ECONOMIC AND ENVIRONMENTAL IMPACTS OF THERMAL INSULATION USED IN DIFFERENT DUCT SIZES

Dileep Kumar[1,*], Sanjay Kumar[1], Bilawal Ahmed Bhayo[1], Khanji Harijan[2], Muhammad Aslam Uqali[3]

ABSTRACT

In this study, the economic and environmental impacts of insulation material are determined for different sizes of heating, ventilation and air conditioning (HVAC) duct. The optimum insulation thickness (OIT), energy-saving (ES) and payback period (PP) for HVAC duct are estimated using Life cycle cost (LCC) analysis. The analysis considers coal, natural gas (NG), liquefied petroleum gas (LPG), fuel oil (FO), bagasse, rice husk (RH) and geothermal as an energy source and the fiberglass as an insulation material. The results indicate the OIT and PP for an HVAC duct increase with the size of the duct while ES decreases. The maximum value of OIT, ES and minimum value of PP for different sizes and energy sources are determined as 48.27 mm in size A (300 mm) and NG, 84.91% in size E (500 mm) and LPG, and 0.2035 years in size A and NG, respectively. Additionally, the environmental analysis results indicate emission of CO_2, CO and SO_2 decreases with insulation thickness. The maximum value of CO_2 and CO emission is determined for size E and NG i.e. 81.8% and SO_2 emission for size E and FO i.e. 76.66%, respectively.

INTRODUCTION

Energy consumption (EC) is escalating throughout the globe due to rapid population growth, improvement in living standard and style of human beings, urbanization, and migration towards large cities and development in technologies [1]. In addition to that the scarcity of energy supply, depletion of existing energy resources and environmental annihilation has raised a concern about EC. Therefore, EC is a critical issue of recent research. Suitable energy conservation measures significantly decrease EC [2]. Generally, there are four main sectors of EC i.e. industrial, transportation, building (commercial and residential) and agriculture. The building is responsible for 40% of the total energy demand of the developed countries [3] and the HVAC system is responsible for 10-20% to maintain a suitable indoor environment [4]. It results in 40% of the total greenhouse gas emissions [5]. However, the use of insulation material in buildings and the HVAC system reduces EC significantly. In an HVAC system, energy loss due to improper use of insulation material and thickness on ducting and piping [6]. Therefore, the use of insulation in an HVAC system not only reduces its EC but also abates emission products.

Mostly engineering investigations consider insulation material and thickness as an important parameter for economic and environmental savings. The economic insulation thickness concept is based on net saving obtained using insulation cost and energy cost for the HVAC system over the expected lifetime. The OIT for HVAC pipe or duct is determined using design, operating and economical parameters [7].

The degree-time concept is one of the simplest methods used to determine the cooling/heating energy requirement of a building under constant operating and environmental conditions. Zaki and Al-Turki [8] determined OIT for the pipelines of oil industry using LCC analysis. They considered superheated steam, furfural, crude oil, and 300-distillate as a working fluid and Rockwool and calcium silicate as an insulation material. The results indicate net saving increases with pipe size. Li and Chow [9] determined OIT for different size pipes to protect them from cold freezing using LCC analysis. The results reveal that insulation thickness decreases with insulation's thermal conductivity and cost, while it increases with insulated pipe exterior surface temperature. Soponpongpipat et al. [10] estimated the OIT for HVAC duct using thermo-economic analysis. They considered galvanized steel duct (0.5 m) with

glass wool and rubber as insulation material for their analysis. The results show that OIT remains constant with a convective heat transfer coefficient, contrary to ES increases. Keçebas et al. [11] estimated that the maximum ES is achieved for pipe (250 mm) and FO, whereas its lower value is determined for pipe (50 mm) and geothermal energy. Additionally, they investigated that the use of geothermal energy for chiller/boiler operation produces both environmental and economic benefits. His other study [12] investigates the effect of fuel inlet, stack gas and combustion chamber temperature and air-fuel ratio on OIT, ES and PP for different pipe sizes using energoeconomic and exergoeconomic method. The results indicate that OIT calculated using energoeconomic method was greater than exergoeconomic method. The effect of wind speed on OIT, ES, and PP for HVAC's duct installed outside the building is estimated using LCC analysis in the city of Usak, Turkey. The analysis considers LPG, NG, FO, and Coal as an energy source and Rockwool and fiberglass as insulation. The results show that the ES increases with wind speed for HVAC's duct [13].

The above literature shows that significant research has been conducted to determine OIT, ES, and PP for pipelines installed in industries, refineries, and the HVAC system. In contrast, fewer studies are conducted for HVAC's duct. Consequently, less attention is given towards the environmental impacts of energy loss through HVAC's duct and piping. On the other hand, significant research has been conducted to investigate the environmental impacts of insulation used in building wall. Comakli and Yüksel [14] estimated 12.13$/m2 net energy saving and 50% reduction in CO_2 emission for building wall over a lifetime of 10 years in city of Kutahya, Turkey. Dombaycı [15] estimated the environmental impacts of OIT for the exterior building wall. The analysis considered coal as a fuel and expanded polystyrene as an insulation material. He estimated that OIT reduces fuel consumption and the CO_2 and SO_2 emission by 46 and 41%. Yildiz et al. [16] estimated that OIT reduces CO_2 emission by 30% for the insulated wall with glass wool insulation and NG, FO, coal, and LPG as a fuel. Basogul and Keçebas [17] determined the environmental impacts of OIT for district heating pipelines. The results indicate a 21% reduction in CO_2 emission. Abdullah and Karameldin [18] estimated that OIT for steam piping (0.225-0.235m) reduces CO_2 form 37.7-26.8 tones/m/year and SO_2 from 72-59 kg/m-year.

In this study, the OIT, ES, PP, annual fuel consumption and emissions of CO_2, CO, and SO_2 for the insulated duct is determined in terms of LCC analysis. The analysis considers fiberglass as insulation material and coal, NG, LPG, FO, RH, bagasse and geothermal as an energy source. The heat conductivity and price of the insulation material, average temperature and relative humidity of conditioned air, fuel price are constant in the analysis. The results drawn from the analysis are evaluated.

SELECTED AIR DISTRIBUTION SYSTEM

The schematic view of the air distribution system for the HVAC system under study is illustrated in Fig. 1. The energy required for the chiller operation is obtained from a boiler, in which fuel sources are commonly oxidized to produce thermal energy. As for the heating coil, the supply air is directly conditioned via heat transfer between supply air and hot water. The heating coil is intended to control the relative humidity of the supply air required for the pharmaceutical zone. In the HVAC system, the conditioned air is supplied to the zone through HVAC ducts. HVAC ducts are usually made out of the galvanized steel, stainless steel and aluminum, and flexible non-metallic materials. Typical HVAC ducts are located outdoor environment, basement floors, attics, garages. There is a significant amount of energy loss occurs in an HVAC duct due to temperature difference between conditioned air and ambient air. Therefore, it is essential to insulate HVAC ducts in terms of energy-saving using different insulation materials.

The design and operating parameters of the air distribution system are obtained from GSK Pharma Pvt. Ltd. are given in Tables 1 & 2. The value of density, specific heat, kinematic viscosity, Prandtl number and thermal conductivity of conditioned air inside the duct are obtained by using the appropriate mean value of operating parameters.

ANALYSIS OF AIR DISTRIBUTION SYSTEM

A life cycle cost analysis considers the net saving resulting from a reduction in energy cost due to a decrease in fuel consumption with added insulation cost over the lifetime of an HVAC system. In building, the LCC analysis is

usually used to calculate the OIT considering the effect of inflation and interest rate, maintenance cost, salvage value, operating hours, and heating value of fuel and cost of fuel and insulation material [23].

The following assumptions are considered in the analysis:
1. Steady-state conditions are considered.
2. Uniform heat gain occurs throughout the duct.
3. The unit length of the duct is considered.
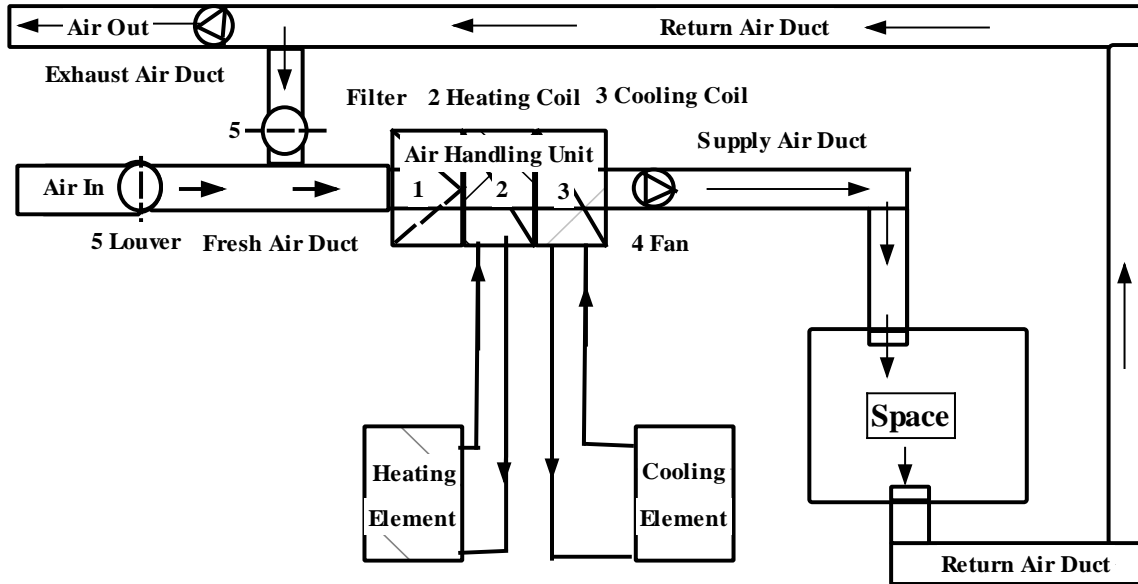4. The working fluid and ambient air temperature and relative humidity are constant.

Figure 1. Schematic layout of simple air-distribution system

Table 1. The duct and insulation material properties [10, 13, 19]

	Insulation	Properties
Insulation	Fiberglass	K_{ins}=0.037 W/m.K and C_{ins}=352USD/m^3
Duct	Galvanized Steel	K_d=60.5 W/m.K, $300 \leq d_d \leq 500$ mm and $0.7 \leq t_d \leq 1.006$ mm

Table 2. Operating parameters [13, 20-22]

Parameters	Value
Supply air in duct	T_i=293K, P_i=1kPa(g) V_i=10m/s
Ambient conditions	T_i=303K, V_o=4.2m/s and h_o=10W/m^{2}K
CDD	2384(°C-days)
Interest Rate	5 %
Inflation Rate	7%
Lifetime	15years

The heat gain and insulation economy for an air distribution system

The annual cooling loss through the HVAC duct due to heat gain from the surrounding is determined on the basis of the degree-days method [13].

$$\dot{Q}_{in} = \frac{86400 \cdot CDD}{R}$$

(1)

where, R is the overall heat transfer coefficient of duct layers [13]. It is calculated by Eq. (2 & 3) for bared and insulated duct as shown in Fig. 2 and CDD is the cooling degree days of the city analyzed:

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

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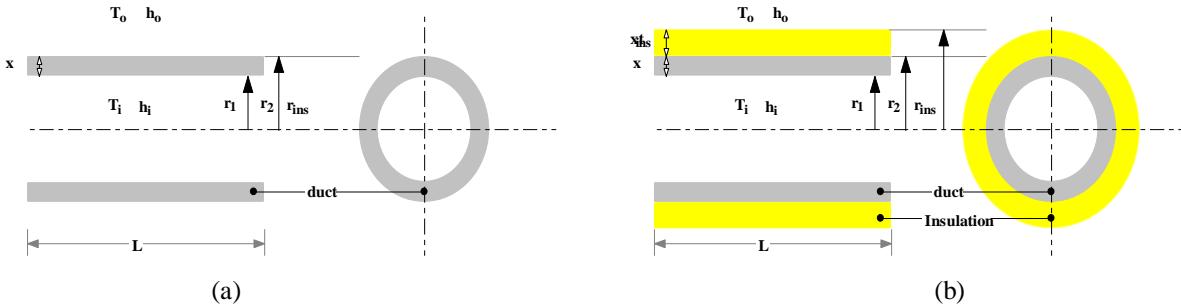

Figure 2. (a) A bared and (b) insulated duct

Figure 2 exhibits a bared and insulated duct. It represents the dimension of an HVAC duct. L is the length of the duct, r_1 and r_2 are interior and exterior radius of the duct ($r_2 = r_1 + t_d$), r_o is the exterior radius of an insulated duct, A_1 and A_2 are the interior and exterior surface area of the duct, A_o is the exterior surface area of an insulated duct. The h_i and h_o are convective heat transfer coefficient of conditioned air and the surrounding air.

The convective heat transfer of conditioned air is calculated as

$$h_i = \frac{\kappa_{air} \, Nu}{D_H} \tag{4}$$

where κ_air is thermal conductivity of conditioned air, DH is a hydraulic diameter of the duct which is calculated by Eq. (5) [24] and Nusselt number (Nu) is calculated by Eq. (7 & 8) laminar and turbulent [25, 26].

$$D_h = \frac{4 \, A_c}{p} \tag{5}$$

where, A_c is the cross-sectional area and P is the perimeter of the duct, respectively. Reynolds Number of air flowing inside the duct is estimated as:

$$Re = \frac{U \, D_H}{\vartheta} \tag{6}$$

where, U and ϑ are the velocity and kinematic viscosity of the conditioned air.

If Re $\leq$ 2800 and Pr $\leq$ 0.7 then flow through duct will be laminar then:

$$Nu = 3.66 + \frac{0.66 \left(\frac{D_h}{L}\right) Re \, Pr}{1 + 0.4 \left(\left(\frac{D_h}{L}\right) Re \, Pr\right)^{2/3}} \tag{7}$$

If $3 \times 10^3 < Re < 5 \times 10^6$ and $0.5 \leq Pr \leq 2000$ then flow through duct will be turbulent then

$$Nu = \frac{f\,(Re-1000)\,Pr}{8\,(1+12.7\,(Pr^{2/3}-1)\sqrt{\frac{f}{8}}}$$

(8)

where f is the friction factor of inside duct surface, it is calculated by Eq. (8) and Pr is Prandtl number of conditioned air inside the duct:

$$\frac{1}{\sqrt{f}} = -2.0\,log\left(\frac{\varepsilon}{3.7\,D_H} + \frac{1}{Re\,\sqrt{f}}\right)$$

(9)

where ε is the relative roughness of duct surface and is calculated as:

$$\varepsilon = \left(\frac{1.5x10^{-4}}{D_H}\right)$$

(10)

The annual fuel consumption is calculated as:

$$\dot{m}_F = \left(\frac{\dot{Q}}{LHV\;COP}\right)$$

(11)

where $\dot{m}$ is annual fuel consumption, LHV is lower heating value of energy source and η is efficiency of an HVAC system. The annual fuel cost (C_F) is calculated as:

$$C_F = \dot{m}_f\,C_f$$

(12)

where Cf is fuel cost. Total initial investment on thermal insulation is calculated as:

$$C_{ins} = c_{ins}\,Z_{ins}$$

(13)

where C_{ins} is thermal insulation cost and $Z_{ins} = A\,t_{ins}$ is the quantity of insulation material.

It is possible to calculate the present worth of the net energy saving with an increment in initial investment by the P_1-P_2 method. P_1 is the ratio life cycle energy cost to initial investment over an expected lifetime. P_2 is the ratio of increase in capital investment during the life cycle of the HVAC system to the initial investment. The P_1 and P_2 are calculated by Eq. (13&14)

$$P_1 = \left(\frac{1}{d-e}\right)\left(1 - \left(\frac{1+e}{1+d}\right)^N\right)\;if\;i \neq d$$

(14)

$$P_2 = 1 + P_1(M) - (SV)(1+d)^{-N}$$

(15)

where M and SV are the ratio of annual maintenance and the salvage value to initial investment, d and e represent inflation and interest rate and N denotes lifetime. The value of P2 will be equal to P1 if operation and maintenance cost is zero [10, 13, 19, 23, 27, 28]. The total life cycle cost of cooling loss is calculated as:

$$C_1 = P_1\,C_F + P_2 C_{ins}$$

(16)

Energy-saving (%) is achieved during the lifetime of the HVAC system will be calculated as [13]:

$$ES = \left(\frac{C_2 - C_1}{C_1}\right) \cdot 100 \tag{17}$$

where C_1 and C_2 is total life cycle cost incurred on a bared and insulated duct. The payback period (PP) of increment in initial investment is calculated as [13]:

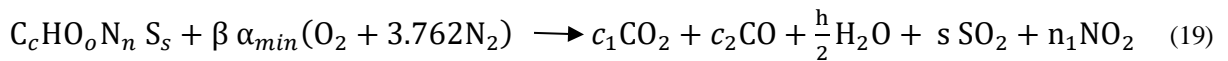$$\frac{C_1}{C_2 - C_1} = \frac{1}{d - i}\left(1 - \left(\frac{1+i}{1+d}\right)^{PP}\right) \tag{18}$$

Calculation of the annual emission gases amount

Heat transmission losses through the HVAC duct are reduced by using appropriate insulation material and thickness. This will reduce the annual fuel consumption of an HVAC system. It reduces emission products. The chemical composition of fuel types and their properties along with cost are given in Table 3.

Table 3: Price, lower heating value (LHV) and chemical formulas of fuels and efficiency of cooling system [29-40]

Fuels	Price ($/kg)	LHV (J/kg)	η (%)	COP (-)	β (%)	Chemical Formula
Natural gas	0.26	50.53×10^6	93	4.5	10	$C_{1.05}H_4O_{0.034}N_{0.02}$
LPG	0.89	46.40×10^6	92	3.0	15	$C_{3.7}H_{4.1}$
Fuel Oil	0.36	41.28×10^6	80	2.1	20	$C_{7.3125}H_{10.407}O_{0.04}S_{0.026}N_{0.02}$
Coal	0.10	29.26×10^6	65	2.4	30	$C_{7.078}H_{5.149}O_{0.517}\,S_{0.01}N_{0.086}$
Bagasse	0.03	9.73×10^6	76	2.2	30	$C_4H_{6.44}O_{2.81}$
Rice Husk	0.08	14.50×10^6	68	2.5	30	$C_{3.75}H_{5.74}O_{2.98}S_{0.0063}\,N_{0.043}$
Geothermal	0.50	80.98×10^6	38	3.2	-	-

The general chemical formula of combustion for fuel is calculated by [17]:

$$C_c H O_o N_n\, S_s + \beta\, \alpha_{min}(O_2 + 3.762 N_2) \longrightarrow c_1 CO_2 + c_2 CO + \frac{h}{2} H_2O + s\, SO_2 + n_1 NO_2 \tag{19}$$

where α_{min}, c_1, c_2 and n_1 are estimated from the oxygen balance formulas given in Eq. 20-23, respectively:

$$\alpha_{min} = c_1 + \frac{h}{4} + s + \frac{o}{2} \tag{20}$$

$$c_1 = c + c_2 \tag{21}$$

$$\beta\, \alpha_{min} = c_1 + c_2 + \frac{h}{4} + s + \frac{o}{2} \tag{22}$$

$$n_1 = 3.762\, \beta\, \alpha_{min} + n \tag{23}$$

The emission rate of combustion products per 1 kg of fuel burned can be calculated by

$$M_{CO2} = \frac{c_1 CO_2}{M} = \text{ kg of } \frac{CO2}{kg} \text{ of fuel} \tag{24}$$

$$M_{CO} = \frac{c_2 CO}{M} = \text{ kg of } \frac{CO}{kg} \text{ of fuel} \tag{25}$$

$$M_{SO2} = c_1 SO_2/M = \text{kg of } SO_2/\text{kg of fuel} \tag{26}$$

$$M_{H2O} = c_1 H_2O/M = \text{kg of } H_2O/\text{kg of fuel} \tag{27}$$

where M denotes the molecular weight of the fuel and it is estimated by Eq. 28

$$M = 12c + h + 16o + 14n + 32s \tag{28}$$

$$M_{CO} = c_2 CO/M = \text{kg of CO/kg of fuel} \tag{29}$$

$$M_{SO2} = c_1 SO_2/M = \text{kg of } SO_2/\text{kg of fuel} \tag{30}$$

$$M_{H2O} = c_1 H_2O/M = \text{kg of } H_2O/\text{kg of fuel} \tag{31}$$

The total emission of CO2, CO, SO2, and H2O can be calculated using the fuel consumption mf (from Eq. (11)), which is total burned fuel within CDD. The equations of emission are given in

$$M_{CO} = \left(\frac{28c_2}{M}\right) \dot{m}_f \tag{32}$$

$$M_{CO2} = (44\, c_1/M)\, \dot{m}_f \tag{33}$$

$$M_{SO2} = (44\, s/M)\, \dot{m}_f \tag{34}$$

RESULTS AND DISCUSSION

This study estimates the economic and environmental impacts of the insulation used in an HVAC duct installed outside the building in the city of Jamshoro, Pakistan. Using LCC analysis, OIT, ES and PP for different duct sizes are estimated. The analysis considers the design, operating, economic and environmental parameters given in Table 1, 2 and 3. Additionally, the environmental impacts of OIT for different duct sizes are determined using various energy sources.
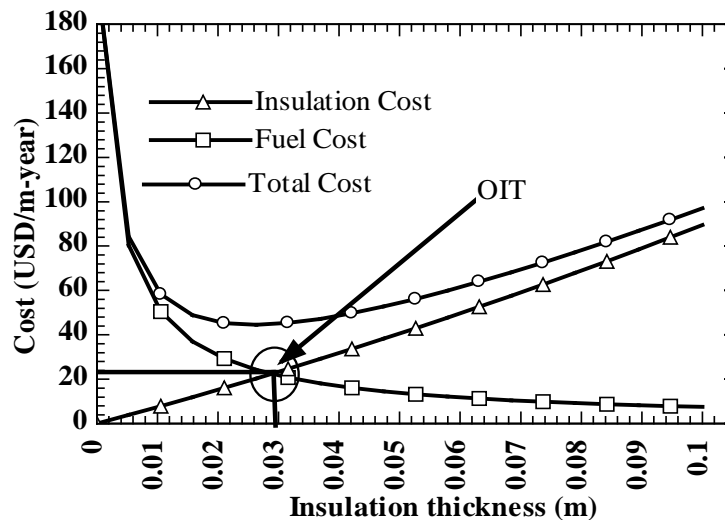

Figure 3. Total cost verses insulation thickness

The effects of insulation thickness on total cost, insulation cost and fuel cost over a lifetime of HVAC system is illustrated in Fig. 3. The fuel cost is inversely proportional to insulation thickness because insulation thickness over the duct reduces energy loss. Moreover, the parabolic relationship occurs between insulation thickness and cost because insulation quantity increases radially with its thickness on the duct. The total cost is the sum of fuel and insulation cost. Therefore, total cost decreases with insulation thickness up to OIT then it increases. The insulation thickness at which total cost is determined is known as OIT and it is equal to 30 mm as shown in Fig. 3. The results indicate the highest value of OIT for the duct in case NG and its lowest value in case of bagasse. The OIT for different duct sizes varies between 36.52-48.27mm for NG, 36.38-42.70mm for LPG, 18.65-24.15mm for coal, 28.79-34.64mm for FO, 16.35-17.29mm for bagasse, 20.07-21.72mm for RH, 32.44-37.16mm for geothermal, respectively. The maximum value of total cost for different duct sizes under various fuel types varies between 11.93-34.98USD/m-year for NG, 10.88-37.52USD/m-year for FO, 11.88-54.51USD/m-year for LPG, 6.83-22.4USD/m-year for coal, 7.67-18.72USD/m-year for geothermal, 4.49-8.91USD/m-year for bagasse and 6.79-17.19USD/m-year for RH, respectively.
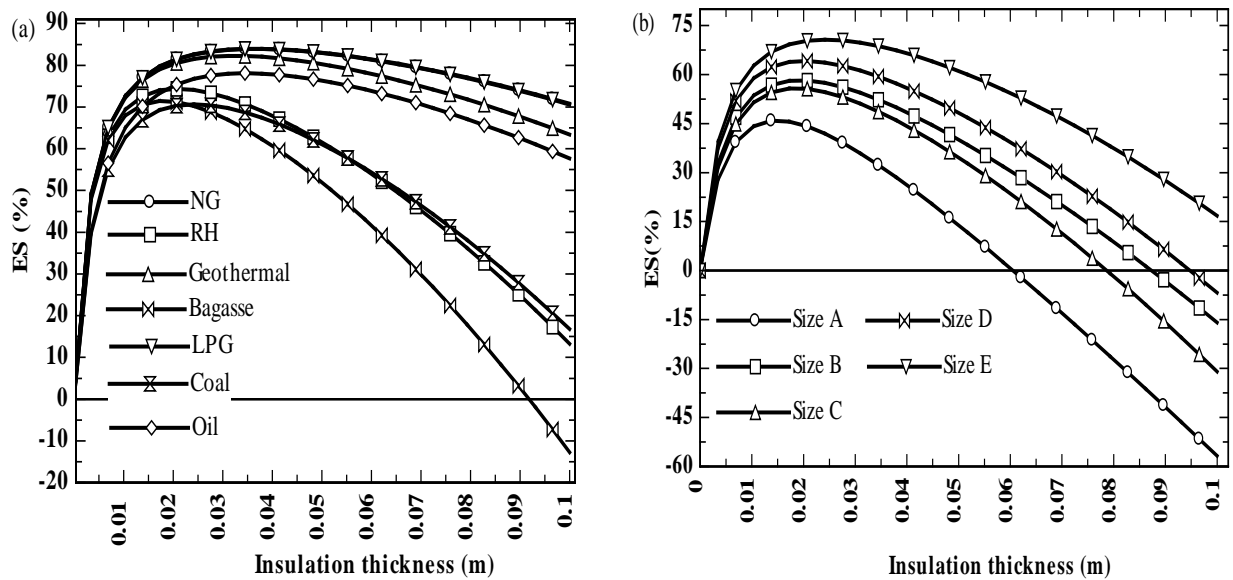

Figure 4. ES V/S insulation thickness for HVAC duct considering different (a) energy source in size E and (b) sizes in case of NG

The effects of insulation thickness on ES in duct size E under different energy sources are illustrated in Fig. 4. The energy-saving in duct size E increases with insulation thickness up to OIT. Once OIT is achieved further increment in insulation thickness reduces ES. Therefore, an additional increment in insulation thickness would be no longer be economical. The ES varies between 74.01-83.95% for NG, 74.02-83.91% for LPG, 54.17-70.67% for coal, 66.44-78.09% for FO, 50.25-70.49% for bagasse, 56.92-74.38% for RH, 71.03-82.87% for geothermal, respectively. The highest value of the ES is estimated for NG and LPG, whereas the lowest for bagasse. Fig. 4b shows the effects of insulation thickness in different duct sizes in the case of NG. The maximum ES occurs in Size E whereas lower value in size A. The maximum value of ES at OIT in different duct sizes for various energy sources is given in Table 4. The OIT is estimated by minimizing the Eq. 16. The outside radius of the insulated HVAC's duct is calculated using OIT and exterior radius of the duct. Total cost is differentiated with respect to r_o and equate to zero. The OIT is calculated ($t_{opt} = r_{ins} - r_o$) using the EES optimization toolbox.

The variation in PP with insulation thickness for duct size E under different energy sources is illustrated in Fig. 5a. The PP of initial investment cost occurs in duct size E decreases with insulation thickness up to OIT. Once OIT is achieved further increment in insulation thickness increases the PP. It is economically fruitless because it delays the recovery of the initial investment. The results show that the PP of initial investment for the duct size E at OIT is

different for various energy sources. The higher value of PP corresponding to OIT is determined for bagasse and coal, whereas the lower value for NG and LPG. Other energy sources have intermediate values. Moreover, the effect of insulation thickness on PP for different duct sizes is illustrated in Fig. 5b for NG. A similar trend of variation in PP is determined for different duct sizes as shown in Fig. 5a. The higher value of PP corresponding to OIT is achieved for size A because it has higher initial investment cost and lowers fuel saving. Therefore, the lower value of PP for different duct sizes is obtained for size E. The PP for different duct sizes decrease with the size of the duct.

The OIT, ES, and PP for different duct sizes at various fuels are given in Table 4. The OIT, ES, and PP vary between 16.35-48.27mm, 52.06-83.95%, and 0.204-1.005years, respectively. The higher ES in different duct sizes are obtained for NG, LPG and geothermal, whereas the lower ES is investigated for bagasse and coal and intermediate value of ES is obtained for RH and FO. The minimum value of PP for different duct sizes is obtained for NG, LPG and geothermal, its intermediate value is obtained for RH and FO, whereas, it's higher value is obtained for bagasse and coal.
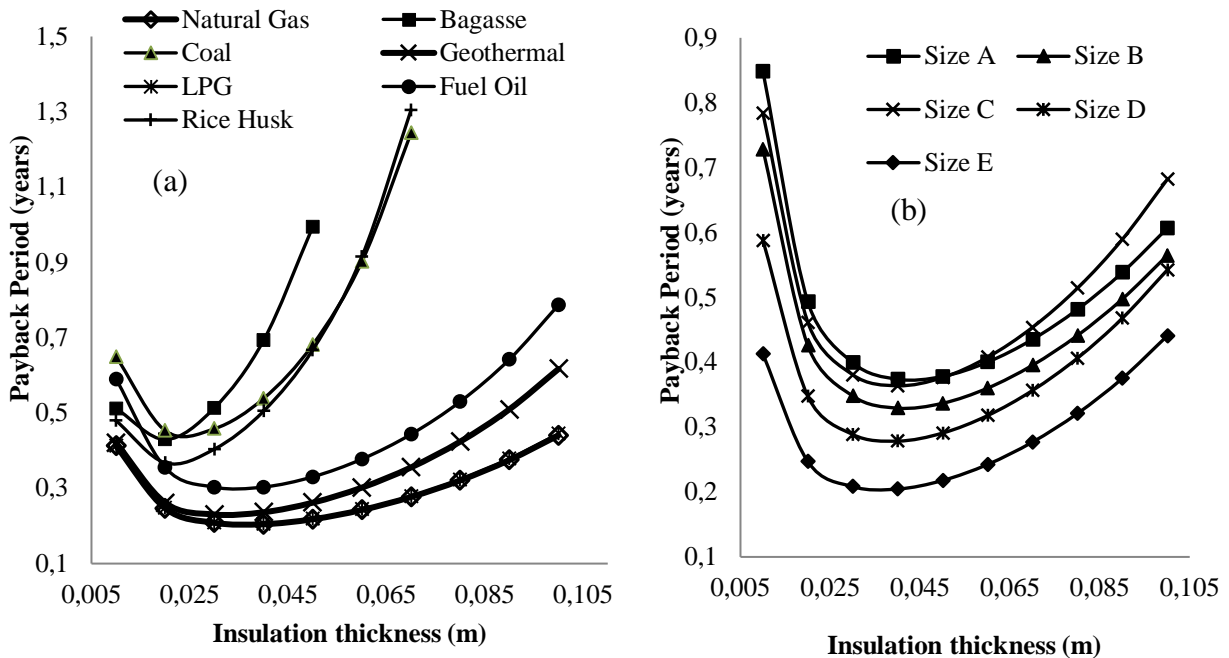

Figure 5. PP V/S insulation thickness for different (a) energy sources in size E and (b) sizes in case of NG

The use of insulation material on the HVAC duct reduces heat loss. Fig. 6a exhibits the effect of insulation thickness on the annual fuel consumption of different fuel types. Fuel consumption decreases with insulation thickness. Once OIT is achieved, further increasing insulation thickness insignificantly reduces fuel consumption. The results show that fuel consumption varies between 4.2-50.12kg/m-year in the duct size E at different energy sources. The higher decrement in fuel consumption is determined in duct size E for bagasse, RH and coal, and its intermediate decrement is determined for FO whereas its lower decrement is determined for LPG, NG and geothermal. Moreover, the effect of insulation thickness on fuel consumption in different duct sizes is illustrated in **Fig. 6b** for NG as a fuel. The high fuel consumption decrement occurs in size A i.e. 19.52kg/m-year and size E has lower value i.e. 6.26kg/m-year corresponding to OIT.

Table 4. OIT, ES and PP for different duct sizes at various fuel types

|	Fuel Type	Parts of air distribution system				
		A	B	C	D	E
OIT(mm)	NG	48.27	41.2	39.72	38.54	36.5
	Bagasse	16.93	16.92	16.35	16.91	17.29
	Coal	19.38	19.22	18.65	21.29	24.15
	Geothermal	37.16	35.93	34.69	33.91	32.44
	LPG	42.7	41.08	39.57	38.4	36.38
	FO	30.67	29.77	28.79	30.31	34.64
	RH	21.32	21.09	21.29	20.69	20.7
ES(%)	NG	74.01	76.41	74.56	79.29	83.95
	Bagasse	50.24	54.63	52.06	60.9	70.49
	Coal	54.17	58.26	55.79	64.13	70.67
	Geothermal	71.03	73.63	71.67	76.97	82.27
	LPG	74.02	76.33	74.48	79.23	83.91
	FO	66.44	69.47	67.36	73.58	78.09
	RH	56.92	60.79	58.35	66.15	74.38
PP(years)	NG	0.3727	0.3291	0.3638	0.2783	0.2035
	Bagasse	1.005	0.8454	0.9436	0.657	0.4296
	Coal	0.9081	0.768	0.8526	0.597	0.4531
	Geothermal	0.4354	0.382	0.4218	0.3189	0.2295
	LPG	0.3744	0.3305	0.3653	0.2793	0.2042
	FO	0.5398	0.4691	0.5177	0.3829	0.299
	RH	0.8112	0.6904	0.7636	0.5468	0.3674
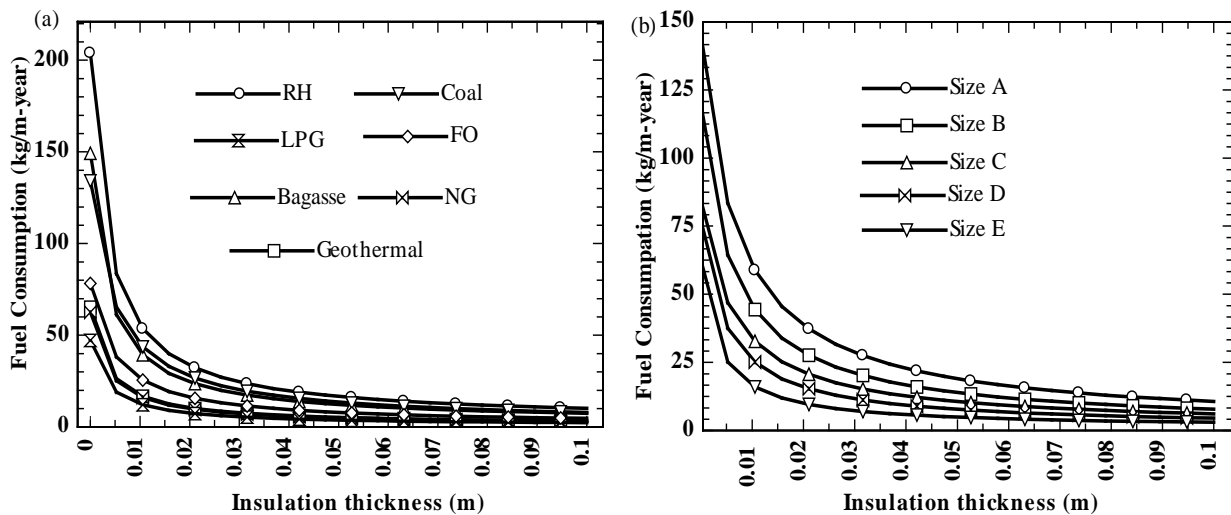
Figure 6. Fuel consumption V/S insulation thickness for different (a) energy sources in size E and (b) sizes in case of NG
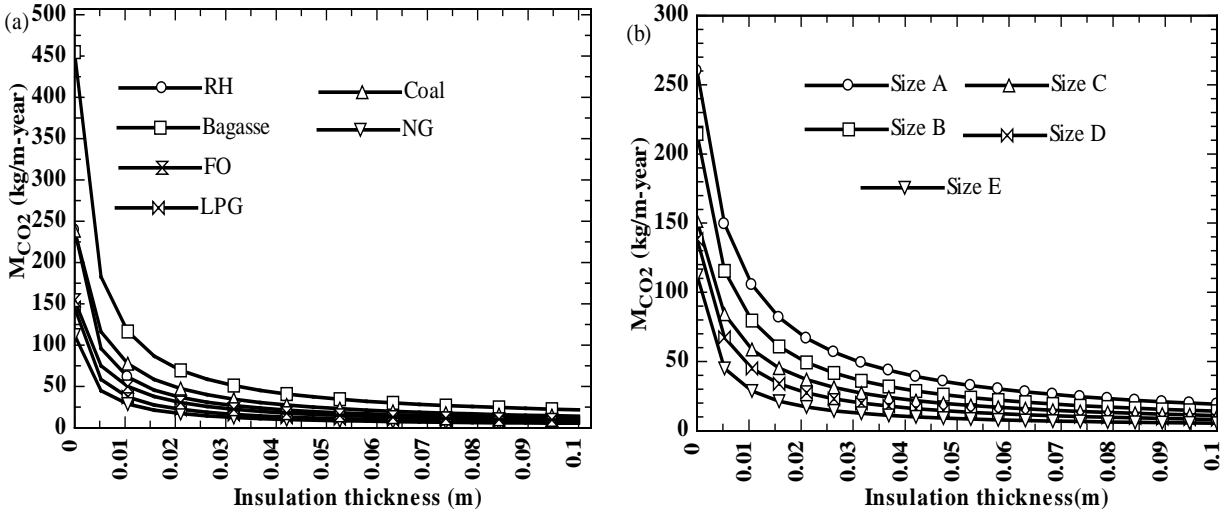
Figure 7. The annual CO_2 emissions versus insulation thickness (a) for different energy sources in size E and (b) sizes in case of NG

Figure 7 (a and b) shows the variation in CO_2 emission with insulation thickness for duct sizes and different energy sources. The use of insulation over the HVAC duct reduces fuel consumption of an HVAC system and resulting emission products. The CO_2 emission decreases with insulation thickness. The higher value of CO_2 emission corresponding to OIT is determined for size A and bagasse i.e. 192kg/m-year, whereas its lower value for size E and NG i.e. 11.27kg/m-year. The decrement in CO_2 emission due to OIT for different duct sizes varies between 11.23-34.04kg/m-year for NG, 81.81-318.33kg/m-year for bagasse, 40.73-123.43kg/m-year for coal, 14.57-50.14kg/m-year for LPG, 20.38-56.39kg/m-year and 37.04-141.59kg/m-year for RH, respectively.
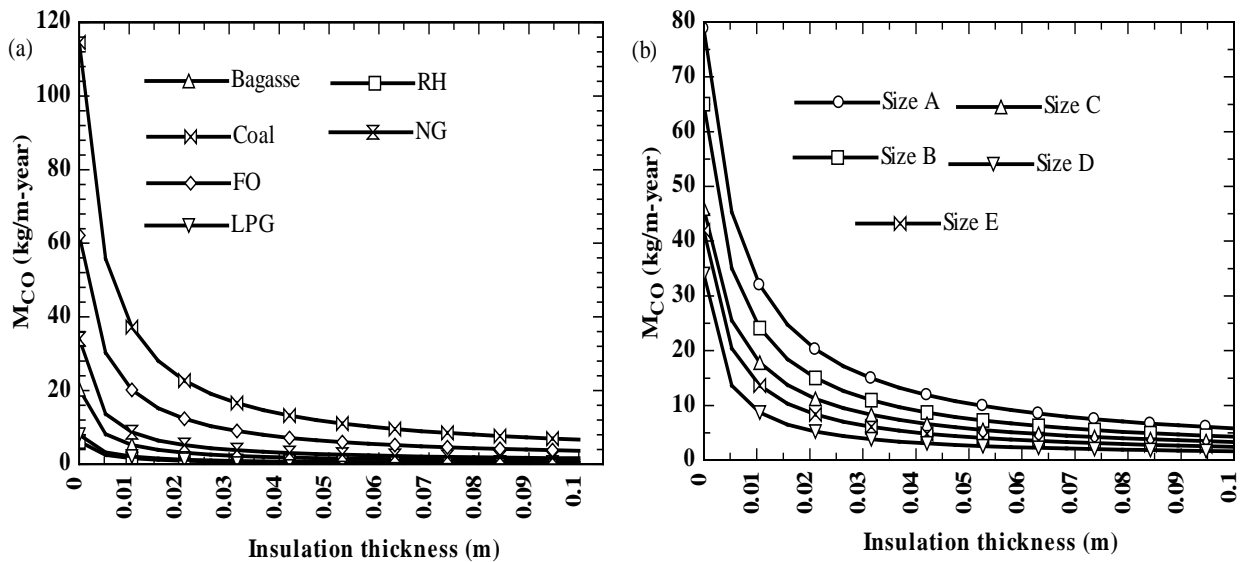

Figure 8. The CO emissions versus insulation thickness for different (a) energy sources in size E and (b) sizes in case of NG
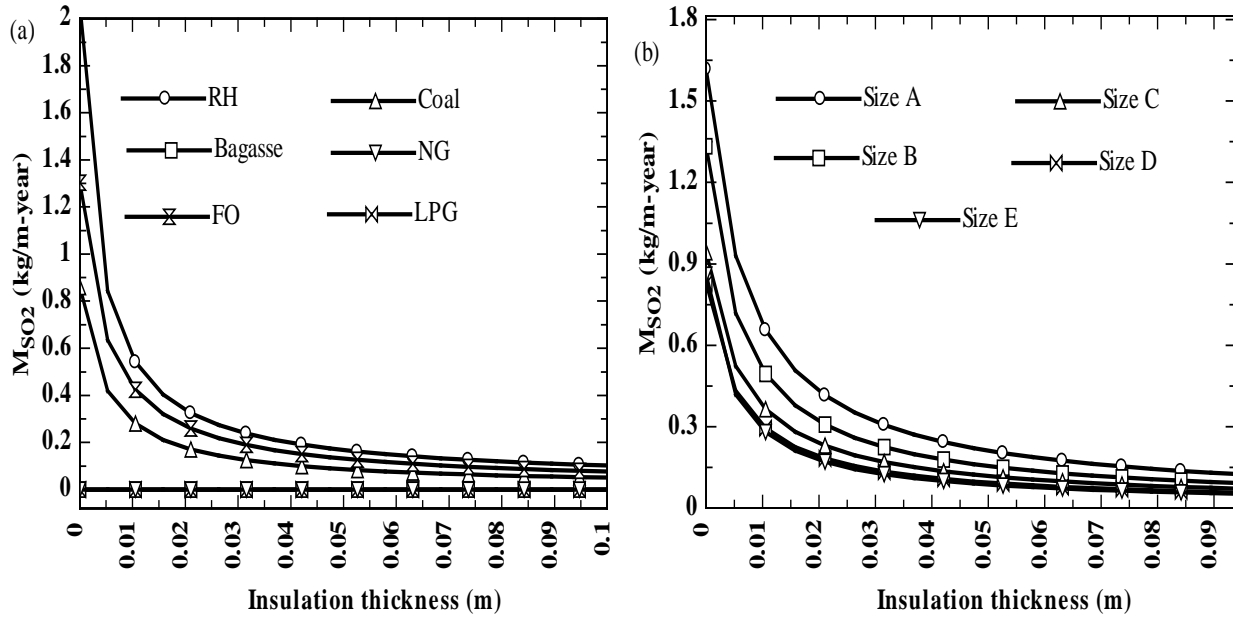
Figure 9. The SO2 emissions versus insulation thickness for different (a) energy sources in size E and (b) sizes in case of coal

       Figures 8 and 9 exhibits the variation in CO and SO_2 emission for different duct sizes with insulation thickness under different fuel types. The CO and SO_2 emission decrease with insulation thickness and duct size. The CO and SO_2 emission determined for size A is higher than size E. The higher value of CO emission corresponding to OIT is determined for size A and coal i.e. 59.28kg/m-year, whereas its lower value for size E and LPG i.e. 0.8kg/m-year. The decrement in CO emission due to OIT for different duct sizes varies between 3.4-10.3kg/m-year for NG, 3.67-14.26kg/m-year for bagasse, 19.56-59.28kg/m-year for coal, 0.8-2.77kg/m-year for LPG, 8.21-22.72kg/m-year and 0.97-3.97kg/m-year for RH, respectively. Similarly, the higher value of SO_2 emission corresponding to OIT is determined for size A and RH i.e. 0.99kg/m-year, whereas it's lower value for size E and coal i.e. 0.15kg/m-year. The decrement in SO_2 emission due to OIT for different duct sizes varies between 0.15-0.45kg/m-year for coal, 0.17-0.48kg/m-year and 0.25-0.99kg/m-year for RH, respectively.

       The percentage of fuel savings with OIT in different duct sizes is illustrated in Fig. 10. The highest value of percentage of fuel consumption reduced with OIT in different duct sizes is varying in between 36.87-40.90% in case of NG, 25.89-33.87% in case of bagasse, 28.45-33.87% in case of coal, 35.56-40.09% in case of geothermal, 36.84-40.88% in case of LPG, 32.72-38.33% in case FO, 27.58-33.74% in case of RH and the total amount of fuel consumption saved is varying in between 29.24-35.98% considering all types of fuel.

       The percentage of emission reduction due to OIT for different parts of the air distribution system using various fuels is illustrated in Figure 11. The highest percentage of CO_2 emission reduced with OIT in different parts of air distribution system is varying in between 37.74-81.1% in case of NG, 53.64-69.5% in case of bagasse, 56.84-70.81% in case of coal, 73.68-81.78% in case of LPG, 67.44-76.66% in case fuel oil, 59.36-73.2% in case of RH and the total amount of CO_2 emission reduced is varying in between 58.48-71.96% considering all types of fuel. Similarly, the percentage of CO, SO_2 emission reduction is estimated.
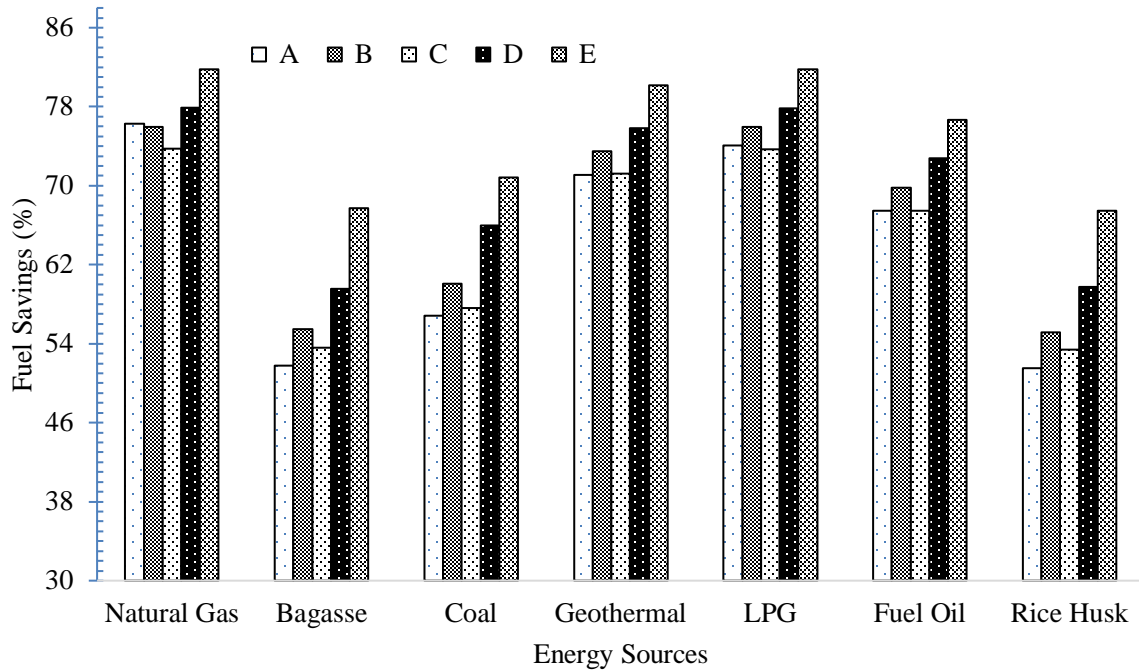
Figure 10. Annual percentage of fuel reduction in different parts of the air distribution system
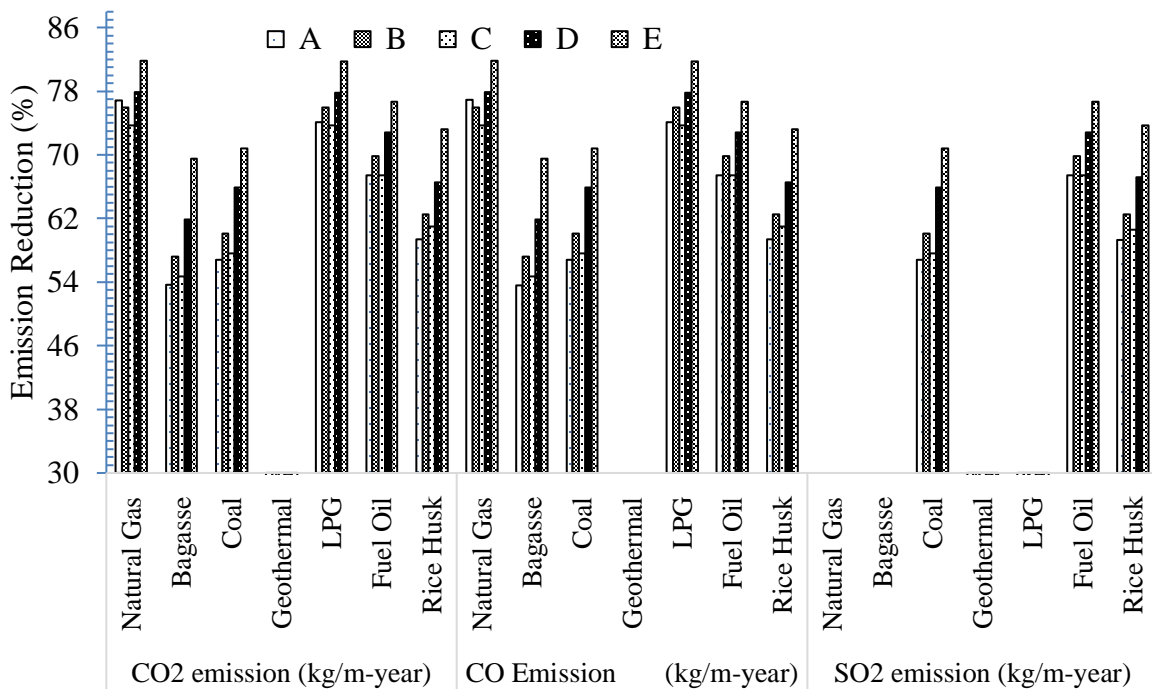

Figure 11. Percentage of emission reduction versus different fuel use in air distribution system HVAC system
Note: Duct size A 300 mm, B 350 mm, C 400 mm, D 450 mm & E 500 mm.

CONCLUSION

In this study, the effect of energy source and HVAC's duct size on OIT, ES, PP are estimated using LCC analysis. This study also investigates the environmental impacts of insulation thickness on different duct sizes of an air distribution system installed outside the building in a pharmaceutical company, in the city Jamshoro, Pakistan. In this analysis, NG, LPG, coal, FO, bagasse, RH and geothermal are considered as energy sources and fiberglass as an insulation material. On the basis of the obtained results, the following conclusion is made from the present study:

The OIT decreases with the duct size for various energy sources.

The higher value of OIT is obtained for duct size A and NG i.e. 48.27 mm and it's lower value for duct size E and bagasse i.e. 17.40 mm.

The ES values decrease with duct size. The highest value of the ES is estimated for size E and NG i.e. 83.95 whereas its lower value is obtained for Part A and bagasse i.e. 50.24%, respectively.

The PP increases with the duct size. The longer value of PP is estimated for part A and bagasse i.e. 1.005year and its smallest value are 0.204year for size E and NG.

The annual fuel consumption, CO_2, CO and SO_2 emission decrease with insulation thickness. The maximum percentage reduction in fuel consumption corresponding to OIT is around 81.8% for size A and NG and lower reduction is 51.78 for size E and bagasse, respectively.

The emission of CO_2, CO and SO_2 vary between 53.64-81.8%, 53.62-81.76% and 49.64-76.66% for different parts and energy sources, respectively.

Considering environmental impacts geothermal as an energy source is a better choice.

Considering economic and environmental impacts bagasse as an energy source is a better choice.

NOMENCLATURE

A	Duct's external surface area, m^2
D	Diameter of the duct, m
d	inflation rate, %
h	Convective heat transfer co-efficient, $W / m^2\ ^oC$
i	interest rate, %
K	Thermal conductivity, $W / m\ ^oC$
L	Length of the Duct, m
$\dot{m}$	Mass Flow Rate, kg/s
N	Life time, year
Nu	Nusselt Number
Pr	Prandtl Number
$\dot{Q}$	Heat gain, W
Re	Reynolds Number
r	Radius,
R	Thermal resistance, $^oC/W$
U	Velocity, m/s
V	Volume Flow Rate (m^3/s)
t	thickness, m
ϑ	Kinematic viscosity (m2/s)
f	friction factor (-)
ε	relative roughness (-)
β	Excess air
f	Fuel
h	hydraulic
i	inlet
ins	insulation
o	outside
T	Total
EC	Energy Consumption
EES	Engineering Equation Solver

ES	Energy Saving
HVAC	Heating, Ventilation and Air Conditioning
LCC	Life cycle cost
OIT	Optimum insulation thickness
PP	Payback Period

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