THEORETICAL ANALYSIS OF HEAT TRANSFER THROUGH UNDERGROUND DUCT FOR ROOM COOLING AND HEATING

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The present work aims at the thermal analysis of an underground duct which has been used to cool/heat the air for direct feeding into the room for comfort. It has been seen that the results predicted by the theoretical model are very much close to the experimental values for which the tests were conducted. The convective heat transfer principle to extract heat from the air and dissipate it to the ground has been exploited in the form of a horizontal ground heat exchanger.

NOMENCLATURE

\( T_i \) Pipe inside temperature at a length \( l \)
\( T_o \) Pipe outside temperature at a length \( l \)
\( h \) Convective heat transfer coefficient
\( R_T \) Thermal resistance
\( r_i \) Pipe inside radius
\( r_o \) Pipe outside radius
\( Q \) Heat transfer over a section of pipe
\( L \) Length of a section of pipe
\( l \) Distance of the elementary section from inlet
\( \dot{m} \) Mass flow rate
\( C_p \) Specific heat of the fluid
\( \rho \) Density of fluid
\( V \) Velocity of the fluid
\( L_C \) Length of the section for Horizontal section
\( T_{in} \) Fluid inlet temperature
\( T_{exit} \) Exit temperature of fluid after a section
\( T_{r0} \) Inlet temperature of fluid for Horizontal section

INTRODUCTION
Factors like rising electricity prices and the environmental factors is the main driving force for execution of the present work. Conventional Air-conditioner is one such device that heavily consumes electricity and its emissions are detrimental to the environment. The high current requirements of the air-conditioners require the installation of the high capacity electric cables. Also, because of the intermittent starting and stopping of the air-conditioners the installed capacity of the electricity has to be very high than required for actual running. Moreover, the gap in the demand and supply of the electricity in our country limits the suitability of the air-conditioners as due to the heavy load on the wiring failures and short circuiting has been observed a number of times.

One of the alternatives that can address the above mentioned concerns is to use the thermal capacity of the earth for exchange of heat in the hot and cold weather. The power consumption in this case would be very less as the heat transfer is as per first law of thermodynamics. Another key benefit of using this kind of system is that we can have 100% fresh air in the case of open loop system. While in case of the air-conditioners only a fraction of the air supplied is fresh while the rest of the air is re-circulated.

WORKING
The air conditioning system consists of a duct buried under the earth through which the fluid (air) is circulated. The air rejects the heat to earth or takes heat from it to be at comfortable temperature around 25 degrees Celsius. In the case of cooling a building, the ground is the system heat sink, and the building
is the heat source. While in the case of heating, these functions are reversed.

In this system, the actual heat transfer to and from the ground loop heat exchanger varies continuously due to changing building energy requirements. Despite the changing environmental conditions the net fall in temperature that can be adjusted with the flow of the air so as to give comfort conditions in the room. The resulting variations impact the coefficient of performance (COP) of the system and thus influence the overall system performance in a significant way.

The system consists of pipes buried inside the ground with at least one end of the pipe being connected to the control environment. Depending upon the arrangement of the pipes under the ground and the way the pipe ends are placed, the system can be classified in following ways.

**MATHEMATICAL MODEL**

The model has been solved by using the thermal resistance model for the heat transfer to develop general expressions for the temperature changes across different sections of the pipe. Various assumptions have been made which are listed below.

1. Earth is considered to be an infinite sink
2. The variations of the properties of fluid are neglected
3. The air temperature at a particular section is assumed to be equal to the mean stream temperature.
4. Steady state is assumed
5. No heat generation
6. Constant Convection Coefficient (h)
7. No Radiation heat transfer

The different sections are analyzed as under

**Vertical down section**

This section is the down section in the temperature gradient of the earth. Consider the elementary area shown by the cross-hatch in the figure. The thermal gradient across this section is \( (T_l - T_{lo}) \). The thermal resistance offered by the elementary section can be calculated by considering the convective resistance and the resistance due the pipe wall which are given by \( 1 / hA = \frac{1}{2\pi hr_d dl} \) and \( \frac{1}{2\pi kdl} \log(r_o / r_i) \) respectively \([1]\). Therefore, the total thermal resistance offered by the elementary section can be calculated by adding the two individual resistances, so the total resistance is given by,

\[
R_T = \frac{1}{2\pi hr_d dl} + \frac{1}{2\pi kdl}\log(r_o / r_i) \tag{1}
\]

The heat exchange in the elementary section can be written as

\[
dQ = \frac{T_{lo} - T_{lo}}{R_T}
\]

The variation of the air temperature in the Vertical Down section is from \( T_A \) to \( T_{X} \). Similarly, the variation of the pipe outside temperature is from \( T_{ei} \) to \( T_{eX} \). Assuming linear variation, the general equation for the temperature variation inside the pipe and the variation of the pipe outside temperature can be written as

\[
T_{lo} = \frac{L}{L} \left( T_X - T_A \right) + T_A
\]

\[
T_{lo} = T_{ei} - l \quad \text{respectively.}
\]

The equation for the heat exchange across the elementary section thus becomes

\[
dQ = \frac{\left[ \frac{l}{L} \left( T_X - T_A \right) + T_A \right] - (T_{ei} - l)}{2\pi hr_d dl} + \frac{1}{2\pi kdl}\log(r_o / r_i)
\]

Integration over the length of the pipe will give us the total heat exchange \( Q \) across the Vertical Down section of the pipe.

\[
Q = \frac{2\pi khr_i}{hr_d} \log(r_o / r_i) + k \left( \frac{T_X - T_{ei} + \frac{L^2}{2}}{2} \right) \tag{2}
\]

This heat exchange across the pipe wall is the heat loss by the air. The heat loss equation for the air can be written as

\[
Q = \dot{m}C_p\Delta T = \rho\pi r_i^2 V C_p \left( T_X - T_A \right) \tag{3}
\]
Combining the equations (2) and (3), we get

\[
\rho \pi r^2 V C_p (T_X - T_0) = -\frac{2 \pi h r_l}{h r_l \log (r_o / r_i) + k} \left( \frac{T_X - T_{ce}}{2} + \frac{L^2}{2} \right)
\]

Thus,

\[
T_X = \frac{\rho \pi r^2 V C_p T_A - \frac{2 \pi h r_l}{h r_l \log (r_o / r_i) + k} \left( \frac{L^2}{2} - T_{ce} \right)}{\rho \pi r^2 V C_p + \frac{2 \pi h r_l}{h r_l \log (r_o / r_i) + k} + k/2}
\]

**HORIZONTAL SECTION**

Similarly the expression for the horizontal section can be obtained. In this case the temperature of the outer surface of the pipe is constant. The resistance is expressed as

\[
R_T = \frac{1}{2 \pi h r_l L_c} + \frac{1}{2 \pi k L_c} \log (r_o / r_i)
\]

The heat flux over the section is given as

\[
Q = \frac{(T_{bo} + T_{bi}) - T_{ce}}{2} - \frac{1}{2 \pi h r_l L_c} + \frac{1}{2 \pi k L_c} \log (r_o / r_i)
\]

**Vertical up section**

The thermal gradient across this section is \((T_b - T_{bo})\). The thermal resistance offered by the elementary section can be calculated by considering the convective resistance and the resistance due to the pipe wall which are given by

\[
1/ h A = \frac{1}{2 \pi h r_l d l} \quad \text{and} \quad 1/ 2 \pi k d l \log (r_o / r_i)
\]

Therefore, the total thermal resistance offered by the elementary section can be calculated by adding the two individual resistances, i.e.,

\[
R_T = \frac{1}{2 \pi h r_l d l} + \frac{1}{2 \pi k d l} \log (r_o / r_i)
\]

The expression for the temperature at any position in this section is given as:

\[
T_X = \frac{\rho \pi r^2 V C_p T_A + \frac{2 \pi h r_l}{h r_l \log (r_o / r_i) + k} \left( \frac{L^2}{2} + T_{ce} \right) L}{\rho \pi r^2 V C_p + \frac{2 \pi h r_l}{h r_l \log (r_o / r_i) + k} + k/2}
\]

**PERFORMANCE STUDY**

*Theoretical simulation based on the model developed*

The general procedure for the calculation of various parameters for the problem starts with identifying the properties of the fluid, like kinematic-viscosity \(\nu\), thermal diffusivity \(\alpha\), thermal conductivity \(k\). In addition to the fluid properties, the data relating to the flow conditions are collected, which include velocity \(u\) and diameter of the flow pipe \(D\). Reynolds’s number, Prandtl number \(Pr\) and Nusselt number were calculated for the turbulent flow.

The next step is to find out the velocity of the fluid and various parameters representing the properties of the fluid. The inlet fluid temperature \(T_{in}\) is measured. Then using the relation derived for the Vertical Down section, the temperature
at the end of the Vertical Down section was obtained after that Horizontal section and then going through the Vertical Up section the final temperature at the exit was calculated. The whole procedure was repeated for a number of times for different input parameters with the help of computer programs and the results were plotted as shown in the following figures.

Figure 8 Variation of Exit Temperature vs Velocity

Figure 9 Variation of Cooling Effect (W) vs Velocity

Figure 11 Comparison of results at 33°C inlet temperature

CONCLUSION

After going through the comparison charts shown in the previous chapter we can see that the results of the theoretical model developed are in close proximity of the experimental values obtained from the site. Thus, the model can be safely used for practical designing purposes with a high degree of conformance between the theoretical values and the actual environmental values. This work can be used as a design tool for the design of such systems depending upon the requirements and the environmental variables. The work can aid in designing of such systems with flexibility to choose different types of pipes, different dimensions of pipes, different materials and for different ambient conditions. So this provides option of analyzing wide range of combinations before finally deciding upon the best alternative in terms of the dimensions of the pipe, material of the pipe, type of fluid to be used.

References


3. Charudatta Bhatt and Dinesh Garh, “Study of heat transfer by natural convection from a horizontal cylinder embedded in a porous medium”.


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