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Integrating Geothermal and Solar Energies for Design and Development of Self-sustainable Cooling System

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ABSTRACT

Geothermal energy uses the internal heat of the planet earth for purpose of electricity generation, space heating and cooling, agriculture, aquaculture etc. With over a 350 potential sites in India for incorporating Geothermal energy in power production there is assured decrease of dependence on non-renewable resources. Indian HVAC (Heating, Ventilation and Air conditioning) market predicts a 7 percent increase in demand of HVAC systems within a decade corroborating the increased use of geothermal energy in space heating and cooling. For cooling purpose heat from space(cooling area) is withdrawn by heat exchanger units and it is transferred to heat sink(ground) using a network of High density polyethylene(HDPE) tubing underground. To run this forced convention power is required for compressor units, injection wells and heat pumps. With the increase in load the power consumption of these units increases making geothermal cooling efficiency redundant. So this paper discusses the study of coupling of PV cells for powering the energy consuming units of geothermal cooling systems. Calculations for dissipation of energy through underground heat exchangers and total length of underground tubing is shown. Parameters of capacity of heat pump, condenser, evaporator and compressor units is discussed. A hypothetical case study of a commercial building in Ahmedabad, Gujarat is done to provide numerical data in calculation of efficiency under different ambient temperatures, COP calculations and to calculate dissipation in heat exchangers etc. Paper also discusses the power consumed by different units and standard size of PV cells panel to produce the required powered.

1. INTRODUCTION

Energy consumed for electrification of residential areas is one third of the total energy production of the world (Abbasi et al., 2016). Considering incessant consumption of fossil fuels which consequently increases pollution, countries have turned towards the renewable energy for power generation (e.g. Solar Energy, Wind Energy, Geothermal and Tidal). Developing country like India aspires to increase its geothermal resources to the 10 GW capacity by 2030 (Prajapati et al., 2020; Sircar et al., 2017). Also, in last 6 years from 2012 there has been an increase of 116% in installation of rooftop solar panels for decentralized small scale power generation. But, single power generation from solar is discontinuous and costly. Same is the case for low and medium temperature geothermal power generation. Although studies for coupling both energies are under progress (Song et al., 2018; Shah et al., 2019).

Increase in demand of geothermal and solar energies in India ascertains its decentralization too. In recent years energy produced by high temperatures is utilized for low exergy systems such as air conditioning and ventilation (Abbasi et al., 2016). Rooftop power generation using photovoltaic cells and use of ground source heat pump for HVAC is system is the most efficient method to drive low exergy systems. Commercial and conventional HVAC systems on large scale contains power consuming units like compressors, evaporators and heat exchangers that have high carbon footprint (Yi et al., 2013). Coupling geothermal based HVAC system with rooftop power generating system using photovoltaic cells not only reduces carbon footprint but also makes its commercial use energy efficient (Abdullah et al., 2010). Geothermal and solar coupled system would effectively reduce the borehole depth for power generation or reduce the number of heat exchangers used to reject the desired amount of heat in the sink (e.g. ground or surrounding atmosphere).

This paper discusses the methodologies to combine geothermal and solar energies for a commercial HVAC system. A theoretical case study is considered to demonstrate the amount of heat rejected from the heat exchangers units to the ground. Along with this the parameters and capacity that should be taken into account for installing compressors and evaporators to be used in HVAC cooling system are analyzed. Also, the length of the High density polyethylene tubing that should be laid underground for heat rejection to sink is calculated. Parameters such as ground annual temperature variations, drilling conditions, space available for ground loop system installation should be considered in design of HVAC systems.

2. SYSTEM DESCRIPTION

Geothermal systems due to its versatile applications can be used different forms. They exploit the principle of constant ground temperature or in other words constant sink temperature for its heat rejection and absorption (Kavanaugh and Rafferly, 2014; Song et al., 2018). Space heating and cooling, water chilling plants, power production are some of the applications of geothermal systems. But, in this paper, we will be focusing on geothermal system employed specifically for Heating, Ventilation and Air conditioning systems (HVAC) (Sircar et al., 2017; Shah et al., 2020; Shah et al., 2019). Main components used in commercial HVAC systems are

i. Heat Pump

ii. Air Handling Units(AHU)

iii. Condenser

iv. Evaporator

v. Pump

Heat exchangers are the crucial parts of geothermal cooling and heating system. Generally, water and a mixture of anti-freeze like ethylene glycol, propylene glycol or R143a are used as a working fluid. This fluid flows through the space that is to be cooled and after collecting the heat from the space it is rejected into the soil using pipe network laid underground (Yang and Wang, 2012; Najideen and Alrwashden, 2017)). This forced flow of fluid to collect the heat from space is carried out using pumps. If the HVAC systems increase in size so will the pump size and flow rates which consequently will result in increased power consumption and cost (Tahera et al., 2018). So, to meet the power demands of the pumps additional-electricity producing sources can be added to the system (Bhuiyan et al., 2000). This will increase the initial cost of establishment but it will prove beneficial in long run (Aggarwal et al., 2020; Dincer and Acar, 2015). Commonly coupled system with geothermal is the solar system due to its easy installation in discrete parts. Size of the PV panels array will depend on the energy demand of the pump to run the fluid in the distribution system for space cooling (Carlson, 2001). Components of solar system used for commercial purpose are

i. PV panels array

ii. Battery unit

iii. Inverter

iv. Charge controller

Heat pump and underground tubing network are one of the most important components that are to be considered while designing a system (Noorollahi et al., 2017). Heat pumps used in the geothermal system are called Ground Source Heat pump or GSHP's. They are further divided based on the heat rejection or absorption method to the ground. It includes Ground coupled Heat pumps (GCHP's) in which a closed loop piping network is buried in the ground, Ground water Heat pumps (GWHP) in which an open loop piping network is incorporated with water wells and lastly Surface water Heat pumps (SWHP) that have a closed loop or open loop piping network connected to the lakes, stream or water bodies (et al kavanaugh).

Most commonly used heat pumps are closed loop ground coupled heat pumps. In this system two high density polyethylene pipes are laid in a vertical or horizontal position in the ground. The vertical and horizontal orientation of the pipes depends on the soil conditions of the particular area. If a heat pump is to be installed in a densely populated area with little space than vertical orientation for pipes is a natural choice meanwhile, if the drilling conditions are severe for the depth of more than 5 meters than the horizontal orientation of pipes is used. Figure 1 shows the schematic layout of possible pipe arrangements (Naicker and Rees, 2008; Raleganonkar et al., 2004).

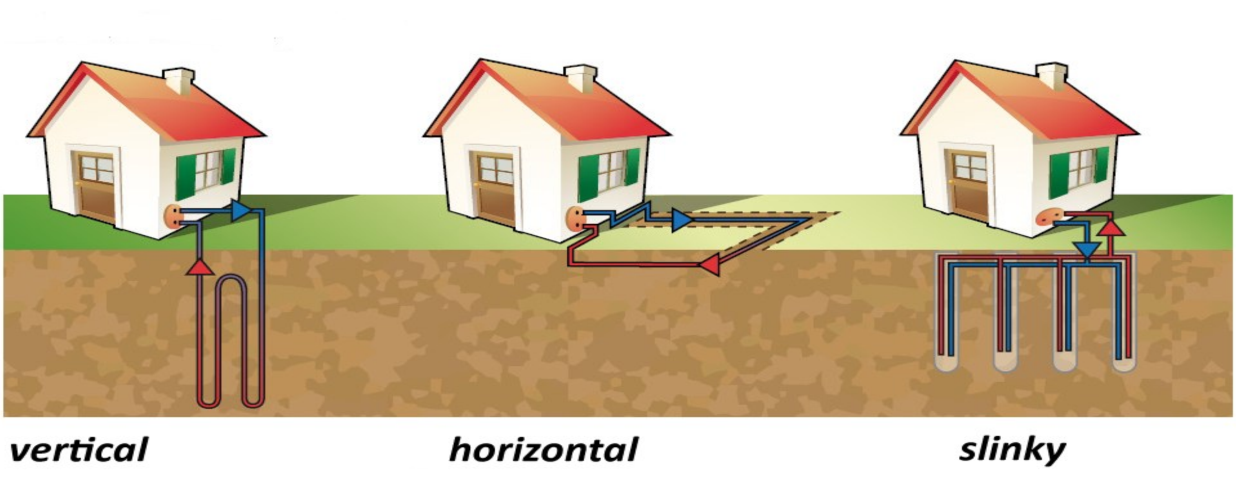

Figure 1: Types of closed loop system

3. DESIGN METHODOLOGY

The HVAC system should abide by the regulations of the respective countries. For space cooling, many factors such as indoor temperature, outdoor temperature, relative humidity, solar irradiation and many others are considered crucial. Air conditioning, heating and Mechanical ventilation under the Building Services section of National Building Codes (NBC) of India were referred before the design of a cooling system for a hypothetical commercial building in Ahmedabad. According to NBC, the HVAC system should be designed to maintain the temperature of space at 26°C (78.8) for cooling. Also, NBC provided the dry bulb temperature for surrounding ambience with the percentage variance. For cooling load calculation we have considered 1.0 per cent variations in 38°C (100.4) for the year 2019. Following parameters are considered for calculating the design load of a commercial building

i. Area of the commercial unit is 300 sq. feet

ii. There are 10 people doing seated light work

iii. 30% of the office area is made of glass in form of windows and doors.

For the simplicity of calculation cooling load is determined based on the sensible heat and latent heat is not considered. Sensible heat depends on the temperature difference of the cooling space and the surrounding. There are mainly four ways through which heat can enter into the commercial unit to be cooled.

3.1 Load Due to Occupants

Heat is constantly generated in the human body. The amount of it depends on the activity that a particular person is doing. There are two types of heats i.e. Sensible heat and Latent heat. Since we are concerned with the sensible heat we would only consider the number of people present in the unit and the type of activity in which they are involved. According to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), sensible heat of 255 Btu/hr is released per person in the commercial office doing light work. This may even go higher to 635 Btu/hr per person doing heavy lifting work. Since, we considered 10 people, total internal load due to occupants will be Q_p = 2550 Btu/hr.

3.2 Load due to lights and plugs

Number of lights and plugs used in the office contribute to the cooling load. If the amount of luminance increase then the heat generated per unit area increase consequently increasing the cooling load. The empirical relation between watt and Btu's for light as well as plugs is 1 watt = 3.41 Btu. The number of watts installed in form of light and plugs can be estimated to compute their contribution in cooling load.

3.3 Load to Solar Irradiation

Solar irradiation is the most important factor that contributes to the cooling load. The heat from the sun enters the room through walls and glass windows. Heat in transferred to the room through conductance and radiation. For a commercial building with 300 ft^2 area 30% i.e. 90 ft^2 of area is considered to be made of glass that contributes to windows or doors. Sensible heat by radiation is given by

$$Q_r = \text{A x SC x SCL} \tag{1}$$

Equation 1 gives the amount of sensible heat by radiation through glass. A is the area of glass in the office. SC is the Glass shading coefficient. Value of SC can be computed by using ASHRAE standards and is affected by different types of glass. SCL is the solar cooling load factor and it is dependent on the orientation of the glass with respect to the standard directions, month of the year, time of the day and geographical location. SCL can also be computed from ASHRAE handbooks. Conductance is another form by which the heat enters into the office that affects the cooling load. Conductance load due to both glass and walls is given as

$$Q_c = \text{U x A x CLTD} \tag{2}$$

In equation 2, U is the overall heat transfer coefficient which is the reciprocal of thermal resistance (R) of the conduction medium. CLTD is the cooling load temperature difference. Greater the thermal resistance of the conduction medium smaller will be the overall heat transfer coefficient and smaller will be the cooling load. Factors such as ambient air infiltration due to opening and closing of door and return of air through ducts are not considered due to their scanty contribution in cooling load.

3.4 Design of Ground Heat Exchanger Length

Design of the vertical ground heat exchangers demands testing of the ground for moisture content, water flow and drilling conditions before they are laid. Sometimes these tests are not economical for small scale HVAC systems. So, empirical analysis is important and most of the times sufficient for small scale HVAC systems. The equation that is used to calculate the length of the vertical pipes is based on the cylindrical model rather than a simpler line model which was developed by Carslaw and Jaeger. Cylindrical is more accurate in predicting hourly temperature compared to the line model. The equation for length of vertical heat exchanger is given as

$$q = \frac{L_{bore}(t_g - t_w)}{R_{ov}} \tag{3}$$

Here, q is the overall heat that is rejected into the ground for cooling. This can be determined by the cooling load of the commercial unit. t_g and t_w are the ground temperature and the average water loop temperature. The ground temperature is assumed to be constant with depth. Energy consumed by pumps, fans and compressors is converted to heat and is also rejected with the cooling load heat. One unit of energy is consumed to remove the four unit of heat from the office. So, heat delivered to the ground is 125% of the heat capacity of pump [4]. The heat relation between the heat rejected by pump to the ground (q_{cond}) and cooling load of the building (q_{cl}) is given by

$$\frac{q_{cond}}{q_{cl}} = \frac{COP+1}{COP} \tag{4}$$

$$q_{cl} = Q_p + Q_r + Q_c \tag{5}$$

The tradeoff value for the better system performance and sufficient ground loop occurs when the entering liquid temperature is between 11°C and 17°C. When water is used as the coolant then suggested flow rate is between is 2.7 and 3.2 L/min.KW and this values are higher by 3 to 5% when the antifreeze solution is mixed in water. Determination of the overall ground resistance is the most difficult task to achieve. It will include the bore resistance, the pipe wall resistance, the grout resistance and film resistance of the fluid flowing. There is a lot of complexity in computing all the aforementioned values and they are susceptible to errors. Carlsaw and Jaeger provided a different solution for the overall ground resistance. They used time of operation, thermal diffusivity of ground and outside pipe diameter and equated it to dimensionless Fourier number (Fo). They considered a system with three heat pulses, a 10 year (3650 days) heat pulse of q_a, a month (30 day) heat pulse of q_m and a 4 hour (0.167 day) heat pulse of q_d.

$$F_o = \frac{4\alpha_g \tau}{d^2} \tag{6}$$
$$\tau_1 = 3650$$
$$\tau_2 = 3650 + 30 = 3680$$
$$\tau_f = 3650 + 30 + 0.167 = 3680.167$$

Fourier numbers can be computed using the following equations.

$$F_{o_f} = \frac{4\alpha_f \tau}{d^2}$$
$$F_{o_1} = \frac{4(\alpha_f - \alpha_1)\tau}{d^2}$$
$$F_{o_2} = \frac{4(\alpha_f - \alpha_2)\tau}{d^2}$$

The effective thermal ground resistance for annual pulse (R_{ga}), monthly pulse (R_{gm}) and a short term pulse (R_{gst}) can be calculated using the following equations. The G factor for the Fourier numbers can be derived from the graph shown in the Figure 2.

$$R_{ga} = \frac{G_f - G_1}{k_g} \tag{7}$$
$$R_{gm} = \frac{G_1 - G_2}{k_g} \tag{8}$$
$$R_{gst} = \frac{G_2}{k_g} \tag{9}$$

Using the above equations, cooling load from the building block, overall thermal resistance of the ground and vertical heat exchanger length can be calculated. In the above equations we have not accounted for the system loses and have taken ideal conditions. If loses are accounted for then the values may change. Fluid pumping loss in U-bends, altered soil thermal properties overtime, heat infiltration, duct loses and many more have not been accounted for.

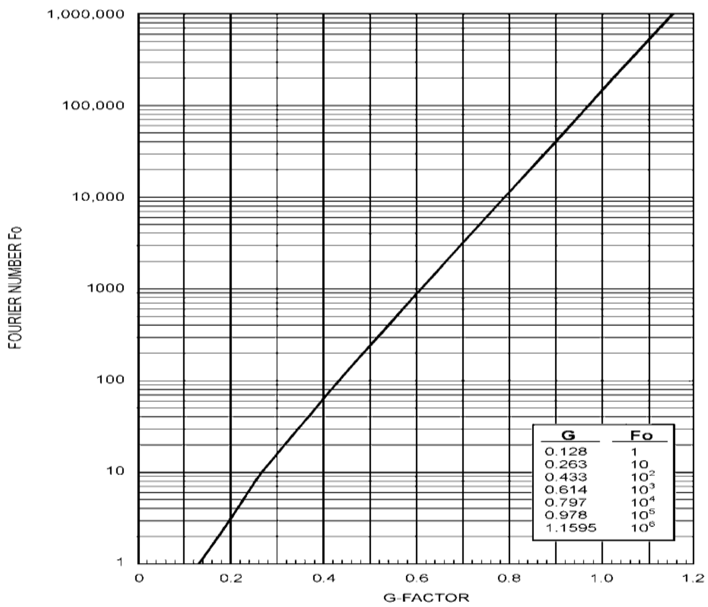

Figure 2: Fourier/G- factor graph for Ground thermal resistance (Ingersoll)

3.5 Design of PV Panels

In order to design a self-sustainable cooling system for a building block the energy consumed to operate pumps, fans and blower should be compensated by other sources. These sources should produce clean and renewable energy. Solar energy is the best way to compensate the demands but it will be futile in the regions where there is scanty sunlight. Alternatives such as wind and small scale hydropower can be used in such places. Design of the solar system is complex and have a number of factors to be considered before installation. Most important factors that affects the power produced is the amount of incident radiation flux and orientation of PV panels. Following steps should be incorporated to design a standalone solar power system.

(i) Calculate the total watt of the appliances in the building block that will be powered by solar panels. While calculations, the AC unit and heat pump should be included which will consume the most power.

(ii) Total numbers of watts consumed per day can be calculated by multiplying the total watts and operating hours. It might be possible that the daily demand may change. So, average monthly operating hours should be used for accurate results.

Total watt hours = Load connected (Watt) x Operating hours.

(iii) Actual power output of the PV panels should be calculated using the Peak power rating (W_p) and operating factor.

Actual Power output = Peak Power rating (W_p) x Operating Factor

Operating Factor = Temperature Co-efficient of P_{max} (Solar Panel Temperature – STC temperature)

Temperature co-efficient of P_{max} can be obtained by the catalogue that is available while purchasing the PV panels. All the PV panels are tested and STC refers to the Standard Testing Conditions. STC temperature is generally in taken as 25℃.

(iv) Battery units are used to store the surplus power that is not used during the day time and it can be used during the night time. PV panels produce DC current and inverters are used to convert DC currents into AC. However, battery and inverter units have innate resistance while working. This reduces the overall power output of the system.

Power available = Actual power output x Combined efficiency

Combined efficiency = Battery efficiency x Inverter Efficiency

In general, both the units have efficiencies between 90% and 98%. We would consider the lowest efficiencies in order to compensate for the other factors such fluctuating loads and improper solar irradiance. Daily power produced by the PV panels can be computed using

Total solar power produced daily = Power available X Solar insolation

No of PV panels (N) = Total load (Watt) / Total solar power produced daily

Solar insolation can vary from location to location To increase the power produced by PV panels they should be erected in such a way that the light rays are incident perpendicular on the PV panels. This can be achieved by orienting the panels at the angle equal to the latitude angle of the particular locality. For example the solar panels in Ahmedabad, India will best operate at the angle of 23 degrees which is equal to the latitude angle. Also, the type of the solar panel affects the energy production. There are three types of solar panels

(i) Mono crystalline Panels

(ii) Poly crystalline Panels

(iii) Thin Film Panels

Mono crystalline panels are the most efficient in converting the solar irradiance into electricity. Pertaining to the high demands of pumps and other ancillary devices the choice of mono crystalline panels is necessary. Battery unit should be installed keeping in mind the possibility of power cut offs and a cloudy that would not help generate any electricity. So, stored power in the battery unit would power both the HVAC system and other electrical appliances.

4. RESULTS AND DISCUSSION

This paper cumulated the empirical formulas to design a geo solar coupled cooling system can be used in any climatic conditions where there is appropriate amount of solar insolation. If there is less than 8-10 hours of solar irradiance then the amount of solar power generated will be less and it would not be enough to power the connected systems. Countries and cities that are near the equator will get good solar irradiance but as we move south or north from the equator then the amount of solar irradiance decreases. The coupled system's main components are the vertical heat exchanger and the PV panels. Most amount of the heat that enters into the building block through conductance and radiation is considered in cooling load. If more complex cooling system is to be designed then more finesse can be incorporated to calculate the cooling load with exact amount of heat by human activity, air infiltration, building block leaks. These are very small in amount but could affect the cooling load if the conditions are harsh. The length of the vertical heat exchanger can vary according the load and the type of the material of the pipe. The total length obtained from the above empirical relations must be divided by the number of the pair of vertical bore that we need to install. This can be calculated by estimating the drill depth by soil testing of the strata. Calculation for daily load will lead to the erroneous heat exchanger length, annual load data should be considered for better design.

5. CONCLUSION

If the material of the ground is not tested rigorously then it might be possible that it may retain the rejected heat for the longer time and would affect the overall efficiency of the system. Also, ground testing for installing HVAC systems are very costly. So, development of tools and technologies for cheap and reliable ground testing should be focus of coupled geo solar research. Anti-freeze solutions that are mixed with the water as working fluid should be chosen in such a way that it has minimum environmental impact and maximum efficiency. Due to the tropical climate of Indian subcontinent it is possible to connect heavy load in the solar system. So, in order to exploit this scenario, geo and solar couple should be used for space heating in cold weather. The power produced by solar can be extended for the use of powering the electrical appliances or the stored energy can lead to self-sustainable homes paving the way for future generations. Coupled system is used for the cooling purpose but its use can be extended for heating purpose in winters. During that time the heat will be absorbed from the ground and rejected in the building block.

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