Optimum insulation thickness for HVAC duct: An Energy Conservation Measure

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Abstract: Building Energy consumption is responsible for major share of global energy demand (40%) which is mainly consumed to maintain building space cooling and heating requirement. Therefore, conservation of energy is a critical issue in building sector. To conserve energy in buildings, an efficient HVAC system must be designed, and it should be operated at optimal design parameters. In this study, different building energy systems are studied to investigate the most effective energy conservation system for building application. It mainly focuses on optimal design of HVAC system specifically its air distribution system. In air distribution system, energy loss occurs due to conditioned air leakages, improper thermal insulation thickness, poor design of ducting layout and ineffective controlling of conditioned space parameters with air handling unit operating conditions. Among above losses, significant amount of energy loss occurs due to improper insulation thickness and material. In this regards, different studies were conducted to determine optimum thermal insulation thickness and associated condensation at external surface of the duct. Therefore, this study is devoted to determining the most effective thermal insulation thickness material for HVAC duct. From different studies, it is summarized that use of air gap, optimizing insulation at point of compression produces economical benefits and environmental amiable by using life cycle cost analysis and life cycle environmental assessment.

Keywords: *HVAC, Thermal Insulation, Insulation Material, HVAC Classification*

1. Introduction

The energy demand is rapidly increasing throughout the globe due to the developmentin technology and improvement in human lifestyle. Moreover, depletion of existing energy resources and use of non-renewable energy sources cause severe destruction to the world ecological system. Moreover, the main environmental problem resulting from the usage of non-renewable energy resources is changing the global climate which is known as the greenhouse effect. During the past couple of decades, energy consumption raised by 49% though CO_2 emission is enhanced by 43% at an annual average rate of 2% and 1.2% in advanced countries. The building services are an energy concentrated sector. It is stated that around 40% of the US total energy utilization is in buildings, of which 60% is consumed in the HAVC systems.

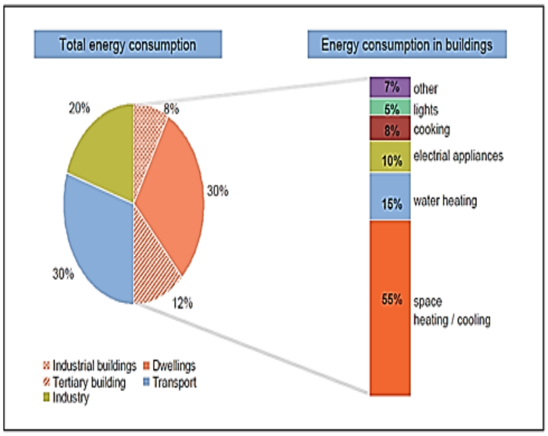

Figure.1. Energy consumption scenario of different sectors

Mostly the space heating and cooling is provided through heating ventilation and air conditioning (HVAC) system. In HVAC system significant energy loss occurs around 16-20% of its total due to heat transfer. The cooling/heating loss to/from the duct enlarges the energy bill of the building to the homeowner and also causes the peak load to the utilities. Usually, Insulation is used to decrease energy loss in the HVAC system. nsulation is the function of economical (initial investment Fuel cost) and operating parameters

2. Air Conditioning System

The term air condition system refers to the combination of various equipment which is used to provide a healthy environment. Thermal comfort is got by varying various parameters such as air humidity, air temperature, and air quality. Sometimes the noiselevel is also reduced to get environmental comfort for the occupant. The conditioned air is passed to the occupants with the help of ducting channel. Thus, to keep conditioned space according to comfort zone various things are considered as per standard set by ASHRAE for occupants, space under consideration and product to be used for conditioning purpose [1].

Air-conditioning is also referred to as heating, ventilating, air conditioning and refrigeration (HVAC & R) because both represent conditioned of air for occupants. Study of numerous characteristics parameters such as indoor environment parameters, room size, cost & arrangement of different components, quality & effectiveness, and occupancy are carried out by using HVAC & R technology [1].

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2.1 Classification of HVAC System

In the thermal distribution system, HVAC systems are classified on the basis of working fluid as [2-3]:

A) Water system
B) Air system
C) Air-Water system

A) Water System

In this type of HVAC system as shown in Figure. 1, the working fluid used is water that transfers thermal energy in between A/C plant and conditioned space. For cooling chilled water is used whereas for space heating hot water is used. HVAC plant only supplies water to the space, thus the supply of fresh air must be maintained by another plant i.e. Indoor air quality and ventilation. Chilled Water System is usually referred to them for cooling applications. They are further categorized based on a number of pipes used in these systems such as 2-pipe system and 4-pipe system. As shown in Figure 2, a 2- pipe system can only provide one function at a time that is either cooling or heating, not both at the same time. It shows that heater only provides hot water or chiller only provides cold water to different spaces. Cold water and hot water circulates over fan coil units (FCU), or convectors or Radiators situated in their respective space is used to give chilled water or hot water as per unit type. Exchange of thermal energy takes place in between water and air in the conditioned space. Water-flow is controlled by flow control valve based on load variation. The thermostat is used as a sensor to control flow. As per load, it providesa signal to adjust the flow rate. Since air inside the conditioned space is repeatedly used by the terminal parts, external parts must supply fresh air for ventilation.

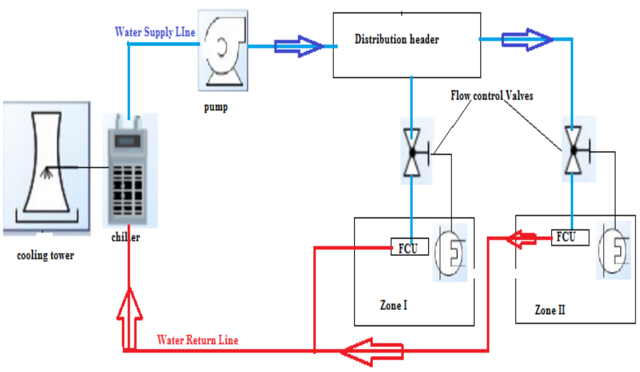

Figure.2. Schematic of water systems

Whereas in terms of 4-pipe system two supply pipelines are used, one for hot and one for cold water, and two pipelines of return water. The hot and cold water are intermixed giving required proportion according to zone load, after that conditioned space is provided with mixed water (one stream flows to the cooling coil whereas other flows to the cooling coil [2-3].

B) Air Systems

These systems are classified based on types of medium that are used to perform work, in the current situation that work is done by air. This air is generally used to transfer thermal energy from occupant space to plant where HVAC system is installed as shown in Figure 3. The unit that basically processes this return is called an Air Handling Unit (AHU). Mixing chamber, Cooling/Heating Coils, Filters, Dampers, Humidifiers, and Blowers/Fans are the essential components of AHU. This processed return air is then retransferred to conditioned space through Air Distribution (AD) system when passing through the AHU. Whereas Diffusers, Ducts, and Dampers are the main components of the AD system. This air extracts (or supplies if the season is winter) latent and sensible heat from the conditioned space. In this cycling process Supply Air Duct is used to supply the air to spaces. To return the air from spaces to A/C plant, Return Air Duct (RAD) is also used. In this cycle, AHU performs the major role of providing adequate fresh air so that Ventilation and Indoor Air Quality (IAQ) can be kept as per comfort ASHRAE 62.1 standards. By using the formula 'Supply Air = Return Air + Fresh Air' both types of air are balanced according to the required condition. Air systems are further classified as:

i. Single duct constant volume single zone system.
ii. Single duct constant volume multi zone system.
iii. Single duct variable volume (VAV) system.
iv. Dual duct constant volume system.
v. Dual duct variable volume (VAV) system.

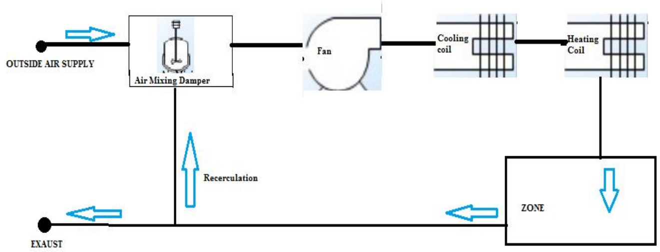

Figure.3. Schematic of Air systems

By using the single duct, the single duct systems can only provide a single job either to maintain cooling or heating. Whereas, the both (heating and cooling) can be simultaneously achieved by using dual duct systems [2-3].

C) Air-Water systems

This type of system is used to provide better features of water and air systems. Combination of the air-water system provides both conditioned air from a central cooling/heating system and hot/chilled water to the separate occupant spaces. Each zone was provided with cooling or heating by using the terminal unit. In this type of system (FCU) is used as a terminal unit and it delivers a major part of the conditioned air and whereas ventilation is supplied into space by central AHUs [1]. Induction units are used as terminal units in another type of air-water system; it works in such a way that it receives supply air from central AHU [1]. In Plenum chamber air is supplied under high pressure and settled under a high nozzle rate into space. It combines with the primary air when it is passed into the room through the induction part. Here the secondary air is referred to the room air. Thus, a combination of primary and secondary air is termed as a mixture of air. This mixture air is the supply air for the conditioned space. Thus, the induction unit does not require a fan. Figure 4 presents a schematic of the induction unit.

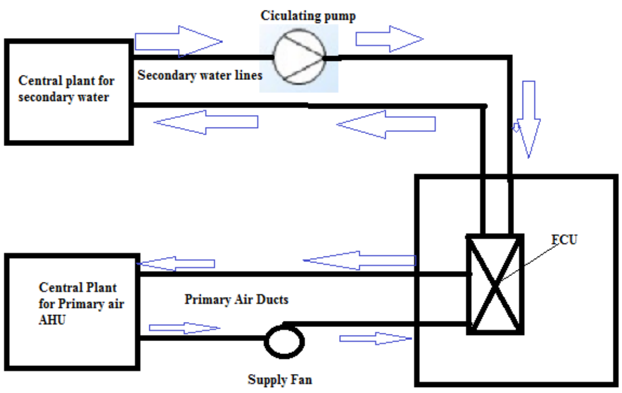

Figure.4. Schematics of the Basic induction unit

Generally, a cooling coil with chilled water keeps a terminal unit like FCU cools. Therefore, the sensible cooling load is controlled by cold water and the latent load is controlled with supplied dehumidified and cooled air provided by the central AHU of the air system. This is the major reason for not having any serious problem in the cooling coils. Same as in winter season, AHU provides heated fresh and humidified air whereas the hot water flows through the heating coil of a terminal part [1-2].

3. Application of Thermal Insulation inthe HVAC system

As there is temperature variation exist between the conditioned air within the duct and its immediate surrounding which results in the loss of thermal energy due to heat transfer thus increase the operating cost of the air conditioning system. Moreover, it creates fluctuation in the conditioned space conditions. In metal ducts even at low-temperature difference cause condensation problem in the humid environment, therefore, minimum insulation should be predetermined to eliminate the condensation problem.

3.1 Thermal Analysis of HVAC duct

Thermal performance of an HVAC duct is conducted using conservation of mass and energy equation. The mass conservation reveals that mass flow rate of supply air is the sum of the mass flow rate of return air and fresh air, while energy conservation equation gives information about energy transfer at the inlet (mass, heat, and work) and out of the duct.

Mass Balance

$$\dot{m}_s = \dot{m}_R + \dot{m}_F \tag{1}$$

Energy Balance

$$\dot{Q} + (\dot{m}\,z)_{in} = (\dot{m}\,z)_e$$

Where, Q represents the heat losses through HVAC duct and Z represents the enthalpy of supply, return and fresh air at their inlet and exit of the duct. Heat losses through HVAC duct normally estimated using degree days approach and basic heat transfer equation as given in Table 1.

Table 1: Heat Losses through HVAC duct.

3.2 Life Cycle Cost Analysis

The life cycle cost analysis is usually used to analyze the energy systems. A life-cycle cost analysis reveals that cost incurred on initial investment on modification on existing energy system that increases the quantity of insulation of air distribution system can result in net energy saving by reducing operation cost (fuel cost) over the lifetime of HVAC system.

To estimate the energy cost incurred due to the presence of compression of insulation at a selected point of the duct, the life-cycle cost analysis is done. This method is practically used to determine the optimum insulation thickness at selected points of the duct. The economic parameters used in the economic analysis of an air distribution system are given in Table 2.

Table 2: Economics parameters are used in calculation [8, 31-33].

Economic parameters	Notation	Values
Natural gas	HV	34.53 MJ/m^3
Cost of fuel	C_f	20.41Cent/m^3
Initial investment	C_{mat}	0.25MUSD
Maintenance cost	C_m	0.012MUSD
Electric efficiency	$_e$	0.93
Operation time	Δt	6500 h
Insulation cost	C_{ins}	13.4USD/m^2
Interest rate	i	5%
Inflation rate	d	7%
Life time	LT	15 years

In order to reduce energy loss to/from HVAC duct from/to surrounding insulation thickness should be optimized by minimizing the energy and insulation cost. Insulation thickness can be achieved at the minimum total cost incurred in HVAC system; it is basically the sum of energy cost (heat transfer) as well insulation cost (installation and maintenance). The total cost is a function of energy loss in the HVAC duct and corresponding economic parameters. The economic optimum insulation thickness for pipe and duct is a function of design, operating and economic parameters. Generally, the minimum total life-cycle cost is used to determine the economic optimum thickness of thermal insulation, as demonstrated in Fig. 5.

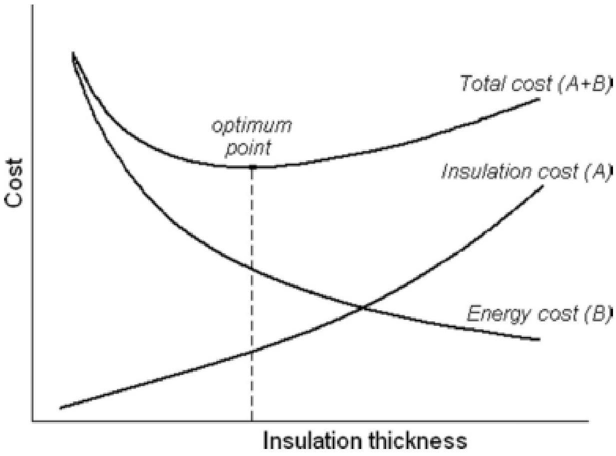

Figure.5. Effect of Insulation Thickness On Total Cost[8]

As the insulation thickness on the HVAC duct increases it reduces the heat loss/gain from/to the duct. Thus, it reduces the energy cost associated with heat loss/gain. So, it is interrupted that the energy loss can be used as input data for an economic model to estimate the effect of insulation thickness on insulation material cost and lost energy cost over an expected lifetime of the HVAC system. The energy loss cost in this analysis is converted into a net present value of energy consumption using economic parameters and operation time. Insulation cost increases with insulation thickness whereas energy cost decrease with insulation thickness. It is seen in Fig. 5 that insulation cost increases with insulation thickness whereas energy cost decrease with insulation thickness. The variation of insulation cost in case piping and ducting is parabolic in contrast to flat surface where it varies linearly.

The sole purpose of HVAC system is to maintain and control the zone parameters i.e. temperature, relative humidity, odour, noise to an acceptable and desirable level for occupants and requirements of manufacturing processing plants (Pharmaceutical, food, beverage, textile companies, automotive, etc.). It is intended to provide cooling in hot climate and heating in cold climate. The required cooling and heating is achieved with the following equipment i.e. chiller, boiler, cooling tower, hot and cold water system, and air distribution system. In air distribution system following psychometric processes occur i.e. simple heating and cooling, heating with humidification and cooling with dehumidification, cleanliness and purification and attenuation of noise level [1,4]. In addition to that, it distributes the chilled/hot air to zone through ducting i.e. supply, return, fresh and exhaust air duct. The chilled air is delivered from the air conditioning unit/air handling unit to the different zones with supply air duct and registers. As air pass through different zones, it gets warm by absorbing heat from the zone. This warm air is then circulated back towards air handling unit with return air duct. The fraction of warm air proport to fresh air is exhausted into the surrounding with exhaust air duct. HVAC’s duct is typically located inside and outside the building. Usually, the plant room is located inside the building. Therefore, most of the HVAC’s ducts are installed inside the building. The ambient temperature of the plant room is lower than outside the building. HVAC’s ducts installed outside the building are subjected to harsh environment whereas those located inside the building are also subject to considerable temperature. There is a temperature difference exist between the conditioned air inside the duct and its immediate surroundings. This temperature difference increases the cooling/heating loss from the duct because heat transfer is directly related with temperature difference in contrast heat transfer decreases with thermal insulation, the thickness of insulation and duct material and lowering the value of thermal conductivity. The cooling/heating loss to/from the duct enlarges the energy bill of the building to homeowner and also causes peak load to the utilities. Therefore, in order to decreases heat transfer to/from the duct, the thermal insulation should be one of the most important tools to avert heat loss from the duct. Moreover, thermal insulation also prevents condensation of water vapor at the external surface of the duct [5-7].

4. Optimum Thermal Insulation Thickness

Mostly engineering investigations consider thermal insulation material and thickness as a key factor from energy, economic and environmental point of views. The economic insulation thickness concept is basically based on the initial investment of thermal insulation used in the HVAC system and ES is achieved by using thermal insulation over the expected lifetime of the HVAC system. In order to decrease heat loss to the surrounding insulation thickness should be optimized by minimizing the energy and insulation cost occurred on the HVAC system. The economic insulation thickness for a pipe and duct is a function of design, operating and economic parameters. The parameters needed to determine OIT area pipe or duct size, cost, the thermal conductivity of the duct and insulation material, operating and ambient temperatures, convective heat transfer coefficient inside and outside the duct, inflation and interest rate, type of the fuel, efficiency of the system and annual operating hours [8-10].

In most of the studies, the degree-time concept is one of the simplest methods used to determine the cooling/heating energy requirement of a building under constant operating and environmental condition. Zaki and Al-Turki[11] performed thermo-economic analysis to estimate the OIT for pipelines (0.1-0.273m) of an oil industry using rockwool and calcium silicate as insulation material. In this analysis working fluid was superheated steam, furfural, crude oil and 300-distillate were used and outside convective heat transfer coefficient was constant. The analysis considers initial investment on insulation and ES achieved over an expected lifetime of piping. Li and Chow [12] determined OIT on tubes (0.02-0.2 m) to protect the pipe from cold freezing using thermo-economic optimization analysis. They analyze the effect of ambient air and design parameters on OIT for the tube. It was investigated that insulation thickness decreases as thermal conductivity and insulation cost increase while insulation thickness increases as outside surface temperature of the insulation decreases. Soponpongpipat et al. [13] estimated the OIT for HVAC's duct using thermo-economic analysis. In this analysis galvanized steel duct (0.5m) with glass wool and rubber as insulation material were chosen. The variation of OIT, ESs, and PP for a duct with a convective heat transfer coefficient was investigated. It was estimated that a variation of convective heat transfer coefficient doesn't affect OIT but ES increases with heat transfer coefficient. Keçebas et al. [14] estimated OIT, ESs, and PP for hot water piping (50-200mm) system with rock-wool insulation over a lifetime of 10years in the city of Afyonkarahisar, Turkey. The highest value of ES is achieved for the pipe size of 250mm using fuel oil while the lowest value of ESs is achieved for the pipe size of 50mm using geothermal energy. It was investigated that geothermal energy is a better choice than fuel oil considering environmental and economic impacts of thermal insulation. In his another study, he investigated the effect of fuel inlet, stack gas and combustion chamber temperature and air-fuel ratio on OIT, ESs and PP for different pipe size using energo economic and exergo economic method. The OIT was obtained using energo economic method was lower than energo economic method [15]. Kayfeci[16] determined OIT, ESs, and PPs for piping (50-250mm) with fiberglass and expanded polystyrene as insulation material in the city Isparta, Turkey using life-cycle cost analysis with different degree-days value. Considering natural gas a fuel, the maximum value of ESs is achieved for pipe size of 250mm with expanded polystyrene and the minimum value of ESs is achieved for pipe size of 50mm with fiberglass. Yildiz and Ersoz estimated the OIT ESs and PP for high and low-pressure gas pipelines and low-pressure liquid pipeline under both heating and cooling mode using life-cycle cost analysis. As a refrigerant R-410A [17] and fiberglass as insulation material were used. The highest value OIT was investigated for the high-pressure gas pipeline, the intermediate value was investigated for low-pressure gas pipeline and the lowest value was obtained for the low-pressure liquid pipeline. In another study, they use R-407C [18] as a refrigerant and fiberglass, rockwool, expanded polystyrene were used. They concluded on the basis of the obtained results of OIT for different insulation material the expanded polystyrene is a better choice. The effect wind speed on OIT, ESs ,and PP for HVAC's duct installed outside the building is estimated using LCCA in the city of Usak, Turkey. They consider four different fuel types such as LPG, NG, Fuel oil and Coal and two different insulation materials i.e. rock wool and glass wool. They investigated that the high wind speed produces the economic benefits for HVAC's duct [19]. Kumar et al. [20] have investigated the impacts of compression of thermal insulation on condensation of water vapor at selected points of an HVAC duct at constant convective heat transfer coefficient of ambient air. To avoid condensation critical insulation thickness must be greater than 35 and 30 mm for supply and return air duct. They also calculated the optimum thermal insulation thickness at selected points of the duct is greater than critical insulation thickness. Therefore, condensation would not occurat optimum thermal insulation thickness. Another, parametric study conducted in [21] to determine the effect of supply air flow rate, temperature, wind speed and insulation thickness on condensation of water vapor at the external surface of the duct. It is calculated that the insulation thickness should be 15-55 mm and 15-35 mm, respectively by varying convective heat transfer coefficient from 6-22 W/m^2 K. Additionally, to avoid condensation supply air should flow at 1.4 m^3/s while wind velocity must be kept at above 2.8 m/s.Daşdemir et al[22] investigated economic impacts of insulation material with air gap for different pipe size using thermo-economic analysis. They found out that the insulation thickness, payback period and energy cost savings is varying in between 0.3cm to 25cm, 0.8yr to 2.2yrs and 20$/m-yr to 423$/m-yr. whereas the air gap is used 0cm to 5cm in small and larger diameter pipe which are insulated with EPS, XPS and rock wool. They found that maximum energy saving achieved for smaller diameter of pipe with different air gap, while negligible impacts of air gaps occur for larger diametrical pipe. therefore, the air gap for smaller diameter pipe is economically feasible but ineffective for larger pipe sizes.

It is obvious from above study that most of the research had been carried out on OIT, PP,and ES for ducting and piping used in buildings and industries [23,24]. Though, many of the researchers had calculated environmental and economic impacts of insulation used in buildings walls and piping of HVAC system. However, no any significant research has been done on the environmental impacts of insulation in the ducting application. For this purpose, Comakli and Yüksel [25] used LCC analysis over an expected period of 10 years to find out OIT, ES, and PP for Building wall. By using insulation ES and CO_2 emission is reduced by 12.13% and 50%. Arsalan and Kosel[26] determined that the increment of ES and OIT in buildings also lies on zone temperature. They calculated that when the zone temperature is 18-22 ºC the CO_2 and SO_2 emission is identical to ES i-e 74.9%-78.8%. Dombaycı[27] determine that the reduction of CO_2 and SO_2emission by 41%[27], 82%[28], 54 %[29] and 30 %[30] whereas the fuel consumption is reduced to 46 %[27] when different insulation material with OIT is used on building wall. Kurt[29] calculated that with increasing the thickness of air gap from 2-6cm the EC is reduced by 45% in the double layered wall of buildings. Basogul and Keçebas[31] calculated environmental and economic impacts of insulation material used in DHS in Afyonkarahisar/Turkey. They founded that 21% emission of CO_2 is reduced with OIT.

5. Conclusion

There are numerous studies conducted recently on the economic and environmental impacts of thermal insulation material at different energy source for the rectangular, circular and oval duct. It improves the thermal performance of an HVAC system. It is investigated that insulation and dut material, fuel source, thermodynamic parameters of conditioned air, duct geometry and economic parameters (inflation and interest rate) are mainly used in life-cycle cost analysis to optimize thermal insulation thickness. Additionally, an air gap is recently most apropos optional to reduce material cost of insulation at given energy loss through the duct. However, parametric and critical analysis were conducted to determine the impact of thermal insulation compression at selected points of an HVAC duct to avoid associated condensation of water vapor at the external surface of the duct. Therefore, optimum thermal insulation thickness not only produces economic and environmental benefits but also reduces premature deterioration of insulation material over an HVAC duct.

6. Acknowledgment

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Annexure-A

Table 1: ***Heat Losses through HVAC duct.***

Paper	Heat Transfer		Thermal Resistance	Con
Yildiz[29]	$\dot{Q} = UA_s(T_{R,m} - T_a)$		$R_{t,un-ins} = \frac{1}{h_i A_{s,i}} + \frac{ln(\frac{r_o}{r_i})}{2\pi L_{pipe} k_{pipe}} + \frac{1}{h_o A_{s,o}}$ $R_{t,ins} = \frac{1}{h_i A_{s,i}} + \frac{ln(\frac{r_o}{r_i})}{2\pi L_{pipe} k_{pipe}} + \frac{ln(\frac{r_{ins}}{r_o})}{2\pi L_{pipe} k_{ins}} + \frac{1}{h_o A_{ins,s,o}}$	h_i = Nu
Soponpongpipat [13]	$Q_{\text{bare duct}} = \frac{\Delta T}{Z_{\text{total, bare duct}}}$ $Q_{\text{ins duct}} = \frac{\Delta T}{Z_{\text{total, Ins duct}}}$		$Z_{\text{total, bare duct}} = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{R_{o,duct}}{R_{i,duct}}\right)}{2\pi L_{duct} k_{duct}} + \frac{1}{h_o A_o}$ $Z_{\text{total, ins duct}} = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{R_{o,duct}}{R_{i,duct}}\right)}{2\pi L_{duct} k_{duct}} + \frac{\ln\left(\frac{R_{ins,1}}{R_{o,duct}}\right)}{2\pi L_{duct} k_{ins,1}} + \frac{\ln\left(\frac{R_{ins,2}}{R_{ins,1}}\right)}{2\pi L_{duct} k_{ins,2}} + \frac{1}{h_o A_o}$	h_o =
Mustafa Ertürk [32]	$Q_p = UA(T_{ad} - T_o)$		$R_{p,un-ins} = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_1}{r_0}\right)}{2\pi L k_1} + \frac{1}{h_o A_o}$ $R_{p,ins} = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_1}{r_0}\right)}{2\pi L k_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L k_{ins}} + \frac{1}{h_o A'_o}$	h_i = h_o =
Dileep				

Dileep et al [20]	$\dot{Q} = \frac{(T_o - T_a)}{R_T}$	$R_s = \left(\frac{1}{a}\right)\left(\frac{1}{h_i r_1} + \frac{\ln(\frac{r_2}{r_1})}{k_{gi}} + \frac{R_s R_c}{R_s + R_c}\right)$ $R_t = \left(\frac{1}{t}\right)\left(\frac{1}{h_i r_1} + \frac{\ln(\frac{r_2}{r_1})}{k_{gi}} + \frac{\ln(\frac{r_{3,t}}{r_2})}{k_{ms}} + \frac{\ln(\frac{r_{4,t}}{r_{3,b}})}{k_{gw}} + \frac{1}{h_o \quad r_{4,t}}\right)$ $R_b = \left(\frac{1}{b}\right) \left(\frac{1}{h_i r_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{gi}} + \frac{\ln\left(\frac{r_{3,b}}{r_2}\right)}{k_{ms}} + \frac{\ln\left(\frac{r_{4,b}}{r_{3,b}}\right)}{k_{gw}} + \frac{1}{h_o r_{4,b}}\right)$	$h_o = 11.58 \cdot \left(\frac{1}{D_h}\right)^{0.2} \cdot \left\{\left(\frac{1}{T_s + T_o}\right) - 546.3\right\}^{0.181} \cdot (T_s - T_o)^{0.266} \cdot (1 + 2.86 V_o)^{0.5}$ $h_i = \frac{0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot k_a}{D_h}$