottest attic and the highest run time. In three families single-story houses in Florida, the annual energy-efficient retrofit had reduced the space cooling, and heating demand by 15%–35% and annual electricity bills were reduced by 6%–25% (Shapiro et al. 2013). Therefore, the pipes and ducts should be insulated with proper insulation materials and thicknesses to minimize the heat losses through pipes and ducts so that economic and ecological benefits should be achieved (Kaynakli 2014).

In the current literature, numerous studies were conducted to investigate the optimum insulation thickness for piping/ducting using Life Cycle Cost (LCC) analysis, in which different analytical and numerical methods were used to estimate the energy loss through pipes and ducts considering different insulation types, pipe materials and energy sources (Kaynakli 2014). In this regard, G. M. Zaki (2000) studied the optimization of multi-layer thermal insulation for hot water pipelines irrespective of radiative heat loss. At the same time, Sahin & Kalyon (2005) investigated that the insulation thickness for hot water pipes was independent of both convective and radiative heat loss. Soponpongpipat et al. (2010) calculated the effect of convective heat transfer coefficient ($h_o$) on optimum insulation thickness and energy savings in the duct insulated with double-layer of glass wool and Aeroflex insulation using thermo-economic analysis. They found that the increase in the convective heat transfer coefficient escalates the energy savings without affecting the optimum insulation thickness for the duct. Yildiz and Ersöz (2016) stated that the energy savings in the duct insulated with glass and rock wool were increasing with wind speed considering natural gas and LPG as an energy source. They found the highest ES was estimated for duct at 7 m/s wind speed for LPG, the lowest proportion of energy was saved at the wind speed of 0.2 m/s for natural gas. Kumar et al. calculated the impact of compression of thermal insulation on the condensation of water vapor on the external surface of the duct with constant (Kumar et al. 2018c) and variable (Kumar et al. 2018b) ambient air convective heat transfer coefficient. They estimated that the volume flow rate of conditioned air and insulation thickness at the point of compression should be greater than 1.4 $m^3/s$ and 30 mm, respectively, to avoid condensation on the external surface of the duct. They found that the optimum insulation thickness (28 to 45 mm) for the ducts was higher than the critical insulation thickness (30 mm). Therefore, the chances of condensation at the external surface of the duct were eliminated, corresponding to its optimum insulation thickness (Kumar et al. 2018c). In (Kumar et al. 2018b), they considered the variable convective heat transfer coefficient to estimate the critical insulation thickness at joints and bends of the duct between 15-55 mm and 15-35 mm at 6-22 $W/m^2.K$, respectively to avoid the chance of condensation. Furthermore, the conditioned airflow rate must be 1.4 and 2.2 $m^3/s$ at a convective heat transfer coefficient of 10 and 22 $W/m^2.K$, respectively.

On the other hand, some studies had determined the environmental impacts of optimum insulation thickness for the duct. Kumar et al. (2017) had calculated the environmental impacts of the proper glass wool insulation thickness on the point of its compression in the duct. They found that the increase in insulation thickness from 10 to 40 mm had decreased the energy consumption from 4.29-2.46 kW and $CO_2$ emission from 4.2-2.3 kg/kW. Yin et al. (2018) calculated the economic and environmental impacts of insulation materials used in the pipelines of the sub-way central cooling system using combined exergy and LCC analysis. They found that the exergoeconomic optimization had a higher value of optimum insulation thickness for pipes than energoeconomic optimization. The energoeconomic method was appropriate for economic impacts, while the exergoeconomic was a better choice to investigate ecological impacts. Cooling energy lost in supply was more than return pipes. Therefore, the impact of supply and return pipe should be considered jointly to calculate optimum insulation thickness for the pipes. Using the same method, Uncar (2018) found that the extruded polystyrene produces the optimum insulation thickness of 30, 36, and 57 cm for Aydın, Tekirdag, Elazıg, and Kars, respectively. The optimum insulation thickness for respective cities also varies with ambient air convective heat transfer coefficient. Finally, the sensitivity analysis proved that the optimum insulation thickness is too sensitive to inflation and discount rate instead of other parameters. Kumar et al. (2018a) had determined that the optimum insulation thickness for different duct sizes decreases with the increase in duct size. They found that the maximum energy savings of 84.91% for smaller duct sizes (30 cm) for natural and emission products were reduced by 81% compared to the bare duct. Martin-Du Pan et al. (2019) optimized pipe size to reduce operation energy (electricity and heat). They found that the proposed optimization criteria lead to lower pipe size than given in the CIBSE CP1 Heat Networks Code of Practice. In peak load demand 90/40 °C, the increment in insulation thickness from 20 to 40 mm had saved 29% of total energy loss. The Supply pipe size was lower than the return because of the low fluid velocity through the return pipe. Plastic pipes were smaller sized than steel because of low internal resistance to flow and low heat loss. The difference between the present study and previous studies are tabulated in Table 1.

**Table 1** Difference between previous studies and the present study.

| Authors | Country | EM | Fluid | Insulation | Duct | Economic | Findings |
|---|---|---|---|---|---|---|---|
| Sahin & Kalyon (2005) | Saudi Arabia 2005 | Thermodynamic | $T_f$–$T_o$=77 K, $h_i$=$h_o$=6– 10 (W/m$^2$ K), | glass wool k=0.035 | k=30 d=50 $t_p$=2 | Insulation thickness of the duct is independent of convective and radiative heat transfer coefficient at | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | uniform external surface temperature. | |
| Soponpongpipat et al. (2010) | Thailand 2010 | Thermo-economic | $T_f$–$T_o$=286 K, $h_i$=$h_o$=6– 22 (W/$m^2$ K), COP= 2.81, Time= 23,040 h. | -Double layer of glass wool k=0.035 rubber k=0.045 | k=60.5 d=0.6 m | i=14.25% d=2.1% y=10 years | The inside and outside duct $h_o$=6-22 W/($m^2$ K) for calculation of optimum thickness. |
| Kayfeci et al. (2014) | Turkey 2014 | Artificial Neural Network | HDD=2607 °C-days, Fuel: Natural gas | -single layer of GW:0.033, EP:0.028, RW:0.034, FB:0.031 & XPS:0.027 | k=54 d=50-250 $t_p$=3.9-9.21 | i=4% d=5% & y=10 years | They found that the proposed ANN model had calculated the OIT and LCC savings in pipes with good accuracy. |
| Yildiz and Ersoz (2016) | Turkey 2016 | $P_1$-$P_2$ | $V_i$=10 m/s,$V_o$=0.2-7m/s $T_o$=265 K & $T_f$=310 K HDD=2300 ºC-days, Fuel: coal, fuel–oil, LPG and natural gas. | -Single layer of fiberglass k=0.037 W/(m K) Rock wool k=0.039 W/(m K) | k=14.9 W/(m K) d=0.4 m $t_d$=0.6mm | i=4.5% d=9.4% y=10 years | The cost-saving increases with the increase of ambient wind speed depending on insulation types and fuel source. |
| Daşdemir et al. (Daşdemir et al. 2017) | Turkey 2017 | LCC | HDD= 2328 °C days Fuel: coal, fuel–oil, and natural gas. | EP:0.028, Rock wool:0.034 Foam board:0.031 & XPS: 0.027 | k=54 $K_p$=0.41 d=50-250 $t_p$=3.9-9.21mm | i=13% d=6.5% y=20 yrs | Steel pipes: 5-16 cm and Copper pipes: 5-12 depending on fuel types, insulation materials, and pipes sizes. |
| Kumar et al. (2018c) | Pakistan 2018 | $P_1$-$P_2$ | $T_f$=291-294 K $T_o$=301-307 K $h_i$=10 (W/$m^2$ K), η=0.93, OH=6500 h Fuel: Natural gas. | -single layer of glass wool k=0.035W/(m/K) | k=60.5 W/(m K) d=0.6 m | i=5% d=7% y=20 years | Effect compression of thermal insulation was determined. To minimize the chances of condensation OIT at the point of compression should be greater than 28-45 mm. |
| Yin et al. (2018) | China 2018 | LCC and EIP | $T_f$=305 K, $T_o$=305 K $h_i$=$h_o$=10 (W/$m^2$ K), COP=5.5, OH= 5040 h Fuel: Electricity | -single layer of GW=0.035 RW=0.040 | k=30 W/(m K) d=0.2 m | i=9% d=5% y=15 years | The OITs were highly sensitive to the heat conductivity of the insulation materials, COP, and the air temperature in the tunnel, while less sensitive to the pipe size. |
| Ucar et al. (2018) | Turkey 2018 | Thermo-economic | HDD= 4772; 2653; 2032 & 1213 °C days $h_i$=10 (W/$m^2$ K), COP=5.5, Fuel coal, fuel–oil, LPG, NG, electricity | -single layer of XP=0.040 GW=0.035 EP=0.035 | k=55 W/(m K) d=50-250 $t_p$=3.9-9.21 | i=9% d=8.81% y=10 years | OIT:19, 30, 36, and 57 m for Aydın, Tekirdag, Elazıg, and Kars, respectively. Insulation thickness increases with an increase in heating degree days. |
| Kumar et al. (2018a) | Pakistan 2018 | LCC and EAM | $V_i$=10 m/s, $V_o$=4.2 m/s $T_o$=265 K & $T_f$=310 K HDD=2384 °C-days, Fuel: coal, fuel–oil, LPG, NG, electricity, RH, DPR and Bagasse. | -single layer of GW=0.035 Rubber=0.03 EP=0.035 RW0.035 | | i=5% d=7% y=20 years | Insulation thickness increase with the size of the duct. |
| Kumar et al. (2019) | Pakistan 2019 | | | | k=60.5 W/(m K) d=0.6 m | | Higher fuel cost maximizes the cost-saving but does not affect the fuel consumption and emission savings. |
| Martin-Du Pan et al. (2019) | UK 2019 | LCC | $T_f$=40-90 °C, $T_o$=12 (buried) and 21ºC (heat space) $U_i$= 0.85-3m/$s^2$, COP=5.5, OH= 5040 h | -single layer of XP=0.025 | $K_s$=14 $K_p$=0.41 W/(m K) d=0.6 m | Recommended pipe size Operational cost of a DH network can be reduced when selecting the recommended maximum pipe diameter, compared to commonly use sizing criteria, and return pipe should be sized at low | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Fuel: Natural Gas | | | velocity. The optimal flow and return pipe diameters are 77.5 and 92 mm. | |
| Present Study | Pakistan | LCC | $T_f$=291-294 K<br>$T_o$=301-307 K<br>COP= 1.2, OH= 6500 h<br>Fuel: Natural gas. | -double layer of an air gap and EP/XP | k=60.5 W/(m K)<br>d=0.6 m | i=5%<br>d=9%<br>y=20 years | The air gap halved the optimum insulation thickness for the HVAC duct and also maximizes the energy savings. |

In previous studies regarding the optimum insulation thickness of the duct, the expanded polystyrene was the most economic insulation material for the duct application, but its higher quantity was needed to achieve maximum cost savings. Therefore, there is a need to understand the impact of an air gap on optimum insulation thickness of different insulation materials used in the ducts from a life cycle cost approach.

This study investigates the use of an air gap in an insulated duct using life cycle cost analysis. Firstly, it determines the energy loss due to heat transfer through the ducts using thermodynamic analysis. Then, the heat transfer is added in life cycle cost analysis to determine the optimum insulation thickness of the ducts corresponding to maximum cost savings and minimum payback period. It afterward determines the impact of an air gap on optimum insulation thickness for the duct using life cycle cost approaches. Finally, it discusses the results and draws a meaningful conclusion before future research recommendations.

# 2. METHODOLOGY

## 2.1. Description of Heating, Ventilation, and Air Conditioning System

An HVAC system consists of a boiler, chiller, air handling unit, chilled and hot water distribution system, and air distribution system. In an HVAC system, chilled and hot water are used to condition air to the preferable thermal comfort of occupants and acceptable for the manufacturing process. The boiler generates hot water and steam. The chiller uses steam to produce chilled water, and hot water is supplied to a heating coil of the air handling unit to control the temperature and relative humidity of supply air. The supply air is supplied to space using an air distribution system. The supply air duct transports conditioned air from the air handling unit to conditioned space, then the air is returned to the air handling unit and some portion exhausted to surrounding to maintain indoor air quality via return and exhaust air duct, respectively. HVAC's duct is made from the galvanized steel, stainless steel and aluminum, and flexible non-metallic materials. Typical HVAC's duct is in an outdoor environment, basement floors, attics, garages.

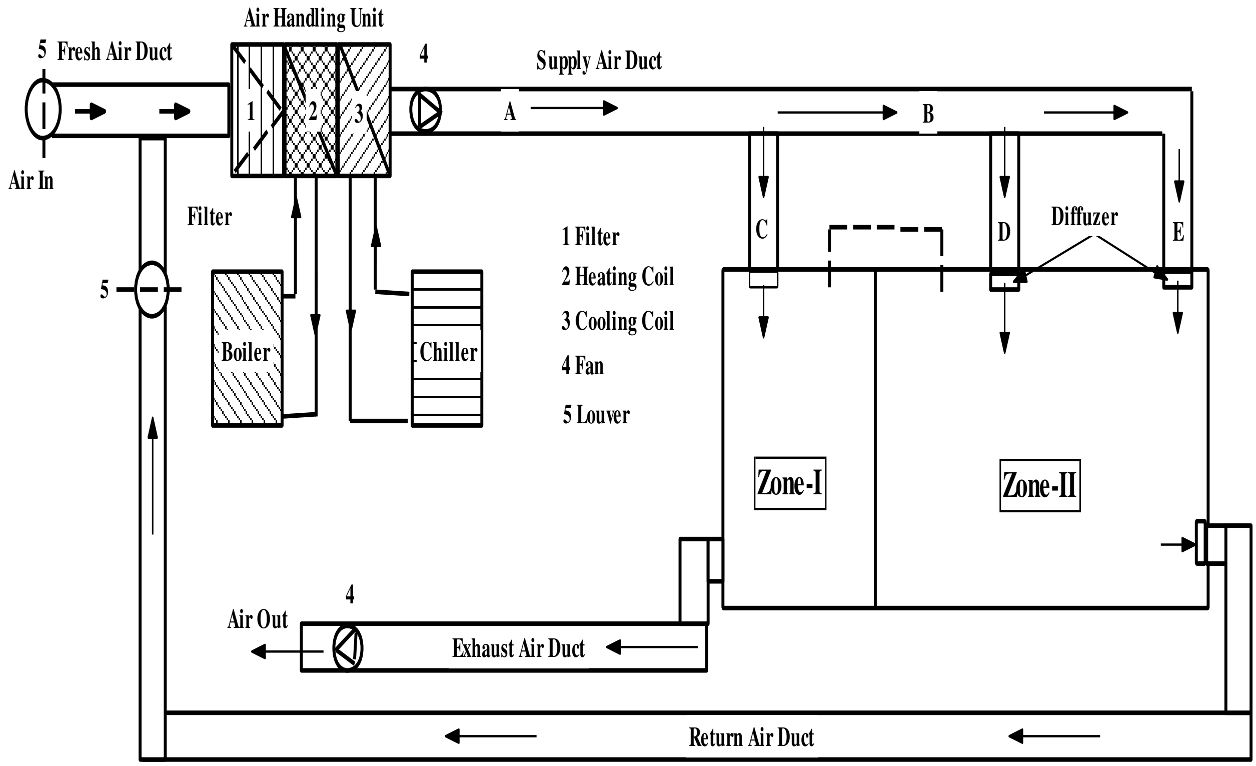


**Fig. 1** Schematic layout of a selected HVAC system.

The ducts are installed in an outdoor environment, basement floors, fall ceiling, attics, and garages. They are subjected to harsh ambient conditions and unconditioned space. Moreover, they are made up of thin metal sheets with high thermal conductivity. Consequently, they account for a significant loss of energy due to heat transfer from their immediate surroundings. The insulation materials are generally used to decrease heat loss and gain to and from the surrounding during the summer and winter seasons. However, the addition of the insulation layer on the duct costs more to save operational energy loss. As a result, a considerable quantity of insulation materials is required to reduce the heat losses, which burdens a high initial investment. Therefore, this study introduced an air gap to decrease the insulation quantity required to reduce energy loss. The optimum insulation thickness corresponding to maximum cost savings of the building envelope (Açıkkalp & Kandemir 2019; Axaopoulos et al. 2019; Orzechowski & Orzechowski 2018), pipes (İlhan 2018; Martin-Du Pan et al. 2019; Ucar 2018; Yin et al. 2018), and ducts (Kumar et al. 2019; Kumar et al. 2018a; Kumar et al. 2018b; Kumar et al. 2018c, Soponpongpipat et al. 2010; Yildiz & Ersöz 2016) was investigated by using LCC analysis. The present research also conducts the LCC analysis to determine the impact of an air gap on optimum insulation thickness of insulated duct installed in a renowned pharmaceutical company, Jamshoro, Pakistan.

In this research, the design and operating parameters were collected from the HVAC duct installed in a pharmaceutical company, Jamshoro, Pakistan, as given in Table 1. The supply air ducts of different cross-sectional areas having different length supply conditioned air to two pharmaceutical zones. The HVAC system is operated on a gas-fired chiller having a coefficient of performance of 1.2. The chiller supplies the chill water to Air Handling Unit (AHU) to condition outdoor air to designed zone conditions, as seen in Figure 1. The supply airflow rate and temperature are given in Table 1. The weathering parameters were obtained from the Metrological Department of Pakistan, as given in Table 2. Natural gas properties were found in (Kumar et al. 2019), and its cost was obtained from the Oil and Gas Regulatory Authority of Pakistan. The insulation cost is based on the Project entitled “Heating, Ventilation and Air Conditioning Works of New Calcium Site and Red Area” of Novartis Pharma, Jamshoro, Pakistan. The economic parameters were online available on the website of the State Bank of Pakistan.

**Table 2** Design and operating parameters of the air distribution system.

| Duct | Width | Height | Length | Thickness | Cross-sectional area | Average pressure | Average temperature | Volume flow rate | Density | Velocity |
|---|---|---|---|---|---|---|---|---|---|---|
| **Notations** | **W** | **H** | **L** | **t** | **A** | **P** | **T** | **V** | **rho** | **$U_s$** |
| **Units** | **m** | **m** | **m** | **mm** | **$m^2$** | **kPa (g)** | **K** | **$m^3/s$** | **$kg/m^3$** | **m/s** |
| SAD(I) | 1.02 | 0.3 | 1.37 | 0.85 | 0.3097 | 102.3 | 291 | 1.534 | 1.212 | 4.953 |
| SAD(II) | 0.91 | 0.3 | 0.3 | 0.85 | 0.2323 | 102.2 | 291.2 | 1.038 | 1.214 | 4.471 |
| SAD(III) | 0.41 | 0.36 | 18.59 | 0.7 | 0.1445 | 102 | 293.5 | 0.495 | 1.207 | 3.428 |
| SAD(IV) | 0.41 | 0.3 | 12.02 | 0.7 | 0.1239 | 101.5 | 293.3 | 0.519 | 1.204 | 4.191 |
| SAD(V) | 0.41 | 0.3 | 14.61 | 0.7 | 0.1239 | 101.7 | 293.4 | 0.519 | 1.2 | 4.191 |
| RAD | 0.71 | 0.3 | 10.06 | 0.85 | 0.3097 | 102.3 | 293.3 | 1.534 | 1.212 | 4.953 |

**Table 3** Ambient conditions of Jamshoro, Pakistan.

| Parameters | Units | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{max}$ | °C | 25 | 30 | 36 | 42 | 44 | 41 | 37 | 37 | 38 | 38 | 32 | 27 |
| $T_{min}$ | °C | 15 | 18 | 23 | 27 | 30 | 30 | 30 | 29 | 28 | 27 | 21 | 17 |
| $T_a$ | °C | 19 | 23 | 29 | 34 | 36 | 35 | 33 | 33 | 32 | 32 | 26 | 21 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_i$ | °C | 20 | 20 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 20 |
| RH | % | 33 | 19 | 25 | 28 | 38 | 51 | 58 | 55 | 50 | 32 | 23 | 21 |
| U | m/s | 2.4 | 2.5 | 2.7 | 4 | 5.4 | 6.7 | 7.7 | 6.7 | 5.4 | 2.3 | 1.9 | 2.4 |

**Table 4** Thermo-economic parameters and fuel properties considered in the analysis.

| Parameters | Value | References |
|---|---|---|
| Ambient conditions | $T_i$=See Table | Memon & Memon et al. (2017) & Baloch et al. (2016) |
| COP of chiller | 1.2 | Nowakowski and Busby (2001) and Sun et al. (2015) |
| Fuel Type | Natural Gas ($C_{1.05}H_4O_{0.034}N_{0.02}$) | Kumar et al. (2019) |
| Lower Heating Value | HV=34.53 MJ/m$^3$ and $C_f$= US$0.37/m$^3$ | Kumar et al. (2019) |
| Expanded Polystyrene | $K_{ins}$=0.036 W/m K and $C_{ins}$= USD$47/m$^3$ | Kumar et al. (2019) and Aditya et al. (2017) |
| Extruded Polystyrene | $K_{ins}$=0.025 W/m K and $C_{ins}$=USD$120/m$^3$ | Kumar et al. (2019) and Aditya et al. (2017) |
| Glass wool | $K_{ins}$=0.038 W/m K and $C_{ins}$= USD$ 104/m$^3$ | Kumar et al. (2019) and Aditya et al. (2017) |
| Rook wool | $K_{ins}$=0.043 W/m K and $C_{ins}$= USD$82/m$^3$ | Kumar et al. (2019) and Aditya et al. (2017) |
| Galvanized Steel | $K_d$=60.5 W/m K | Kumar et al. (2019) |
| Interest Rate | 10.25% | State Bank of Pakistan |
| Inflation Rate | 7.48% | State Bank of Pakistan |
| Operating hours | 6500 h | Kumar et al. (2019) |
| Lifetime | 20 years | Kumar et al. (2019) |

## 2.2. Life Cycle Cost Analysis

Thermal engineering systems' design modifications such as reconfiguration of components, implementation of new technology, waste heat recovery, and phase change, low carbon, and insulation materials are analyzed using the LCC analysis. The LCC analysis investigates the energy savings associated with modification. For instance, insulation costs are used to save operation energy costs by reducing fuel consumption related to heat loss. The net savings is achieved by decreasing the heat gain and loss to/from the duct into the surrounding because it overcomes the insulation cost required over the expected service time of the building services. The LCC analysis estimates the optimum insulation thickness corresponding to maximum cost savings of the building envelope (Açıkkalp & Kandemir 2019; Axaopoulos et al. 2019; Orzechowski & Orzechowski 2018), pipes (İlhan 2018; Martin-Du Pan et al. 2019; Ucar 2018; Yin et al. 2018), and ducts (Kumar et al. 2019; Kumar et al. 2018a; Kumar et al. 2018b; Kumar et al. 2018c; Soponpongpipat et al. 2010; Yildiz & Ersöz 2016) considering the prevailing economic circumstances of a country (inflation and interest rate) on insulation investment and fuel billings (Huang et al. 2019; Kumar et al. 2019). In this analysis following assumption are made:

1. Steady State conditions are evaluated.
2. The uniform cross area and the unit length of the duct are considered.
3. The radiation heat transfer mechanism is neglected.
4. The pressure drop through the duct is neglected.

### 2.3. Heat gain through the HVAC duct and insulation materials economy

The energy loss through the HVAC duct is due to conduction heat transfer takes place radially, and it is calculated as (Sahin & Kalyon 2005)

$$\dot{Q} = \frac{(T_s - T_a)}{R_T} \tag{1}$$

Where, $\dot{Q}_{in}$ represent heat gain, $T_a$ and $T_s$ show the average dry bulb temperature of supply air and surrounding air, the total thermal resistance sum of different layers of duct, air gap, and insulation, inside and outside duct air is illustrated by $R_T$. The total thermal resistance of bare duct, insulated duct, and insulated cavity duct is determined as

$$\frac{1}{R_{un-ins}} = \frac{1}{A_i \cdot h_i} + \frac{\ln\left(\frac{r_1}{r_i}\right)}{2\pi \cdot L_d \cdot k_d} + \frac{1}{A_o \cdot h_o} \tag{2}$$

$$\frac{1}{R_{ins}} = \frac{1}{A_i \cdot h_i} + \frac{\ln\left(\frac{r_1}{r_i}\right)}{2\pi \cdot L_d \cdot k_d} + \frac{\ln\left(\frac{r_o}{r_2}\right)}{2\pi \cdot L_d \cdot k_{ins}} + \frac{1}{A_o \cdot h_o} \tag{3}$$

$$\frac{1}{R_{ins}} = \frac{1}{A_i \cdot h_i} + \frac{\ln\left(\frac{r_1}{r_i}\right)}{2\pi \cdot L_d \cdot k_d} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi \cdot L_d \cdot k_{air}} + \frac{\ln\left(\frac{r_o}{r_3}\right)}{2\pi \cdot L_d \cdot k_{ins}} + \frac{1}{A_o \cdot h_o} \tag{4}$$

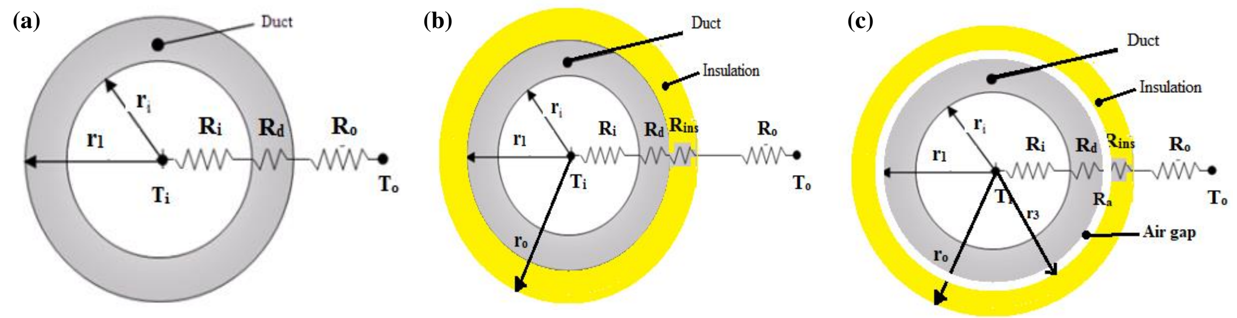


**Fig. 2** The cross-sectional area of the bared duct **(a)** and duct insulated with insulation materials without **(b)** and with **(c)** an air gap.

Fig. 2 shows the hydraulic radius of (a) bare duct, (b) insulated duct, and (c) insulated duct with an air gap. As seen in Fig. 2, the **r** denotes the radius of duct, air gap, and insulation layer, **R** illustrates the thermal resistance offered by interior air, metal sheet, air gap, insulation, and the surrounding air. The Ti and To represent the temperature at the flowing fluid and ambient air. The surface area of the duct is a function of hydraulic radius, which is represented as $A_i = \pi {r_i}^2$ and $A_o = \pi {r_o}^2$ for internal and external surface, respectively. The heat transfer coefficient of supply air and ambient air are denoted by $\mathbf{h_i}$ and $\mathbf{h_o}$**,** respectively. The hi and ho are determined by (Kaynakli 2014).

$$h_i = \frac{0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot k_a}{D_h} \qquad (5)$$

$$h_o = 11.58 \cdot \left(\frac{1}{D_h}\right)^{0.2} \cdot \left\{\left(\frac{1}{T_s + T_o}\right) - 546.3\right\}^{0.181} \cdot (T_s - T_o)^{0.266} \cdot (1 + 2.86 U_o)^{0.5} \qquad (6)$$

Where, $\mathbf{R_e}$ and $\mathbf{P_r}$ illustrate the Reynolds number (determined by Eq. 7) and Prandtl number (a function of thermodynamic parameters), respectively. The thermal conductivity of supply air is denoted as $\mathbf{k_a}$**.** $\mathbf{U_o}$ denotes the ambient air wind velocity. $\mathbf{T_s}$ and $\mathbf{T_o}$ illustrate the temperature at the external surface of the duct and surrounding air. The Reynolds number is calculated as

$$Re = \frac{U_{SA} \cdot D_h}{\vartheta_{SA}} \qquad (7)$$

Where $V_{SA}$ and $\vartheta_{SA}$ represent the velocity and kinematic viscosity of supply air and $D_h$ illustrates the hydraulic diameters of the duct which is estimated by using the Huebscher equation for equivalent hydraulic diameter for rectangular ducts as (Kong & Chong 2019)

$$D_h = \frac{1.3\,(w \cdot h)^{0.625}}{(w + h)^{0.25}} \qquad (8)$$

The annual operation energy loss through the duct is estimated as

$$\dot{E}_{loss} = (T_a - T_s).\left(\frac{1}{R_{un-ins}} - \frac{1}{R_{ins}}\right) \cdot \Delta h \tag{9}$$

The annual fuel billing is a function of fuel consumption and natural gas price, which is illustrated as

$$C_E = \frac{\dot{E}_{loss}}{HV \cdot COP} \cdot C_F \tag{10}$$

Where $HV$ and $COP$ denote the heating value of the fuel (kJ/m$^3$) and chiller's coefficient of performance as given in Table 3. The insulation cost is estimated as

$$C_I = u_{ins} \cdot C_{ins} \tag{11}$$

Where the quantity of insulation used to insulate the duct is denoted by $u_{ins}$ which depend on the external surface area of the duct and the thickness of the insulation layer. The one cubic meter of insulation quantity cost is $C_{ins}$ (\$/m$^3$). To calculate the economic feasibility of the insulation materials in HVAC duct application, the ratio of life cycle energy cost ($P_1$) and operating expenses ($P_2$) to initial cost must be identified because they are a function of service lifetime (LT), interest rate (ί) and inflation rate (ɗ). The $P_1$ and $P_2$ are calculated as

$$P_1(LT, ί, ɗ) = \sum_{j=1}^{LT} \frac{(1+ί)^{j-1}}{(1+ɗ)^j} = \begin{Bmatrix} \frac{1}{ɗ-ί}\left[1 - \left(\frac{1+ί}{1+ɗ}\right)^{LT}\right] & if\ ɗ \neq ί \\ \frac{LT}{1+ί} & if\ ɗ = ί \end{Bmatrix} \tag{12}$$

$$P_2 = 1 + P_1 MR - SV(1+ɗ)^{LT} \tag{13}$$

Where, the ratio of maintenance to initial cost (MR) and salvage value to initial cost (SV), which are equal to zero because maintenance is not needed for the insulated duct and insulation is not resalable at its end life as reported in (Kumar et al. 2019; Kumar et al. 2018a; Kumar et al. 2018b; Kumar et al. 2018c; Soponpongpipat et al. 2010; Yildiz & Ersöz 2016). Therefore, $P_2$=1. On the basis of $P_1$ and $P_2$, the total LCC of insulation materials and associated fuel savings in the duct are determined by,

$$C_T = C_E P_1 + C_I P_2 \tag{14}$$

The cost-saving (\$/m-year) associated with the insulated duct is determined as

$$CS = \frac{\dot{Q}_{save} C_F\, P_1}{HV\ COP} + C_I P_2 \tag{15}$$

The payback period (PP) of insulation cost would be recovered by decreasing the operational cost associated with fuel savings over the expected service life of the HVAC system.

$$PP = \begin{cases} \ln\left[\left(1 - \frac{C_I(d-i)}{\left(\frac{Q_{save}C_F}{HV\ COP}\right)}\right) - \left(\frac{1+i}{1+d}\right)\right], & if\, d \neq i \\ \left[\frac{C_I(1+i)}{\left(\frac{Q_{save}C_F}{HV\ COP}\right)}\right], & if\, d = i \end{cases} \tag{16}$$

# 3. RESULTS AND DISCUSSIONS

## 3.1. Summary of the results

The present study investigated the use of an air gap in an insulated duct using LCC analysis. It first increases the insulation thickness over the bared duct to determine the optimum insulation thickness corresponding to maximum cost savings and minimum payback period for the duct with and without an air gap. The effect of insulation and air gap thickness is on life cycle cost, cost savings, and payback period are illustrated in Figs. 3-5. The value of optimum insulation thickness of the duct with and without air gap corresponding to maximum cost savings and a minimum payback period of insulation cost is tabulated in Table 4. The outcomes of the present study are compared to the other relevant previous studies as given in Table 5. The results of the present study are discussed as follow:

### 3.1.1. Influence of increases in insulation thickness along with duct size and insulation types on LCC with and without air gap

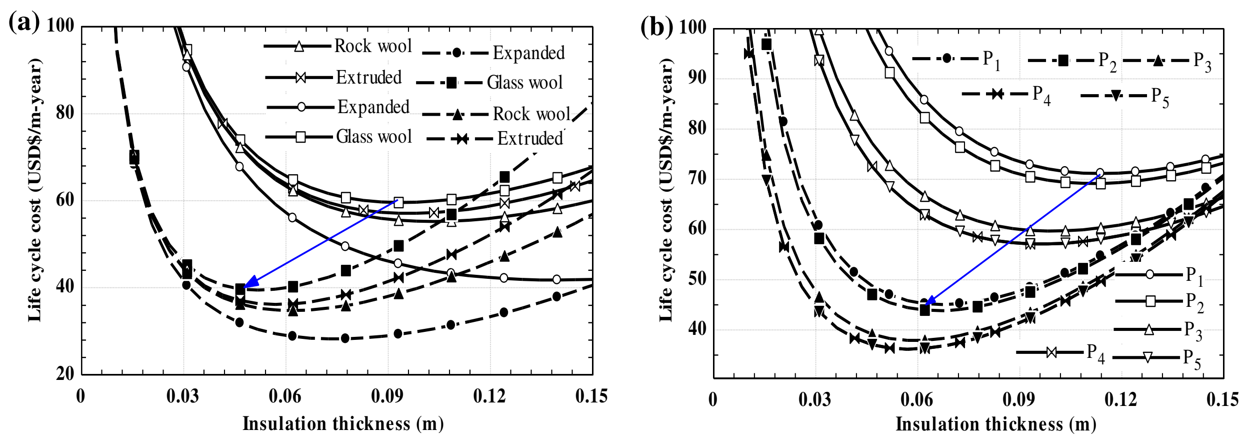


**Fig. 3** Variation in LCC with insulation thickness, insulation types, air gap, and duct size in the HVAC duct application.

Fig. 3 shows that an increment in insulation thickness first lowers the LCC of the insulated duct up to the minimum point and then counteracts insulation thickness. It happens because the use of insulation on the duct diminishes the fuel cost dramatically, while the insulation cost increases steadily. The insulation thickness corresponding to minimum LCC is termed as economic or optimum insulation thickness of the duct. Once insulation thickness is minimized afterward, the addition of the insulation layer is not economically feasible. It minimums the cost-saving (Fig. 4) and prolongs the payback period on insulation cost (Fig. 5). The rise of an air gap and insulation thickness on the duct is represented by dash lines, while thick dark lines denote the rise of only insulation thickness. As seen in Figs. 3 (a & b), the dash lines show a lower value of minimum LCC than the dash lines. It has been confirmed that the air gap reduces the minimum LCC of the insulated duct and dwindles the optimum insulation thickness for the duct depending on the insulation types (Fig. 3a) and duct size (Fig. 3b).

Thermal conductivity of different insulation materials and their costs are tabulated in Table 4. It is noted that rock wool has the highest value of thermal conductivity (0.43 W/m.K), whereas the extruded polystyrene has the most negligible value of thermal conductivity (0.25 W/m.K). However, the expanded polystyrene is the cheapest, and expanded polystyrene is the most expensive insulation material with a unit cost of USD 47/m$^3$ and USD 120/m$^3$, respectively. Therefore, the LCC of an insulated duct with and without air gap had a different value for each insulation material, as seen in Fig. 3a. For example, the least value of LCC is investigated for expanded polystyrene, i.e. USD 79/m/year for the duct size of 580 mm corresponding to insulation thickness of 140 mm. Contrarily, the same duct size insulated with glass wool costs a minimum LCC of USD 59.59/m/year with an insulation thickness of 93 mm. The use of extruded polystyrene and rock wool produces the minimum LCC of USD 57.11 and 55.22/m/year, corresponding to insulation thickness of 98 mm and 103 mm, respectively. The air gap has further minimized the LCC of extruded and expanded polystyrene, glass, and rock wool by USD 21, USD 13.74, USD 20, and USD 20.44/m/year, respectively.

The impact of insulation thickness on the minimum life cycle cost of different ducts is illustrated in Fig. 3b. The central duct has equivalent hydraulic diameters of 580 mm and 550 mm, respectively, connected with three branches to supply air to two different zones, as seen in Fig.1. The duct size of 420 mm supplies air to zone-I, while two duct branches of equal size with 380 mm of equivalent hydraulic diameter supply air to zone-II. The larger duct size of 580 mm insulated with extruded polystyrene requires a higher life cycle cost than a smaller duct size of 380 mm because both insulation and fuel cost is high for larger size ducts. The increment in duct size increases the life cycle cost and maximums the insulation thickness of the duct. The use of the air gap lowers the insulation thickness for smaller duct sizes by 41 mm, whilst the larger duct size shows a decrement of 47mm. Consequently, the air gap is more effective in a larger size than a smaller one. The insulation thickness corresponding to a maximum cost savings potential of insulation and its minimum payback period is considered optimization criteria. The effect of insulation thickness on the cost savings and payback period for the duct with and without air gap is illustrated in Fig. 4 and 5, respectively.

#### 3.1.2. Influence of increases in insulation thickness along with duct size and insulation types on annual cost-saving potential of an insulated duct with and without air gap

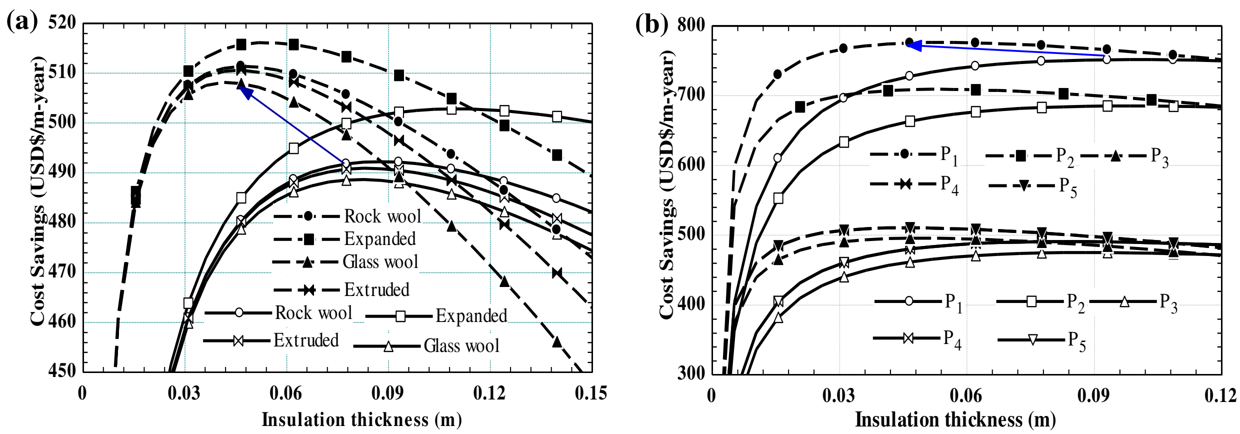


**Fig. 4** Variation in cost savings with insulation thickness, insulation types, air gap, and duct size in the HVAC duct application.

Fig. 4 shows the variation in cost savings (USD$/m-per year) of (a) different insulation types in (b) different duct sizes with increases in insulation thickness with and without air gap. The cost-saving increases dramatically with insulation and air gap thickness then gradually curve to peak and finally drop with further increment in insulation and air gap thickness. The insulation thickness at which cost savings potential peaks is known as optimum insulation thickness. The optimum insulation thickness varies with insulation materials and duct sizes. For instance, the cost savings potential of different insulation materials differs from each other because of their thermal conductivity and cost. As a result, the cheapest insulation material saves more fuel than the expensive one. For example, the thermal conductivity of glass wool is just 0.002 W/m/K more significant than the expanded polystyrene, yet glass wool saves USD 17.6/m/year lesser than expanded polystyrene because of its high initial cost. Despite this, expanded polystyrene (128 mm) is more than glass wool (98 mm) to maximize the cost savings. The extruded polystyrene has the least value of thermal conductivity and the highest insulation cost among different insulation materials. The cost-saving potential of extruded polystyrene (USD 751.7/m/year) is higher than glass wool (USD 749.2/m/year); even extruded polystyrene optimum insulation thickness is larger by 3 mm. The thermal conductivity and insulation cost are both influencing parameters to be considered to determine optimum insulation thickness. The rise of insulation thickness along with the air gap has increased the cost savings potential of expanded and extruded polystyrene and rock and glass wool by 2.1%, 3.3%, 3.1%, and 3.2%, respectively. Their respective optimum insulation thickness is dropped from 128 mm to 64 mm, 101 mm to 55 mm, 104 mm to 58 mm, and 98 mm to 48 mm.

The ducts are insulated with extruded polystyrene to investigate the impact of duct size along with insulation thickness and air gap. As seen in Fig. 4b, the cost savings escalates with the increase in duct size depending on insulation types. An air gap further enhances cost savings. Both main branches of 580 mm and 550 mm show maximum cost savings potential of USD 752/m/year and USD$685/m/year, respectively, which are increased to USD 776.2 and USD 709.2 by an air gap. The zone-II branches (380 mm) show a cost-saving of USD 491/m/year, followed by the zone-I branch of 420 mm diameter, having cost savings of USD 475/m/year. The air gap drops optimum insulation thickness for larger duct sizes by 45-47% as opposed to smaller sizes, i.e. 44.4-44.8%. Moreover, the cost savings corresponding to optimum insulation thicknesses of different insulation materials used in different duct sizes are tabulated in Table 4.

### 3.1.3. Influence of increases in insulation thickness along with duct size and insulation types on payback period of insulation cost of an insulated duct with and without air gap

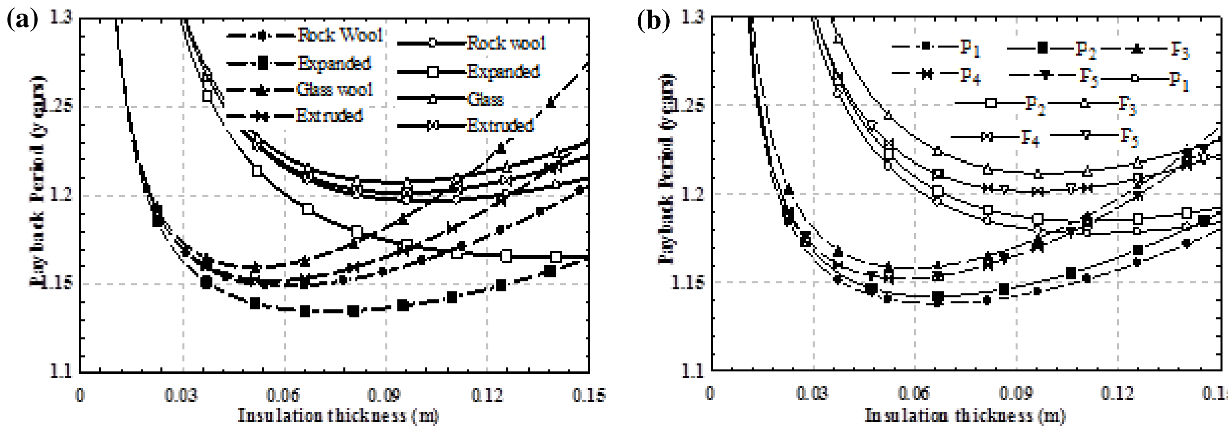


**Fig. 5** Variation in a payback period of different insulation materials **(a)** used in different duct sizes **(b)**.

Figs. 5(a & b) shows the effect of the air gap (dash lines) and insulation thickness (dark lines) on the payback period of four insulation types and five duct sizes. The payback period of insulation cost incurred on the duct without the air gap is more extended than the insulated duct with an air gap. As seen in Fig. 5a, the expanded polystyrene cost recovers within the shortest time interval because of its highest cost savings potential. On the other hand, the duct insulated with glass wool insulation has the highest payback period of above 1.2 years, which is further dropped to 1.15 years by an air gap. Extruded polystyrene is the most expensive insulation material that requires 1.178 years to pay back its initial investment, followed by glass wool. An air gap in an insulated duct with rock wool lowers its payback period by 0.04 years compared to the insulated duct.

The influence of duct size along with the insulation thickness of extruded polystyrene is illustrated in Fig. 5b. The larger duct sizes, such as main branches, require a shorter time to recover the initial investment in insulation materials. Conversely, the payback period of the insulated duct of smaller sizes is higher than the larger one because of their lower cost savings potential. The payback of selected ducts having an equivalent hydraulic diameter of 580 mm, 550 mm, 420 mm, and 380 mm recover initial insulation cost with a period of 1.178 years, 1.185 years, 1.212 years, and 1.202 years, respectively. The use of an air gap averagely dropped the payback period by 0.05 years for selected duct sizes. Among different insulation materials, expanded polystyrene is determined as the most economic insulation material used in HVAC duct application because of its minimum payback period. However, the air gap is more effective in a larger diameter duct because of the maximum drop in the payback period. The optimum insulation thicknesses corresponding to maximum cost savings and a minimum payback period of insulated ducts with and without air gap are given in Table 5.

**Table 5** The life cycle cost, annual cost savings, and a payback period of different insulation materials used in the duct with and with an air gap.

| Insulation materials/duct sizes | | Insulated duct without air gap | | | | | Insulated duct with an air gap | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | V | I | II | III | IV | V |
| OIT (m) | RW | 104.1 | 101 | 91.84 | 79.59 | 79.59 | 58.16 | 55.1 | 48.98 | 45.92 | 45.92 |
| | GW | 97.96 | 94.9 | 82.65 | 79.59 | 79.59 | 48.98 | 48.98 | 45.92 | 42.86 | 42.86 |
| | XPS | 101 | 97.96 | 88.78 | 82.65 | 82.65 | 55.1 | 52.04 | 48.98 | 45.92 | 45.92 |
| | EPS | 128.6 | 125.5 | 119.4 | 104.1 | 104.1 | 64.29 | 61.22 | 58.16 | 52.04 | 52.04 |
| LCC ($/m$^2$-year) | RW | 68.36 | 66.52 | 57.65 | 55.23 | 55.23 | 43.06 | 41.92 | 36.37 | 34.78 | 34.78 |
| | GW | 73.88 | 71.87 | 62.21 | 59.59 | 59.59 | 49.21 | 47.87 | 41.32 | 39.44 | 39.44 |
| | XPS | 71.13 | 69.15 | 59.68 | 57.1 | 57.1 | 45.06 | 43.84 | 37.87 | 36.17 | 36.17 |
| | EPS | 52.02 | 50.51 | 43.66 | 41.79 | 41.79 | 35.25 | 34.28 | 29.6 | 28.25 | 28.25 |
| Cost Savings ($/m$^2$-year) | RW | 753.7 | 687.3 | 476.6 | 492.3 | 492.3 | 777.4 | 710.4 | 496.7 | 511.4 | 511.4 |
| | GW | 749.2 | 682.8 | 472.7 | 488.6 | 488.6 | 773.2 | 706.2 | 493.1 | 508.2 | 508.2 |
| | XPS | 751.7 | 685.4 | 475.1 | 490.9 | 490.9 | 776.2 | 709.2 | 495.8 | 510.6 | 510.6 |
| | EPS | 766.8 | 700.2 | 488.2 | 502.8 | 502.8 | 783.1 | 716.1 | 502 | 516.2 | 516.2 |
| Payback Period (years) | RW | 1.174 | 1.18 | 1.207 | 1.197 | 1.197 | 1.135 | 1.139 | 1.155 | 1.149 | 1.149 |
| | GW | 1.182 | 1.19 | 1.218 | 1.208 | 1.208 | 1.144 | 1.149 | 1.166 | 1.16 | 1.16 |
| | XPS | 1.178 | 1.185 | 1.212 | 1.202 | 1.202 | 1.138 | 1.142 | 1.158 | 1.152 | 1.152 |
| | EPS | 1.149 | 1.154 | 1.173 | 1.166 | 1.166 | 1.124 | 1.127 | 1.139 | 1.135 | 1.135 |

Note: Rock wool (RW), glass wool (GW), extruded polystyrene (XPS), and expanded polystyrene (EPS).

## 4. Discussion: comparison of current results with previous studies

The present study's results are compared to the related studies conducted regarding thermodynamics and LCC analysis of HVAC duct in different countries tabulated in Table 5. For instance, Sahin & Kalyon (2005) investigated that the convective and radiative heat transfer coefficient did not affect the insulation thickness on the duct at constant surface temperature. This study was extended by Soponpongpipat et al. (2010). They found that the optimum insulation thickness of the duct is independent of the variation in indoor and outdoor convective heat transfer coefficient. The found optimum insulation thickness of double-layered duct with glass wool and rubber was 32 and 125 mm, respectively. In Turkey, Yildiz and Ersoz (2016) investigated that the optimum insulation thickness of glass and rock wool of the duct increases with wind velocity. They determined optimum insulation thickness for duct insulated with glass and rock wool were varying between 128.5 and 239.1 mm and 118.7 and 222.1 mm, respectively, depending on fuel types and duct sizes. Gao et al. (2018) introduced a novel duct tee that had lowered the resistance to airflow by 42% as opposed to conventional duct tees. Kumar et al. (2018c, 2019) used degree-days and LCC analysis to determine the optimum insulation thickness considering different duct sizes, insulation types and cost, fuel characteristics, and four regional fuel prices. They investigated the optimum insulation thickness in the range of 42-96 mm depending on the considered parameters. When compared to the findings of the studies mentioned above, it is clear that the optimum insulation thickness of the insulated duct with and without an air gap is in the same range as reported by previous studies. The difference between the results of the present study (42-128 mm) and other related studies (23-239 mm) occurs because parameters such as insulation types and cost, climatic conditions, economic conditions (inflation and interest rate) and fuel types and cost, and insulation material service lifetime which are different from previous studies.

**Table 5** The results summary of the present study and other studies related to optimum insulation thickness for HVAC duct.

| **Reference Study** | **Location and Year** | **Method** | **Insulation materials** | **Fuel Types** | **Optimum Insulation Thickness (mm)** |
|---|---|---|---|---|---|
| Present Study | Pakistan | The thermodynamic and LCC analysis | RW, GW, XP, EP | NG | All: 80-128 mm and 42-61 mm for insulated duct without and with an air gap, depending on insulation types and duct size. |
| Kumar et al. (2019) | Pakistan 2019 | Degree-Days and LCC analysis | RW, GW, Aeroflex, EP | Coal, fuel–oil, LPG, NG, electricity, RH, DPR, and Bagasse. | EP: 161.8 mm and 83.5 mm for gas and coal-fired heat sources. |
| Herranz García & García Navarro (2018) | Spain 2018 | LCA | GW | | |
| Gao et al. (2018) | China 2018 | Thermodynamic analysis | Tee design modification | Fuel is not considered. Introduced a novel duct tee which had lowered the resistance | |

| | | | | | |
|---|---|---|---|---|---|
| | | | | to airflow by 42% as opposed to conventional duct tees. | |
| Kumar et al. (2018c) | Pakistan 2018 | Thermodynamic and LCC analysis | GW | NG | All: 40-90 mm depending on insulation materials and fuel types. |
| Yildiz & Ersoz (2016) | Turkey 2016 | Degree-Days and $P_1$-$P_2$ Method | GW and RW | Electricity, NG, LPG FO & Coal | GW: 128-239mm and RW: 118-222mm for different duct sizes, depending on fuel type. |
| Soponpongpipat et al. (2010) | Thailand 2010 | Thermodynamic and LCC analysis | GW and Rubber | Electricity | All: 23 and 125 mm for rubber and glass wool, respectively. |
| Sahin (2005) | Saudi Arabia 2005 | Thermodynamic analysis | GW | Fuel is not considered. Insulation thickness of the duct is independent of convective and radiative heat transfer coefficient at uniform external surface temperature. | |

Note: Rock wool (RW), Glass wool (GW), Extruded Polystyrene (XP), Expanded Polystyrene (EP), Bubble Pack Reflective Insulation (BPRI), Liquefied natural gas (LNG), Natural Gas (NG), and Fuel Oil (FO).

## 5. CONCLUSION

### 5.1 Summary of Results

This research estimates the optimum insulation thickness of the ducts with and without an air gap using life-cycle cost analysis, cost-savings, and payback period approach. In total, four insulation materials and five duct sizes were in the optimization analysis. The findings showed that the use of an air gap in an insulated duct lowers the optimum insulation thickness for the duct and maximizes the cost savings potential of selected insulation types. Moreover, the payback period of insulation cost has been shortening by implication of an air gap. In the largest duct sizes, an air gap is most effective in terms of cost savings and payback period corresponding to optimum insulation thickness for the duct. Conversely, in the case of smaller duct sizes, an air gap minutely prolongs the cost savings but lowers the optimum insulation thickness by 44% instead of simply insulated one. The optimum insulation and air gap thicknesses for different duct sizes are in the range of 42-61 mm and 38-67 mm, respectively, depending on insulation types and duct size.

Among different insulation materials, minor cost savings of USD 488-749/m/year and the most extended payback period of 1.18-1.21 years are determined for glass wool because of its higher cost and thermal conductivity. On the other hand, the expanded polystyrene has produced the highest cost savings of USD 503-767/m/year and the shortest payback period of 1.149-1.166

years despite having higher thermal conductivity than extruded polystyrene. The cost savings and payback period of rock and glass wool are increased from USD 753 to USD 777.4/m/year and USD 749 to USD 773/m/year, respectively, by an air gap. Similarly, the air gap in duct insulated with extruded and expanded polystyrene has enhanced the cost savings by USD 24.3 and USD$16.3/m/year, respectively. Moreover, the air gap is most effective with a cost savings increment potential of 3.4% of the duct insulated with rock wool compared to others. It means that the insulation material with a high thermal conductivity value needs extra thermal resistance to reduce the heat transfer for maximum cost savings.

In conclusion, the use of expanded polystyrene is investigated as the most economic option to be used in HVAC duct applications. An air gap is found to be most effective in terms of cost and energy savings for the duct insulated with rock wool.

### 5.2 Implication and Future Research Recommendations

The research can be employed to the HVAC ducts installed in residential and commercial buildings at the preliminary design stage of the HVAC system for a particular climatic region and economic condition. In addition, the outcomes will help to build service engineers, designers, architects, and policymakers to consider the air gap an energy-efficient and cost-effective design option for the ducts.

The passive and nearly or net-zero energy buildings (NZEB) consume lesser operation energy than conventional buildings (Klingenberg et al. 2016). For example, according to Wu and Skye (2018), the HVAC system integrated into a solar-assisted ground source heat pump (GSHP) system in NZEB has lessened the operation energy consumption by 39% instead of a conventional HVAC system. Therefore, insulation and air gap must be selected from a life cycle energy (production and operation energy use) and cost perspective to ensure a sustainable built environment.

## Ethical Approval and Consent to Participate

Not applicable.

## Consent to Publish

All authors read and approved the final manuscript.

## Authors' Contributions

**Dileep Kumar**: Conceptualization, investigation, methodology, formal analysis, writing-original draft and editing and answered reviewers' comments. **Muhammad Haris Khan**: Conceptualization, prepared the data, helped in investigation and validation, **Muhammad Ali Abro**: Data Review, supervised writing and editing, draft finalization, and answered reviewers' comments.


## Funding

Authors are thankful to the Higher Education Commission (HEC) Pakistan for supporting their research work under the HEC-SUT joint scholarship.


## Competing Interests

The authors declare that they have no competing interests.

## Availability of data and materials

All data generated or analyzed during this study are included only in this paper and are not available in any other works.


## Acknowledgment

The authors would like to thank Engr. Muhammad Hakeem for collection of required design and operating parameters date for the analysis.

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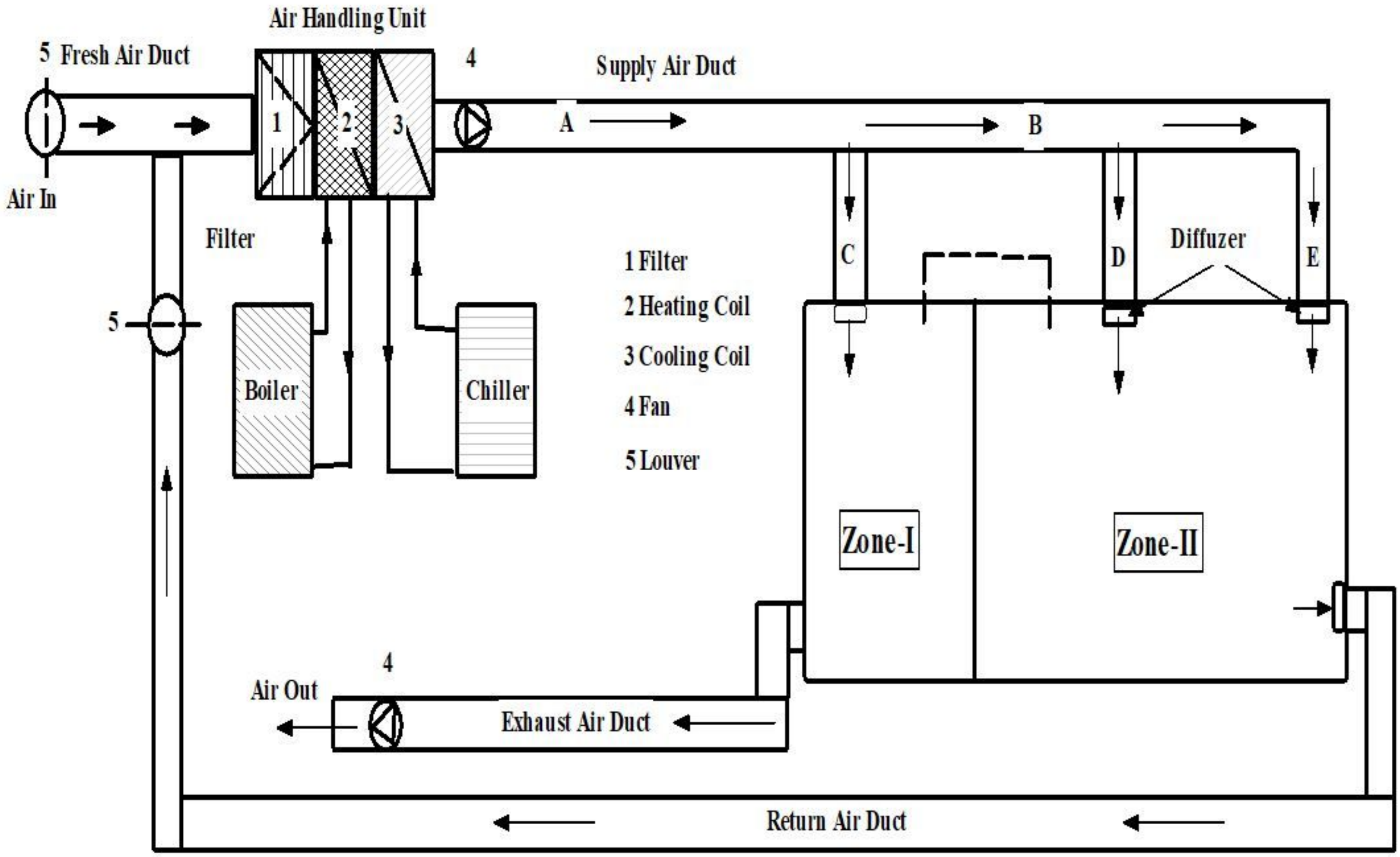
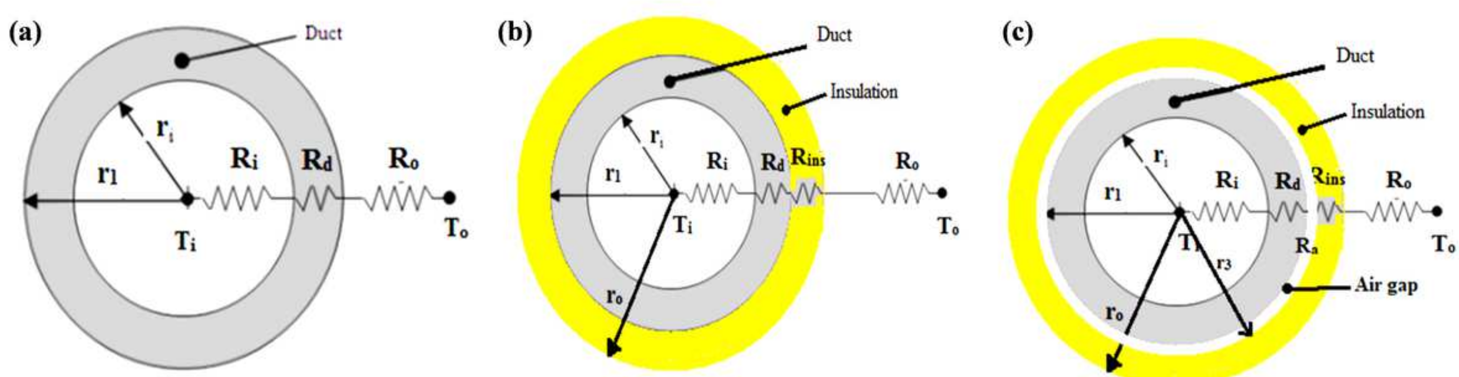
# Figures



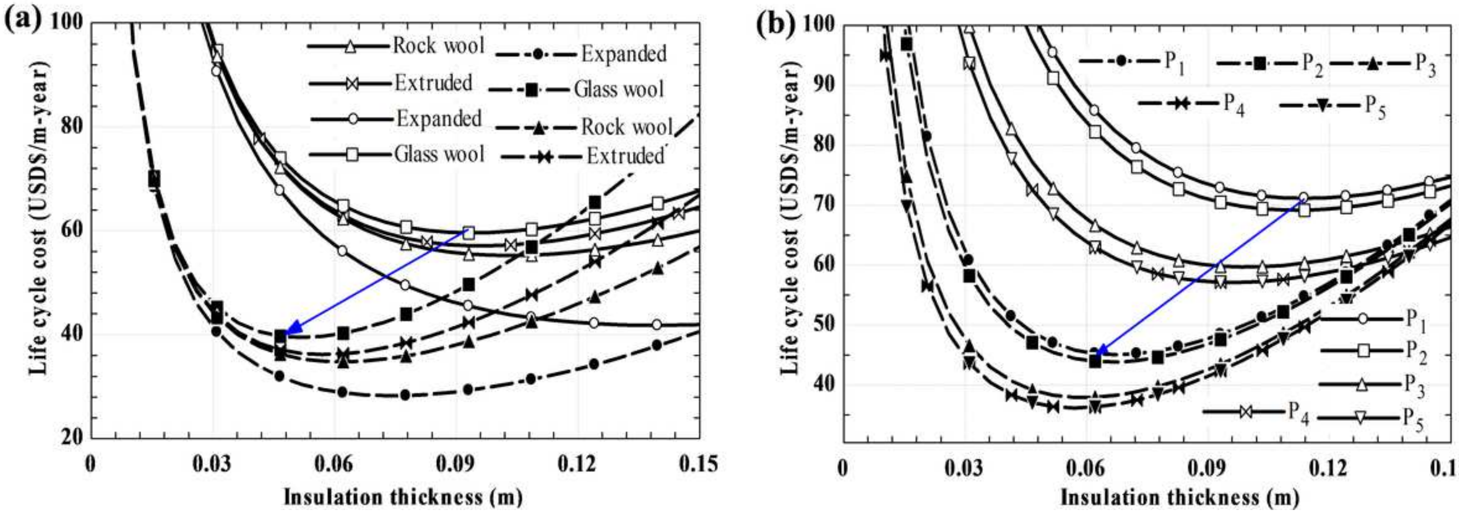

## Figure 1

Schematic layout of a selected HVAC system.



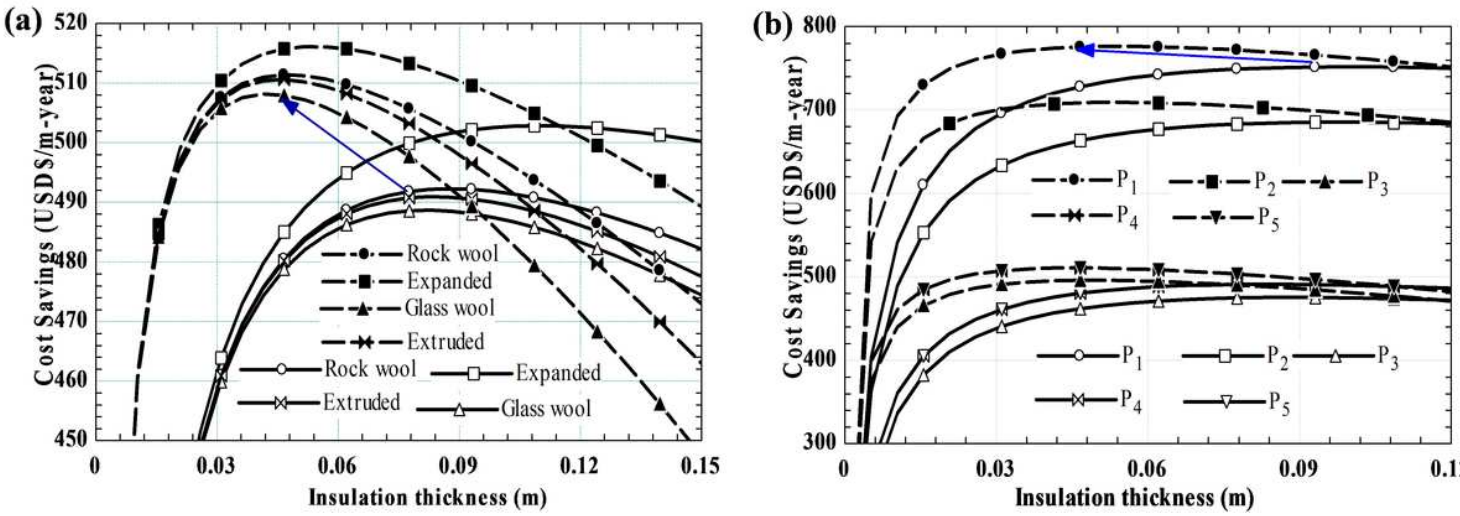

## Figure 2

The cross-sectional area of the bared duct (a) and duct insulated with insulation materials without (b) and with (c) an air gap.



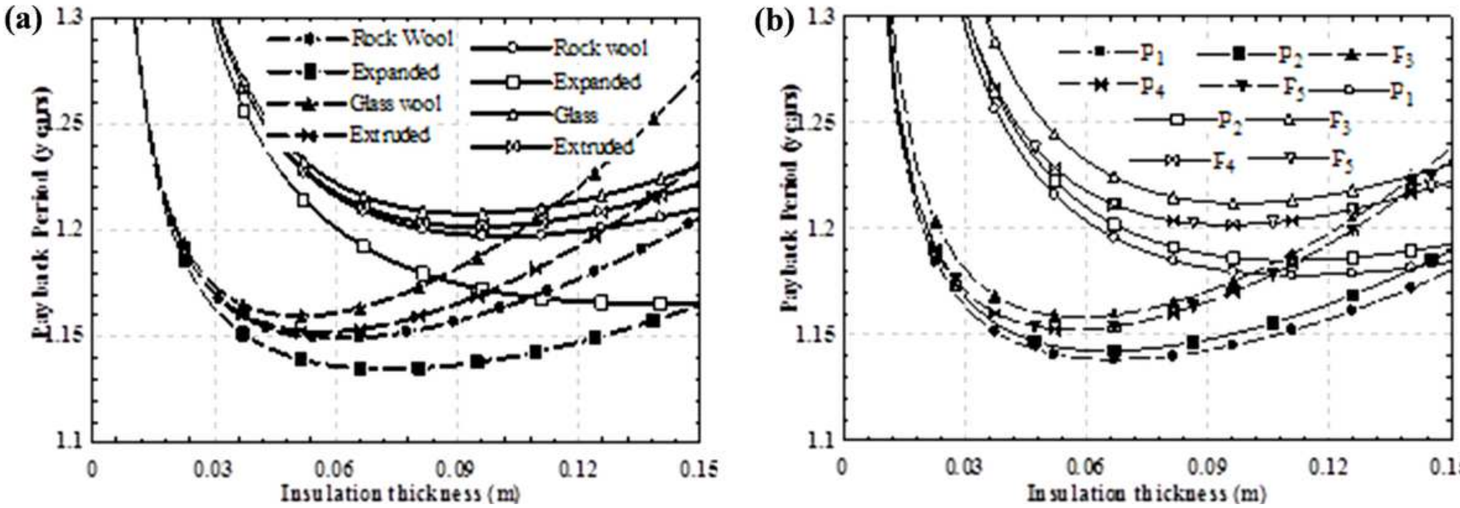

## Figure 3

Variation in LCC with insulation thickness, insulation types, air gap, and duct size in the HVAC duct application.




## Figure 4

Variation in cost savings with insulation thickness, insulation types, air gap, and duct size in the HVAC duct application.




## Figure 5

Variation in a payback period of different insulation materials (a) used in different duct sizes (b).