EXPERIMENTAL STUDY ON THERMAL PERFORMANCE OF OPEN LOOP GROUND SOURCE HEAT PUMP SYSTEM

A DISSERTATION

Submitted in partial fulfilment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

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MECHANICAL ENGINEERING

(With specialization in Thermal Engineering)

By

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Candidate's declaration

I hereby certify that the work which is being presented in the thesis entitled **"EXPERIMENTAL STUDY ON THERMAL PERFORMANCE OF OPEN LOOP GROUND SOURCE HEAT PUMP SYSTEM"** in partial fulfilment of the requirements for the award of the Degree of "Master of Technology" and submitted in the Department of Mechanical and Industrial Engineering of the Indian Institute of Technology Roorkee is an authentic record of my own work carried out during the period from July, 2018 to June, 2019 under the supervision of Dr. K. Murugesan, Professor, Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Abstract

The predicted end of an oil era, along with increasing concentration of carbon dioxide, nitrogen, and dust particles causes pollution in our environmental system. This results in climate changes of earth leading to rapid increase in global warming effects. This has forced us to explore the urgent need of alternative renewable energy sources. In these context Ground Source Heat Pump (GSHP) systems has attracted the researchers because it is green, sustainable and environment-friendly energy source option. GSHP systems are considered very efficient for space heating and cooling applications as they interact with the ground which has constant heat source/sink temperature throughout the year, resulting in improved performance compared to the conventional climate control systems which interact with the atmosphere.

As part of the present MTech dissertation work, an attempt is made to study the performance of an open loop GSHP system for space cooling and heating applications. In the open loop GSHP system the heat interaction between the heat pump and the ground takes place through a plate heat exchanger, which enables heat transport between the water coming from the heat pump and the ground water extracted from a bore well drilled for this purpose. After absorbing heat from the coolant from the heat pump, the ground water is re-injected back into another injection bore well. The thermal performance of an open loop GSHP system depends on the groundwater flow rate, temperature of extraction and injection groundwater, power consumption by compressor and pumps and efficiency of plate heat exchanger etc. Experiments were conducted on an 8 TR open loop GSHP system established in the dining hall of the guest house in NETRA (NTPC Energy Technology Research Alliance), Greater Noida during space cooling and heating operations. A computer program in FORTRAN has been developed to calculate COP and effectiveness of plate heat exchanger using the experimental data.

Results were obtained for the experimental data observed during 23rd May, 18th July and 19th July 2018 for space cooling mode and show that the COP of the GSHP system varied from 3.48 to 3.92 whereas the effectiveness of the plate heat exchanger varied from 0.72 to 0.75. During winter season, on 28th, 29th and 30th January 2019, the results indicate that the COP of the GSHP system varied from 4.2 to 4.5 and effectiveness of PHE varied from 0.70 to 0.74. Based on theoretical analysis, with the assumption of average combined efficiency of submersible pump as 34.5%, it is observed that if mass flow rate of groundwater increases then the overall heat transfer coefficient, power consumption by submersible pump and COP of the system increases whereas effectiveness of PHE decreases.

Table of Contents

List of Figures

List of Tables

Nomenclature

c_{pcw}	Specific heat of cold water (kJ/kg.K)
c_{phw}	Specific heat of cold water (kJ/kg.K)
c_{pw}	Specific heat of water (kJ/kg.K)
C_{min}	Minimum heat capacity (kJ/kg.K)
COP_c	Coefficient of performance of the system at cooling mode
COP_h	Coefficient of performance of system at heating mode
H_p	Pump head (m)
$\dot{m}_{cw}$	Mass flow rate of cold water (kg/s)
$\dot{m}_{gw}$	Mass flow rate of groundwater (kg/s)
$\dot{m}_{hw}$	Mass flow rate of hot water (kg/s)
P	Power consumption of submersible pump (kW)
Q	Discharge of extracted groundwater $\left(\frac{m^3}{s}\right)$
Q_a	Actual heat transfer (kW)
$Q_{absorbed}$	Heat absorbed from groundwater (kW)
$Q_{cooling}$	Cooling effect (kW)
$Q_{heating}$	Heating effect (kW)
Q_{max}	Maximum heat transfer (kW)
$Q_{rejected}$	Heat reject to groundwater (kW)
S	Specific weight $\left(\frac{N}{m^2}\right)$
T_{ci}	Inlet temperatures of cold water at PHE (˚C)
$T_{gw,e}$	Temperature of extracted groundwater (˚C)
$T_{gw,i}$	Temperature of injected groundwater (˚C)
T_{hi}	Inlet temperatures of hot water at PHE (˚C)
$T_{wphe,in}$	Temperature of secondary loop water inlet to PHE (˚C)
$T_{wphe,out}$	Temperature of secondary loop water outlet to PHE (˚C)
W_{cr}	Work input of compressor (kW)
W_T	Total power consumption of the system (kW)
ΔT	Temperature difference of extracted and injected groundwater (˚C)
ΔT_c	Temperature difference of inlet and outlet at cold side water (˚C)
ΔT_h	Temperature difference of inlet and outlet at hot side water (˚C)

ε	Effectiveness of plate heat exchanger
η_c	Combined efficiency of submersible pump
η_{PHE}	Efficiency of plate heat exchanger

Abbreviations

AF	Anisotropy factor
ANOVA	Analysis of variance
BHE	Borehole heat exchanger
CAR	Controlled Activities Regulations
CCHS	Conventional central heating system
CFD	Computational fluid dynamic
COP	Coefficient of performance
CPT	Cost payback time
CRR	CO_2 reduction ratio
DHW	Domestic hot water
EGN	Entropy generation number
EPT	Energy payback time
FCU	Fan coil unit
GCHP	Ground couple heat pump
GHE	Ground heat exchanger
GHEX	Ground heat exchanger
GLHX	Ground loop heat exchanger
GSH	Ground source heat
GSHP	Ground source heat pump
GWHP	Ground water heat pump
HDPE	High density polyethylene
HVAC	Heat ventilation and air conditioning
LCA	Life cycle assessment
LCC	Life cycle costing
LCEC	Life cycle energy consumption
LMTD	Logarithmic mean temperature difference
LPM	Liter per minute
MOGA	Multi objective genetic algorithm
NBR	Nitrile butadiene rubber
NTU	Number of transfer unit

P	Pressure gauge
PE	Polyethylene
PHE	Plate heat exchanger
PVC	Polyvinyl chloride
S	Sensor
SAGSHP	Solar assisted ground source heat pump system
SCOP	System coefficient of performance
SCW	Standing column well
SEPA	Scottish Environmental Protection Agency
SGHP	Solar-ground water heat pump
SWHPS	Surface water source heat pump system
TRNSYS	Transient system simulation
TRT	Thermal response test
UPVC	Un-plasticized polyvinyl chloride
VGCHP	Vertical ground coupled heat pump

Chapter 1

Introduction

The early and rather a known prediction of the end of oil era with increasing atmospheric carbon dioxide and pollution has resulted in drastic climate change and many other anthropogenic processes. To avoid undesirable processes, there has been a need to find alternative energy sources. Today a small, yet important fraction of our energy demand from a variety of alternative, "more sustainable" energy sources is obtained. These include the use of solar power, wind power, nuclear energy, hydrogen fuel and tidal energy, etc. This is a rapidly growing field, and the present study looks specifically at certain aspects of the use of ground source heat as an alternative energy source. There are two alternative sources of energy that can be directly obtained from beneath the earth's surface:

- **Geothermal energy**
- **Ground source heat (GSH)**

Geothermal is the combination of Greek words, geo, meaning earth, and thermal, meaning heat. A geothermal energy system uses heat directly from earth's mantle that is emitted via a natural process such as hot springs, volcanic hot spots and geysers. The hot water or steam originating from deep underground is used to heat buildings or power turbines for electricity generation. A ground source heat pump system, also known as geo-exchange, uses electricity to move heat from one place to another through a heat pump. It does not generate energy. These systems are working on the principle of heat pump or reverse heat pump. Ground temperatures are relatively constant at a depth of 40 to 50 m below the earth surface. These soil temperatures are warmer than the mean ambient temperature in winter and cooler than the mean ambient temperature in summer. Therefore, a ground source heat system will transfer heat from warmer earth to the cold building in winter and the ground can absorb heat from the warmer building in summer. Thus, ground acts as a source and sink depending on the season.

1.1 Types of Ground Source Heat Pump Systems

Ground source heat pump (GSHP) system uses either water or soil as a heat source and sinks which depend on the type of the system. In this section, various GSHP system has been discussed based on the type of heat source and heat sink.

1.1.1 Groundwater from aquifers

Open-loop ground source heat pump system (GSHP) is also known as a ground water heat pump system (GWHP) (Figure 1.1). It uses water from aquifers as heat source for extracting the heat as well as a heat sink for rejecting the heat. This system consists of an extraction well to supply groundwater from aquifer to heat exchanger and an injection well to reject the water from the heat exchanger back to the aquifer. It uses submersible pump to extract water from extraction well and circulate into a plate heat exchanger to exchange heat with secondary loop in which water is flowing with the help of water circulation pump and subsequently discharges the water back into the earth via the injection well. The extraction and injection wells should be installed farther so that the colder and warmer water do not mingle, which affect the heat pump's performance. A secondary water loop exchanges heat with a primary refrigerant loop with the help of heat exchanger known as evaporator or condenser depending on cooling or heating mode of operation of the system. They also depend on sufficient water availability and pumping power. If the flow rate of groundwater and pumping power is less, then there will be lesser heat transfer from water to the building.

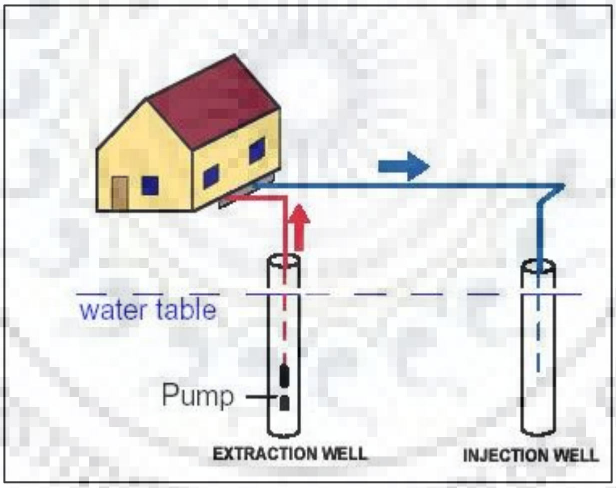


Figure 1.1 An open loop GSHP system (Florides and Kalogirou, 2007).

Standing column well system (SCW)

Standing well column system is also known as semi open-loop system and compared to other GSHP systems, its installation area is small. Therefore, it is applied in small drilling area. It uses subsurface water and surface water directly. By drilling, geothermal exchanger are buried approximately 350 m into the ground and for heat exchange with the heat pump, subsurface water brings up with a column well and return it under the ground with the same column well. The installation cost of the SCW system is marginally higher than other GSHP systems, but its coefficient of performance is higher (Lee et al., 2019). During operation, by returning some part of the flow water bleed to the well, the remainder is discharged. This induces groundwater flow from surrounding to the well. Because of this groundwater flow formation, it cools the well and surrounding ground in summer during heat rejection and heats the well and surrounding ground in winter during heat extraction. SCW system efficiency is maintained for a longer time and alteration in the well temperature can be reduced or increased by regulating the quantity of bleed water (Deng et al. 2011). A diagram of the SCW system is shown in Figure 1.2.

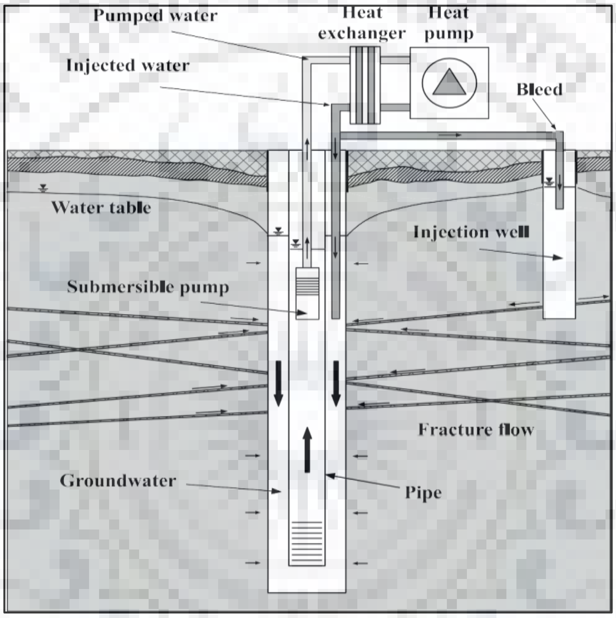


Figure 1.2 Standing Column Well system (Nguyen et al., 2015).

1.1.2 Earth soil (geothermal)

Vertical type closed-loop GSHP system

The vertical type close-loop GSHP system is installed by inserting one or two polyethylene U-tubes in vertical boreholes, called single U-tube or double U-tube ground heat exchangers (GHEs), respectively. The depth of the borehole ranges from 40 to 200 m with diameter of 75 -150 mm (Yang et al., 2012). Two high-density polyethylene (HDPE) pipes are connected by U- shaped pipe at the bottom of the borehole to make the single closed-loop connection, because of this type of connection, the system is called as U-tube GHEs. This system occupies small land areas and yields efficient performance. To provide better thermal conductance, the borehole should be grouted using bentonite-cement mixture and it also prevents the groundwater from contamination. In double U-tube GHE, two tubes are installed in the single borehole and flow circuit between the pipes are made either parallel or series (Figure 1.3).

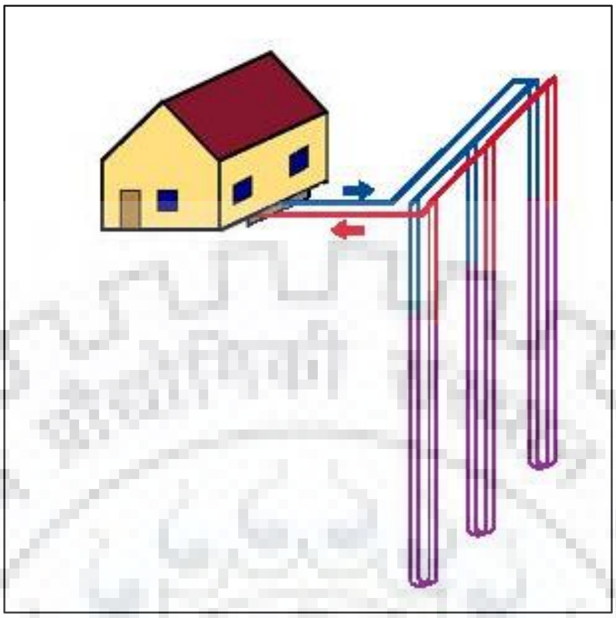


Figure 1.3 Vertical type ground source heat pump system (Kalogirou and Florides, 2007).

Horizontal type closed-loop GSHP system

Closed loop horizontal ground heat exchangers (GHEs) are U-shaped pipes, which is laid in 2 m shallow depth in the ground. These closed-loop pipes contain antifreeze solution and exchange heat with the soil as well as refrigerant flowing in the heat pump. The installation of the horizontal GHEs are cost-effective operation and involves digging of the ground surface. It requires a large area to install the system conveniently. Horizontal GHEs can be divided into three configurations known as linear, slinky and spiral-coil-type. Figures 1.4 to 1.6 depict the linear, slinky and spiral type horizontal GHEs. Slinky and spiral GHEs have curved geometry which cause to enhance flow attribute by generating secondary flow due to centrifugal force. They also provide a higher heat exchange rate per trench unit length due to higher heat transfer coefficient as compared to linear type GHE (Selamat et al., 2016). Therefore, horizontal GHE in slinky and spiral configuration provides larger thermal performance compared to the linear configuration (Adamovsky et al., 2015).

Figure 1.4 Linear type horizontal GHE

(http://www.mesh-energy.com/wp-content/uploads/2015/07/Ground-loops.jpg)

Figure 1.5 Slinky type horizontal GHE

(https://s3-eu-west-2.amazonaws.com/homebuilding-assets/prodwebsite/content/uploads/2017/05/31141309/ground-source-heat-pumps-1.jpg)

Figure 1.6 Spiral type horizontal GHE (Jeon et al., 2018)

1.2 Space cooling and heating operation using open loop GSHP system

Groundwater temperature is relatively constant at depths of 10 -15 m below the ground surface and with increasing depths, temperature also get raises with average 3 - 4˚C per 100 m. Thus, in most of the seasons in a year, there is a temperature difference between above ground temperatures and below ground temperatures. During summer, groundwater is colder than the ambient temperature and warmer than the ambient temperature during winter. An open-loop GSHP system accomplishes this natural temperature gradients for cooling and heating purpose inside the buildings. During summer, for space cooling operation groundwater is an extracted from the extraction well by using a submersible pump. The groundwater is colder than the atmospheric air which exchanges heat with the heat pump and could extract heat from the space. As a result, the air temperature inside the building is reduced and can maintain the temperature for human comforts. After this, groundwater is re-injected into the ground through an injection well. Similarly, during winter for space heating, the groundwater is warmer than atmospheric air which in turn rejects heat to the space to be heated. As a result, the air temperature inside the building increases and provides comfort atmosphere inside the building in the winter season.

1.3 Influence of components efficiency in the performance of the system

The performance of an open-loop GSHP system depends on the power consumed by all the electrical systems such as submersible pump, circulation pump, heat pump and fan coil units.

Therefore, the efficiency of these components has major role to operate the system with better performance. Some important components have been considered in this section to discuss their influences on the performance of GSHP system.

Submersible pump

The submersible pump is built in extraction well to extract the groundwater and transfer it through the plate heat exchanger (PHE) and inject it again under the ground via an injection well. The submersible pump consumes electrical power to pump the groundwater which affects the performance of the system. And volumetric discharge of groundwater is directly proportional to the power used by the pump. During operation, whenever water release is increased then electricity consumed by the pump increased. Also, the amount of power consumption by the submersible pump depends on the groundwater level. When groundwater level drops then power consumed by the pump increases. As a result, an increase in power consumption of submersible pump, will reduce the performance of the GSHP system. Therefore, a submersible pump with higher efficiency should be used to operate an open-loop GSHP system to achieve better performance.

Heat pump

The heat pump is a central component of the GSHP system. It consists of a primary loop in which refrigerant is flowing and this loop is integrated with compressor, condenser, expansion valve and evaporator. In the heat pump, only the compressor consumes electric power during operation which influences the performance of the GSHP system. Therefore, for better performance of GSHP system, compressor work should be minimum.

Plate heat exchanger

A plate heat exchanger (PHE) is a type of heat exchanger in which heat exchange between two moving fluids take place through metal plates. Fluids are exposed in large surface area of plates; therefore, heat transfer rate increases. Effectiveness and efficiency of the PHE influence the performance of the heat pump. A substantial value of the effectiveness will give a higher rate of heat transfer and also highly efficient heat exchanger can provide better heat transfer rate. As a result, a significant value of the heat transfer rate of PHE will give a better performance of the GSHP system.

Fan coil unit

Fan coil unit (FCU) is a device which consists of a cooling or heating coil and a fan. It is used to control the temperature in the space. It is controlled either by a manual on/off switch or by the thermostat. FCU also consumes electric power during operation of the GSHP system. Therefore, the performance of GSHP system depends on the efficiency of FCU, which should be more significant value for better performance of the GSHP system.

1.4 Scope and objectives

As part of the dissertation work, a detailed literature survey has been carried out to understand the ongoing research on the thermal performance of the open-loop GSHP system. This research work focuses on different type of GSHP systems based on the kind of heat source and heat sink. From the literature study it is observed that closed loop vertical or horizontal type of GHEs are more popular compared to the ground water heat pump systems. Especially, in countries where the water source is highly limited, the open loop GSHP system is not preferred. Hence only a limited amount of literature is available on experimental work. Through open loop systems have higher COP compared to closed loop systems, the research has been limited to some specific case studies only. In order to sustain the higher COP in an open loop system, it is essential to understand how the COP is affected by different influencing parameters such as variation in extracted ground water, effectiveness of plate heat exchanger, power consumption etc. In many Western and European countries, GSHP systems have been installed for heating mode operation only, however, for Indian climatic conditions, investigation of the performance of GSHP for both space cooling and space heating operations has to be carried out. Therefore, a well-defined study on open-loop GSHP system is required for Indian climate but very few research works are available on open-loop GSHP system. Therefore, as part of the present dissertation work, a detailed study has been carried out on the performance of open loop GSHP system with the following objectives:

(i) To estimate the performance of an open-loop ground source heat pump system for both space heating and cooling applications.

(ii) To investigate the effect of change in mass flow rate of extracted ground water and effectiveness of plate heat exchanger on the performance of the open loop GSHP system.

(iii) To continuously monitor the power consumption by the open loop GSHP system during space cooling and heating operations.

(iv) Analysis of temporal variation of coefficient of performance (COP) of the open loop GSHP system during space heating and cooling operations.

1.5 Organization of report

The dissertation report is organized as follows: In the first Chapter, Introduction to the basic principles of ground source heat pump systems are explained and discussed different types of GSHP system. In the Second Chapter the detailed literature review carried out is discussed under different headings. In Chapter 3, the experimental setup of open-loop GSHP system installed in NETRA, Greater Noida is explained. In Chapter 4, the governing equations used to analyse the performance of open-loop GSHP system are detailed. Calculation procedure for the effectiveness of the plate heat exchanger is also discussed in this chapter. Detailed discussion on the results obtained are elaborated in Chapter 5. Summary, conclusions and suggestions for the future work are discussed in Chapter 6.

Chapter 2

Literature Review

In this section, the literature works associated with ground source heat pump systems have been discussed. From a complete literature review, it is found that many experimental, theoretical and mathematical models have been developed to improvise the performance of GSHP systems for space cooling and space heating applications. Some of the important literature relevant to the present dissertation work have been discussed under different sub-headings in the following sections.

2.1 Open-loop ground source heat pump system

Choi et al. (2016) introduced an excellent operation method for open loop ground heat exchangers (GHEX) by into account of the subsurface temperature gradient. The standing column well (SCW) was operated for heating and cooling operation and a thermal response test was carried out by observing the temperature. The ground temperature increased with depth, but the temperature distribution can be altered by using a switch between the heating and cooling mode. This effect was calculated by performing computational fluid dynamics (CFD) and logarithmic mean temperature difference (LMTD) analyses for a compact model of well of 150 m depth. In this study, the variation in underground temperature with depth was measured during the TRT by maintaining energy input of about 107-108 kW. The TRTs used hot water as a heat source so that there is an increment of ΔT along the GHEXs length. In a parallel performance, the results showed that the heat source decreased with the depth so that there is a different volume of addition between the top and bottom of the GHEX. During TRTs, the temperature gradient was 2.1˚C per 100 m. In LMTD analysis, the upstream model produced better performance in cooling operation while in the heating operation, the downstream model showed well performance. Using CFD analysis (COMSOL, Multi-physics), three different configurations were simulated based on heat exchange in the ground. To reduce the computational effort, the numerical model was run assuming 150 m depth. In CFD analyses different ground thermal conductivities, such as 3.0, 3.5 and 4.0 W/m K were considered to evaluate its effect on the performance of GHEXs. As a result, the heat exchange occurred along the GHEX from top to down in downstream model, while in upstream model heat exchange occurred from bottom to up, along the GHEX.

Kim et al. (2016) proposed that groundwater heat pumps have the potential to save energy at the location of sufficient availability of groundwater resources. This study has discussed about the effects of groundwater temperature of 12, 15 and 18˚C on the performance of the groundwater heat pump system and set the groundwater level constant at 25 m for the analysis. As a result, at 12˚C of groundwater temperature, the COP of the system during cooling operation was higher than the COP of the system during heating operation, while this trend reversed in the case of groundwater temperature of 18˚C. The system COP at 15˚C of groundwater temperature lies between the temperature of 12˚C and 18˚C. The system COP also varied with the change in the mass flow rate of groundwater. As the mass flow rate of groundwater varied from 144.0 to 395.3 LPM, COP of the system during cooling operation dropped by 19.8%, 19.0% and 18.3% at groundwater temperature of 12˚C, 15˚C and 18˚C respectively and during heating operation, the COP of the system dropped by 12.7%, 12.7% and 12.6% at groundwater temperature of 12˚C, 15˚C and 18˚C respectively. As per the results, it was concluded that when the groundwater temperature improved, the COP of the system during heating operation would be increased, conversely, when the groundwater temperature decreased, the COP of the system during cooling operation rose, and heating operation reduced. The groundwater temperature was different according to the depth of the well. Therefore, the depth of well should be decided based on the groundwater temperature and building load. For example, shallow wells should be designed for cooling dominant buildings.

Rode et al. (2015) directed a numerical parametric study on the evaluation of the feasibility of geothermal groundwater consumption by the combined extraction-injection one-well system. One-well system needs small space, but due to the thermal short circuit, it is critically essential to sidestep circulation flow. In this study, four parameters have been tested which influenced the occurrence of a circulation flow field. These parameters are the horizontal hydraulic conductivity K, the natural hydraulic gradient I, the pumping rate Q and the anisotropy factor AF. A schematic numerical heat transport model and groundwater flow model were designed using the finite element groundwater modelling software FEFLOW. Numerous parameters must be selected to generate the most favourable (best case model) and unfavourable (worst case model) conditions for thermal use. They help to determine the circumstances where thermal use is possible or not. As a result, it was found that due to the higher effect of screen length, the best case curves were very flat, reached fast to their maximum and descended again as related to the worst case curve. The positive influence of lateral groundwater flow is more strengthened than the adverse effects of the vertical flow between production and injection screen. Therefore, the impact of the hydraulic conductivity is a favourable condition which increases from a value 10-4 m/s. A reduction in K value up to 10-5 m/s also creates favourable conditions. This study concludes that for an energy efficient operation lower hydraulic gradients, hydraulic conductivities, and screen length were considered carefully. There is no feasibility of thermal use of combined extraction-injection well only at small hydraulic gradients of less than 0.5% and shallow distance of well screens of about 5 m. So, the smaller plant depends on a lower pumping rate and distance between the well screen which must be small. For larger plant, pumping rate should be higher and higher hydraulic conductivities starting from 10-2 m/s are required.

Wang et al. (2012) proposed that the system energy efficiency of an open-loop surface water source heat pump system (SWHPS) is affected by the water-intake temperature. In this paper, three design options were proposed, namely the linear water-intake port, single water-intake port, and the multiple water-intake ports. A different numerical simulation model was established to examine the corresponding design options and relate their energy-saving results. The numerical simulation was carried out based on water intake velocities at 2.75 m/s, 2.0 m/s and 1.0 m/s using the CFD software Fluent. After the simulation, it was concluded that in single water intake port when water intake velocity declines from 2.75 m/s to 2.0 m/s, then the maximum velocity of the water body decreases at 1-3 m and water intake temperature decreases by 0.05˚C. In multiple water intake ports, based on first and second design option, the integral mean temperature of the water intake at the outlet are 27.70˚C and 26.41˚C respectively. In both, the options the flow rate of water from water-intake pipe was constant at 700 m^3/h. In linear water-intake, when the water-intake velocity is 0.17 m/s, then the integral temperature is 24.80˚C. It means that the integral average temperature of the linear water-intake port is approximately 2.9˚C and 1.6˚C lower than the integral average temperature of the conventional simple and double water-intake ports. These illustrate that among three water-intake design options the linear water-intake port can diminish the water-intake temperature efficiently. For energy-saving rate analysis operating conditions were taken as: 27.7˚C as water-intake temperature, as 2.75 m/s as water velocity, and temperature difference of cooling water are 5˚C and 10˚C. As a result, it was found that when the temperature difference of cooling water is 5˚C, then the energy saving rate of linear and multiple water intake ports is 8.72% and 3.42% respectively. In the case of 10˚C of temperature difference of cooling water, the energy-saving rate in linear and multiple water intake ports is 7.34% and 2.93% respectively. The linear water-intake design option obtained had the highest energy-saving effect. At 1.0 m/s flow velocity for operating condition of temperature difference of cooling water 5˚C and 10˚C, the energy-saving rate of the single water-intake port was 0.41% and 0.33% respectively. It showed that by reducing water velocity there is no enhancement in the energy efficiency of SWHPS and shows that the highest energy saving effect was obtained by linear water-intake port.

Nam and Ooka (2010) developed a simulation model to analyse the effect of groundwater and heat flow on the performance of groundwater heat pump system or open-loop system. In this study, 3D numerical water-heat transfer simulation and experiments utilizing real-scale equipment have been showed to develop the optimization method for groundwater heat pump systems. In this experiment, the extracted groundwater from production well was kept at a constant temperature of about of 18˚C for the entire experimental period. As a result, it was found that the reduction in pumping rate caused a decrease in power consumption of the pump. Since pumping rate decreased, the difference of temperature at the inlet and outlet of heat pump increased which caused an increase in power consumption of the heat pump unit. Therefore, there would be an increase in COP of the groundwater heat pump system. In this experiment, groundwater level and groundwater temperature have been monitored, and will be compared with simulation results and found good agreement. They also conducted case study analyses on several conditions by evaluating the performance of the ground water heat pump system on various well conditions and groundwater. It was concluded that for the design of ground water heat pump system, the decision criteria of the position of the wells and the state of groundwater flow should be proper for better performance of the system.

2.2 Performance of ground source heat pump systems

Ground source heat pump (GSHP) systems have high energy efficiency and low greenhouse gas emission; therefore, GSHP research has received a lot of attention from many researchers. The benchmark of many researchers is the thermal performance of GSHP system using experimental and mathematical modelling. The performance of a GSHP system is dependent on different parameters such as the type of ground heat exchangers, soil condition, the flow rate of groundwater, local climate, system design, building load characteristics, and control factor optimization. Some of the essential parameters relevant to increase the performance of GSHP system have been discussed using experimental and mathematical modelling methods under different sub-headings in the following section.

2.2.1 Mass flow rate of groundwater

Smith et al. (2018) compared the effectiveness of the borehole heat exchanger (BHE) with the change in the groundwater flow within the closed-loop geothermal system and the change in groundwater flow rate was done by using a large municipal well with its periodic pumping. It was done on 144 borehole BHE which is portion of the ground coupled heat pump (GCHP) system for the building. These boreholes were drilled up to a depth of 122 m. The effectiveness of the BHE was calculated to determine out the effect of groundwater flow on the system. It measures the groundwater flow rates of 1.1×10^{-3} m/year. This study concludes that the effectiveness of BHE is improved by current groundwater flow when the level of water rises in the aquifer. The flow of groundwater in BHE was reversed by pumping of municipal well, which decreases the groundwater velocity. Due to this circumstance, the effectiveness of BHE decreases and when the aquifer saturation is less than 0.513 then the effectiveness was less than 0.5.

Farabi et al. (2017) proposed that in semi-open loop GSHP system the heat transfer rate of Ground Heat Exchangers (GHEs) was increased by water-pumping and injection inside the GHE wells. Due to water-pumping and injection, the system performance was analysed in four field tests on GSHP system installed at Akita University Campus, Japan. A sensitive analysis was performed in heating mode by developing a numerical model. For sensitive analysis, they considered two cases: first is, analysis with water pumping and injection rate and the second one is, without water pumping and injection rate. About 15L/min circulation rate of the heat medium in each GHE was maintained for heating periods of 30 days and daily operating hours of 12 hours/day or 24 hours/day. Based on the outcome of the results this work showed that in semi-open loop system with fast groundwater flow, the maximum coefficient of performance (COP), and system coefficient of performance (SCOP) were improved by 12% and 9% respectively. Without groundwater flow, the COP and SCOP were enhanced by 40% and 20% respectively with increasing system capacity significantly. Therefore, the enhancement of performance of the semi-open loop GSHP system was limited by the groundwater flow.

Li et al. (2017) analysed that the performance of the GSHP system was influenced by the unsaturated soil properties and groundwater flow. A general numerical model was introduced to examine the parameters that affect the performance of GSHP system. This mathematical model considered three main elements of behaviour that is, heat transfer within the BHE, the coupling of the BHE to a heat pump and heat transfer into and within the adjacent ground. Both conduction and convection heat transfer take place within the BHE, whereas heat conduction in the wall and heat convection between the pipe and circulating fluid took place in the BHE. A transient heat transfer model in porous media was used to describe the heat transfer phenomena in the adjacent ground. For the coupling of the heat pump and BHE, the inlet and outlet temperatures were considered and it was described by satisfactory boundary conditions. A three-phase soil model was defined for the thermal properties of the ground and this model considered change in properties with the depth of the ground. Numerical simulations were carried out in cooling mode operation, and observed that with the rise in groundwater flow rate, the outlet temperature decreased and the COP of the heat pump increased. In heating mode operation, it can be perceived that the COP of the heat pump and outlet temperature were lower when the groundwater flow was higher.

2.2.2 Heat exchanger

Tang et al. (2019) proposed that BHE is the main component of GCHP system and directly dependent on the performance of the heat pump system. This study was carried out on the shallow BHE established in different soils. These soils were subjected to periodic hydrothermal variations on their land surface. A comprehensive numerical simulation model was developed to determine the performance of shallow BHE and selected two reference models for soil and clay for the calculation. The study found that BHE fitted in the sand was better than the clay. In this paper they studied that 15 principal factors were hydraulic condition, meteorological condition, groundwater flow, grout thermal conductivity, grout diameter, grout volumetric heat capacity, shank spacing, multi-pipe solution, pipe inner diameter, pipe thickness, pipe thermal conductivity, carrying fluid material, carrying fluid velocity, heat load level and heat load mode. The influence of these parameters on the performance of the shallow BHE were observed by covering 108 different cases and compared the annually average COPs of heat pump in dissimilar cases with the reference's models. It observed that the BHE installed in sand and clay had same impact of different factors. As a result, it was found that the COP of the heat pump in the sand was 3.55 and in clay it was 3.27.

Noorollahi et al. (2018) overviewed the GHEs parameters to enhance the efficiency of GHE by an effect on heat exchanger type, outlet temperature, heat exchange rate, pressure loss, thermal conductivity, thermal resistance, and thermal interference etc. This paper was divided into three parts based on those effective parameters and these parts consisted of inside the pipe, outside the pipe and pipe material. Among all the three parts, the analysis for inside the pipe were difficult for checking the effective parameters. By doing the variation in parameters of all three parts different conclusions were drawn. Inside the GHE pipe, due to decrease in velocity of fluid, the difference between inlet and outlet temperatures improved. Also, the amount of heat transfer rate and outlet temperature of the fluid were influenced by the inlet temperature of the fluid inside the GHE pipe. Outside of the GHE pipe, the most significant for the performance of the system was thermal coefficient of backfill material. It was more effective than the thermal coefficient of the soil. The pipe length can be reduced by increasing the thermal conductivity of the backfill material and can increase heat transfer rate simultaneously. In the third part, large variation can be done in thermal performance by varying the centre-to-centre distance of vertical pipe, pipe arrangement and pitch of the spiral pipe.

Nilpuenge et al. (2018) performed an experimental work on plate heat exchanger (PHE) performance under various chevron angles, surface roughness the and working conditions. The PHE performance contained heat transfer coefficient, pressure drop, and thermal performance factor. In these experiments, hot and cold water was used as a fluid at a temperature of 40˚C and 25˚C respectively. This experiment was conducted at Reynold numbers having a range of 1200 - 3500. The plate used in PHE having surface roughness was in the range of 0.95 µm-2.75 µm and chevron angles were 30˚ and 60˚. As a result, it was found that with increasing values of Reynolds number and the surface roughness and reduction in chevron angle, the heat transfer coefficient and pressure drop increased. Under the various working conditions, it was observed that the thermal performance factor appeared with a chevron angle of 30˚ were optimum and also found the highest surface roughness and lowest Reynold number produced better performance. Based on the experimental data, correlation of friction factor and Nusselt number were proposed for the practical application at different surface roughness and chevron angle. The predicted mean absolute deviation of this practical application was 4.47% and 5.69%.

Ren et al. (2018) performed an experiment on two different GSHP systems with steel tubes and polyethylene (PE) tubes compared for seasonal performance with full-scale experiment monitoring throughout the operation procedure using life cycle assessment (LCA) method. LCA was defined by energy profits, economic impacts and environmental impacts. In this study, first operation efficiency such as power consumption and the heat exchange rate of GSHP systems were found by experimental study for assessment of energy profits. Then, energy profits and economic efficiency were analysed based on life cycle energy consumption (LCEC) and life cycle costing (LCC) inventory. Finally, COP and energy payback time (EPT) were deliberated for energy benefits and cost payback time (CPT) was considered for economic efficiency and CO_2 reduction ratio (CRR) was measured for environmental efficiency. Based on their study, the following conclusions arrived for various performance parameters: (i) Operation efficiency - The inlet and outlet temperature difference of the steel tubes was apart from the PE tubes by 1.4-1.7˚C and the heat exchange per tube depth of the steel GHE surpassed the PE one by 70% correspondingly. The power consume by the steel system was slightly lower than the PE one. The COP of the steel tube system was higher than the PE system by 31.3% in winter and 61.9% in summer. The overall conclusion is that the performance of steel GSHP system was better than the PE one, (ii) Economic efficiency and energy benefits - The cost of the steel system and energy consumption were less than the PE system by 45.6% and 35.2% respectively. Consequently, the LCC and LCEC of the steel system went below the PE by 43.6% and 24.6% which shows that the steel system consumed less energy and expense in the life cycle. The energy payback time and cost payback time between two GSHP were reduced to 0.24 and 1.83 years respectively. This specified that the steel system could save more traditional energy and reduce additional investment than the PE in the long-term period, (iii) Environmental efficiency - The steel system diminished CO_2 emissions by 300.57 tons in the whole life cycle and the CRR was 0.45, which shows that the steel system was energy efficient. More greenhouse gases can be reduced by replacing diesel oil with renewable energy and (iv) Seasonal performance - In the whole life cycle, the steel system was found to perform better compared to the PE system. The heat exchange per tube depth was higher in summer with less energy consumption and total cost.

Kim et al. (2016) analysed the effects of UA value of the heat exchanger on the performance of the groundwater heat pump system. The heat exchanger was expressed as polynomial equations and the regression analysis was applied to find the coefficients of polynomial equations. The system performance was calculated by solving these equations numerically. In the groundwater heat pump, generally, a plate heat exchanger (PHE) is used in between the submersible pump and the heat pump of the system. The heat exchange takes place inside the PHE and between the groundwater and fluid circulate in the secondary loop. The heat transfer fluid circulates in the secondary loop or in between heat exchanger and heat pump unit influences the capacity and power consumed by the heat pump unit. In this study, UA values of 9, 12 and 15 W/K were used to analyse its effects on the performance of the system. As a result, it was found that as the UA value decreased from 12 to 9 W/K, the COP of the system during the cooling and heating operation dropped by 4.6% and 4.2% respectively. When the UA value was increased from 12 to 15 W/K, the COP of the system during the cooling and heating operation rose by 3.0% and 2.7% respectively. This study concluded that for better performance of the groundwater heat pump system, the UA value of the heat exchanger should be larger.

2.2.3 Water pump

Rafferty et al. (2009) proposed that for calculating the system performance well pump power is added with the heat pump power and well pump power is influenced by the groundwater flow. It shows that the increase in groundwater flow rates, results in increase of COP of the system. It was determined that for both heating and cooling mode operations an optimum flow exists and when the flow rate exceeds this optimum flow value, it will result in greater cost and lower efficiency. Based on this optimum flow, the water pump, heat exchanger, piping and bore well were designed.

Sfeir et al. (2005) studied different practical surveys which give a correlation of efficiency for small water circulating pump. The power of the circulating pump obtained from the correlation is 2.9 to 3.8 kW for 100 kW of refrigeration effect. Using this correlation, it is found that 15 to 48% of total energy consumption of GCHP system is consumed by water pump only. It was concluded that higher groundwater flows are preferred for the performance of building loop. But exceeding the flow rate of groundwater may increase the energy consumption of the water pump.

2.3 Hybridization of ground source heat pump system

Li et al. (2018) performed the combined operation of the GSHP system and solar thermal system for space cooling and space heating. Solar thermal is used as supporting system of heat pump unit. This paper mentioned a well optimized operation of the combined system. In this paper three operation methods were applied on the combined system by simulation and discussed its effect on the performance of the system and changes in soil temperature. The operation strategy in winter is to collect the solar thermal heat and send it into the ground to increase the water temperature and reduce the machine work in winter. This collected heat can be used directly for heating the building. In the second method, solar heat is captured and stored into the ground via borehole tubes. This higher temperature of water enters the evaporator and enhance the performance of the heat pump in the winter season. If the water temperature is not sufficient for heating purpose then the GSHP system was operated and to assist the GSHP system, solar thermal was used. Firstly, this combined system was operated for office heating and then real operation was performed for a building heating in Beijing, north of China. In this study, TRNSYS simulation tool was used for different operation strategies in combined system.

As a result, it was found that in the condenser side, if the return water was preheated by using solar thermal, then the system would be more efficient, but in evaporator side consumption of solar thermal is maximized if the return water was pre-heated. In a real operation in an office building, operation data was analysed in a day and GSHP system could perform for the time with the solar thermal system and found a COP of 5.2. It was concluded that during three years of operation of the combined system, the soil temperature maintained its equivalency. In summer, the soil temperature may increase and after that, it could be decreased to its equivalent value.

Razavi et al. (2018) proposed a sustainable renewable energy system as well as domestic hot water (DHW) system for heating purpose inside the residential buildings in Zahedan, Iran and simulated the solar assisted ground source heat pump (SAGSHP) system using TRNSYS software with following five different combinations. The first scenario is the GSHP system without a solar collector and for heating the building, all the heat was provided by the GSHP system only. In the second scenario, when the solar collector temperature goes beyond the mean temperature of water storage tank, then it heats required to heat up the water comes from GSHP through a counter-flow plate heat exchanger. When the temperature of water stored in the tank reaches the desired value then the combined heating operation of both the GSHP system and collector stopped. In the third scenario, DHW was heated by the solar collector. If the temperature of the solar collector and DHW becomes equal and if the collector cannot reach up to the desired value or water temperature reduces below the desired value, then the GSHP system was used for heating the building as well as DHW. In the fourth scenario, the GSHP system was directly assisted by the solar collector. When the ground fluid temperature reaches the maximum allowable temperature of the evaporator, then the solar collector provides heat to the storage tank and stops the assistant duty of the ground source heat pump system. In the last fifth scenario, ground fluid stream directly heats up by the solar collector. When the solar collector is capable of heating up the ground fluid, then the GSHP is assisted with direct solar collector; otherwise, ground fluid directly enters the evaporator which bypasses the solar collector. Considering all these scenarios, different parameters such as COP and power consumption of the GSHP system, building temperature, DHW temperature and soil temperature were obtained for 10 years of operation. As a result, it was shown that to provide heating to the building and heating the DHW throughout the winter, a 12 kW GSHP system assisted with solar collector can be used. It was found that the maximum and minimum average COP per year were 3.75 and 3.52 respectively. This paper concluded that 8.7% of energy consumption by the GSHP system can be reduced when solar collector assisted the GSHP system.

Verma and Murugesan (2017) conducted an experiment to evaluate the effectiveness of U-tube ground heat exchanger which absorbing solar energy from 9 AM to 5 PM and stored it under the ground. The stored energy was utilized for space heating in the night time from 7 PM to 3 AM. The experiments were carried out for three days on 11th February, 14th February and 20th February at the facility installed in Mechanical & Industrial Engineering Department of Indian Institute of Technology Roorkee, Roorkee, India. The maximum solar intensity was monitored which changed from 570 to 655 W/m^2. The change in ambient temperature and solar radiation followed the same outline with time. The maximum ambient temperature of about 17.5˚C was monitored on all the three days. In this study, during day time it was observed that the outlet temperature increased from 18.2˚C at 9 AM and reached to a maximum value of 20.5˚C at noon, then started decreasing after 1 PM. The solar collector absorbed the energy and injected it under the ground through the ground heat exchanger. Thus, the earth was used as a thermal energy storage system. Therefore, during night time the stored energy can be utilized for heating purpose inside the building. During night time, initially, the outlet temperature of the ground heat exchanger fluid was increased from 7 PM to 9 PM and reached up to a maximum value of 15.5˚C at 9 PM. The temperature of the fluid decreased up to 3 AM. The temperature of the fluid circulating inside the ground heat exchanger extracted heat from the ground so that the outlet temperature was always higher than the inlet temperature. Based on the obtained results, it was concluded that the increase in the mass flow rate of fluid from 0.23 to 0.33 kg/s resulted in 20% increase in heat extraction from the ground. The COP of the GSHP system increased by 23% because of charging of ground in day time. In this study, it can be seen that there was 5% variation in the COP of the system with variation in mass flow rate of fluid circulated inside the ground heat exchanger.

Choi and Jang (2017) performed numerical analyses and an experimental investigation was carried out to study the impact of building load and heat pump performance for vertical closed-loop ground heat exchanger. For numerical analysis, ground loop design software was used. The GSHP system with thermal storage tank has the potential of reducing the peak load of the building. From this work, results were outlined as follows: Decrease in flow rate of fluid resulted in a decrease in the ground loop heat exchanger env(GLHX) in both cooling and heating operation mode, while the COP of heat pump increased with a decrease in ground loop heat exchanger length. The use of thermal storage tank reduced the peak load of building with reduction of the GLHX length. Experimental results suggested that the peak load of the building with thermal storage tank has to be considered to design the GSHP system for saving the installation cost.

Ma et al. (2016) done an experimental work on solar-ground water heat pump (SGHP) system by using a different methodology. This SGHP system has been designed with radiant floor heating in Tianjin, China. In this study, the performance of the SGHP system was linked with the conventional central heating system (CCHS) with the same indoor and outdoor atmospheric conditions. The other objectives of this paper were to justify the thermal comfort, energy saving and reliability of SGHP system. The experiment on a traditional heating system was carried out from 9th January to 11th January in 2014 and on the SGHP system experiment was carried out from 14th January to 16th January 2014. The ambient temperature varied from –11˚C to 0˚C at the time of experiment. The methodology used in this experiment are as follows: in the first methodology the total energy consumed by the traditional heating system was measured on the heat monitoring system installed at the inlet pipe of each of the three radiators columns. These columns were connected to the network used for municipal heating. Indoor air temperature and inner surface wall temperature of the building were measured and stored in the temperature monitoring system. In the second methodology, experiment was carried out on the SGHP system. In this experiment, the total power consumed by the compressor of the heat pump, water circulating pump and power consumption monitoring system were measured. The energy consume by radiant floor heating was the total energy output by the SGHP system which was measured and stored by a heat monitoring system. As a result, it was found that the SGHP system can save 30.55% energy as compared to CCHS. Comparison with the traditional radiator, floor heating system can save 18.96% energy. It is found that in China, the solar energy contributes 27% of energy in SGHP system and also proved that SGHP system could provide thermal comfortableness, feasibility of new heating system with low energy consumption and reliable to operate.

2.4 Environmental issues related to open-loop GSHP system

In UK most of the GSHP systems are used in domestic buildings for heating and approximately 500 systems have been installed in commercial area for cooling, which discharge hot water to the natural environment and affect local ecology and aquifers (Le Feuvre and St John Cox, 2009). Problems can arise when injected water is drawn towards the extraction borehole, resulting in thermal interference and dropping effectiveness of the system (Ferguson and

Woodbury, 2005). They reported that open-loop installation in Carbonate aquifer of Winnipeg, Canada experienced temperature raise due to thermal feedback and their results indicated that after few years of implementing the schemes and modelling of the area, it was found that using groundwater for cooling is not sustainable. In London, many GSHP cooling systems were installed within 250 to 500 m distance from each other, which became very risky for thermal interference and hydraulic interference. Optimized system design and operational strategies can lead to reduce the thermal interference and improve sustainability (Fry, 2009). Many problems occur due to the re-injection of water into the aquifers (Bank, 2009). When discharge water was brought to the surface, that causes undesirable chemical reactions which result in CO_2 degassing and increase in pH and minerals precipitation, dissolution of oxygen in groundwater and oxidation of dissolved metals resulting from the formation of poorly soluble metal precipitates and formation of bio films. These problems have potential to cause clogging, abrasion or corrosion of pump and pipe and can also affect the extracted water (Bouwer, 2002).

Regulatory approaches in worldwide

The regulations should provide a structure for managing the use of geothermal resources. It generally observed that heat can cause pollution and must control. The extraction or re-injection of groundwater is regulating by Water Protection Legislation. Many different European countries have found where regulation of GSHP is different. In England (Fry, 2009; Le Feuvre and St John Cox, 2009), the Environment Agency's regulate the operation of the open loop GSHP system. This agency approves the project of installation of the GSHP system. To drill a well, a number of surveys were carried out. These may include constant rate extraction and recharge tests to find water features surveys that estimate the influence of the system on local water features and receptors. In Scotland, the open loop GSHP system was regulated by the Scottish Environmental Protection Agency (SEPA). It works on risk-based regulation and the Controlled Activities Regulations (CAR). Open-loop GSHP system that extracts and re-injects into the same geological formation but the chemical composition of water was not altered and were considered as low risk to the environment. In Switzerland, the operation of the GSHP system regulated at canton-level via water resource laws (Bank, 2008). In the US (Bloomquist, 2003), the operation of the GSHP system is regulated under reasonable water resource law. This law regulates the size, design and additives used in the system.

2.5 Optimization of ground source heat pump system

Optimization of a ground source heat pump system is essential to achieve reduction in electricity input to the system. When a GSHP system is operated for space cooling or heating application, there is number of parameters which influence the overall performance of the system. It is essential to determine those influencing parameters so that with proper control the optimum performance of the system could be achieved.

Pandey et al. (2017) researched on optimization of eight influencing operating parameters of Ground Heat Exchanger (GHX) to obtain minimum lengths of vertical and horizontal GHX for space cooling and heating operations. A 1.5 TR GSHP system was used assuming a different combination of cooling and heating periods. Eight influencing parameters such as fluid's specific heat capacity, thermal conductivity, viscosity, density, mass flow rate, GHX pipe's thermal conductivity, diameter and depth of ground were considered. These GHXs parameters with three different levels were assumed and L_{27} orthogonal array was employed to get experimental trials. Taguchi method was used to achieve optimum length for cooling and heating applications and then utility concept was applied to evaluate a single optimum range for a given weighting factor for cooling and heating periods. They found that for horizontal GHX in space cooling condition the optimized GHX length was estimated to be 247.76 m with significant contributions by 46.4% of thermal conductivity of GHX pipe, 26.24% of fluid's specific heat capacity and optimized length of 198.512 m in space heating with significant contributions by GHX pipe's thermal conductivity and diameter of 44.3% and 26.4% respectively. After employing utility concept, the horizontal GHX lengths calculated are 254.736 m for space cooling and 240.646 m for space heating using a standard set of parameters. For vertical GHX, Taguchi analysis predicted that GHX pipe's thermal conductivity and diameter are the major effective parameters for both space cooling and space heating conditions with 61.95% and 31.97% of involvement respectively in space cooling condition and 61.870% and 31.971% of participation in space heating conditions and the GHX lengths predicted are 155.899 m and 117.544 m for space cooling and space heating modes respectively.

Liang Pu et al. (2017) used a multi objective genetic algorithm (MOGA) joint with Kriging response surface method to optimize the ground heat exchanger (GHE) design parameters. The influence of design parameters was analysed including inlet flow temperature, inlet flow velocity, borehole diameter, U-tube diameter and pipe spacing on the entropy generation number (EGN) and the integrated evaluation factor. The MOGA approach optimization results were compared to screening approach. Their results illustrated that both screening approach and MOGA optimization method using Kriging model improved the thermal performance of GHEs. They claimed that thermal performance optimal results in MOGA approach are larger than that in screening approach. When compared to original GHE, the average energy consumption of GSHP of the optimal GHE in MOGA approach reduced by 215.86 kJ/h, and that in the screening approach decreased by 133.64 kJ/h.

Ma and Xia (2017) developed an optimization plan for GSHP systems furnished with variable speed pumps in ground loop system with an objective of optimization to minimize the system power consumption while providing required cooling and heating demand. The optimization problem was formulated using a model-based method in which the component models were used to ascertain the system performance under numerous trial settings and an exhaustive search approach was used to identify the optimal settings. The variable used for optimization was outlet water temperature from the ground heat exchangers and the performance of planned strategy was tested in three successive days in Sydney weather conditions under cooling mode operation. The proposed strategy saved 4.2% of total power consume by water to water heat pumps.

Esen and Turgut (2015) conducted experimental studies on vertical ground coupled heat pump (VGCHP) system with varying depth of borehole, inlet and outlet temperatures of condenser and evaporator. Taguchi method was applied to these influencing parameters to optimize the COP of VGCHP system. Study of variance (ANOVA) and signal to noise ratio (S/N) were used to evaluate the experimental results. Five influencing parameters (condenser inlet-outlet, evaporator inlet-outlet temperatures and depth of borehole) were used with three levels and L_{27} orthogonal array was use for Taguchi analysis for heating mode only. According to their experimental results, the average COP values for borehole depths of 30 m, 60 m and 90 m were found to be 1.93, 2.37 and 3.03 respectively. According to Taguchi analysis, the COP of the system was found to be 3.98 and the depth of borehole was the most significant parameter influencing the COP of the system with the percentage of contribution of 67.77%.

Sivasakthivel et al. (2014) employed Taguchi and utility techniques to optimize eight control parameters (viz., U tube radius, borehole radius, heating load, grout thermal conductivity, temperature of entering water, U tube thermal conductivity, distance between U tubes and mass flow rate) influencing on working of GHX in space heating applications. The objective functions considered are the length of GHX, COP and GHX's thermal resistance. In Taguchi analysis, lower the better concept was employed to attain a favourable value of the length of GHX, thermal resistance and higher the well concept for the COP of the GSHP system. Higher the better concept was used in the utility concept. In this study, two levels for heat exchanger pipe's thermal conductivity and three levels for the remaining parameters were used with an experimental plan of L_{18} orthogonal array (2×1 and 3×7). Utility concept was employed by assigning weighting factors of 0.35, 0.35 and 0.3 on GHX length, COP and thermal resistance respectively. It was found that the length of GHX, borehole resistance reduced by 15.17%, 17.1% respectively and COP increased by 2.5%. After the application of utility concept, the length of GHX increased by 3.2%, COP and borehole resistance reduced by 1.2% and 13.23% respectively.

Verma and Murugesan (2014) projected a methodology to optimize the solar collector area and ground heat exchanger length to achieve a higher coefficient of performance of solar assisted ground source heat pump (SAGSHP) system. In this work, Taguchi and utility concept were applied over eight operating parameters (viz., installation depth of GHX, inner radius of GHX pipe, thermal conductivity of GHX pipe, specific heat capacity of GHX liquid (water), reflectivity of glass cover, mass flow rate of GHX liquid (water), solar collector pipe's thermal conductivity and inner radius of solar collector pipe) with mixed level variation using an L_{18} (2×1, 3×7) orthogonal array. Lower the better concept was applied for GHXs length and solar collector area, whereas higher the better concept was applied for the performance of SAGSHP system by considering 2-ton heating load for space heating application. Utility concept predicted a COP of 4.23 which was 8.74% higher than the optimum COP calculated by Taguchi method whereas solar collector area and ground heat exchanger length values were reduced by 2.3% and 1.6% respectively compared to those values optimized by the Taguchi method.

Chapter 3

Experimental setup

3.1 Introduction

An 8 TR open loop GSHP system has been installed for cooling and heating operation in the dining room of the guest house in NETRA, Greater Noida and this work was executed as part of a research project by IIT Roorkee. An open loop GSHP system consists of a heat pump unit, plate heat exchanger (PHE), extraction borewell and re-injection borewell. A photograph of the open loop GSHP system used for the present dissertation work is shown in Figure 3.1.

Figure 3.1 Experimental setup of an open loop GSHP system

During cooling mode operation, the heat absorbed from the space to be cooled is transported to the ground water through a PHE. That means the hot heat transfer fluid in the chiller of the heat pump unit is cooled using ground water extracted from a bore well known as extraction well and heat transfer is achieved through a plate heat exchanger. In order to preserve the extracted water from the bore well, the water is being re-injected back into another re-injection bore well with provision of a soak pit. During heating mode operation, heat is absorbed from the extracted ground water by passing through the PHE and heat is transported to the heat transer fluid in the heat pump, which in turn heats the space to be heated.

3.2 Components of an open-loop GSHP system

Heat pump

Heat pump is the main component of the GSHP system (Figure 3.2). It consists of evaporator, compressor, condenser and expansion valve. These components are involved in primary loop in which refrigerant R410A is being circulated in the refrigeration fluid loop. A reverse valve is provided in the heat pump to reverse the operation mode by altering the flow direction of water used to interact with the refrigerant. Thus, a single system can perform for cooling as well as for heating operation. This system uses an inverter, hence first the electricity is rectified to direct current and then inverted back to alternating current using pulse width modulation. Thus, according to the room temperature, the compressor can increase and decrease the speed in order to meet the cooling/heating demand. Due to variable speed of compressor, the heat pump is energy efficient and consume less power than the conventional model heat pump. The manufacturing description of the heat pump is water to refrigerant unit of Make – SAMSUNG, Model – 10 HP AM100FXWA and nominal cooling and heating capacity of 28 kW and 31.5 kW respectively.

Figure 3.2 Heat pump unit

Indoor HVAC unit

Indoor unit is used to circulate the air inside the building (Figure 3.3). It consists of a coil in which refrigerant is circulating. During cooling mode, it extracts heat from inside the building and distribute cool air and during heating mode, it rejects heat to the space and distribute hot air. The model of indoor unit is refrigerant multi split units - 4 Nos - Make – SAMSUNG, Model – AM071KNQDEH and nominal cooling and heating capacity of each unit is 6.8 kW and 7.0 kW respectively.

Figure 3.3 Indoor HVAC unit

Borewells

In an open loop GSHP system two bore wells are used, one as extraction well and another, injection well. These wells were created by boring to the level below the water table in the earth which is observed at a depth of 10 m from surface. A bore well machine is used to drill a bore of suitable diameter and in the present case, a 400 mm diameter bore wells were made to a depth well below the water table. Boring was done up to a depth of 60 m. A casing pipe of 200 mm outside diameter was lowered into the bore well with required number of filter pipe lengths at required levels. The area outside the pipe was filled with pea gravel having typical size of 3/8’’ and round and smooth sides. It is used as a filter medium for groundwater coming into the casing pipes. Then a compressor is used to develop the bore well to clean the bore well of fine mud particles and helps in getting clean continuous water flow into the bore well casing.

Submersible pump

A submersible bore well pump is selected for the required flow rate of groundwater and head (Figure 3.4). This is power-driven centrifugal pump, type CORA – 7C/07G, 1.5 hp, Make – KSB. A submersible pump is lowered into the bore well up to a depth of 24 m with polyvinyl chloride (PVC) column pipes of 50 mm diameter. The average value of efficiency of the submersible pump is 34.5% approximately.

Figure 3.4 A submersible pump

Plate Heat Exchanger

It is a water to water counter current plate heat exchanger (Figure 3.5) designed for heat exchange of 40.44 kW with a flow rate of 96 l/min. This PHE has two number of passes and total number of plates are 30 in which number of effective plates are 28. The material of the plates is AISI316 having thickness of 0.50 mm. Sealing material used in PHE is Nitrile Butadiene Rubber (NBR). Efficiency of the PHE is better than other heat exchanger due its compact design, therefore, it is used to provide better performance of the open loop GSHP system.

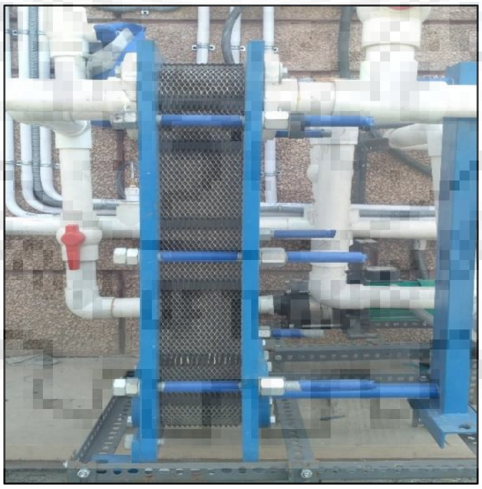


Figure 3.5 Plate heat exchanger

Closed Loop Water circulation pump

Close loop water circulation pump is used to circulate the water in between PHE and heat pump (Figure 3.6). The manufacturing description of this pump is WILO, Model – 503 – 3 phases.

The power consumption capacity of the pump is 0.75 hp and average efficiency is approximately 48%.

Figure 3.6 Close loop water circulating pump

Open water loop

This consists of an open loop connection between extraction well, submersible pump, sand filter, PHE and injection well. This loop is made of un-plasticized polyvinyl chloride (UPVC) pipe of 50 mm diameter. Its working system is based on submersible pump which extracts groundwater from the extraction well and circulates through PHE where groundwater exchanges its heat with water circulated in the secondary loop. This thermally modifies the groundwater which is re-injected back into the aquifer through injection well. There is a sand filter provided before the PHE to remove the sand particles from extracted groundwater and to prevent the entry into the PHE with groundwater.

Primary loop

Primary loop is also known as refrigeration loop. This involves four indoor heating ventilation and air conditioning (HVAC) units inside the canteen area. These units are connected to outdoor HVAC unit with copper piping. The circulation medium used in primary loop is refrigerant R410A. This involves transfer of heat between indoor and outdoor HVAC units.

Secondary loop

Secondary loop is also known as closed water loop in open loop GSHP system. This involves a loop between PHE to heat pump in which water is circulating with the help of water circulation pump. This allow transfer of heat between outdoor unit and PHE. The pipe is made of 50 mm diameter of UPVC. This loop is installed to protect the PHE from varying quality of groundwater coming from the extraction well. Thus, required quality of water as per the outdoor unit specification is filled in this loop.

3.3 Procedure to operate the system

An open loop GSHP system is hard to operate because number of electrical equipment are used with this system, such as indoor unit, outdoor unit, submersible pump and close loop water pump. To overcome this problem this system is provided with flow switches and electronic sensors to operate automatically. When the indoor unit is switched on it sends electrical command to the sensor connected with the submersible pump and gives command to the submersible pump to switch on and then starts to extract groundwater through the extraction well. The groundwater flows through the PHE, when it is switched on by the flow switch placed after the PHE inside the pipe. This flow switch is connected with the sensor of closed loop water pump and starts the water pump for circulating the water in the secondary loop. While the water is circulating inside the secondary loop, the flow of water activates the flow switch provided in the secondary loop. When this flow switch is activated it sends signal to the heat pump unit via electronic sensor to complete starting operation. With this complete procedure open loop GSHP system can be started by switching on a single switch and easily operates for both cooling and heating modes.

3.4 Measuring instruments

In this experimental work, parameters like groundwater flow rate, temperatures of the cold and hot fluids and power consumption by the system has been recorded with the help of different measuring instruments. All the measuring instruments used in the present are discussed in the following sections.

Water flow meter

Water flow meter helps to detect the flow rate of the groundwater. It works on the principle of turbine; therefore, it is also called turbine flow meter. It consists of a rotor in which a number of blades are attached. The rotor is supported by sleeve gearing on a shaft and mounted perpendicular to the axis of the flowing water. The rotor rotates freely about its axis. The flowing water impinges on the blade surface to induce force which causes rotation of the rotor. This rotational speed is proportionate to the flow velocity. Since the volumetric flow rate is directly proportional to the flow velocity, the rotational speed of rotor is proportional to the volumetric flow rate of water. The rotational speed is observed by a magnetic pickup which is connected outside the meter housing. The pick-up coil generates voltage pulses when each rotor blade passes through it and the total number of pulses measures the total volumetric flow rate of the groundwater. The model of water flow meter used in the experimental setup is Kranti 50 mm flange type water flow meter as shown in Figure 3.7.

Figure 3.7 Water flow meter

Filled type thermometer

A filled type thermometer is used to measure the temperature of groundwater as well as water circulating in the secondary loop (Figure 3.8). The thermometer is filled with mercury fluid in the glass tube; therefore, it is also called filled type thermometer. It works on the principle of thermal expansion of fluid with change in temperature. Thus, the amount of expansion of fluid indicates the temperature value. In this setup four thermometers are connected to measure the temperature of water at four different locations, such as inlet and outlet of groundwater and well water circulated in the secondary loop into the PHE.

Figure 3.8 Filled thermometer

Energy meter

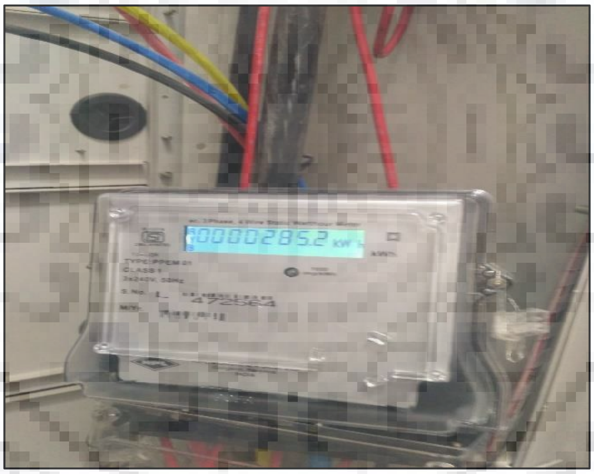


Figure 3.9 Energy meter

Energy meter is used to measure the power consumption by the ground water coupled open loop GSHP system. It is an AC, 3 phase, 4 wire static Watt-hour meter and measures the energy consumption in kWh digitally.

Chapter 4

Governing equations

The present dissertation work aims at estimating the performance of an 8 TR open loop GSHP system installed at the dining hall of guest house in NETRA, NTPC, Greater Noida (UP) for space-cooling and space-heating operations. The governing equations and formulae used for the calculation are explained in the following sections.

4.1 Thermal performance of open-loop GSHP system

In GSHP technology water cooled heat pumps are used for providing cooling/heating effect. The cooling water for the condenser of the heat pump is extracted from an extraction well generally drilled up to a depth of 60 m. The cooling of condenser fluid takes place through an intermediate heat exchanger; generally, a plate heat exchanger (PHE) is employed to serve this purpose. After cooling the condenser water, the ground water is re-injected back into another re-injection bore well at a depth of 60 m. However, sometimes all the used water cannot be re-injected into the well, in such case in order to minimize the water over flow, a suitable water conservation strategy has to be followed. Figure 4.1 depicts the schematic diagram of an open-loop GSHP system. The design of open loop system involves estimating water flow rate to be extracted from the well for the given heating/cooling load and then design of the plate heat exchanger. Finally, the overall COP of the system is computed. In the case of space-cooling the heat is removed from the room and it is rejected to the ground through the continuous supply of water from the extraction well, which can be seen in Figure 4.1.

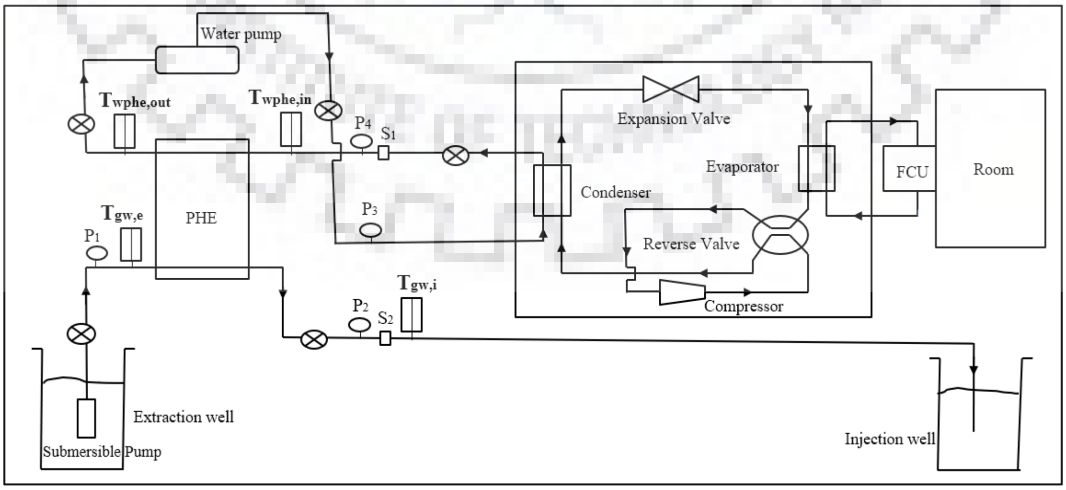


Figure 4.1 Schematic diagram of an open loop GSHP system for space cooling operation

For a heat pump that absorbs heat from the room to be cooled and rejects heat to the sink, the work input to the compressor is expressed as

$$W_{cr} = Q_{rejected} - Q_{cooling} \tag{4.1}$$

From which one can get

$$Q_{cooling} = Q_{rejected} - W_{cr} \tag{4.2}$$

and $Q_{rejected}$ is calculated as

$$Q_{rejected} = \frac{m_{gw} \times c_{pw} \times \Delta T}{\eta_{PHE}} \tag{4.3}$$

where $Q_{cooling}$ is the cooling effect, $Q_{rejected}$ is the heat to be injected into the ground or sink through plate heat exchanger, W_{cr} is the power supplied to the heat pump in kW, m_{gw} is mass flow rate of groundwater, c_{pw} is the specific heat of water, ΔT is the temperature difference between injection water to the ground and extraction water from the ground, η_{PHE} is the effectiveness of plate heat exchanger and assumed as 0.70 approximately (as per specification by the manufacturer) and W_T is total power supplied to the overall GSHP system in kW including power supplied to the heat pump and pumps used for water circulation.

$$COP_c = \frac{Q_{cooling}}{W_T} \tag{4.4}$$

COP_c is the coefficient of performance of the overall GSHP system for cooling mode.

In the case of space-heating, the heat is extracted from the ground water and it is supplied to the room, which can be seen in Figure 4.2.

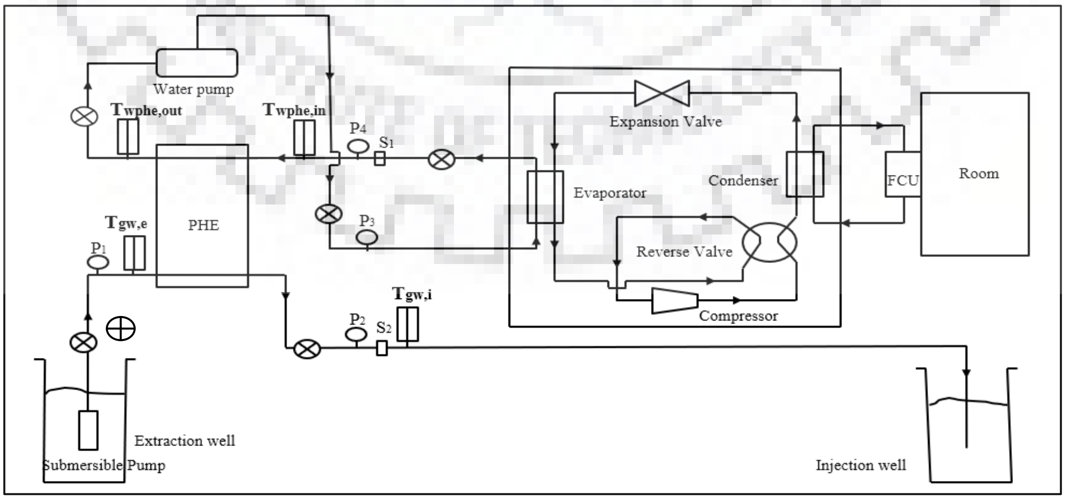


Figure 4.2 Schematic diagram of an open loop GSHP system for space heating operation

For a heat pump in heating mode, the work input to the compressor is expressed as

$$W_{cr} = Q_{heating} - Q_{absorbed} \tag{4.5}$$

From which one we can get

$$Q_{heating} = Q_{absorbed} + W_{cr} \tag{4.6}$$

and $Q_{absorbed}$ is calculated as

$$Q_{absorbed} = m_{gw} \times c_{pw} \times \Delta T \times \eta_{PHE} \tag{4.7}$$

where $Q_{heating}$ is the heating effect, $Q_{absorbed}$ is the heat absorb from the sink, and W_{cr} is power supplied to the heat pump in kW. Now

$$COP_h = \frac{Q_{heating}}{W_T} \tag{4.8}$$

COP_h is the coefficient of performance of the overall GSHP system for heating mode.

4.2 Effectiveness of plate heat exchanger

Figure 4.3 shows the schematic diagram of the plate heat exchanger used in the open loop GSHP system for heat exchange between groundwater and water flow inside the closed loop pipe connected between PHE and the heat pump system,

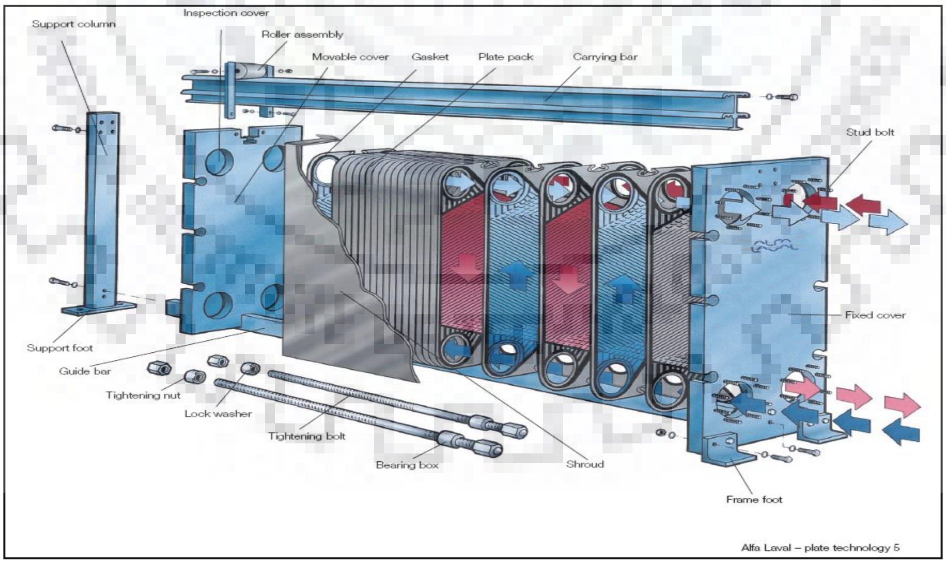


Figure 4.3 Schematic diagram of plate heat exchanger (Haslego and Polley, 2002).

The performance of the heat exchanger is indicated by its effectiveness and it should be maximum for better performance of the heat exchanger. Based on the temperature of the fluids, two methodologies are used to estimate the effectiveness of the heat exchanger. In the first method, if all the temperatures of the fluids are known then the effectiveness is defined as the ratio of actual amount of heat transfer to the maximum possible amount of heat transfer between the two fluids flowing in the PHE. In the second method, if any one temperature is unknown then the number of transfer units (NTU) is introduced to estimate the effectiveness of the PHE. In this study, all the temperatures are measured from the experimental setup with the help of thermocouple and thermometer. In the present work, the first method is applied to calculate the effectiveness and following are the governing equations and the formulae used to estimate the effectiveness of the plate heat exchanger.

$$\text{Effectiveness } (\varepsilon) = \frac{\text{Actual heat transfer } (Q_a)}{\text{Maximum heat transfer } (Q_{max})} \tag{4.9}$$

where,

$$Q_a = \dot{m}_{cw} \times c_{pcw} \times \Delta T_c = \dot{m}_h \times c_{ph} \times \Delta T_h \tag{4.10}$$

and

$$Q_{max} = C_{min} \times (T_{hi} - T_{ci}) \tag{4.11}$$

thus,

$$\varepsilon = \frac{(\dot{m}_{cw} \times c_{pcw} \times \Delta T_c)}{C_{min} \times (T_{hi} - T_{ci})} = \frac{(\dot{m}_{hw} \times c_{phw} \times \Delta T_h)}{C_{min} \times (T_{hi} - T_{ci})} \tag{4.12}$$

where, $\dot{m}_c$ and $\dot{m}_h$ are mass flow rate of cold water and hot water respectively, c_{pc} and c_{ph} are specific heat capacity of cold water and hot water respectively and ΔT_c and ΔT_h are inlet and outlet temperature difference of cold and hot water respectively. C_{min} is minimum heat capacity, T_{hi} and T_{ci} are the inlet temperatures of hot and cold water at PHE.

4.3 Performance of the submersible pump

The performance of the submersible pump is an important factor which influences the performance of the overall GSHP system. The main factors that affect the performance of submersible pump are, the amount of power consumption, overall efficiency and discharge of the pump. The overall efficiency of the pump depends on different parameters such as pump efficiency and motor efficiency. Pump efficiency consists of major factors such as, friction in disk, volumetric efficiency and hydraulic efficiency. Similarly, motor efficiency depends on the stator winding and the number of poles. Therefore, the overall efficiency is also called combined efficiency and can be calculated by using the following governing equation (Haque et al., 2017).

$$\eta_c = \frac{Q \times H_p \times S}{366 \times P} \tag{4.13}$$

where, η_c is combined efficiency, Q is discharge in $\frac{m^3}{s}$, H_p is pump head in meter, S is specific weight in $\frac{N}{m^2}$ and P is power consumption of submersible pump.

The total dynamic head of a submersible pump is shown in Figure 4.4.

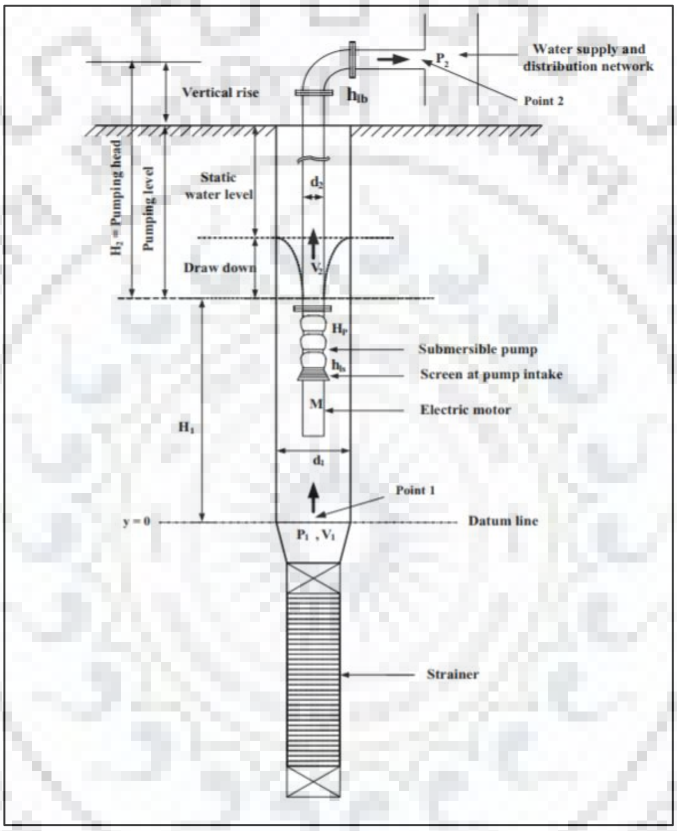


Figure 4.4 Schematic diagram of a submersible pump (Haque et al., 2017)

In the Figure 4.4, the pumping head is shown which is measured by using Avometer. The pump head of a submersible pump can be estimated by applying Bernoulli's equation.

Applying the Bernoulli's equation with consideration of the head loss between point 1 and 2, we get

$$y_1 + \frac{P_1}{\rho g} + \frac{V_1^2}{2g} + H_p = y_2 + \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + h_{ls} + h_{fm} + h_{lb} + n \times h_{lf} + h_{lo} \tag{4.14}$$

From Figure 4.4, we can get

$y_1 = 0;\ y_2 = H_1 + H_2;\ P_1 = \rho gH;\ V_1 = \left(\frac{d_2}{d_1}\right)^2 \times V_2;\ h_{ls} = f_{ls} \times \frac{V_2^2}{2g}\ ;\ h_{fm} = f_m \times \frac{L}{d_2} \times \frac{V_2^2}{2g}\ ;$
$h_{lb} = f_{lb} \times \frac{V_2^2}{2g}; h_{lf} = f_{lf} \times \frac{V_2^2}{2g}; h_{lo} = f_{lo} \times \frac{V_2^2}{2g}$

After substituting all these value in Equation (4.14), we get

$$H_1 + \left(\frac{d_2}{d_1}\right)^4 \times \frac{V_2^2}{2g} + H_p = H_1 + H_2 + \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + f_{ls}\frac{V_2^2}{2g} + f_m \frac{L}{d_2}\frac{V_2^2}{2g} + f_{lb}\frac{V_2^2}{2g} + n \times f_{lf}\frac{V_2^2}{2g} + f_{lo}\ \frac{V_2^2}{2g}$$

$$H_p = H_2 + \frac{V_2^2}{2g}\left\{1 - \left(\frac{d_2}{d_1}\right)^4 + f_{ls} + f_m \frac{L}{d_2} + f_{lb} + n \times f_{lf} + f_{lo}\right\} + \frac{P_2}{\rho g} \qquad (4.15)$$

since for a distinct pumping system

$$K = 1 - \left(\frac{d_2}{d_1}\right)^4 + f_{ls} + f_m \frac{L}{d_2} + f_{lb} + n \times f_{lf} + f_{lo} = \text{constant}$$

hence

$$H_p = H_2 + K\frac{V_2^2}{2g} + \frac{P_2}{\rho g} \qquad (4.16)$$

4.4 Computational algorithm

Computational algorithm consists of a logical procedure for solving the various equations using FORTRAN programming language. A computer code in FORTRAN program is developed to calculate the effectiveness of plate heat exchanger and coefficient of performance of open loop GSHP system. For calculating the effectiveness of the PHE and COP of the system, the following steps are used:

(i) Temperature of hot fluid (water) and cold fluid (water) at inlet and outlet of PHE and mass flow rate of extracted groundwater are used as an input in the program.

(ii) Compute the mass flow rate of hot fluid (water) flowing between heat pump and plate heat exchanger.

(iii) Use specific heat capacity of hot and cold water as an input data.

(iv) Estimate the effectiveness of the plate heat exchanger.

(v) Compute the heat absorbed/rejected as per the requirements for cooling/heating operation.

(vi) Estimate the power consume by the submersible pump, water circulating pump and heat pump unit.

(vii) Finally, determine the coefficient of performance of overall system using cooling or heating loads.

Chapter 5

Results and discussion

Experiments were conducted on the 8 TR open loop GSHP system installed at NETRA, Greater Noida during May and July 2018 for space cooling trial runs for three days, 23rd May, 18th and 19th July 2018 and during January 2019 for space heating runs for three days 28th, 29th and 30th January 2019. Data of observations, detailed calculations and results obtained are discussed in detail in the following sections.

5.1 Analysis of results for space cooling mode

For cooling mode operation, the following data were taken during the experiments conducted for 5 to 7 hours as depicted in Tables 5.1 to 5.3 respectively for three days, 23rd May, 18th and 19th July 2018.

Table 5.1 Experimental data observed on 23rd May 2018 for cooling mode

Time (hour)	$T_{gw,e}$ (˚C)	$T_{gw,i}$ (˚C)	$T_{wphe,in}$ (˚C)	$T_{phe,out}$ (˚C)	$\dot{m}_{gw}$ (kg/s)	Power consumption (kW)
11.45	27.1	30.1	34	29.2	0.0	0
12.15	27.0	30.2	34.1	29.1	3.19	11.0
12.45	27.0	30.2	34.1	29.1	2.02	11.4
13.15	26.9	30.1	34.0	29.0	2.59	11.4
13.45	26.9	30.1	34.0	29.0	3.16	11.4
14.15	26.8	30.0	33.8	28.9	2.06	11.2
14.45	26.9	30.0	33.6	28.8	2.61	11.6
15.15	26.9	30.0	33.6	28.8	2.61	11.4
15.45	26.9	29.9	33.6	28.8	2.59	11.2

Table 5.2 Experimental data observed on 18th July 2018 for cooling mode

Time (hour)	$T_{gw,e}$ (˚C)	$T_{gw,i}$ (˚C)	$T_{wphe,in}$ (˚C)	$T_{phe,out}$ (˚C)	$\dot{m}_{gw}$ (kg/s)	Power consumption (kW)
11.51	27.5	29.5	33.2	29.6	0.0	0
12.51	27.1	28.9	32.6	29.7	2.57	6.1
13.51	26.6	28.4	32.8	29.6	2.57	6.0
14.51	26.5	28.5	32.5	29.6	2.86	6.1
15.51	26.9	28.7	32.9	29.2	2.29	5.9
16.51	27.2	28.9	32.6	29.4	2.57	5.9
17.51	27.5	28.8	32.5	29.6	2.57	5.8

Table 5.3 Experimental data observed on 19th July 2018 for cooling mode

Time (hour)	$T_{gw,e}$ (°C)	$T_{gw,i}$ (°C)	$T_{wphe,in}$ (°C)	$T_{phe,out}$ (°C)	$\dot{m}_{gw}$ (kg/s)	**Power consumption (kW)**
10.41	27.5	29.3	33.1	29.6	0.0	0.0
11.41	27.3	28.9	32.6	29.4	2.48	6.2
12.41	27.0	28.7	32.4	29.1	2.51	5.9
13.41	26.9	28.7	32.4	30.3	2.54	5.9
14.41	26.9	28.7	32.4	29.9	2.53	5.9
15.41	26.5	28.5	32.5	29.5	2.53	5.9
16.41	27.0	28.9	32.6	29.1	2.53	5.9
17.41	26.9	28.9	32.6	30.0	2.53	5.9

5.1.1 Analysis of transient behaviour of parameters

Temperature of ground water

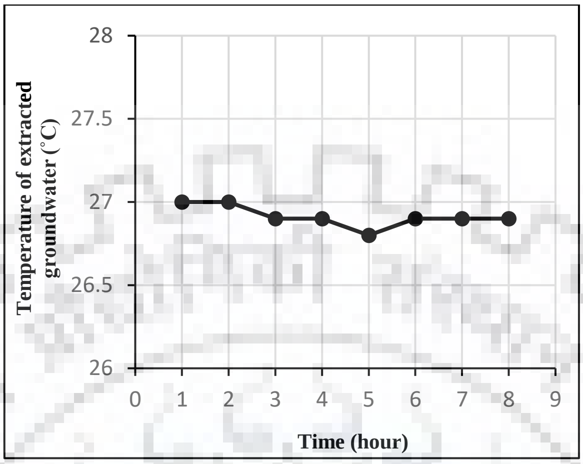
Using the experimental data obtained, the COP of the open loop GSHP system has been computed for all the three days, 23rd May, 18th and 19th July 2018 and are plotted against time. Experiments were conducted for a duration varying from 5 to 7 hours because of the availability of the system installed in the dining hall of the Guest house of NETRA. Figure 5.1 shows the variation of temperature of water extracted from the extraction bore well with time. Generally, the experiments were started around 10.30 to 11.30 AM and carried out till evening about 4.30 to 6 PM. The temperature seems to remain almost constant at about 27°C on 23rd May 2018 whereas it fluctuates by 1 degree from the mean of 27°C on the other two days. These variations may be attributed to the sensitivity of the temperature sensors used for the measurement. Figure 5.2 depicts the variation of temperature of water re-injected into the bore well after use in the plate heat exchanger (PHE) with time. The mean temperature is found to be around 30°C on 23rd May and 28.5°C for the other two days. The temperature difference between the temperatures of water extracted and re-injected into the bore holes are shown in Figure 5.3. It can be seen during 23rd May the temperature difference was about 3.2°C, whereas it decreased to about 1.8°C for the other two days in July 2018. Higher temperature difference will make the GSHP system work more efficient.

Mass flow rate and power consumption

The cooling water flow rate that is extracted from the extraction bore well is measured using a Kranti flange type water flow meter. The water flow rate is continuously measured with time and is plotted in Figure 5.4 for three days. The average water flow rate for all the three days is observed to be 2.5 kg/s. The flow rate of cooling water can be varied using a valve provided along the cooling water line. After interacting with the water from the heat pump through the PHE, the cooling water is re-injected back into the bore well. It may not be possible to achieve 100% re-injection back into the bore well as the back pressure within the borehole will be much higher than the pressure in the line, hence a soak pit is provided surrounding the re-injection bore hole to minimize water evaporation in case all the water is not taken back into the bore hole. Water flow rate is an important parameter that affects the heat interaction between the heat transfer fluids in the GSHP system. The electric power input to the GSHP system is measured using an energy meter installed in the electrical control panel. The electricity input to the compressor of the heat pump, circulation water pump of the heat pump and the extraction water pump are measured using this energy meter. Figure 5.5 shows the variation of power consumption by the GSHP system with time during the experiments. The average power consumption on 23rd May is found to be around 11.5 kW and about 5.8 kW during the other two days in July as depicted in the above figures.

COP and effectiveness of PHE

The coefficient of performance of the open loop GSHP system has been computed with time using the experimental data obtained. Figure 5.6 shows the variation of COP of the system for 23rd May, 18th and 19th July 2018. An average COP of about 3.5 was obtained for 23rd May, whereas about 3.8 were calculated for the other two days in July. Similarly, the effectiveness of PHE were computed for all the three days and found to vary from 0.72 to 0.75 for the three days.



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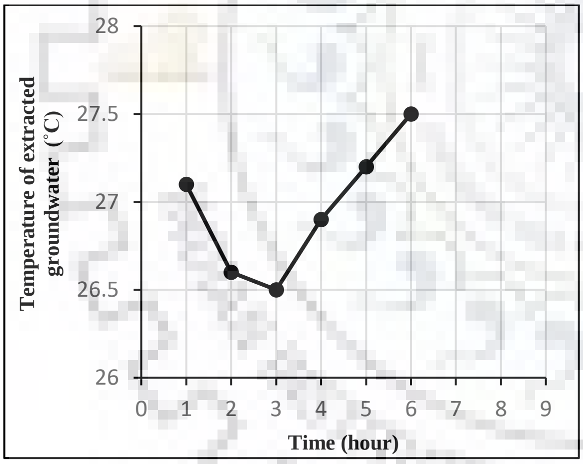

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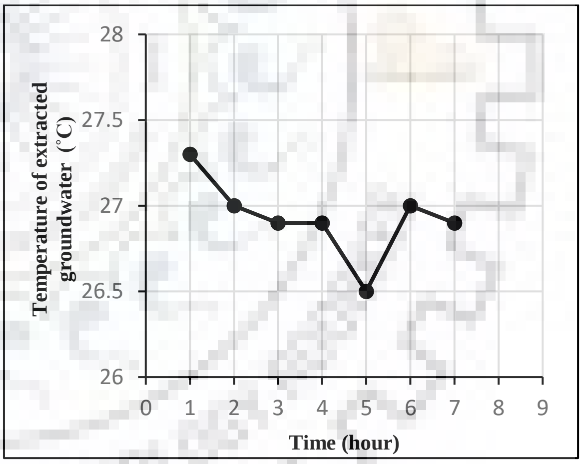
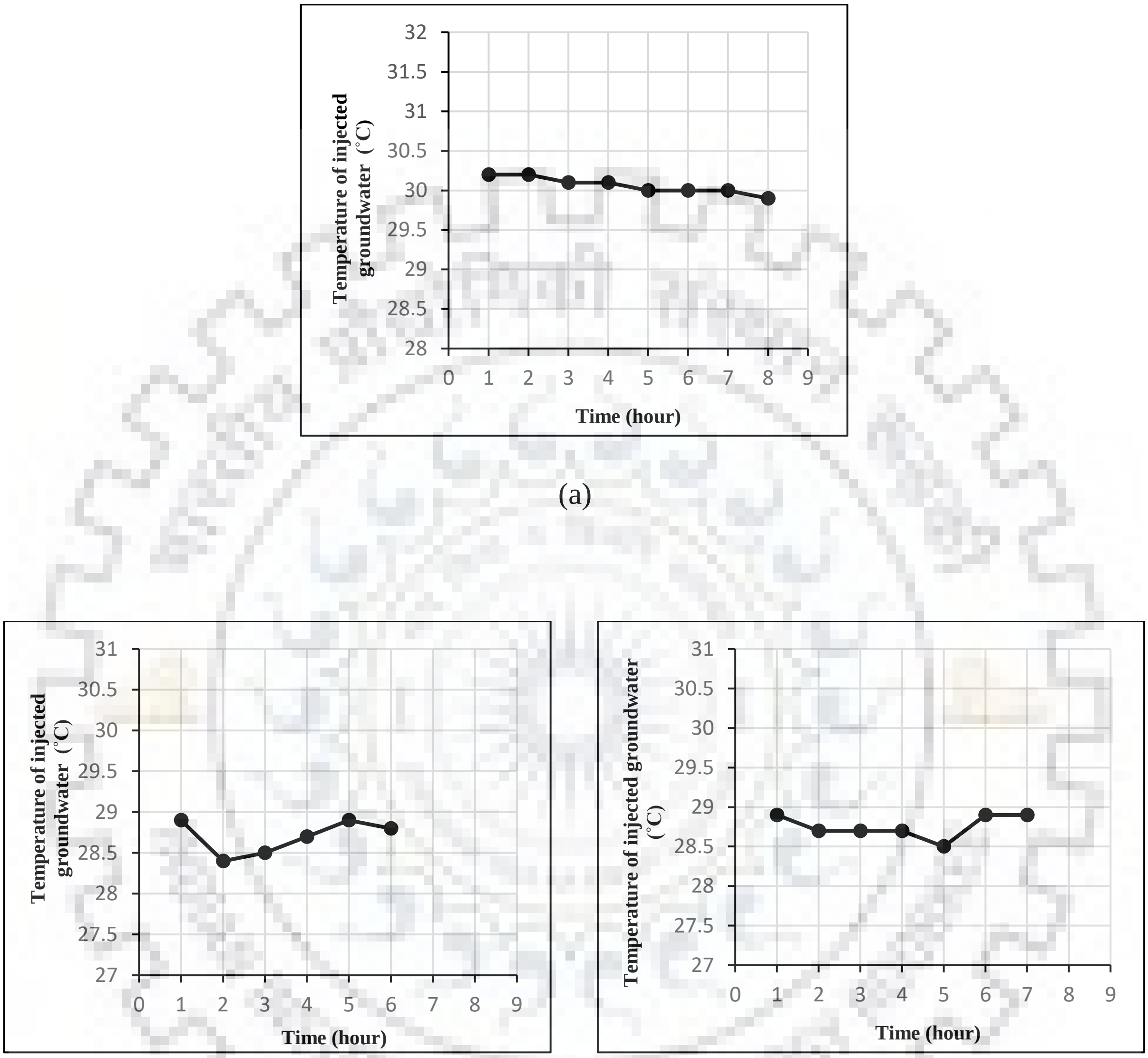


(c)

Figure 5.1 Variation of temperature of extracted groundwater with time.

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.



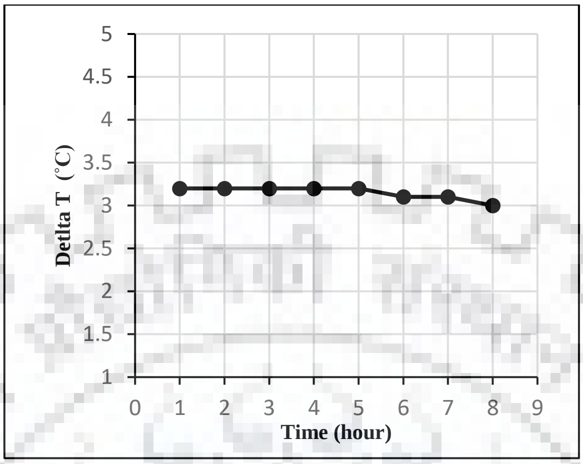
(a)

(b)

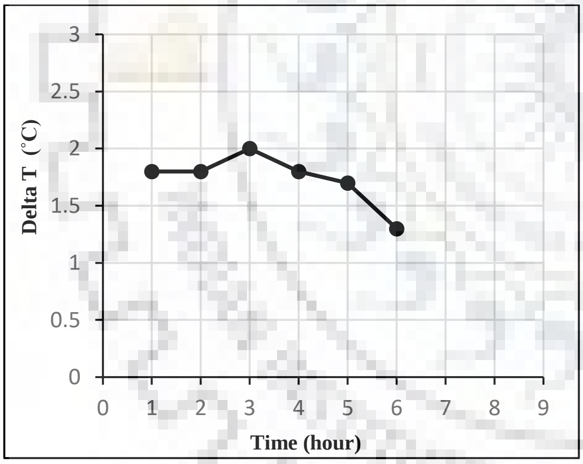
(c)

Figure 5.2 Variation of temperature of injected groundwater with time.

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.



(a)



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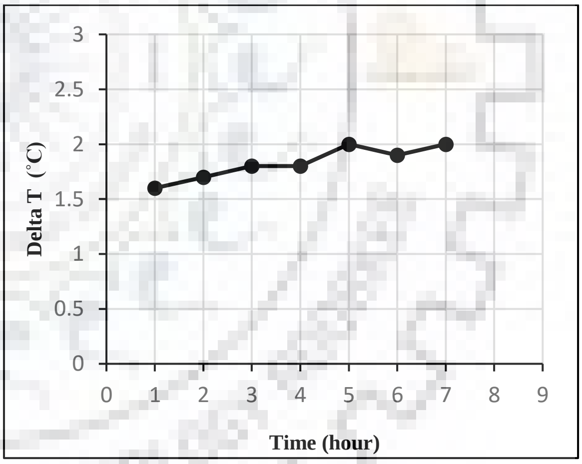
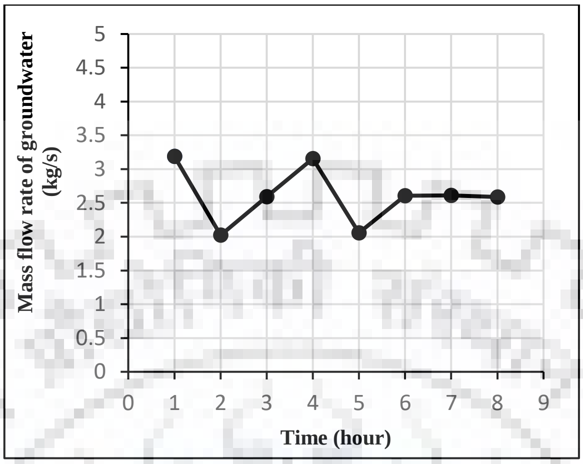


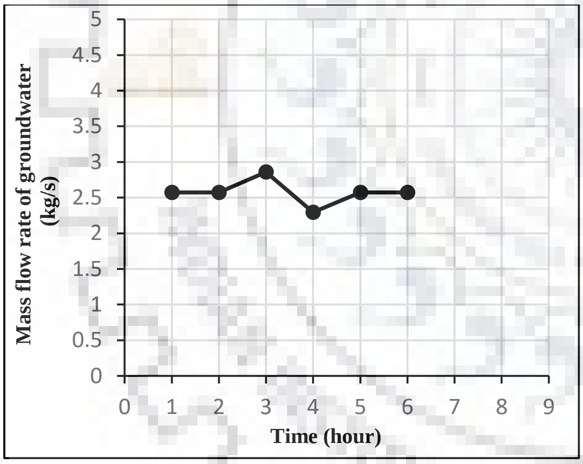
(c)

Figure 5.3 Variation of ΔT with time.

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.



(a)



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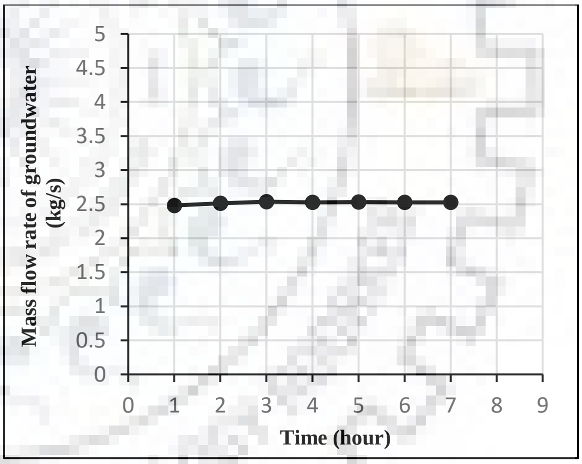
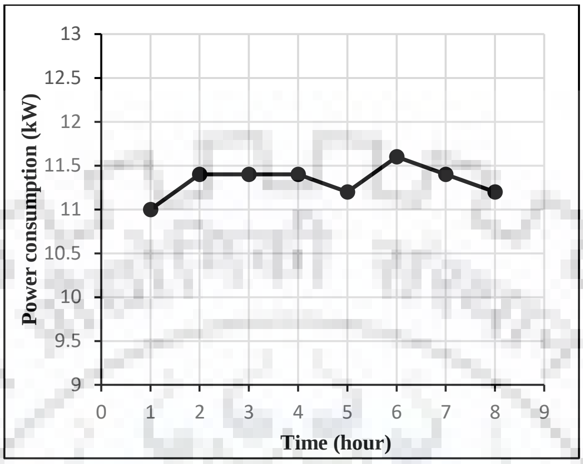


(c)

Figure 5.4 Variation of mass flow rate of groundwater with time.

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.



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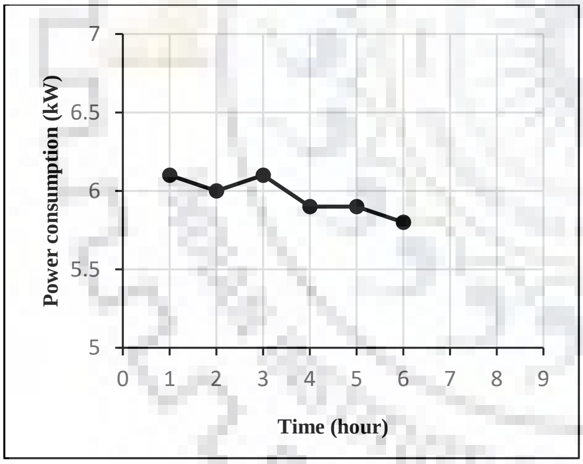

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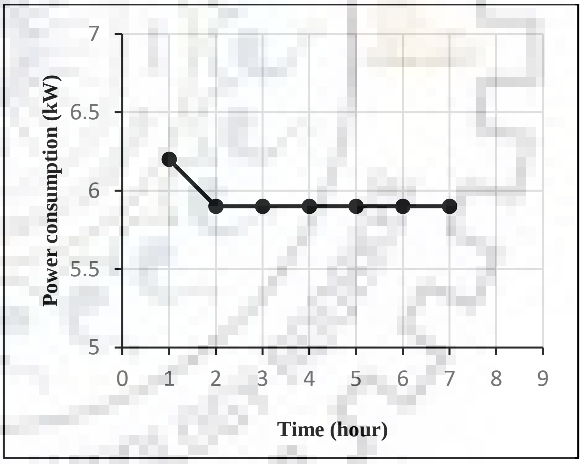
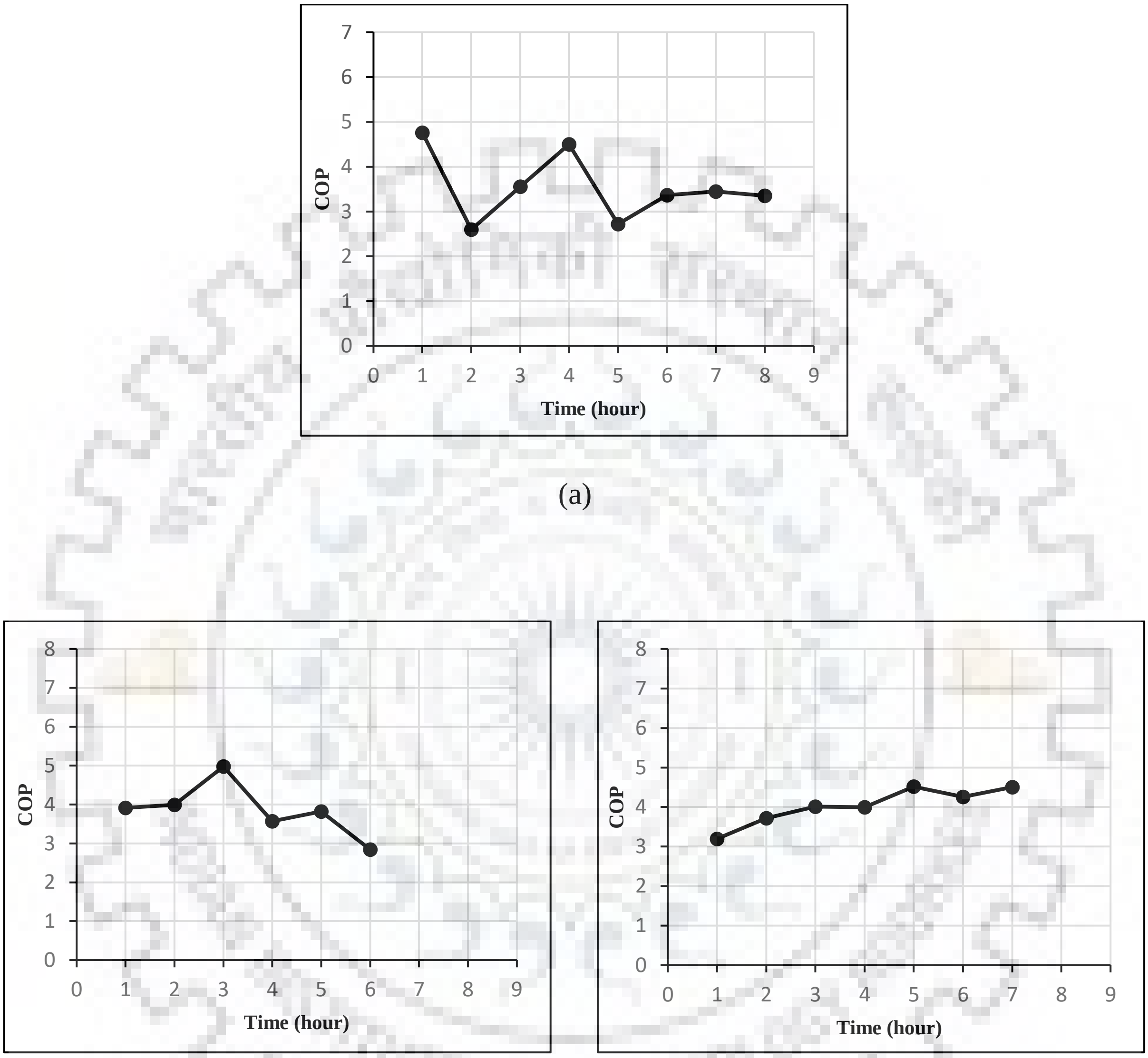


(c)

Figure 5.5 Variation of Power consumptions by the system with time.

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.



(a)

(b)

(c)

Figure 5.6 Variation of COP of the system with time.

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018

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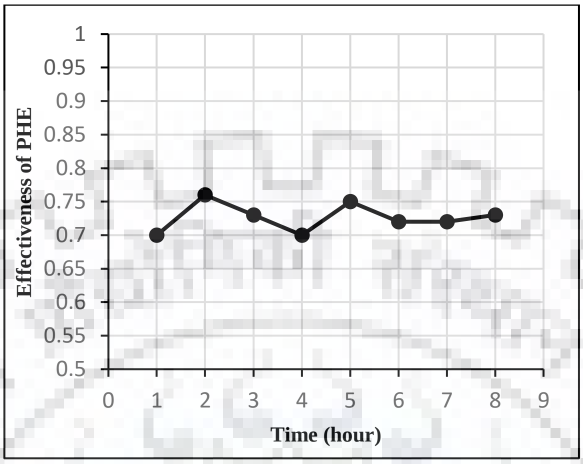

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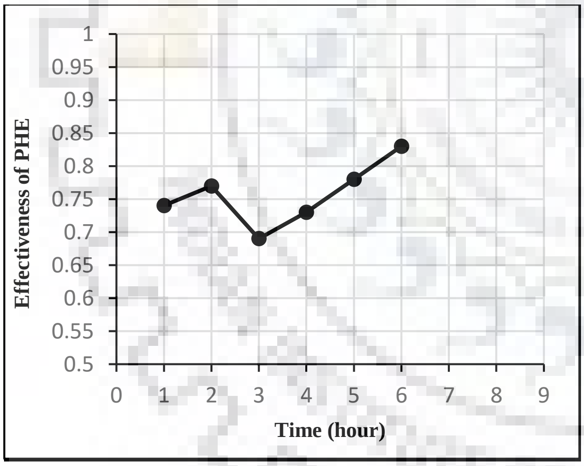

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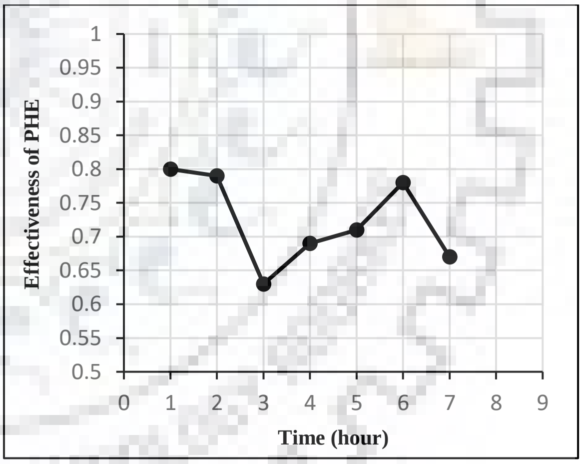


(c)

Figure 5.7 Variation of effectiveness of plate heat exchanger (PHE) with time.
(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.

5.1.2 Variations in parameters with mass flow rate of groundwater

In this experimental study, there is no provision to operate the system with variation of mass flow rate of groundwater. Thus, a theoretical analysis is conducted based on experimental data by varying the mass flow rate of groundwater from minimum to maximum value. In this study, minimum and maximum value of mass flow rate of groundwater are considered as 1.5 kg/s and 3.3 kg/s respectively. The parameters such as overall heat transfer coefficient, power consumption of submersible pump, COP of the system and effectiveness of PHE are analysed with increase in mass flow rate of groundwater. The outcome of the results has been discussed in the following section.

Overall heat transfer coefficient

Many of the heat transfer processes involve composite system and combination of different modes of heat transfer such as conduction and convention. The heat transfer rate is related to thermal resistance which depends on the geometry. Therefore, total thermal resistance of the composite system is defined by the overall heat transfer coefficient and it is proportional to the heat transfer rate in the system. Figure 5.8 depicts the fluctuation in overall heat transfer with increase in mass flow rate of groundwater. It can be observed that the overall heat transfer value increases with increase in mass flow rate of groundwater and with decrease in temperature of extracted groundwater.

The power consumption of submersible pump

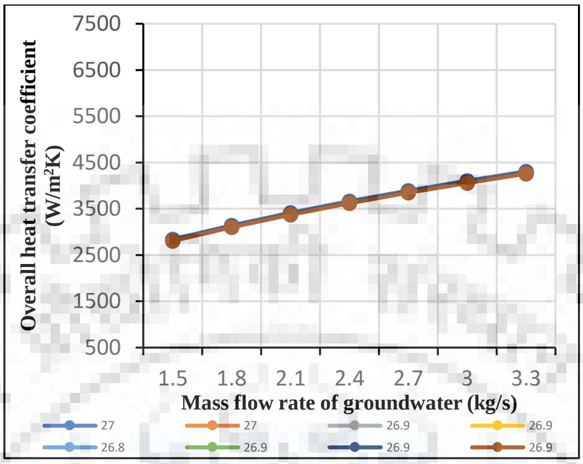
The performance of the submersible pump has major role in the overall performance of the GSHP system. One third of the total power is consumed by submersible pump only. Therefore, for better performance of the system power consumption of the submersible pump should be minimum. For this analysis, the efficiency of submersible pump was considered as an average value of about 34.5%. Figure 5.9 shows the increase in power consumption of the submersible pump with increase in mass flow rate. It was found that at minimum and maximum mass flow rate of groundwater about 1.5 kg/s and 3.3 kg/s, the energy consumption of submersible pump is about 1.18 kW and 2.6 kW respectively.

Coefficient of performance of the GSHP system

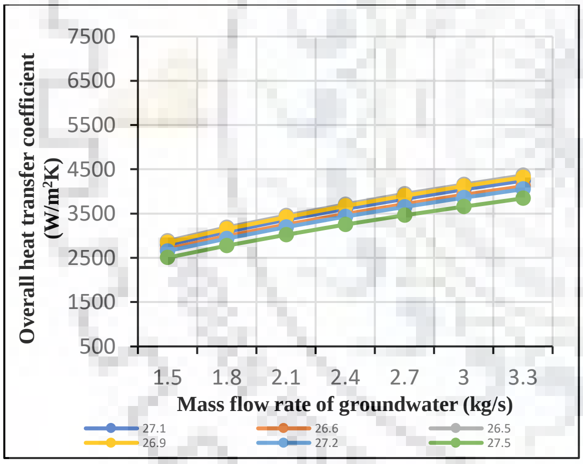
The coefficient of performance of the open loop GSHP system has been computed with increase in mass flow rate of groundwater and consider that the total power consumption of the system is constant at 6.0 kW. Figure 5.10 shows the variation in COP with increasing mass flow rate of groundwater and it is found that COP increases with increase in flow rate. A maximum COP of about 4.4 was obtained for 23rd May, similarly 4.3 was calculated for the other two days.

The effectiveness of the plate heat exchanger

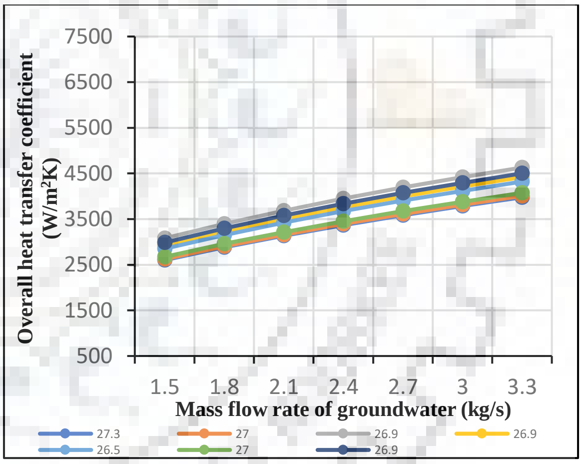
The plate heat exchanger contributes important role in the performance of the heat pump unit as well as overall GSHP system. The extraction/rejection of the energy from/to the groundwater occurs in the PHE. The performance of the PHE is indicated by the effectiveness of the PHE. Higher value of effectiveness shows better performance of the PHE. This effectiveness mainly depends on the mass flow rate and temperature of the cold and hot fluids flowing inside the PHE. Figure 5.11 shows the variation in effectiveness with increase of the mass flow rate of groundwater. When the mass flow rate of groundwater increases then the effectiveness of the PHE decreases due to reduction in the temperature difference. It is found that the effectiveness of the PHE at maximum and minimum value of mass flow rate of groundwater are 0.79 and 0.69 respectively for 23rd May. For the other two days, it can be seen that the effectiveness increases with rise in temperature of extracted groundwater. For 18th July, when the mass flow rate of groundwater is 1.5 and 3.3 kg/s then the effectiveness of PHE varies as 0.77 to 0.88 and 0.69 to 0.8 respectively. Similarly, for 19th July, the effectiveness of PHE are 0.69 to 0.87 and 0.59 to 0.78 at mass flow rate of 1.5 and 3.3 kg/s respectively.



(a)

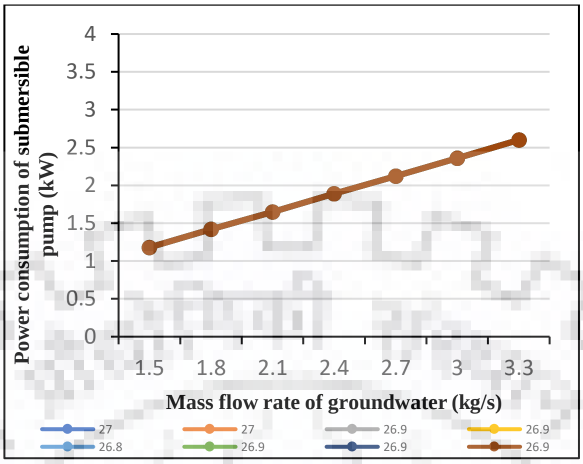


(b)

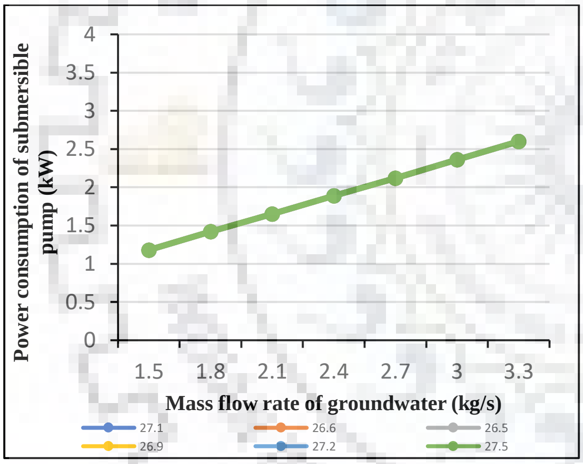


(c)

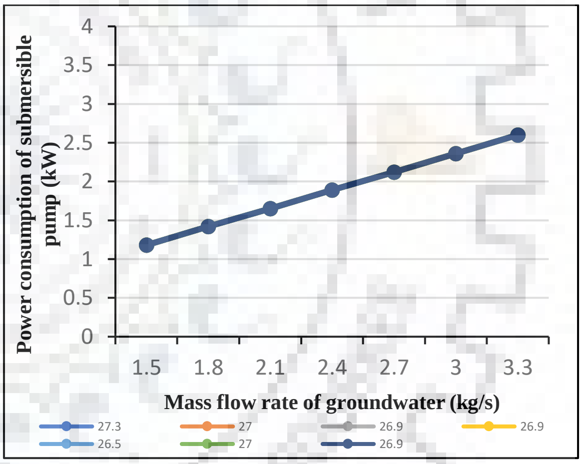
Figure 5.8 Variation in overall heat transfer coefficient with mass flow rate of groundwater (a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.



(a)



(b)



(c)

Figure 5.9 Variation in power consumption of submersible pump with mass flow rate of groundwater

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.

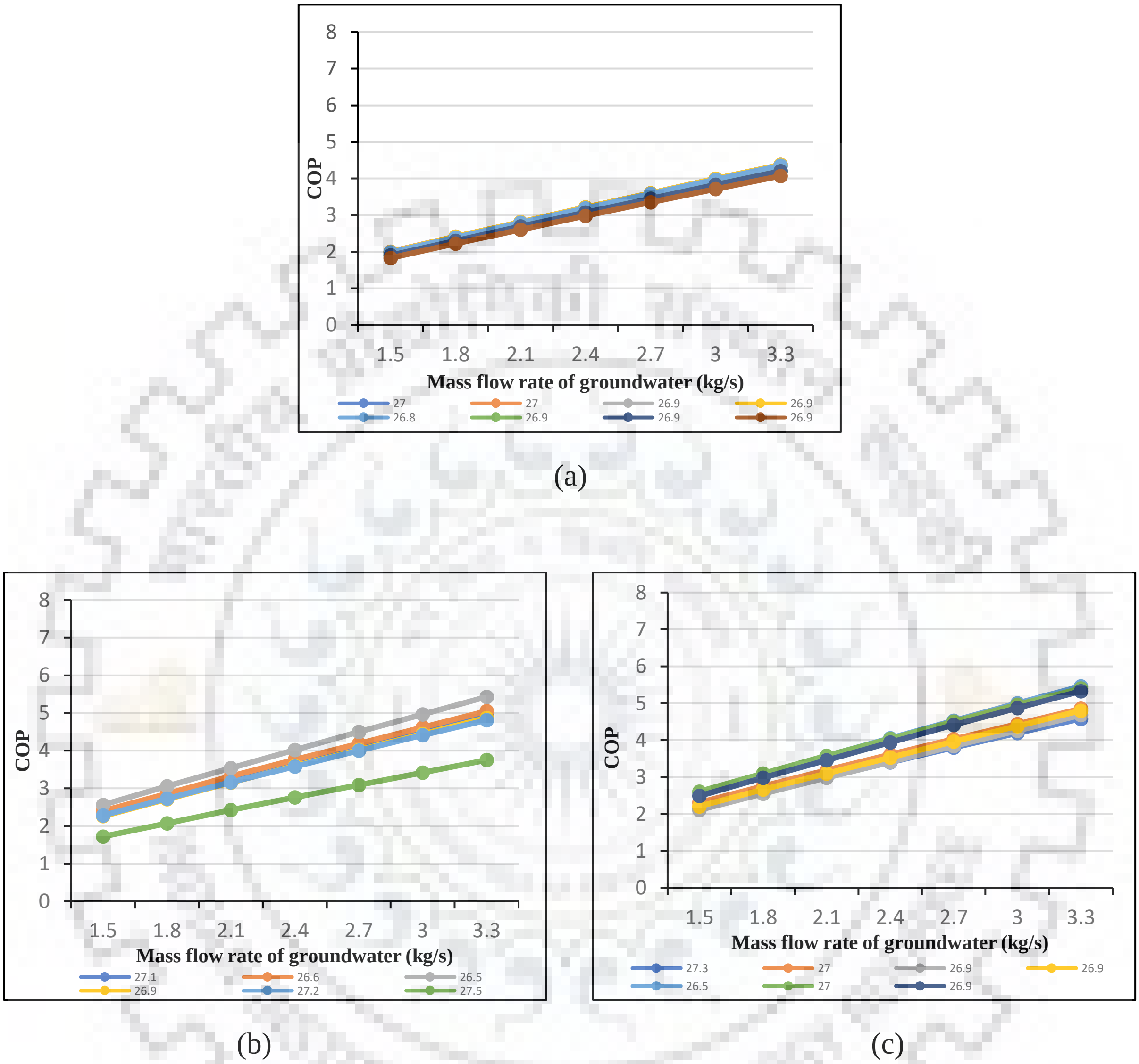
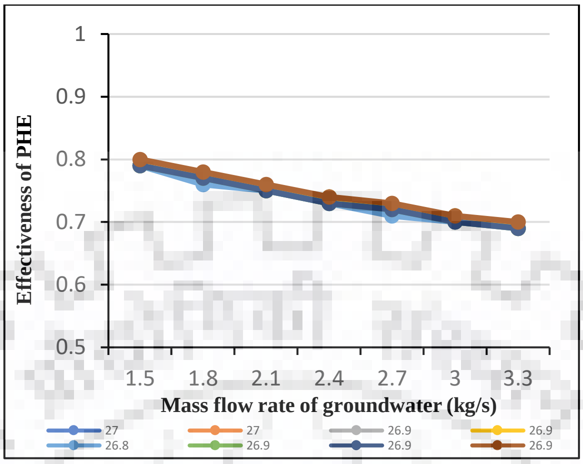
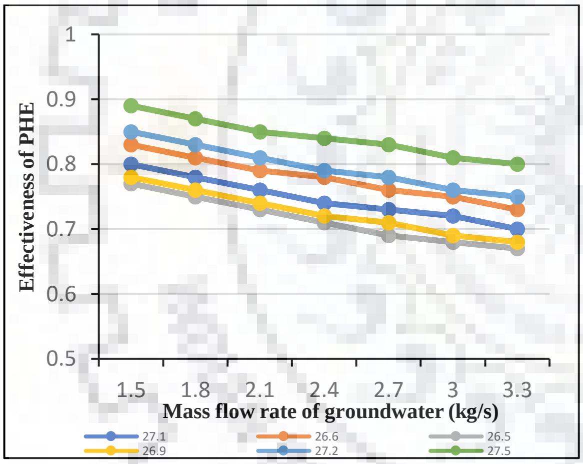


Figure 5.10 Variation in COP of the system with mass flow rate of groundwater

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.



(a)



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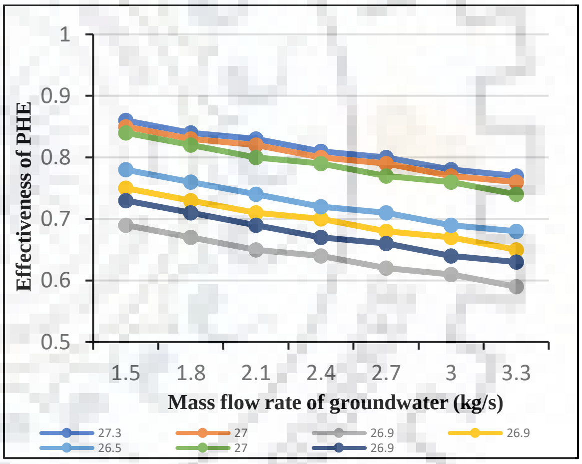


(c)

Figure 5.11 Variation in effectiveness of plate heat exchanger (PHE) with mass flow rate of groundwater

(a) 23rd May 2018, (b) 18th July 2018 and (c) 19th July 2018.

5.2 Analysis of results for space heating

For heating mode operation, the following data were taken during the experiments conducted for 9 hours as depicted in Tables 5.4 to 5.6 respectively for three days, 28th, 29th and 30th January 2019.

Table 5.4 Experimental data observed on 28th January 2019 for heating mode

Time (hour)	Temp. Ext. hot (˚C)	Temp. Inj. hot (˚C)	Temp. Out. cold (˚C)	Temp. In. cold (˚C)	$\dot{m}_{wc}$ (kg/s)	Power consumption (kW)
10.00	27.1	23.6	24.1	18.5	0.0	0.0
11.00	27.0	23.7	24.3	18.8	2.514	7.1
12.00	27.1	23.7	24.2	18.6	2.481	7.1
13.00	27.1	23.6	24.2	18.8	2.525	7.0
14.00	26.9	23.5	24.0	18.4	2.536	7.0
15.00	26.9	23.5	24.1	18.7	2.531	7.1
16.00	27.2	23.7	24.3	18.6	2.528	7.1
17.00	26.9	23.6	24.2	18.5	2.525	7.1
18.00	27.1	23.6	25.2	18.7	2.492	7.0
19.00	27.0	23.6	24.1	18.5	2.513	7.0

Table 5.5 Experimental data on observed on 29th January 2019 for heating mode

Time (hour)	Temp. Ext. hot (˚C)	Temp. Inj. hot (˚C)	Temp. Out. cold (˚C)	Temp. In. cold (˚C)	$\dot{m}_{wc}$ (kg/s)	Power consumption (kW)
10.00	27.1	23.6	24.1	18.7	0.0	0.0
11.00	26.9	23.5	24.2	18.8	2.528	7.2
12.00	27.0	23.6	24.1	18.4	2.531	7.1
13.00	27.2	23.7	24.0	18.5	2.536	7.2
14.00	27.1	23.7	24.2	18.6	2.489	7.1
15.00	27.0	23.5	24.3	18.6	2.487	7.0
16.00	27.0	23.6	24.3	18.5	2.521	7.0
17.00	27.2	23.7	24.2	18.5	2.479	7.1
18.00	27.1	23.7	24.2	18.5	2.533	7.1
19.00	27.1	23.6	24.1	18.7	2.512	7.1

Table 5.6 Experimental data observed on 30th January 2019 for heating mode

Time (hour)	Temp. Ext. hot (˚C)	Temp. Inj. hot (˚C)	Temp. Out. cold (˚C)	Temp. In. cold (˚C)	$\dot{m}_{wc}$ (kg/s)	Power consumption (kW)
10.00	26.9	23.7	24.0	18.8	0.0	0.0
11.00	27.1	23.9	24.2	18.9	2.572	7.1
12.00	27.0	23.8	23.9	18.8	2.585	7.1
13.00	27.1	23.8	23.9	18.6	2.572	7.1
14.00	27.1	23.7	24.1	18.6	2.572	7.0
15.00	27.2	23.8	24.1	18.7	2.858	7.0
16.00	27.1	23.7	24.2	18.6	2.294	7.1
17.00	26.9	23.6	24.2	18.7	2.581	7.2
18.00	27.1	23.7	24.2	18.7	2.562	7.1
19.00	26.9	23.7	24.0	18.8	2.566	7.1

5.2.1 Variations in different parameters with time

Temperature of ground water

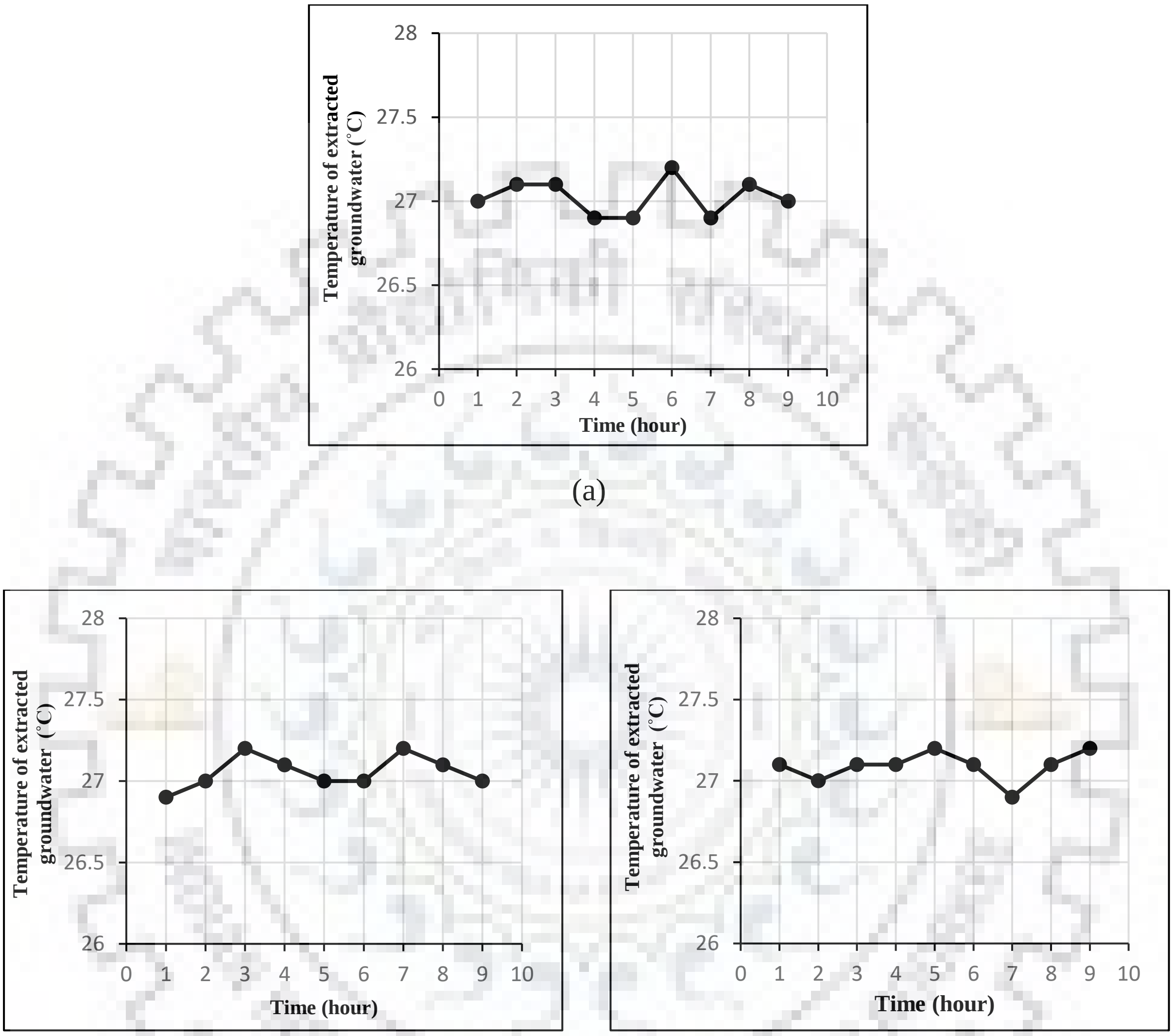
Using the experimental data obtained, the COP of the open loop GSHP system has been computed for all the three days, 28th, 29th and 30th January 2019 and are plotted against time. Experiments were conducted for a duration for 9 hours as per the availability of the system. Figure 5.12 shows the variation of temperature of water extracted from the extraction bore well with time. Generally, the experiments were started around 10 AM and carried out till evening about 7 PM. The temperature seems to remain almost constant at about 27°C on all the three days. Figure 5.13 depicts the variation of temperature of groundwater re-injected into the bore well after use in the plate heat exchanger (PHE) with time. The mean temperature is found to be around 23.7°C on all the three days. The difference between the temperatures of groundwater extracted and re-injected into the bore holes are shown in Figure 5.14. It can be seen that the temperature difference was about 3.4°C. Higher temperature difference will make the GSHP system work more efficient.

Mass flow rate and power consumption

The groundwater flow rate is continuously measured with time and is plotted in Figure 5.15 for three days. The average water flow rate for all the three days is observed to be 2.5 kg/s. After interacting with the groundwater from the heat pump through the PHE, the cold water is re-injected back into the bore well. Water flow rate is an important parameter that affects the heat interaction between the heat transfer fluids in the GSHP system. Similar to cooling mode, the electricity input to the compressor of the heat pump, circulation water pump of the heat pump and the submersible pump are measured using the energy meter in heating operation. Figure 5.16 shows the variation of power consumption by the GSHP system with time during the experiments. The average power consumption on all the three days are found to be around 7.1 kW as depicted in the above figures.

COP and effectiveness of PHE

The coefficient of performance of the open loop GSHP system has been computed with time using the experimental data obtained. Figure 5.17 shows the variation of COP of the system for 28th, 29th and 30th January 2019. An average COP of about 4.3 was obtained for all the three days in January. Similarly, the effectiveness of PHE were computed for all the three days and found to vary from 0.70 to 0.73 for three days.

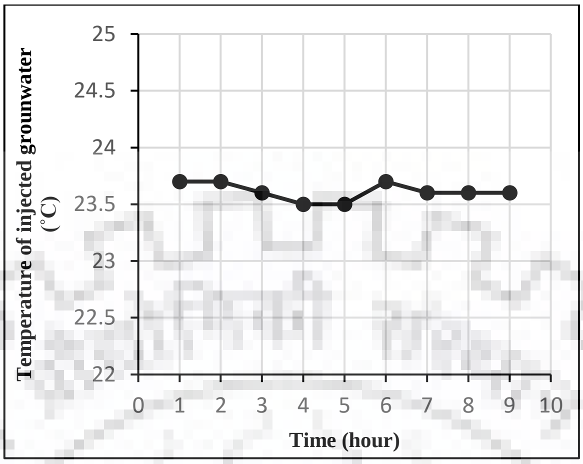


(a)

(b) (c)

Figure 5.12 Variation in temperature of extracted groundwater with time.

(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



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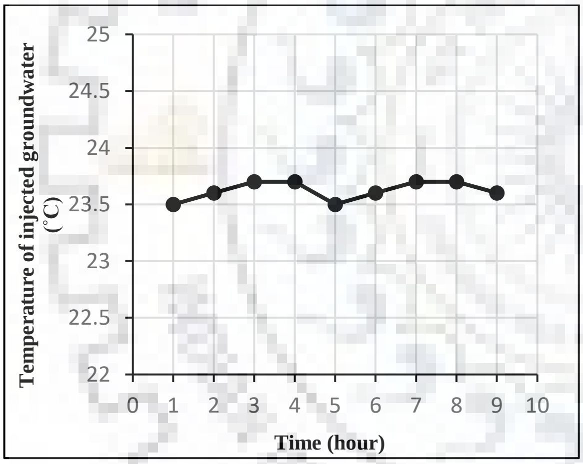

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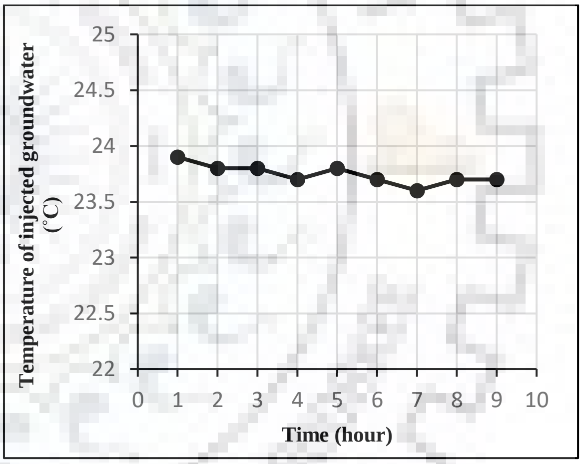

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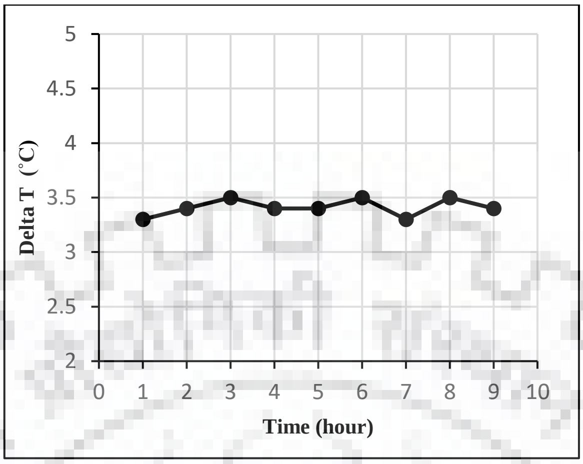
Figure 5.13 Variation of temperature of injected groundwater with time.

(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



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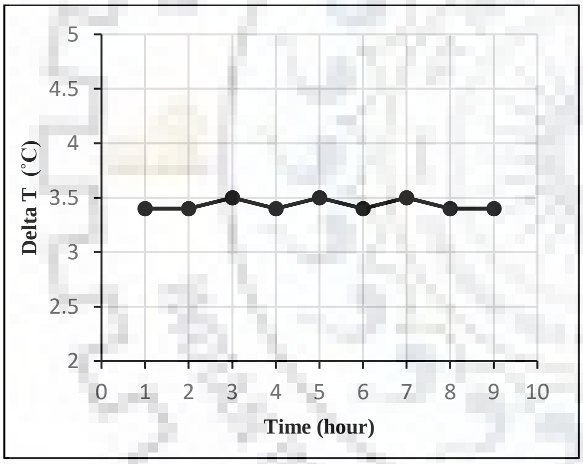

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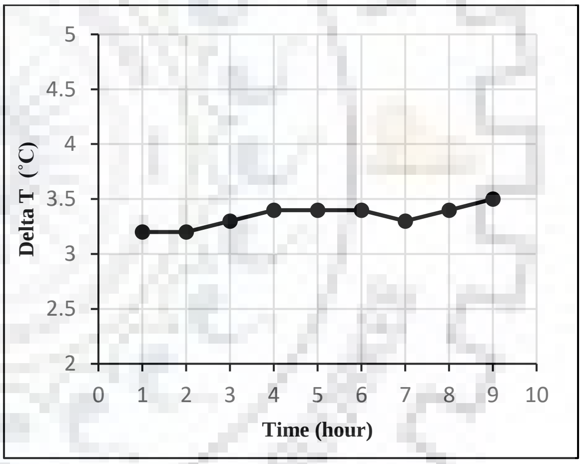
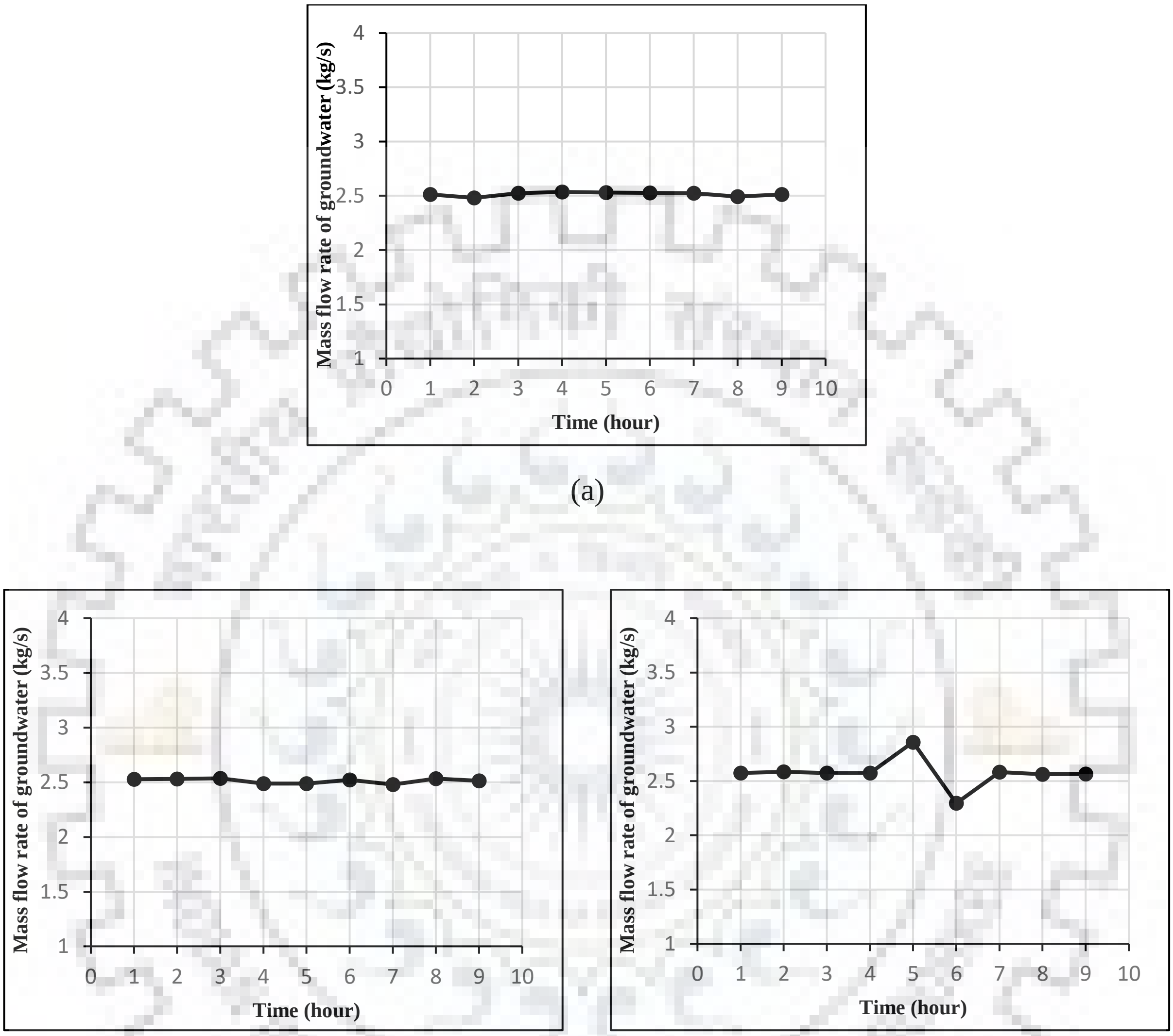


(c)

Figure 5.14 Variation of ΔT with time.

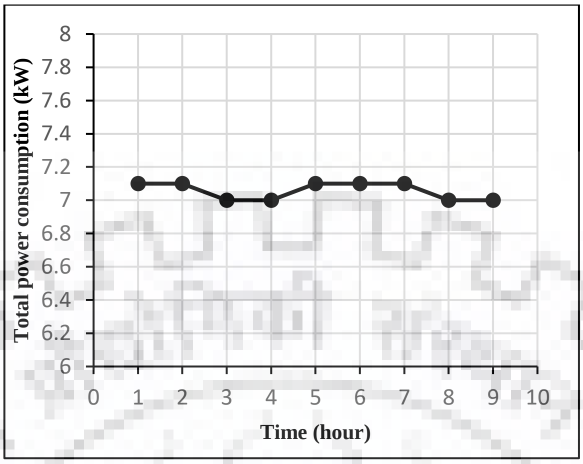
(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



(b) (c)

Figure 5.15 Variation of mass flow rate of groundwater with time.

(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



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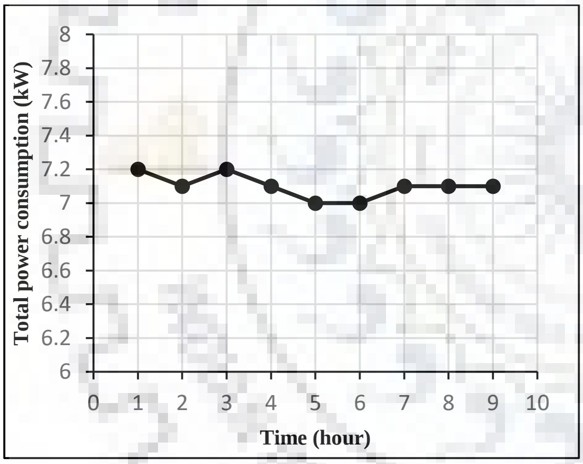
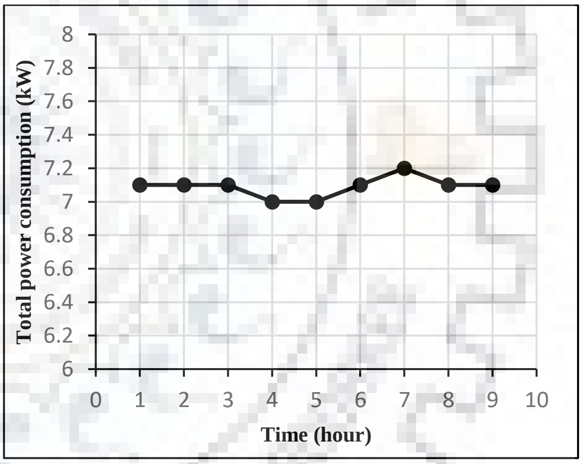




(b) (c)

Figure 5.16 Variation of total power consumption with time.

(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.

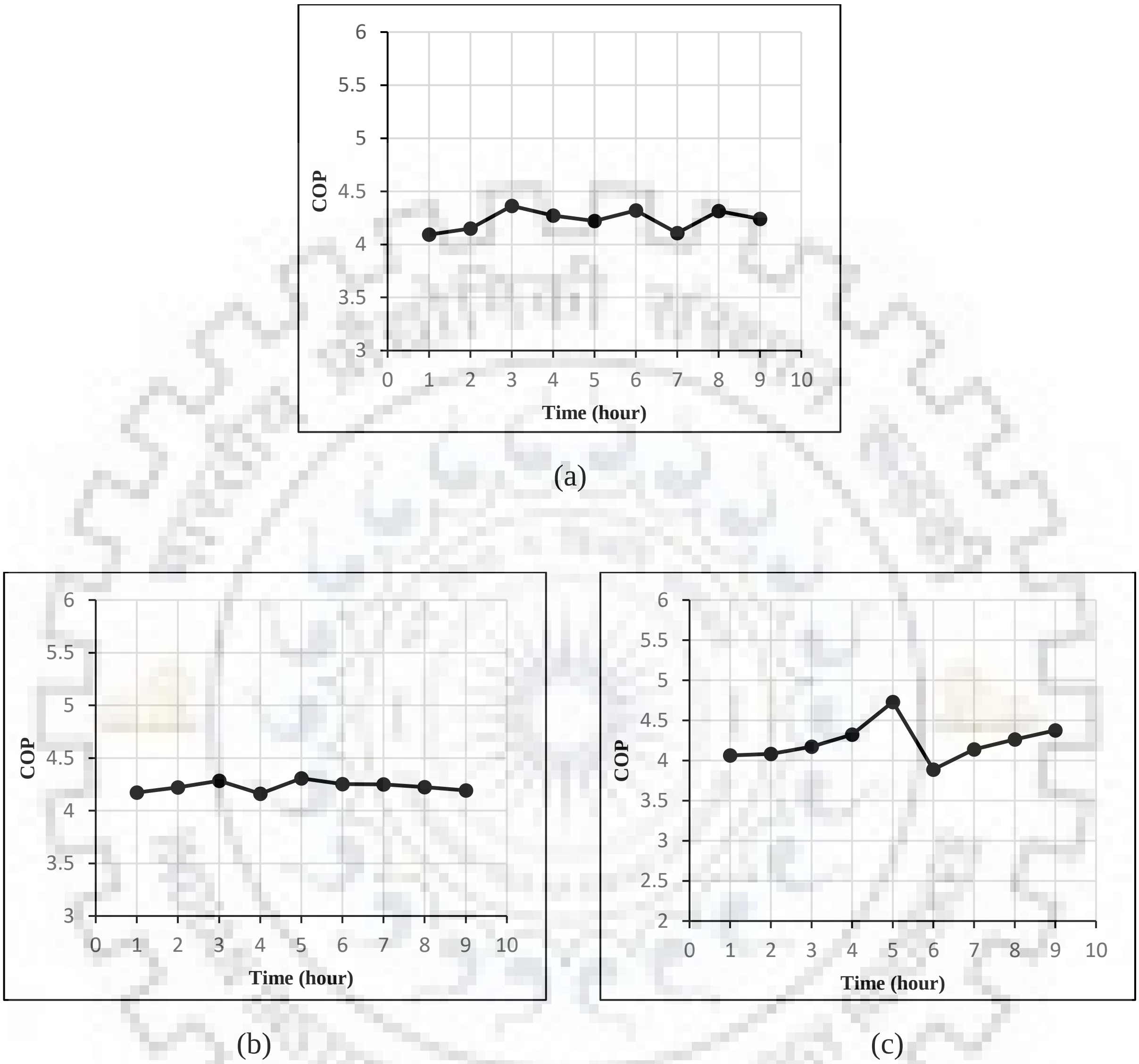
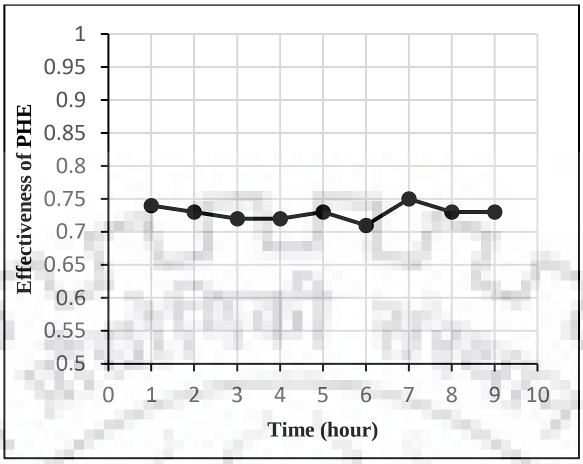
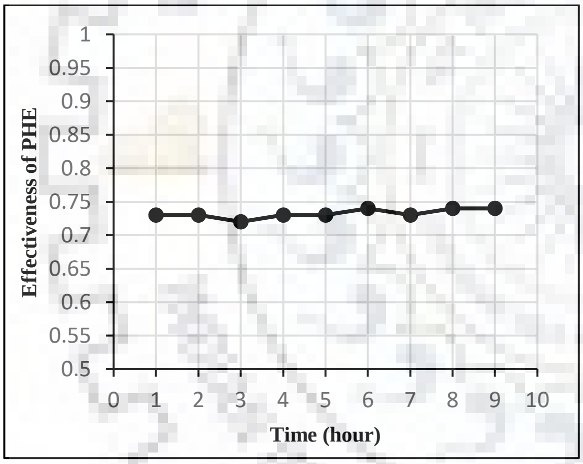


Figure 5.17 Variation of COP with time.

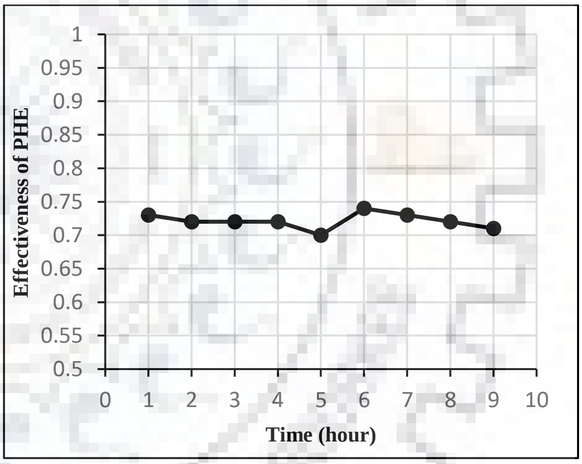
(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



(a)



(b)



(c)

Figure 5.18 Variation of effectiveness of plate heat exchanger (PHE) with time. (a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.

5.2.2 Variations in parameters with mass flow rate of groundwater

Similar to cooling mode, in heating operation, a theoretical analysis is conducted to check the influence of mass flow rate of groundwater on the overall heat transfer coefficient, power consumed by the submersible pump, COP of the system and effectiveness of PHE. The variation in mass flow rate of groundwater were assumed from 1.5 kg/s to 3.3 kg/s. The results obtained are discussed in the following sections.

Overall heat transfer coefficient

Figure 5.19 shows that the overall heat transfer value increases with rise in mass flow rate of groundwater. As a result, it seems that for all the three days of heating operation the mean value of overall heat transfer coefficient at mass flow rate of groundwater of 1.5 and 3.3 kg/s are 2500 and 4100 W/m^2K respectively.

The power consumption of submersible pump

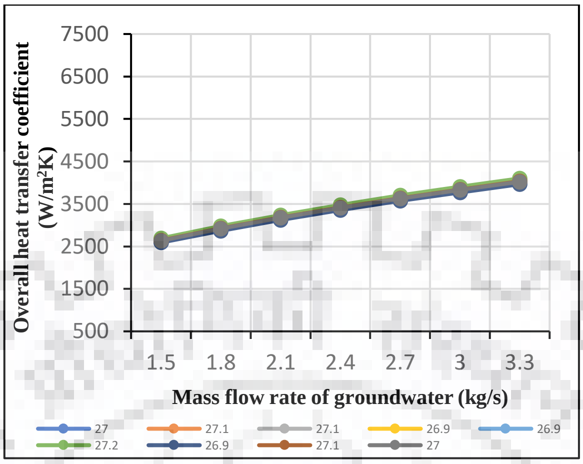
Figure 5.20 shows that there is an increase in power consumption of the submersible pump with increase in mass flow rate of groundwater. The efficiency of submersible pump is assumed as an average value of about 34.5%. It was found that when the mass flow rate of groundwater was of about 1.5 and 3.3 kg/s, the energy consumption of submersible pump was about 1.18 kW and 2.6 kW respectively.

Coefficient of performance of the GSHP system

In heating mode operation, for the analyses of the COP of GSHP system with rise in mass flow rate of groundwater, the total power consumption of the system is assumed constant at 7.1 kW. Figure 5.21 depict the influence of mass flow rate of groundwater on the performance of the system. It is found that COP increases with increase in mass flow rate of groundwater. A COP of about 2.7 was obtained at 1.5 kg/s of mass flow rate for all three days, similarly an average value of COP, 5.8 is obtained at mass flow rate of water of 3.3 kg/s for all the three days. It can be seen that the value of COP also increases with rise in temperature of extracted groundwater.

The effectiveness of the plate heat exchanger

In heating operation, heat is rejected from extracted groundwater to the water circulated in the secondary loop. This heat transfer phenomenon takes place in the PHE. The heat transfer rate depends on the effectiveness of the plate heat exchanger. It means to get better performance of the GSHP system, the effectiveness must be high. Figure 5.22 shows the variation in the effectiveness of the plate heat exchanger with increase of the mass flow rate of groundwater. It can be seen that when the mass flow rate of groundwater increases then the effectiveness of the PHE reduces. It is found that for all the three days, the effectiveness of the PHE at 1.5 and 3.3 kg/s of mass flow rate of groundwater are 0.78 to 0.72 respectively, and from the above figure, it is also seen that with reduction in the extracted groundwater temperature, the effectiveness value increases.



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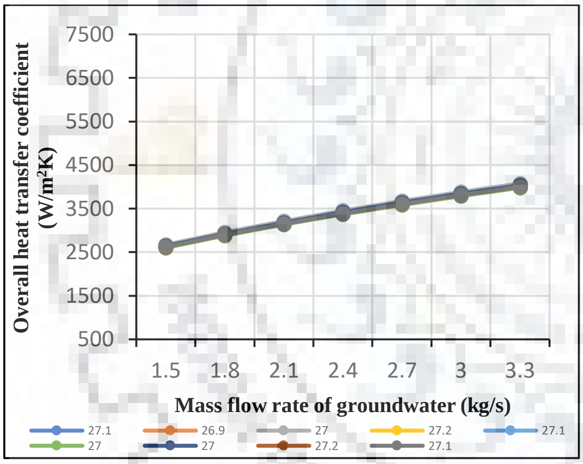

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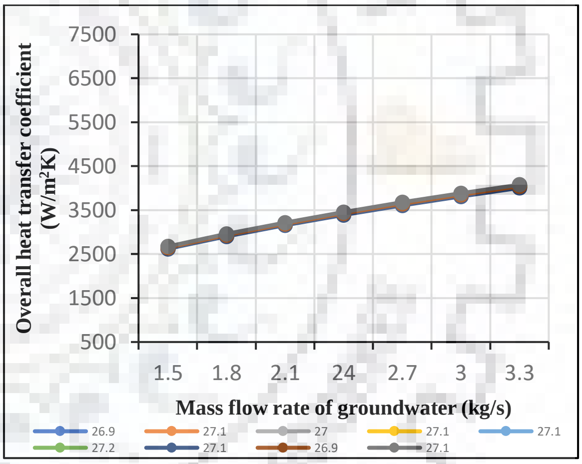
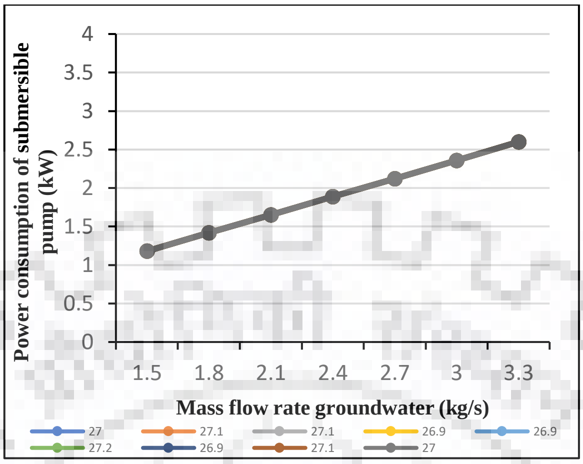
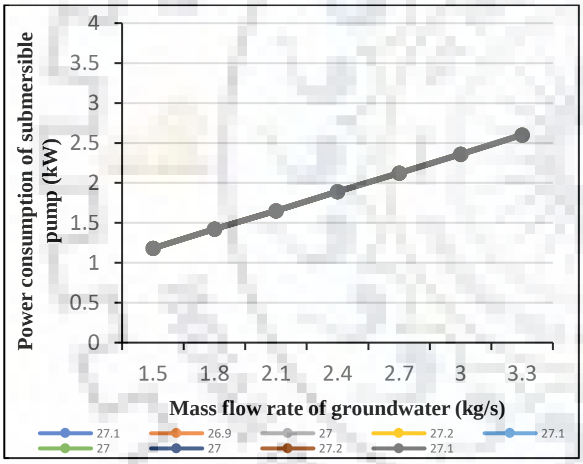


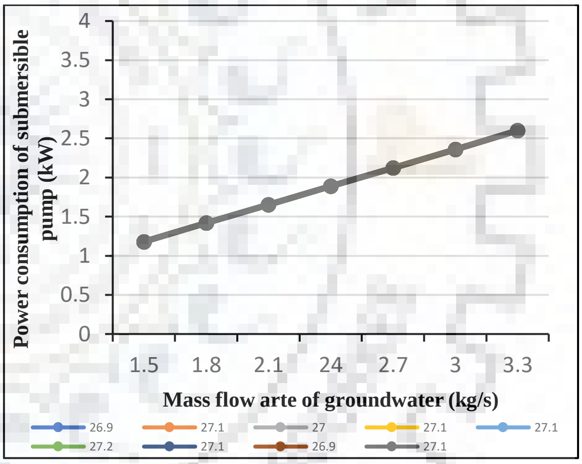
(c)

Figure 5.19 Variation in overall heat transfer coefficient with mass flow rate of groundwater. (a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



(a)

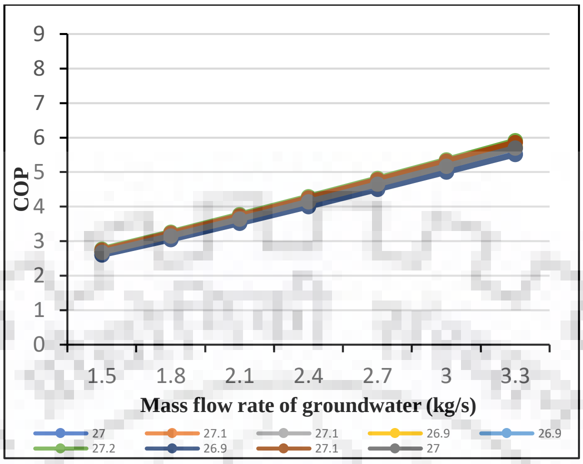




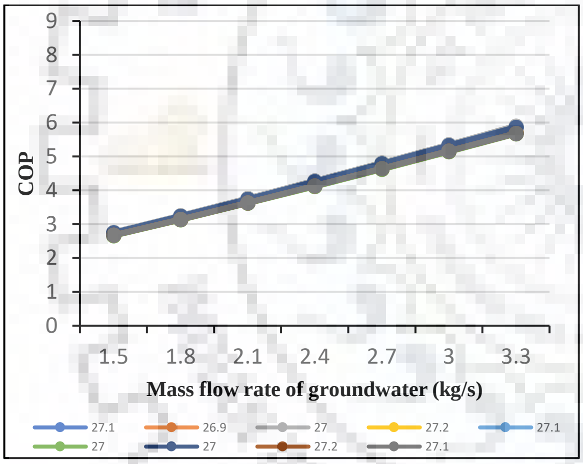
(b) (c)

Figure 5.20 Variation in power consumption of submersible pump with mass flow rate of groundwater.

(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



(a)



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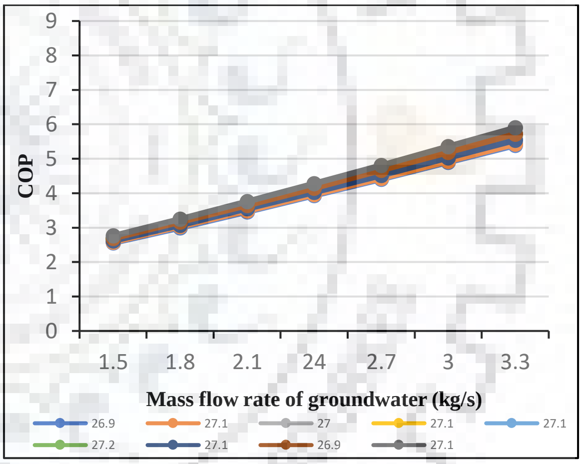
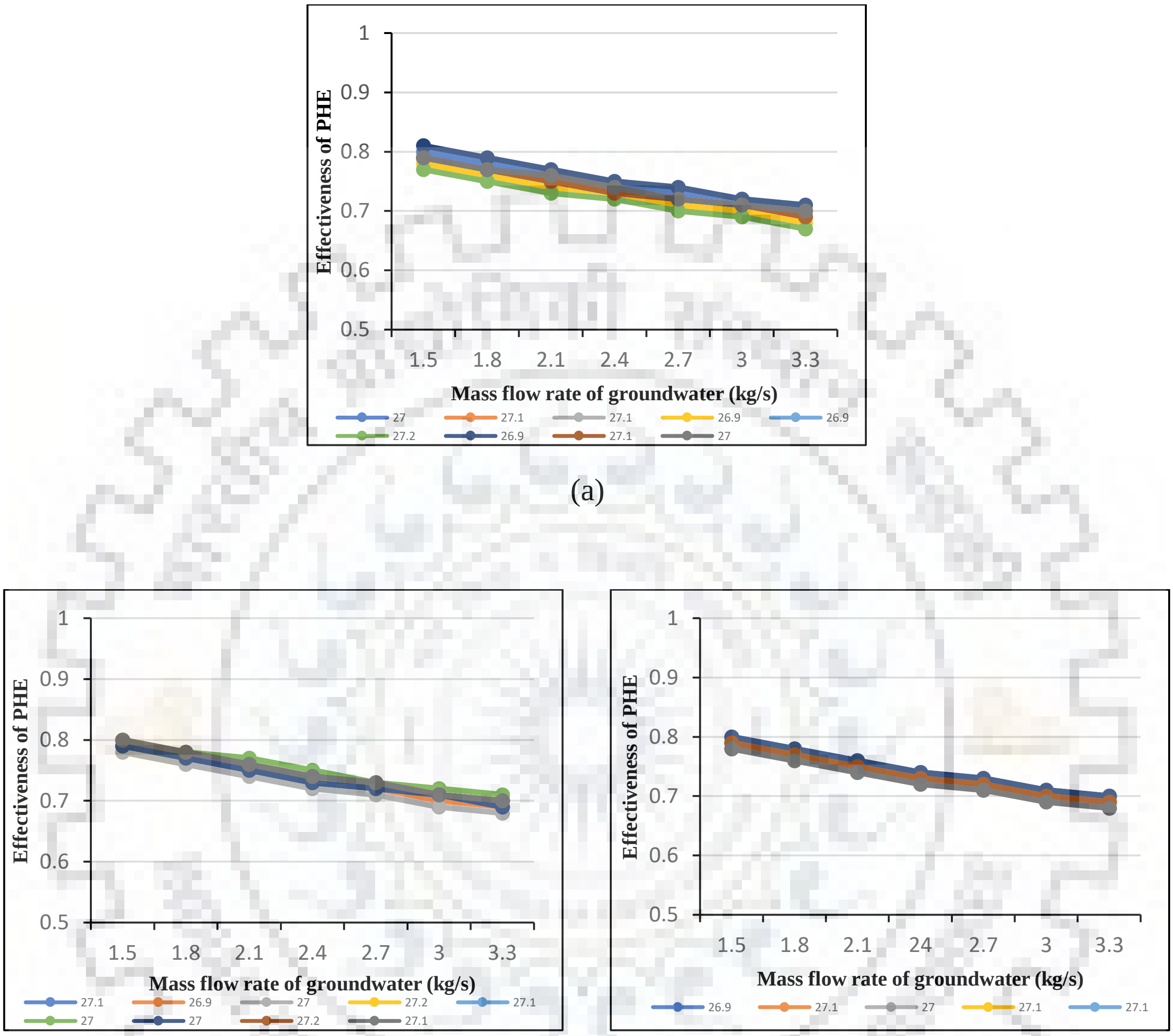


(c)

Figure 5.21 Variation in COP of the system with mass flow rate of groundwater.

(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.



(a) (b) (c)

Figure 5.22 Variation in effectiveness of plate heat exchanger (PHE) with mass flow rate of groundwater.

(a) 28th January 2019, (b) 29th January 2019 and (c) 30th January 2019.

Chapter 6

Summary and Conclusions

6.1 Summary

In this dissertation report experimental study on cooling and heating mode operation of an 8 TR open loop GSHP system established at NETRA, Greater Noidais is discussed as part of dissertation work. An open loop GSHP system consists of a heat pump unit, plate heat exchanger (PHE) and extraction and re-injection bore wells. During cooling mode operation, the heat absorbed from the space to be cooled is transported to the ground water through a PHE. That means the hot heat transfer fluid in the chiller of the heat pump unit is cooled using ground water extracted from a bore well generally drilled to a depth of about 60 m and the heat transfer is achieved through a plate heat exchanger. In order to preserve the extracted water from the bore well, the water is being re-injected back into another re-injection bore well with provision of a soak pit. During heating mode operation, heat is absorbed from the extracted ground water by passing through the PHE and the heat is transported to the heat transer fluid in the heat pump, which in turn heats the space to be heated. As the ground water is used directly through a PHE for both modes of cooling and heating, there is efficient transport of heat energy between the heat transfer fluids, resulting in higher coefficient of performance (COP) compared to a closed loop GSHP system wherein heat transfer from the heat transfer fluid takes place to the ground through the borehole medium. However, as open loop GSHP system utilizes ground water for heat transport, this technology has limited application as it requires a significant amount of water. As part of a research project, an 8 TR open loop GSHP system has been established in the dining room of the guest house in NETRA, Greater Noida. During summer season experiments were conducted for cooling mode operation for three days on 23rd May, 18th and 19th July 2018. Similarly, during winter season experiments were conducted for heating mode operation for three days on 28th, 29th and 30th January 2019. Data of temperatures of extracted and re-injected ground water, total power consumed by the pumps, heat pump and mass flow rate of water were continuously monitored and measured. Using these experimental data calculations were performed to estimate the overall COP of the GSHP system and effectiveness of the PHE. For this purpose a program in FORTRAN has been developed. Effect of variation in mass flow rate of extracted ground water on the performance of the open loop GSHP system is also analyzed in the thesis.

6.2 Important findings

Based on the thermal performance calculations for cooling and heating mode operations, the following important findings are obtained:

(i) The overall COP of the open loop GSHP system is computed as 3.7 for cooling mode and 4.3 for heating mode.

(ii) The effectiveness of the plate heat exchanger is computed as 0.74 for cooling mode and 0.72 for heating mode.

(iii) The maximum COP of the system was observed to be achieved at 1 to 2 pm because the system was operating at its full load capacity to meet the cooling demand.

(iv) The overall COP increases with rise and drop in temperature of extracted groundwater for heating and cooling mode operation respectively.

(v) It was observed that for both cooling and heating operations, increase in the mass flow rate of extracted ground water by 50% has resulted in about 48% increase in the COP of the system..

(vi) The power consumption of the submersible pump is directly related to the mass flow rate of extracted groundwater. The power consumed by the submersible pump increases with increase in mass flow rate of extracted groundwater while considering the constant head of 24 m and 34.5% avaerage value of overall efficiency of the pump.

(vii) It is found that the overall heat transfer coefficient increases with increase in mass flow rate of extracted groundwater for both cooling and heating operations. It can be observed that the overall heat transfer coefficient also depends on groundwater temperature and it decreases with rise in temperature of extracted groundwater for cooling mode operation and for heating mode the overall heat transfer coefficient increases with increase in grounwater temperature.

(viii) In cooling operation, the effectiveness of the PHE is observed to fluctuate with mass flow rate of extracted groundwater as well as its temperature. It is found that the effectiveness increases by 4.8% with 1.5% increase in temperature of groundwater and reduced by 10.1% with 50% increase in mass flow rate of extracted groundwater.

(ix) In the case of heating operation, the temperature of extracted groundwater is almost constant at a value of 27.1˚C, so the effectiveness was found to fluctuate with 1-2%. Similar to cooling operation, in heating operation, the effectiveness decreases with increase in mass flow rate of groundwater.

6.3 Suggestions for future work

Ground source heat pump system is ecofriendly technology that is used for space cooling and space heating inside the buildings. A prescribed literature survey indicates that less number of research works were established to improve the performance of an open loop ground source heat pump system. In the present dissertation work experiments were conducted to find out thermal performance of an open loop ground source heat pump system. However, there are many scopes to identify the methodologies to enhance the performance. Following are some of the suggestions to continue this research as future work.

(i) In this dissertation work, not much number of parameters have been considered for parametric study. The influence of plate heat exchanger parameters can be considered in detail for the improvement of the performance of the GSHP system.

(ii) The cascade heat exchanger can be taken up for large capacity GSHP systems for both space heating and cooling applications.

(iii) An investigation can be conducted to achieve zero water draining in the open loop GSHP system.

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