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Various design methods of Geothermal Heat Exchanger – A review

*Ankur Sukhija, #Amit Sharma

*M. Tech. Scholar, #Assistant Professor, Department of Mechanical Engineering, D C R University of Sci. and Tech. Murthal, Sonepat (Haryana), India.

*ankursukhija999@gmail.com, #amitsharma.me@dcrustm.org

Abstract **The Geothermal Earth Heat Exchanger (GEHE) is a very effective method for the cooling of air in winters and heating in summers. In today's world with a rapid growing need for the HVAC industry this is a very good method to save the earth from the dangerous effects of the refrigerants used in the different conventional methods. There are lot of methods for the design of different types of GEHE; in this paper, a brief summary of the various design methodologies of the GEHE is mentioned. Various design tools are also included. Two commonly used design methods used for the horizontal and vertical system are discussed in detail. For the better understanding of the method an example is also explained in this paper in which several parameters like the length of the heat exchanger, heat transfer rate, outlet temperature of air, etc. are calculated. These methods shall develop understanding and help to appreciate the energy conservation aspect of the GEHE.**

Keywords — **Geothermal Earth Heat Exchanger, Air Conditioning System, Vertical and Horizontal Heat Exchanger.**

I. Introduction

The use of refrigerants and high grade energy for the HVAC industry has increased to a great extent over the last few decades and is increasing day by day. It is essential to save the environment from the harmful effects of the refrigerants which lead to the ozone layer depletion and to reduce the use of the high grade energy which is increasing the Global Warming Potential. The Geothermal Earth Heat Exchanger (GEHE) is a very effective method which uses Geo-thermal energy of Earth for the cooling as well as heating in summers and winters respectively. System uses simple property of- the temperature variation of the earth below a certain depth becomes negligible and it remains constant throughout the year [10]. The atmospheric air is made to pass through the pipes installed in the earth below few meters where the temperature is more in winters and significantly less in summers; as shown in figures 1 and 2. So, there will be a transfer of heat between the air to be conditioned and earth thus, the air will become significantly cooler in summers and vice versa.

The earth is being used as a heat sink since ancient time. Around 3000 B.C., the architects of Iran used Geothermal energy in the form of wind towers and tunnels for the cooling purposes [25], [5]. The Geothermal Energy was first identified as heat source in Heat Pumps around 1910 and the first record of it was found in a swiss patent in 1912. In this patent Geothermal energy was utilized as a heat source for heat pumps [2], [43].

There are various types of GEHE. These types of GEHE differ in the formation and way of installation of the pipes. Firstly they are classified as open and closed loop GEHE [32]. In the closed system, same air is circulated again and again while in open system, fresh ambient air is used every time. They are also classified as horizontal loop system, as depicted in figure 1, and vertical loop system, shown in figure 2. In the horizontal loop GEHE system, pipes are installed horizontally w.r.t. to the surface of the earth below few meters and in the later the pipes are buried vertically.

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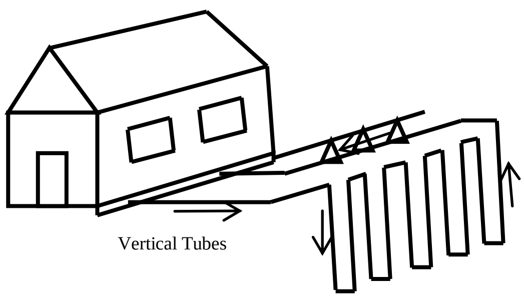

Figure 1. Simple Line Representation of Vertical GEHE [32].

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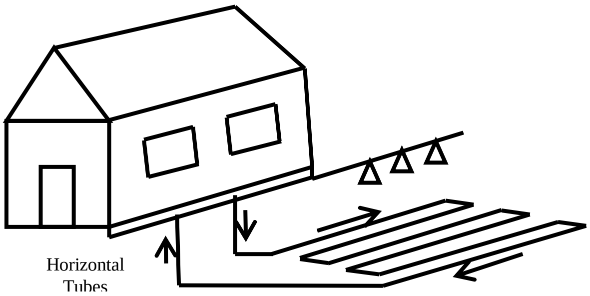

Figure 2. Simple Line Representation of Horizontal GEHE [32].

The design procedure for both the methods are different as the earth's temperature along the horizontal system is almost constant and the earth's temperature along the vertical system varies with depth. That is why there are different methods used for the design and analysis of the above two types of systems.

Commercial software are also available for the design of GEHE such as Earth Energy Designer (Blocon AB) which is available at 720 US Dollars for one user for an year [48], Ground Loop Design (Thermal Design Inc.) whose professional version known as GLD professional is available for 2800 USD for two years subscription [49]. Other software are also available such as GLHEPRO (Oklahoma State University) [50], GS2000 (Caneta Research inc.) [50], GCHP Calc (University of Alabama)[50], etc.

II. Design methods of GEHE

There are many methods available for the design of the GEHE. One-dimensional [32], [18], [22], two-dimensional [8], and three-dimensional models [9] are worked upon by different researchers for the design and performance calculations of the GEHE. In the performance calculation of the GEHE, the amount of heat that is transferred from the earth to the flowing air and the changes in the pressure and humidity is calculated [31]. The modeling of the system can also be done by the use of several modeling tools such as EnergyPlus [46] and TRNSYS [47] which are easily available.

Finite element analysis (FEA) approach can also be used for the design and performance analysis of the GEHE [12]. In the FEA approach a 3-Dimensional finite volume model is formed and numerical solutions are obtained with the help of the FLUENT solver. An unsteady and 3-dimensional model of heat transfer is considered in the model.

Another tool for the optimization and performance analysis for the GEHE is Genetic Algorithm. Genetic Algorithm has emerged as a very powerful tool for the optimizations of the simple design problems and GEHE is one of them. The use of GA to develop a tool for the optimization and performance analysis of the GEHE was done [14], [19], [34]. The developed algorithm was used to calculate the temperature of the air at the outlet and therefore can be used to calculate the performance analysis of the GEHE. This method is also applicable to a lot of other fields like the choice of buildings such as green house, solar house, etc. [32].

Another approach which is very common now days is the use of Computational Fluid Dynamics (CFD) for the design of the GEHE. CFD uses a very simple technique of breaking the problem into discrete elements and then governing equations are then applied on these discretized elements to get the numeral solution for all the required parameters like pressure distribution, temperature gradients, etc. at a reasonable cost and in very less time, because very less work is to be done experimentally [17]. CFD gives very accurate results of the analysis but it can be used only by those who have a very good command over it. Several other authors has used this approach for the design of different heat exchangers like Corrugated plate heat exchangers which can also be used for the design of the GEHE [15], [16], [24], [35].

Another module is available for the design of GEHE in which the simulation of heat exchanger is done using the EnergyPlus tool [20], [38], [41]. Using the module an analysis can be conducted to evaluate the change in the performance of the GEHE due to the change in the various geometrical factors of the heat exchanger like radius of tube, length, tube depth and flow rate of the fluid considering several conditions during winters. The validation of the module was done against various experimental and theoretical data and found to be similar to the various data previously obtained by several other methods. The results obtained from the study showed that the heat transfer rate of the GEHE is affected by tube length and tube depth. While the effect of change in radius and flow rate of the fluid is mainly observed on the inlet temperature of the fluid. It is concluded that by using a proper design of GEHE up to 50% of the total cooling load can be saved [42].

Another approach which used to calculate the performance of GEHE is an experimental method [23] in which the author in southern Germany experimentally drilled holes of diameters: - 121mm, 165mm and 180mm. Then the thermal efficiencies of the different systems are calculated. It was concluded that if the drill-hole diameter is increased than the thermal performance of the GEHE will improve, contradictory to the fact that the thermal resistance of the pipe is more than that of the resistance of the earth.

A numerical model of GEHE is also proposed using the two dimensional theory [21]. A discretized modal of the GEHE is prepared and the modal is solved by the use of the response factors method to simplify the required complex

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calculations. All factors are calculated by the use a finite element program. A finite element 2D heat conduction problems solver is used to solve each response factor. "A response factor represents the flux (here in W/m) resulting from a unitary triangular temperature solicitation on one of the boundaries while leaving another boundary at a temperature equal to zero [21]". There are several advantages of using this model. With the use of these response factors the time required for calculation was reduced. It was precise for both short period i.e. one day, and a long period i.e., one year. Also, all the type of soils and of different geometry can be solved by this calculation in a 2D finite elements program. Another advantage of this method is that multiple pipe heat exchangers can also be designed by this model [33], [42].

A GEHE using water as the flowing fluid was designed and simulated by TRNSYS (v 17.0). The study was performed in Rajasthan, India [37]. The effect of rate of flowing water, length of the tube, diameter, and the pipe material was studied on the performance of the GEHE. The flow rate of the fluid and diameter of the tube was kept constant for the study. The effect of the variation of the length was obtained by considering the tubes of different lengths. According to the results obtained it was found that the increase in the length of the tube cause an increase in temperature drop. The variation in the size of tube at the assumed flow rate was also recorded. It was concluded from the study that with the increase in the tube size the temperature at the outlet of the tube decreases gradually. Another model of the GEHE using air as fluid was presented by the same authors, which was simulated using a tool known as TRYNSS 17. The validation of the tool was done using the data obtained from an experimental setup [37], [39]. It was concluded from the studies that about 82 % to 85 % of the rise in the fluid temperature along the GEHE tube was obtained after a length of 34 m from the beginning [42].

The literature discussed above is summarized in the following table 2.

Table 1. A Summary of the designed methods mentioned above

YEAR	METHODS USED	GEOGRAPHICAL LOCATION	TYPE OF SYSTEM	REFERENCE
2001	Finite Element Analysis	Belgium (Europe)	Earth Air Heat Exchanger (Horizontal)	[12]
2006	Genetic Algorithm	Mathura (India)	Horizontal GEHE	[14]
2007	Computational Fluid Dynamics	Southern China	Earth air Pipe System (Horizontal)	[17]
2008	Modeling and Simulation	Hong Kong (China)	Borehole Heat Exchanger (Vertical)	[20]
2013	Experimental Method	Nuremberg (Germany)	Borehole Double Pipe Heat Exchanger (Horizontal)	[27]
2009	Numerical Method (2D)	Cedex (France)	Earth to air heat exchanger (Horizontal)	[21]
2016	Simulation (Transys)	Pilani (India)	Earth to water heat exchanger	[37]

In the next sections two methods for the design of the vertical and horizontal GEHE are explained in detail which uses a set of equations to calculate various parameters like the length of the tube required and amount of heat transferred, etc.

A. Design of Vertical GEHE

In this method, the design methodology for vertical GEHE which was shown in figure 1 is discussed. Design method for the vertical and horizontal systems are completely different because the variation of temperature along the length of the tube is almost constant in the horizontal system but it varies with depth in vertical system as already mentioned in section 1.

There is a method which uses a simple thermodynamic heat conduction equation to design the vertical loop GEHE [1]:

$$q = L(t_g - t_w)/\ R \qquad (1)$$

This equation is a steady state heat transfer equation and it can be converted to variable state heat transfer equation by the use a set of constant heat rate pulses. Length

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of the tube can be calculated by the use of the equation if the amount of heat to be transferred is known. Equation 1 is based on the assumption that thermal resistance along the tube is negligible, only the earth's resistance is considered [11].

A more precise and accurate equation for design of vertical GEHE is suggested by Kavanaugh and Rafferty in his book in chapters 3 and 4 [7] for the calculation of the coil length. By including a minimum of three pulses which is an average yearly pulse, month wise average pulse preceding the design day, and a short term pulse of one to six hours in length. The effect of bore resistance (R_b) is also considered in the equation that accounts for the thermal resistance of the pipe (R_t), the film resistance between the fluid and pipe (R_{film}), and the resistance of the fill or grout material ($R_{annulus}$).

Thus the relating equation for the length of the cooling and heating coil is [7]

For cooling:-

$$L_c = \frac{q_a R_{ga} + q_{cond}(R_b + PLF_m R_{gm} + F_{sc} R_{gst})}{t_g - \frac{ELT + LLT}{2} + t_p} \quad (2)$$

For heating:-

$$L_h = \frac{q_a R_{ga} + q_{evap}(R_b + PLF_m R_{gm} + F_{sc} R_{gst})}{t_g - \frac{ELT + LLT}{2} + t_p} \quad (3)$$

The above equations are based on the assumption that the system is designed along with a heat pump clubbed with it, therefore the q_{evap} is taken as positive, q_{cond} is taken as negative and t_p is taken as positive for a rise in ground temperature[45].

B. *Design of Horizontal GEHE*

The Horizontal loop system which was shown in figure 2 is designed in this section. Because the temperature of the earth along the tube is constant heat exchanger design theory can be used to design the GEHE [6], [8], [9], [13], [28], [25], [30], [44] and performance analysis of various GEHE located in different locations like Bhopal, Chandigarh, Pilani, etc. in India and around the world like in Germany, Dublin, etc. This method uses a one dimensional model of the heat exchanger to calculate the performance and it gives very close results to the accurate with a very simplified procedure [36].

This method is based on several assumptions that:-

i. The Earth's temperature is constant across the axial direction.

ii. Surface temperature of the ground is equal to the inlet air temperature.

iii. Pipe's Thermal Resistance is neglected.

iv. Thermo-physical parameters of air and ground are constant.

v. Entrance Length of the tube is neglected.

vi. Temperature of the tube is same as that of the ground.

In this method length of the GEHE, outlet temperature of air and power required for the flow of air shall be calculated. To calculate these parameters several other parameters such as Earth's Temperature, mass flow rate of fluid, overall heat transfer coefficient, etc. are also needed which are later discussed in this section.

Length of the tube required: The length of the Heat exchanger tubes [4] for the assumed value of NTU will be:-

$$L = NTU \frac{m\, c_p}{2\pi r_i U_t} \quad (4)$$

Power Required: The fan power (P) which is required to circulate the air through the tube length can be calculated by using the total pressure drop [4]:-

$$P = Q\, \Delta p \quad (6)$$

Outlet temperature of the air: Thus the average temperature of the air leaving the tube (T_o) and the Length of the tube can be calculated by using the NTU-effectiveness equation [4]:

$$\varepsilon = \frac{T_o - T_{in}}{T_g - T_{in}} = 1 - e^{-NTU} \quad (7)$$

This equation of effectiveness came from the assumption that the temperature of the earth remains constant and thus the specific heat of the earth considered infinite and same as the case of the heat transfer while phase change of one fluid and the equation of the above case become same.

Now, if we will put different values of NTU in the above equation the value of the effectiveness becomes steeper [36] i.e. the value of the effectiveness increases very slowly after NTU > 3. The effectiveness at NTU=3 is almost 95%.

One can design the Heat Exchanger for the effectiveness value of 95% by assuming the value of NTU as 3, or if we know the dimensions of the heat exchanger we can calculate the effectiveness of the GEHE.

Several other parameters like the mass flow rate of the air, Earth's temperature, overall heat transfer coefficient are which are used in the above equations can be calculated using the following set of equations discussed below.

Earth's Temperature below a certain depth: The variation of the temperature of the earth below some depth is almost

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negligible and it is difficult to measure the temperature of the earth at various depths for various soil conditions at different locations. So, to calculate the earth's temperature at a depth z below the earth's surface and time t, an equation can be used [3] which is also mentioned in the ASHRAE District Cooling Guide:

$$T_g = T_m + A_s exp^{-z\sqrt{\frac{\pi}{365\alpha_s}}} sin\frac{(2\pi(t - t_{lag})}{365} - z\sqrt{\frac{\pi}{365\,\alpha_s}} \quad (8)$$

The different properties of soil used in the equation (8) are available on the different meteorological and climate control websites for particular locations or is also available in the ASHRAE Handbook [36]. It is generally seen that the values of the properties of soil are often not commonly available and thus it becomes very strenuous to calculate the exact Ground temperature, so the Earth's temperature below a particular depth can be assumed to the annual average of the earth' surface temperature which was previously assumed to be equally to the ambient temperature throughout the year.

Mass Flow Rate of air: Some of the arbitrary dimensions of the Heat Exchanger are first fixed according to the availability of the pipe dimensions and by a little trial and error. The other parameters will then be calculated by invoking simple heat transfer equations. First we assume an arbitrary diameter of the pipe (D) and with the help of the known volume flow rate (Q), the mass of the fluid flowing per unit time (ṁ), and the number of tubes (n) will be calculated and by the sound considerations that will be produced in the ducts we will limit the maximum velocity (v).

The number of tubes will thus be calculated as:\

$$NTU = \frac{UA}{\dot{m}c_p} \quad (11)$$

$$n = \frac{4Q}{v\pi D^2} \quad (9)$$

And the mass flow rate can be calculated as simply:

$$\dot{m} = \frac{\rho Q}{n} \quad (10)$$

Heat Exchanger (NTU-Analysis): There are general approaches to design a simple heat exchanger i.e., The NTU approach and the Logarithmic Mean Temperature Difference (LMTD) approach. Generally, for the design purposes, NTU approach is used while LMTD approach is used for the analysis purposes. In this paper NTU approach will be discussed for the design of GEHE. NTU stands for Number of Transfer Units which is a non-dimensional quantity and is defined as [26]:

The overall heat transfer coefficient can be calculated as [26]:

$$U = \frac{1}{\left(\frac{1}{h_c} + \frac{1}{2\pi k_t} ln\frac{r_o}{ri}\right)} \quad (12)$$

Where the value of h can be determined by using the equation [26]:

$$h = \frac{Nu\,k}{D} \quad (13)$$

For the calculation of the Nusselt number a simplified equation can be used proposed by Mc Adams for heating and cooling of all fluids in forced heat transfer for turbulent flow [26]:

$$Nu = 0.023\,(Re)^{0.8} Pr^n \quad (14)$$

Where,
n = 0.4 while heating, and
n = 0.3 while cooling.
The equation (10) can be used if, $0.7 < Pr < 160$, $Re \geq 10^4$, $L/D \geq 60$.

III. EXAMPLE

In general horizontal system is commonly used for most of the applications where there are no space constraints because it is very tedious to dig holes for the vertical systems and install the system. For the better understanding of the methodology - design of horizontal system is presented in this section considering the Bhopal(India) as geographic location; heat exchanger is designed using the conventional methods explained in section 2.2 A horizontal GEHE is designed by assuming a required air flow rate of air in the system as $11.5 m^3/s$.

The mass flow rate of the air can thus be calculated using the equation (10). The mass flow rate of the air comes out to be 13.8 kg/s.

The properties of air which are used in the above equations are taken for the room temperature because there is very less variation in these properties at small temperature variations.

The several properties used in the example are shown in the table 2.

Table 2. Properties of air at room temperature

1.	Density	$1.2 kg/m^3$
2.	Dynamic Viscosity	$1.8*10^{-5} Nm/s^2$
3.	Thermal Conductivity	$0.024 W/m^0k$

The pipe material of the system is assumed to be concrete which is having an outer and inner diameter as 92 cm and

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90 cm. The friction factor of concrete is taken as 0.08 which is calculated using moody chart by using the Reynolds's number and relative roughness of concrete. The value of maximum velocity which can be used according to maximum Noise and Friction considerations is 5m/s for general residential buildings [29].

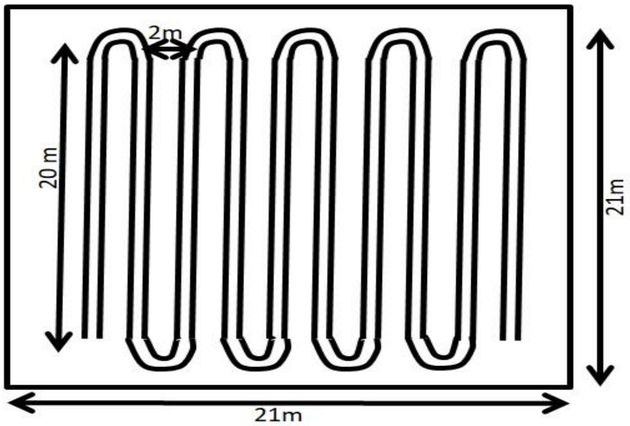

Figure 3. Line Diagram for general arrangement of tubes.

The value of the convective heat transfer and overall heat transfer will thus be calculated using the equation (13) and equation (12) and there values come out to be 0.08 W/m^{2}k and 0.792 W/m^{2}k. For the calculation of the convective heat transfer coefficient nusselt no. is required which is calculated using equation (14).

The year round average temperature for Bhopal is 25^{0}C [32]. The entry inlet temperature for air is assumed to be equal to 45^{0}C which is general room temperature in summer afternoon in the city. The number of loops required for the tube can be obtained by using the area available for the installation heat exchanger. For Example let us assume we have a land space available of 21 m * 21 m for the GEHE than the maximum length available in a single row for will be 20 m in a single row and the total rows required for the Heat exchanger will thus be 10 rows and the spacing between them will become around 2 m each. A line diagram for the better understanding of this arrangement is shown in Figure 3.

The results of the calculation for the above mentioned values are presented in Table 3

Table 3. Results of the above mentioned sample calculations

Diameter (m)	Velocity(m/s)	Outlet Temperature(^{0}C)	Length (m)	Power Required(kW)
0.9	5	26.5	197.4	1.513

IV. CONCLUSION

Geothermal Energy is one of the largest sources of natural inexhaustible energy available. In the past few decades, many researchers have done a lot of work in this field to optimally design the GEHE by various methods so that the material and power requirements of the GEHE can be optimized and the maximum effectiveness can be obtained from the system. A few of the methods that are available in different researches were discussed in this paper to give the readers a brief idea about the design methodologies of the system. Two analytical methods are explained in detail in the later sections of the paper. The methods were explained for the design of the horizontal and vertical GEHE. A horizontal system is also designed in the paper for the better understanding of the method. The horizontal system is convenient to use as it is easier to install because it is not installed at much depths. Various parameters of the GEHE like the required length of the heat exchanger, Power required etc.

V. ABBREVIATIONS USED

"GEHE = Ground Earth Heat Exchanger.
HVAC = Heating, Ventilation, and Air Conditioning.
FEA = Finite Element Analysis.
CFD = Computational Fluid Dynamics.
q = amount of heat transferred per unit time (W).
L = total length of the GEHE (m).
t_g = average ground temp. (^{o}C).
t_w = average temp. of the flowing air (^{o}C).
R_g = earth's thermal resistance (m.^{o}C/W).
F_{sct} = short-circuit heat loss factor between inlet and outlet pipes into the ground.
L_c = calculated bore length required for heating (m).
L_h = calculated bore length required for cooling (m).
PLF_m = part-load factor during design month.
q_a = net yearly average rate of transfer of heat to the earth (W).
R_{ga} = yeraly pulse rate for effective thermal resistance of the earth, h-ft. (mK/W).
R_{gst} = short-term pulse rate for effective thermal resistance of the earth, h-ft. (mK/W).
R_{gm} = monthly pulse rate for effective thermal resistance of the ground, h-ft. (mK/W).
R_e = earth's thermal resistance, h-ft. (mK/W).
t_g = constant earth's temp. (°C).
t_p = long-term ground temp. penalty caused by the heat transfer variations of the earth (°C).
EET = temp. of the liquid that enters the heat pump, (°C).
LET = temp. of liquid leaving the heat pump, (°C).
L = optimum tube Length required for the GEHE (m).
NTU = Number of Transfer Units.

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m = flow rate of fluid (kg/s).
c_p= Specific Heat Capacity (Kj/Kg^{0}K).
r_i= inner radius of the tube (m).
U_t= overall Heat Transfer Coefficient (KJ/Kg^{0}K).
Δp = pressure drop across the tube length (N/m^2).
ρ = density of fluid (Kg/m^3).
v = velocity of fluid (m/s).
P = power required for the flow (W).
Q = volume flow rate of fluid (m^3/s)
T_g = ground temperature time t (s).
z = depth below the surface of the earth (m).
T_m = mean of the temperature of the surface of earth (°C).
A_s = amplitude variation of soil surface (°C).
α_s = soil thermal diffusivity (m2/s; m2/day).
t = time elapsed from the beginning of the calendar year (day).
t_{lag} = phase constant of soil surface (s; days).
A = area for the transfer of heat (m2).
k_t = thermal conductivity of tube (KW/m0k)
h_c = coefficient of convective heat transfer between the air and pipe material.
r_o and r_i = external and internal radius of the tube respectively.
Nu = Nusselt number.
D = pipe diameter (m)."

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