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RESEARCH ARTICLE

Lifecycle cost analysis of an insulated duct with an air gap

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Abstract

The insulation materials are used to reduce heat loss to/from the ducts with additional investment. This study introduces an air gap between insulation and duct surface to reduce the quantity of insulation. It uses lifecycle 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 was fed in LCC analysis to determine the impact of the air gap on optimum insulation thickness (OIT) corresponding to the minimum LCC and payback period. Results revealed that OIT thickness for a duct with an air gap was lower than insulated duct without an air gap, resulting in maximum cost savings within a shorter payback period. Among different insulation materials, insulated duct with expanded polystyrene was investigated as cost-effective insulation material with maximum cost savings of USD (508.8–766.8)/m/year and a payback period of 1.15–1.17 years. On the contrary, the air gap was the most effective in terms of cost savings for the ducts insulated with rock wool. In conclusion, an air gap is a cost-effective design approach for duct applications.

Keywords Air gap · Cost savings · LCC analysis · Ducts · Insulation materials

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%) (Pérez-Lombard et al., 2008). It is responsible for 36% of greenhouse gas emissions in developed countries (Rashad, 2021). In an HVAC system, a significant share of energy is 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 (Mageshwaran et al., 2018).

The insulation materials are used to decrease heat transfer through HVAC ducts and pipes (Kaynakli, 2014), and building envelopes (Kumar et al., 2020a). The pipes and ducts are made up of fragile metallic sheets; thereby, they have very high thermal conductivity and meagre 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 energy loss due to heat gain and loss into the immediate surroundings. Heat transfer accounts for 10–45% of space cooling and heating demand in a single-family residential building (Shapiro et al., 2013). The heat transfer through the

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duct is particularly severe in hot climatic regions because of the high-temperature difference between conditioned air and its surroundings, exacerbating the heat transfer. It worsens in peak hours, substantially lowering the duct system efficiencies under the hottest attic and the highest run time. In three family's 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, 2012).

Several studies have investigated the OIT for piping/ducting using LCC analysis, calculating heat transfer analytically and numerically through pipes and ducts, considering different insulation and pipe materials, energy sources, and climates (Kaynakli, 2012). For instance, Zaki and A. M. A.-T. (2000) studied the optimization of multi-layer thermal insulation for hot water pipelines irrespective of radiative heat loss. At the same time, Sahin and Kalyon (2005) investigated that the insulation thickness for hot water pipes was independent of both convective and radiative heat loss. Soponpongpipat and Jaruyanon (2010) determined that energy savings through ducts were increasing with the convective heat transfer through the duct without changing its OIT. Yildiz and Ersöz (2016) determined the impact of wind speed on glass wool and rock wool insulation thickness on the duct, considering natural gas and LPG as fuel for chiller operation. They found that LPG-operated HVAC systems have saved energy at high wind speed, while natural gas-fired chiller system has the lowest energy savings at a low wind speed of 0.2 m/s.

Kumar et al. (2017) have investigated that the insulation compression on HVAC ducts' external surface, installed in Pharmaceutical company, increasing cooling energy use by 14% and supply air temperature by 0.4 °C impairing indoor thermal comfort. They developed a heat transfer equation for estimating energy loss and condensation on the insulated duct due to compression of thermal insulation, considering constant (Kumar et al., 2018b) and variable (Kumar et al., 2018a) ambient air convective heat transfer coefficient for HVAC duct installed in the ceiling area and plant room. Parametrically, the volume flow rate of conditioned air through the duct should be greater than 1.4 m^3/s with a critical insulation thickness of 30 mm on the point of compression for eliminating chances of condensation on the insulated duct surface. Moreover, they found that the OIT (28 to 45 mm) corresponding to maximum cost saving for ducts was higher than their respective critical insulation thickness (30 mm). Therefore, they suggested OIT for the duct due to cost-effectiveness without condensation (Kumar et al., 2019). Ucar (2010) has used rigid insulation materials such as extruded polystyrene for avoiding compression of insulation. He determined that the OIT for pipe varies with the climatic conditions. For instance, they investigated OITs of 30–57 cm for piping networks installed in different cities of Turkey. Moreover, the OIT is highly variable with inflation and discount rate instead of operating parameters. Kumar et al. (2020b) had investigated that insulating smaller duct size produces maximum energy savings (84.91%) than larger duct sizes (50.24%) depending on fuel type. The maximum value of CO_2 and CO emission is determined for smaller duct size in the case of natural gas (81%) and SO_2 emission of 76.66% in the case of fuel oil. The OIT was investigated around 42–96 mm and 118–239.1 mm for the duct installed in a pharmaceutical building, Pakistan (Kumar et al., 2020b) and commercial buildings in Turkey (Yildiz and Ersöz, 2016), respectively. The investigated thicknesses were higher than commercially available insulation materials for building applications (Schiavoni et al., 2016). Hence, there is a need to reduce the duct's insulation thickness without increasing energy loss through the duct (Kumar et al., 2017). Therefore, this study introduced an air gap in an insulated duct to reduce insulation thickness without increasing energy loss because the air gap resists heat loss/gain through the duct due to its lower thermal conductivity than metal (Cengel, 1997). Ducts are made of galvanized aluminium sheets with thermal conductivity of 60 W/m–K (Pan et al., 2018) (Kumar et al., 2019). The difference between the present study and previous studies is tabulated in Table 1.

This study aims to reduce insulation thickness for HVAC ducts without increasing energy loss and cost by introducing an air gap in an insulated duct. Firstly, it determines the energy loss due to heat transfer through the ducts using thermodynamic analysis, considering operating conditions of ducting network installed in a renowned pharmaceutical company, Jamshoro, Pakistan. Then, the estimated energy loss was added in LCC analysis to determine the OIT for ducts corresponding to maximum cost savings and minimum payback period. It afterward determines the impact of an air gap on OIT for the duct using LCC approaches. Finally, it discusses the results and draws a meaningful conclusion before future research recommendations.

Methodology

Figure 1 shows the process diagram of research methodology, including a description of a selected HVAC system, energy analysis, and LCC analysis. Section "Energy loss through the HVAC duct" describes the air distribution network of the HVAC system and its operating parameters (temperature, relative humidity, and airflow rate) and climatic conditions. Secondly, it presents the duct's energy analysis, including two laws such as conservation of mass

Table 1 Difference between previous studies and the present study

Authors	Country	Estimation methods	Fluid	Insulation	Duct	Economic	Findings
(Sahin and 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	The insulation thickness of the duct is independent of convective and radiative heat transfer coefficient at uniform external surface temperature	
(Soponpongpipat and Jaruyanon, 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 and 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, and 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 Ersöz, 2016)	Turkey 2016	P_1–P_2	V_i = 10 m/s V_o = 0.2–7 m/s T_o = 265 K T_f = 310 K HDD = 2300 °C-days Fuel: coal, fuel–oil, LPG, and natural gas	-Single layer of fiber-glass k = 0.037 W/(m K) and rock wool k = 0.039 W/(m K)	k = 14.9 W/(m K) d = 0.4 m t_d = 0.6 mm	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., 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 = 3.9–9.21 mm	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., 2018b)	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 = 0.035 W/(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 and 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

Table 1 (continued)

Authors	Country	Estimation methods	Fluid	Insulation	Duct	Economic	Findings
(Ucar, 2018)	Turkey 2018	Thermo-economic	HDD = 4772; 2653; 2032; and 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, and 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
(Pan et al., 2018)	UK 2019	LCC	$T_f = 40$–90 °C $T_o = 12$ (buried) and 21 °C (heat space) $U_i = 0.85$–3 m/s^2 COP = 5.5 OH = 5040 h Fuel: Natural gas	-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 the return pipe should be sized at low velocity. The optimal flow and return pipe diameters are 77.5 and 92 mm	
(Kumar et al., 2019)	Pakistan 2019	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, and RW0.035		$i = 5\%$ $d = 7\%$ $y = 20$ years	Insulation thickness increases with the size of the duct
(Kumar et al., 2020b)	Pakistan 2020				$k = 60.5$ W/(m K) $d = 0.6$ m		Higher fuel cost maximizes cost saving but does not affect fuel consumption and emission savings
Present Study	Pakistan	LCC	$T_f = 291$–294 K $T_o = 301$–307 K COP = 1.2 OH = 6500 h Fuel: Natural gas	-Double layer of an air gap and EP/XP	$k = 60.5$ W/(m K) $d = 0.6$ m	$i = 5\%$ $d = 9\%$ $y = 20$ years	The air gap halved the OIT for the HVAC duct and also maximizes the energy savings

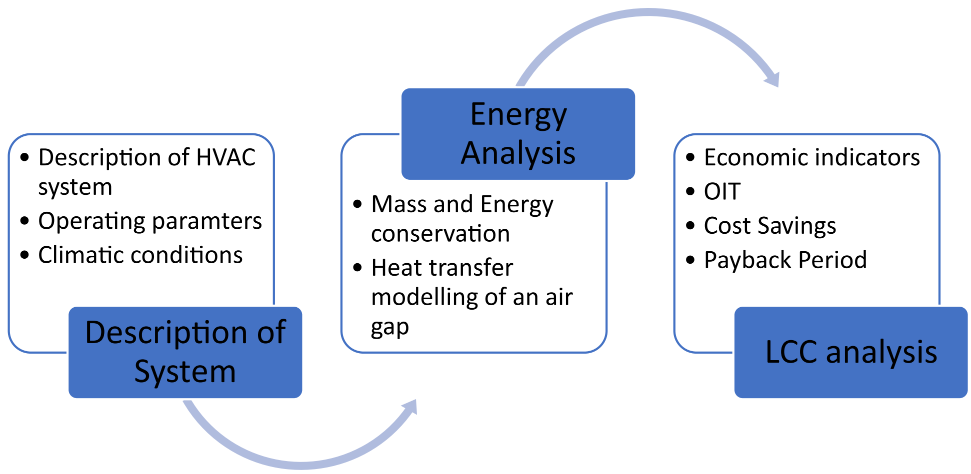

Fig. 1 Process diagram of research methodology

and conservation of energy. The appropriate assumption is made to calculate energy loss through the duct. Finally, it describes LCC analysis to investigate the cost-benefits of air gap in an insulated duct. It calculates the OIT insulation thickness corresponding to cost saving and payback period considering its performance parameters and economic indicators.

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 an acceptable level of thermal comfort and indoor air quality for occupants in residential and office buildings and manufacturing processes in industrial buildings. The boiler generates hot water and steam to operate the humidifier and chiller producing chilled water. The air handling unit conditions air consuming chilled and hot water which is supplied to condition space through an air distribution system including a ducting network of fresh air-conditioned air, return air, and exhaust air. HVAC's duct is made from the galvanized steel, stainless steel and aluminium, and flexible non-metallic materials. Typical HVAC's duct is in an outdoor environment, basement floors, attics, and garages.

In this study, the design and operating parameters were collected from the HVAC duct installed in a pharmaceutical company, Jamshoro, Pakistan, as given in Table 2. The supply air ducts are designed with different sizes and lengths according to airflow and the location of the zone. The HVAC system is operated on a gas-fired chiller having a coefficient of performance (COP) of 1.2. The chiller supplies the chilled water to air handling unit (AHU) to condition outdoor air to designed zone conditions (Fig. 2). The supply airflow rate and temperature are given in Table 2. The weathering parameters were obtained from the Metrological Department of Pakistan, as given in Table 3. Natural gas properties were found in Kumar et al. (2019), and its cost was obtained from the Oil and Gas Regulatory Authority (OGRA) of Pakistan. The insulation cost

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

Note: *SAD*, supply air duct; *RAD*, return air duct.

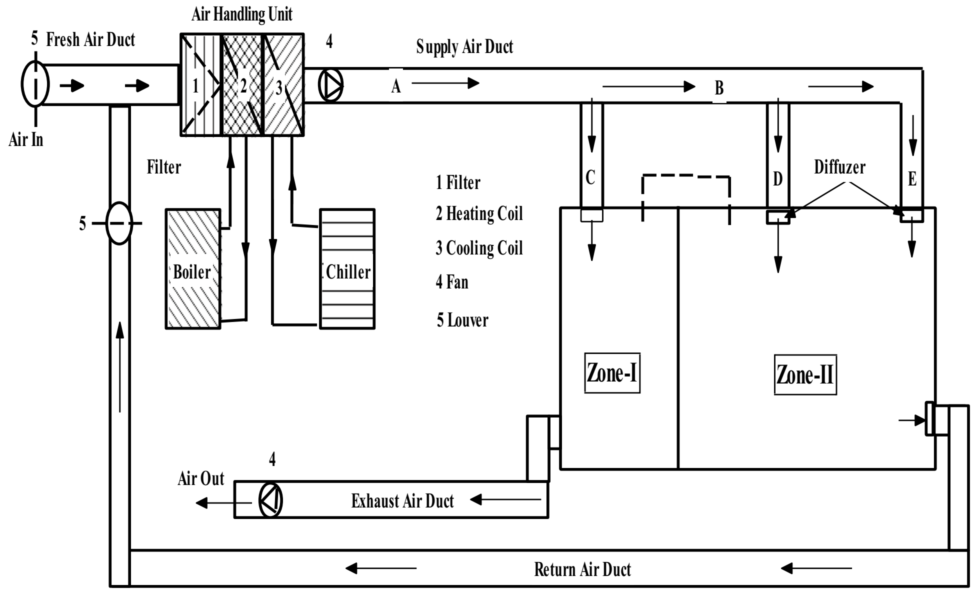

Fig. 2 Schematic layout of a selected HVAC system

Table 3 Ambient conditions of Jamshoro, Pakistan (Baloch et al., 2016)

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

is based on the Project entitled "Heating, Ventilation and Air Conditioning (HVAC) Works of New Calcium Site and Red Area" of Novartis Pharma, Jamshoro, Pakistan. The economic parameters were obtained from the official website of the State Bank of Pakistan (SBP) (Pakistan, 2019).

Energy loss through the HVAC duct

It estimates energy loss through HVAC duct using two basic laws, i.e., conservation of mass and conservation of energy through HVAC duct assuming the following conditions:

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 is negligible because ducts are installed in the plant room and inside the ceiling of the building.
4. Air leakage is negligible due application of duct sealant at joints and bends.
5. Heat generation and pressure drop are negligible due to the smooth surface of the duct.

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

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

where $\dot{Q}_{in}$ represents 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

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

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

$$\frac{1}{R_{\text{ins}}} = \frac{1}{A_{\text{i}} \bullet h_{\text{i}}} + \frac{\ln\left(\frac{r_1}{r_{\text{i}}}\right)}{2\pi \bullet L_{\text{d}} \bullet k_{\text{d}}} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi \bullet L_{\text{d}} \bullet k_{\text{air}}} + \frac{\ln\left(\frac{r_{\text{o}}}{r_3}\right)}{2\pi \bullet L_{\text{d}} \bullet k_{\text{ins}}} + \frac{1}{A_{\text{o}} \bullet h_{\text{o}}} \quad (4)$$

Figure 3 shows the hydraulic radius of (a) bare duct, (b) insulated duct, and (c) insulated duct with an air gap. As seen in Fig. 3, the ***r*** denotes the radius of duct, air gap, and insulation layer, and ***R*** illustrates the thermal resistance offered by interior air, metal sheet, air gap, insulation, and the surrounding air. The T_{i} and T_{o} 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 $A_{\text{i}} = \pi r_{\text{i}}^2$ and $A_o = \pi r_{\text{o}}^2$ for internal and external surfaces, respectively. The heat transfer coefficient of supply air and ambient air are denoted by $\boldsymbol{h_{\text{i}}}$ and $\boldsymbol{h_{\text{o}}}$, respectively. The h_{i} and h_{o} are determined by Kaynakli (2014).

$$h_{\text{i}} = \frac{0.023 \bullet \text{Re}^{0.8} \bullet \text{Pr}^{0.4} \bullet k_{\text{a}}}{D_{\text{h}}} \quad (5)$$

$$h_{\text{o}} = 11.58 \bullet \left(\frac{1}{D_{\text{h}}}\right)^{0.2} \bullet \left\{\left(\frac{1}{T_{\text{s}} + T_{\text{o}}}\right) - 546.3\right\}^{0.181} \bullet (T_{\text{s}} - T_{\text{o}})^{0.266} \bullet (1 + 2.86U_{\text{o}})^{0.5} \quad (6)$$

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 $\boldsymbol{k_{\text{a}}}$. $\boldsymbol{U_{\text{o}}}$ denotes the ambient air wind velocity. $\boldsymbol{T_{\text{s}}}$ and $\boldsymbol{T_{\text{o}}}$ illustrate the temperature at the external surface of the duct and surrounding air. The Reynolds number is calculated as

$$\text{Re} = \frac{U_{\text{SA}} \bullet D_{\text{h}}}{\vartheta_{\text{SA}}} \quad (7)$$

where V_{SA} and ϑ_{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 and Chong 2019)

$$D_{\text{h}} = \frac{1.3(w \bullet h)^{0.625}}{(w + h)^{0.25}} \quad (8)$$

The annual operation energy loss through the duct is estimated as

$$\dot{E}_{\text{loss}} = \left(T_{\text{a}} - T_{\text{s}}\right) . \left(\frac{1}{R_{\text{un-ins}}} - \frac{1}{R_{\text{ins}}}\right) \bullet \Delta h \quad (9)$$

Lifecycle cost (LCC) 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 are 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 OIT corresponding to maximum cost savings of the building envelope (Kumar et al., 2020c), pipes (Kaynakli, 2014), and ducts (Khan et al., 2018) considering performance parameters of systems and economic indicators (inflation and interest rate) of country and insulation investment and fuel billings as given in Table 4 (Kumar et al., 2019).

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

$$C_E = \frac{\dot{E}_{loss}}{HV \bullet COP} \bullet C_F \quad (10)$$

where $HVandCOP$ denote the heating value of the fuel (kJ/m^3) and chiller's coefficient of performance as given in Table 4. The insulation cost is estimated as

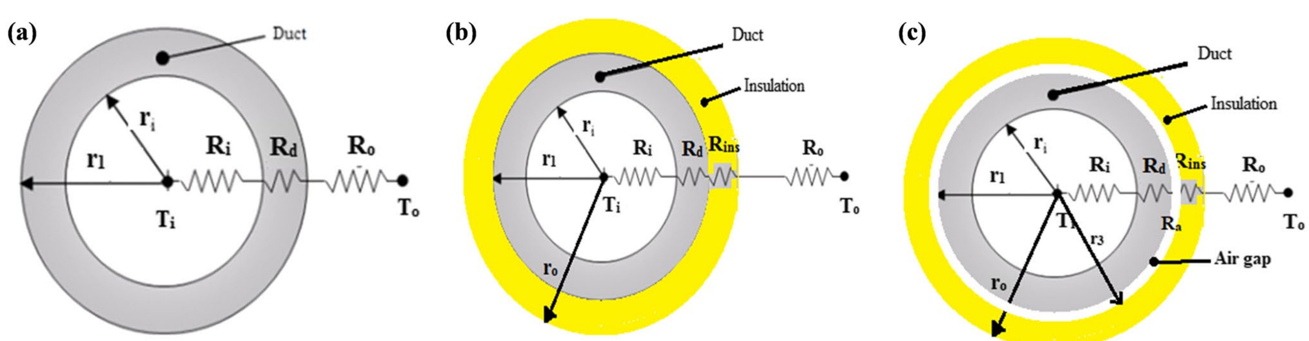

Fig. 3 The cross-sectional area of the bared duct (**a**) and duct insulated with insulation materials without (**b**) and with (**c**) an air gap

Table 4 Thermo-economic parameters and fuel properties considered in the analysis (Nowakowski and Busby, 2001; Sun et al., 2015; Kumar et al., 2019; Pakistan, 2019)

Parameters	Value
Ambient conditions	T_i = see table
COP of chiller	1.2
Fuel type	Natural gas ($C_{1.05}H_4O_{0.034}N_{0.02}$)
Lower heating value (HV)	HV = 34.53 MJ/m^3 and C_f = USD0.37/m^3
Expanded polystyrene	K_{ins} = 0.036 W/m K and C_{ins} = USD47/m^3
Extruded polystyrene	K_{ins} = 0.025 W/m K and C_{ins} = USD120/m^3
Glass wool	K_{ins} = 0.038 W/m K and C_{ins} = USD104/m^3
Rook wool	K_{ins} = 0.043 W/m K and C_{ins} = USD82/m^3
Galvanized steel	K_d = 60.5 W/m K
Interest rate	10.25%
Inflation rate	7.48%
Operating hours	6500 h
Lifetime	20 years

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

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 1 m^3 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 lifecycle 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 (í), and inflation rate (d). The P_1 and P_2 are calculated as

$$P_1\left(LT, \acute{i}, d\right) = \sum_{j=1}^{LT} \frac{\left(1+\acute{i}\right)^{j-1}}{(1+d)^j} = \left\{ \begin{array}{c} \frac{1}{d-\acute{i}}\left[1-\left(\frac{1+\acute{i}}{1+d}\right)^{LT}\right] ifd \neq \acute{i} \\ \frac{LT}{1+\acute{i}} ifd = \acute{i} \end{array} \right\} \tag{12}$$

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

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). 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

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

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

$$PP = \left\{ \begin{array}{c} ln\left[\left(1-\frac{C_I(d-\acute{i})}{\left(\frac{Q_{save}C_F}{HVCOP}\right)}\right)-\left(\frac{1+\acute{i}}{1+d}\right)\right], ifd \neq \acute{i} \\ \left[\frac{C_I(1+\acute{i})}{\left(\frac{Q_{save}C_F}{HVCOP}\right)}\right], ifd = \acute{i} \end{array} \right\} \tag{16}$$

Results and discussions

Summary of the results

The present study aims to investigate the cost benefits of introducing an air gap in an insulated duct using LCC analysis considering different insulation materials. The effect of insulation and air gap thickness on LCC, cost savings, and the payback period is illustrated in Figs. 4, 5, and 6. The OIT for different duct sizes with and without air gap corresponding to maximum cost savings and a minimum payback period is tabulated in Table 5. The outcomes of the present study are compared to the other relevant previous studies as given in Table 6. The results of the present study are discussed as follow:

Influence of increase in insulation thickness along with duct size and insulation types on LCC with and without air gap

Figure 4 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 OIT of the duct. Once OIT is achieved, afterward application of insulation is an economic burden, reducing the cost saving (Fig. 5) and prolongs the payback period (Fig. 6). As seen in Fig. 4, dashed and dark lines show the lifecycle cost incurred on an insulated duct with and without an air gap. The dash lines show minimum LCC than the dark lines, reducing the cost of the insulated duct and almost halve the OIT for the duct depending on the insulation types (Fig. 4a) and duct size (Fig. 4b).

The thermal conductivity of different insulation materials and their costs are tabulated in Table 4. It is noted that rock

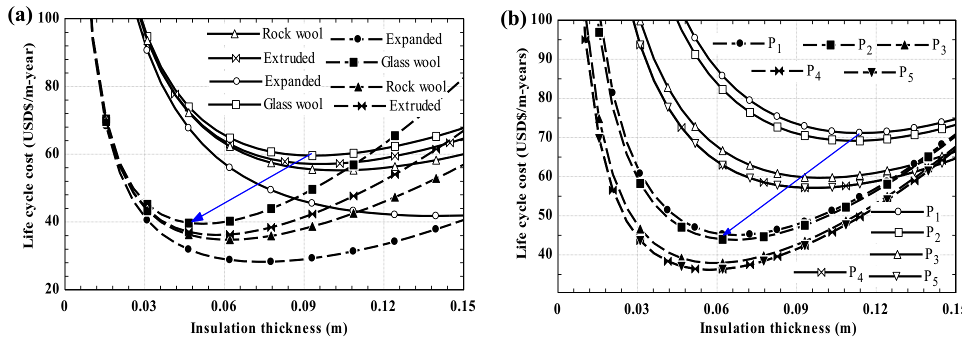

Fig. 4 **a**–**b** Variation in LCC with insulation thickness, insulation types, air gap, and duct size in the HVAC duct application.

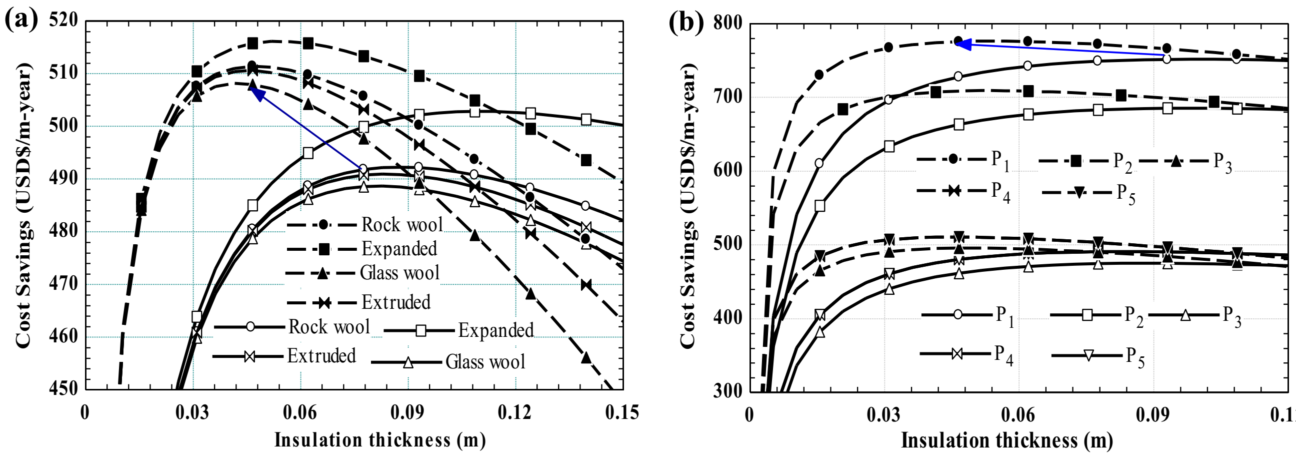

Fig. 5 **a**–**b** Variation in cost savings with insulation thickness, insulation types, air gap, and duct size in the HVAC duct application.

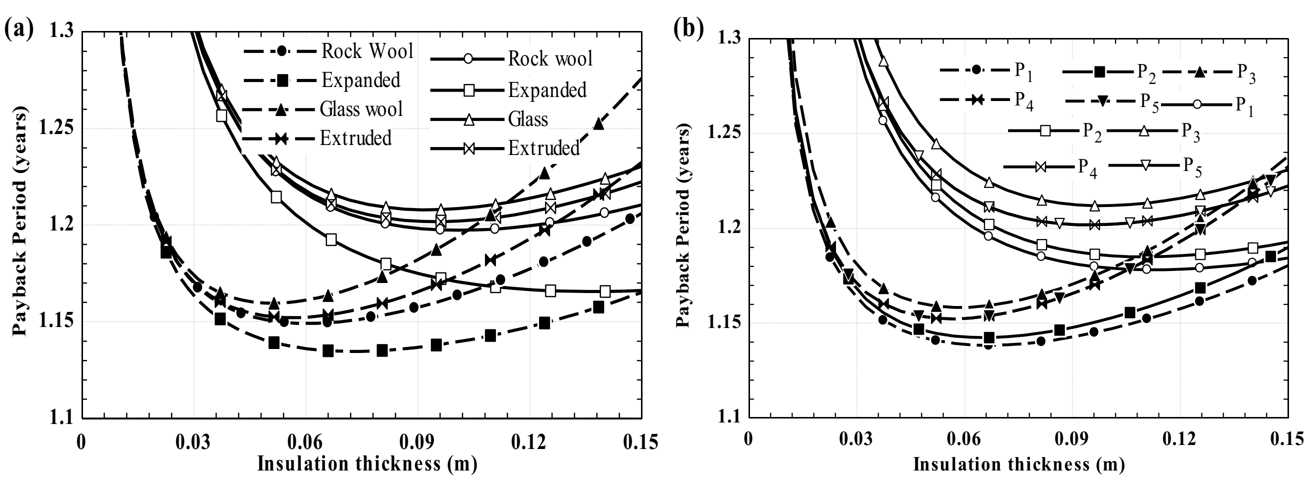

Fig. 6 Variation in a payback period of different insulation materials (**a**) used in different duct sizes (**b**)

wool has the highest thermal conductivity (0.043 W/m.K), whereas the extruded polystyrene has the lowest thermal conductivity (0.025 W/m.K) among different selected insulation materials. However, the expanded polystyrene is the cheapest, and extruded 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

Table 5 OIT thickness corresponding to cost savings and payback period of the insulated duct without and with an air gap considering different insulation materials and duct sizes

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
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: *RW*, rock wool; *GW*, glass wool; *XPS*, extruded polystyrene; *EPS*, expanded polystyrene.

insulation material, as seen in Fig. 4a. For example, the minimum 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. However, 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 LCC of different ducts is illustrated in Fig. 4b. 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. 2. 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 LCC than a smaller duct size of 380 mm because both insulation and fuel cost are high for larger size ducts. The larger duct sizes required a thicker insulation layer to minimize LCC. Moreover, an air gap is reducing the thicker layer of insulation over a larger duct size of around 47 mm, which is 6 mm larger than a smaller size duct. 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 Figs. 5 and 6, respectively.

Influence of insulation thickness cost-saving an insulated duct with and without air gap considering insulation materials and duct sizes

Figure 5 shows the cost savings (USD/m-per year) of (a) different insulation materials used to insulate and (b) different duct sizes 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 OIT which depends on insulation and duct sizes. For instance, the cost savings potential of different insulation materials differ from each other because of their thermal conductivity and cost, resulting in more cost savings with cheap insulation than expensive insulation. For example, the thermal conductivity of glass wool is close to expanded polystyrene with a very small difference of 0.002 W/m K, but glass wool has lower cost savings USD 17.6/m/year than expanded polystyrene because of its high initial cost. Moreover, a thicker layer of expanded polystyrene (128 mm) is used to insulate the duct than glass wool (98 mm) for high 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 OIT is larger by 3 mm. Consequently, thermal conductivity and insulation cost should be considered to determine OIT for the HVAC duct. The application of an air gap insulated duct not only reduces OIT from 98–128 mm to 48–64 mm for different duct sizes insulated with selected insulation materials but also maximizes cost savings by 2.1–3.2%. Moreover, larger size ducts save more cost than smaller ones as seen in Fig. 5b.

Table 6 The results summary of the present study and other studies related to OIT for HVAC duct

Reference study	Location and year	Method	Insulation materials	Fuel types	OIT (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
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. (2018b)	Pakistan 2018	Thermodynamic and LCC analysis	GW	NG	All: 40–90 mm depending on insulation materials and fuel types
Yildiz and Ersöz (2016)	Turkey 2016	Degree-days and P_1–P_2 method	GW and RW	Electricity, NG, LPG, FO, and coal	GW: 128–239 mm and RW: 118–222 mm for different duct sizes, depending on fuel type
Soponpongpipat and Jaruyanon (2010)	Thailand 2010	Thermodynamic and LCC analysis	GW and rubber	Electricity	All: 23 and 125 mm for rubber and glass wool, respectively
Sahin and Kalyon (2005)	Saudi Arabia 2005	Thermodynamic analysis	GW	Fuel is not considered. The insulation thickness of the duct is independent of convective and radiative heat transfer coefficient at uniform external surface temperature	

Note: *RW*, rock wool; *GW*, glass wool; *XP*, extruded polystyrene; *EP*, expanded polystyrene; *BPRI*, bubble pack reflective insulation; *LNG*, liquefied natural gas; *NG*, natural gas; *FO*, fuel oil.

Influence of increase 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.

Figures 6a and b show the effect of the air gap (dash lines) and insulation thickness (dark lines) on the payback period selected insulation material for different duct sizes. Hence, the air gap shortens the rate of return on the initial investment by reducing the OIT for different duct sizes. As seen in Fig. 6a, 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. 6b. 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 recovers 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 applications 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 OIT corresponding to maximum cost savings and a minimum payback period of insulated ducts with and without air gap are given in Table 5.

Discussion: comparison of current results with previous studies

The results of the present study are compared with the relevant study in different countries, summarized in Table 6 on thermodynamics and LCC analyses of the HVAC conduct. For instance, Sahin and 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 and Jaruyanon (2010). They found that the OIT of the duct is independent of the variation in indoor and outdoor convective heat transfer coefficient. They found OIT of a double-layered duct with glass wool and rubber was 32 and 125 mm, respectively. In Turkey, Yildiz and Ersöz (2016) investigated that the OIT of glass and rock wool of the duct increases with wind velocity. They determined OIT 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. Kumar et al. (2019) used degree-days and LCC analysis to determine the OIT considering different duct sizes, insulation types and fuel cost and properties, and four regional fuel prices. They investigated the OIT in the range of 42–96 mm depending on the considered parameters. When compared to the findings of the studies mentioned above, the OIT 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.

Conclusion

Summary of results

This research aims to reduce the OIT for different duct sizes by introducing an air gap. It investigates cost savings, and payback period using LCC analysis, considering four insulation materials and five duct sizes. The findings showed that the use of an air gap in an insulated duct lowers the OIT 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 OIT for the duct. Conversely, in the case of smaller duct sizes, an air gap minutely prolongs the cost savings but lowers the OIT by 44% of an 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 longest payback period of 1.18–1.21 years are determined for glass wool because of its higher cost and thermal conductivity. However, 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 but air gap is the most cost-effective duct insulated with rock wool.

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 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 lifecycle energy (production and operation energy use) and cost perspective to ensure a sustainable built environment.

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Declarations

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