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Investigation of the Waste Heat Recovery System of a Biomass Combustion Plant through Ground Source Heat Pumps

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Abstract - Renewable energies are to respond to the challenges raised by the growing energy demands, consumption of fossil fuels and the resultant emission of greenhouse gases. Biomass is regarded as a very promising source of renewable energy for electricity and heat generation and transportation fuels in the future. However, in a biomass plant, large amounts of high temperature heat is wasted into the environment and one of the main goals of the current study is to present and investigate the beneficial use of the these waste heats through ground source heat pump systems. To analyze the thermal performance of the waste heat recovery system, computationally-efficient modelling framework is developed and rigorously validated. This is based upon an implicit computational modelling approach of the ground together with an empirical modelling of heat and fluid flow inside U-tube ground heat exchangers and waste heat calculations. The coupled governing equations are solved simultaneously and the influences of parameters on the performance of the whole system are evaluated. The outcome of the developed framework is, the underground storage and recovery process of the waste heat through flue gases generated by a biomass combustion plant are modelled numerically. The results show that for a biomass combustion plant generating flue gases at 485.9 K as waste heat with the mass flow rate of 0.773 kg/s, the extracted heat from the ground is increase by 7.6%, 14.4% and 23.7% per unit length of the borehole corresponding to 40℃, 50℃ and 60℃ storage temperatures. It is further shown that the proposed storage system can recover a significant fraction of the thermal energy otherwise wasted to the atmosphere. Hence, it practically offers a sizable reduction in greenhouse gas emissions.

Keywords: Biomass system; Waste heat recovery; heat transfer modelling; ground source heat pump

1. Introduction

Renewable energy technologies are to respond to the substantial challenges of growing energy demands and emission of greenhouse gases[1]. Biomass is regarded as a very promising source of renewable energy for electricity and heat generation and transportation fuels . Compared with that of fossil fuels, biomass combustion is an environmentally friendly technology due to being CO2 neutral. In recent years, co-firing of pulverized biomass and coal for electricity generation and the usage of biomass pellets for domestic water heating have received considerable attention [2]. The thermal efficiency is in the range of 60% to 90% for most industrial boilers, while a considerable fraction of thermal energy is often lost to atmosphere by the flue gases [3]. Currently, the temperature of the exhaust flue gas of an industrial boiler is generally in the range of 150℃-180℃, and in some cases, it can reach up to 220℃ [4]. This makes the heat loss with exhaust flue gas the most significant source of heat losses. Also, after a period of operation, the temperature of exhaust flue gases generated by industrial boilers usually increase by 10%~30% due to the reduced heat transfer efficiency between the high-temperature flue gas and heat exchanges [5]. It follows that there is a significant potential to recover the waste heat of the flue gases from industrial boilers [5]. This is of higher importance in the case of a biomass-based boilers as the waste heat is essentially carbon-free. More importantly, the limitations in biomass resources further necessitate saving biomass and therefore minimizing heat losses and recovery of waste energy.

There have been already studies on the waste heat recovery from flue gases. The early investigations proposed to increase the heat exchanging surface areas of air or water preheating, but it is limited to space constraints or high cost. Another method for the flue gas heat recovery involves applying gas/gas heat exchangers (GGHs) in which cleaned flue gas is heated by the uncleaned flue gas, decreases the temperature of the uncleaned flue gas while maintains the temperature of the cleaned flue gas for venting. The technology however does not have any effect on energy saving [6]. Organic Rankine Cycle (ORC) [7] is also a practical way to recover the exhaust waste heat. The low-grade energy in the exhaust flue gas is used to generate high-grade energy with ORC system, which improves the combined system efficiency. However, the high cost and complex operation of the integrated systems are the disadvantages [7]. As a result, the methods of waste heat recovery from combustion systems are still under development and constantly call for more research.

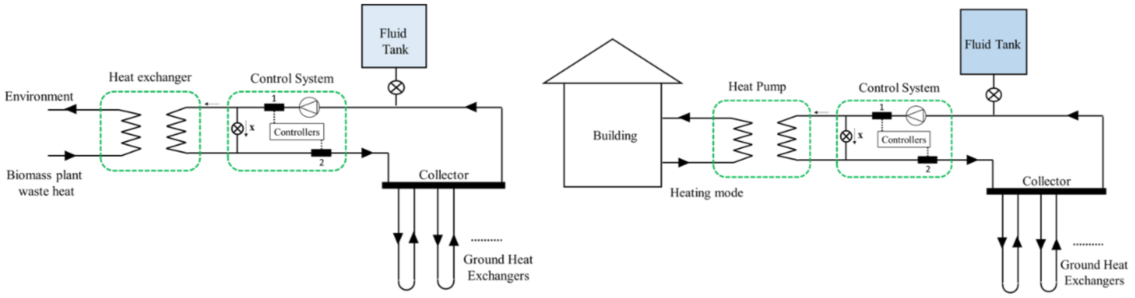
Ground has been found to be an excellent medium for storing heat for a long time with a relatively low cost due to its proper heat capacity [8]. Thermal energy can be stored in the ground with the applications of Ground Heat Exchangers (GHEs) made of high-density polyethylene (HDPE) pipes with different shapes such as boreholes with U-tube pipes, slinky, spiral etc. As a general rule, polyethylene (PE) pipe for pressure applications can be safely used for temperatures as low as -40°C and as high as 60°C[9]. For non-pressure service, the allowable temperature range widens up to 82°C. There are a few PE piping materials that have qualified for a pressure rating at 82 °C [9]. Applying ground source heat pump (GSHP) system for waste heat storage and recovery from industrial boilers, especially biomass plants have great potential for waste heat usage. The technology used for the storage process is typically dependent on the temperature of waste heat [10]. However, the performance of GSHP system, which can be predicted numerically or analytically, need to be further investigated. In doing so, the ground and heat pump should be analyzed separately. Several studies have modelled GSHP systems of waste heat utilization. These are reviewed briefly in the following. Recently, industrial waste heat storage process using large scale heat storage medium was explored by Moser et al. [11]. Their research focused on the case study of the industrial city of Linz (Austria) and advantages and disadvantages of seasonal heat storage were discussed vastly. The results indicate that the number of annual cycles is crucial for a seasonal heat storage. In Dehghan's work [8], waste heat from micro gas turbine exhaust gases was stored in ground through spiral (helical) GHEs in the ground and then recovered the GSHP system. The process was simulated by COMSOL and the results show that amount of extracted heat from the ground is considerably increased after the waste heat storage process. Furthermore, for the storage process, the optimum distance between GHEs was calculated to be 7 m.

Central to the wide application of underground heat storage, is analysis and simulation of the storage medium to aid the design process. However, simulation of heat storage in the ground by using computational packages such as COMSOL [12, 13] and ANSYS or through analytical methods such as Green's function [14, 15] method can be time-consuming and often involves complex procedures. Therefore, efficient and reliable framework should be developed to model thermal performance of GSHP systems. To achieve these goals, ground storage of the thermal energy of exhaust, gasses generated by combustion of biomass, is modelled numerically. The heat system under investigation includes U-tube GHEs and storage during warm season followed by heat extraction in cold seasons. The current work puts forward a novel accurate and yet simple numerical framework for evaluation of GSHP system performance by using Engineering Equation Solver software (EES). In comparison with other simulation techniques, the developed framework can solve complex problems of GSHP modelling faster and more accurately.

2. System description

2.1 Integration of underground thermal energy storage and heat recovery systems

As it is shown in Fig. 1, the waste heat from the flue gases can be utilized beneficially by storing it in the ground and recovering that through a GSHP system during cold seasons. The recovered heat can be used to meet the thermal demands of buildings. Given the carbon neutrality of the biomass combustion as the source of energy, the resultant thermal technology will be a low-carbon one and is therefore environmentally benign. In this study, U-tube GHEs, as shown in Fig. 1, are employed to investigate the effects of waste heat storage on the performance of GSHP system. High temperature waste heat coming from biomass thermal plant is cooled in a heat exchanger by external fluid loop and then stored in the ground. After completing the storage process, the stored heat can be recovered by GSHP system as shown in Fig. 1b. In this case, more heat is expected to be extracted from the ground as the temperature difference between U-tube GHEs and ground is large. Therefore, more heat can be delivered to the building.



(a) (b)

Figure 1: Schematics of waste heat storage and recovery system.

2.2. Ground and ground heat exchangers modeling

Thermal performance of U-tube GHEs and efficiency of GSHP is greatly influenced by the distance between GHEs , shank space, borehole vertical length, major diameter of borehole [16]. All these parameters should be properly optimized to achieve maximum efficiency. To resolve this issue, a numerical modelling framework using EES is developed in this section.

2.2.1. Implicit modelling of ground

Time dependent boundary conditions are a frequently encountered problem in transient modelling of thermal systems. The transient boundary conditions and the complicated geometry of GHEs hinder investigation of GSHP system performance by mathematical modelling except for the high-fidelity numerical techniques [14, 15]. An implicit method is employed in this study due to some of its advantages. In explicit methods, the stability of the calculations is governed by the selection of x and t, however no such restriction is imposed on the solution of equations in implicit methods. This means that larger time increments can be selected to speed up the calculations. Although in implicit methods the number of iterations is generally large, problem can be still solved very fast with no restriction[17].

Inside the U-tube GHEs, heat is mainly transferred by convection and conduction. As shown in Fig. 2, the borehole and ground are divided into nodes in i and j directions.

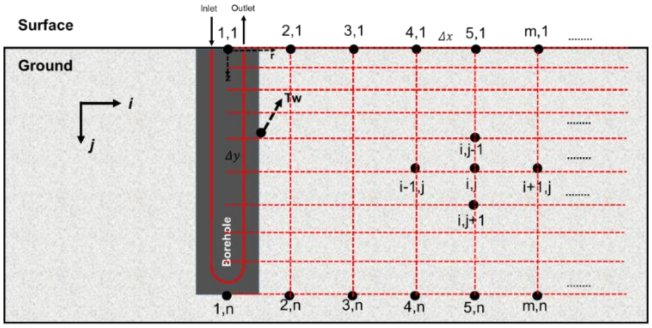


Figure 2: Single U-tube GHE application area

In point 1 heat is transferred by convection since there is fluid flow inside pipes, and in later points (2, 3, 4 …) heat is transferred by conduction by assuming that the borehole is situated above the water table. Transient behavior of each point is investigated by numerical solutions of one-dimensional unsteady condition and convection problems. 1 denotes the average value of inlet and outlet fluid temperatures. Temperatures of points 2, 3, 4 … (m) which vary as time passes are evaluated by using the following implicit equation:

$$\frac{T^{1}_{i,j}-T^{0}_{i,j}}{\alpha\cdot t}=\frac{T^{1}_{i+1,j}+T^{1}_{i-1,j}-2\cdot T^{1}_{i,j}}{\Delta x^{2}}+\frac{T^{1}_{i,j+1}+T^{1}_{i,j-1}-2\cdot T^{1}_{i,j}}{\Delta y^{2}}\quad \textbf{(for } i=1 \textbf{ to } m\textbf{)}\quad \textbf{(for } j=1 \textbf{ to } n\textbf{)} \tag{1}$$

where m and n are horizontal and vertical numbers of nodes, α is thermal diffusivity of the ground, t is time and Δx and Δy are horizontal and vertical distances between nodes (shown in Fig. 2).

In the first part of the current work, initial temperature of all nodes is assumed to be the same is the ground temperature (T_g). That is

$$T^{0}_{i,j}=T_{g}\qquad \textbf{(for } i=1 \textbf{ to } m\textbf{)}\quad \textbf{(for } j=1 \textbf{ to } n\textbf{)} \tag{2}$$

Eq. 4 shows that, temperature of any location in the ground ($T^{1}_{i,j}$) can also be affected by the ground surface temperature ($T^{1}_{i,0}$) which is usually the annual average temperature of the storage site.

$$T^{1}_{i,0}=T_{surface}\qquad \textbf{(for } i=1 \textbf{ to } m\textbf{)} \tag{3}$$

Borehole wall temperature (T_W) is another significant parameter, which needs to be considered in the numerical approach. T_W varies in different time steps and wall temperature of each segment ($T_{W,j}$) is assumed to be the average value of all horizontal nodes of that segment. Expectedly, increasing the number of nodes leads to more accurate model. T_W is determined by:

$$T_{w,j}=\frac{1}{n}\sum_{i=1}^{n}T^{1}_{i,j}\qquad \textbf{(for } j=1 \textbf{ to } n\textbf{)}, \tag{4}$$

where n is the number of nodes. In the current study 240 nodes with 0.1m distance are employed, based on a previously published work [12]. Further, diffusivity of heat is decreased significantly in far distance from the borehole wall (specially more than 6m) [12].

1. 2.2.2. Empirical modelling of the thermo-hydraulics of the flow inside pipes

Experimental results of the fluid flow and heat transfer inside the U-tube GHEs are usually expressed in the form of empirical correlations. A large number of empirical relations for pipe and tube flows under different flow configurations can be found in the literature [17]. In this study, an accurate empirical formula, expressed by Eq. 7 [18], is used.

$$Nu_{d}=\frac{f\cdot Re_{d}\cdot Pr/8}{12.7\cdot\left(\left(f/8\right)^{0.5}\right)\cdot\left(Pr^{2/3}-1\right)+1.07} \tag{5}$$

where f is friction factor and is calculated by;

$$f=\left[1.82\cdot ln\left(Re_{d}\right)-1.64\right]^{-2} \tag{6}$$

and Re_d is Reynold number given by:

$$Re_{d}=\frac{\rho_{f}\cdot u_{d}\cdot d_{i}}{\mu_{f}} \tag{7}$$

u_d is the fluid velocity (m/s) and d is the pipe diameter (m). It is important to note that the thermophysical properties of fluid flow including Prandtl number, density, viscosity, thermal conductivity and heat capacity are not set to constant and dependent on the flow conditions in the modeling, which could enhance accuracy of the developed framework.

Heat transfer coefficient of fluid, h_f (W/m2.K) plays an important role in thermal performance of U-tube GHEs and is calculated based on Nu_d given in Eq. 8. General definition of Nusselt number renders

$$h_{f}=\frac{Nu_{d}.k_{f}}{d} \tag{8}$$

where k_f is thermal conductivity of fluid and d is the internal radius of the pipe.

2. 2.2.3. Calculation of heat transfer rate in the U-tube

Ground implicit model and empirical model of fluid flow inside the pipes should be coupled to investigate dynamic thermal behavior of GHE and calculate heat transfer rate. There are two ways to calculate the heat transfer rate inside the U-tube. Firstly, since there is no phase change in the fluid, the heat transfer rate can be determined by the following thermodynamic equation;

$$Q_t\ [W] = m_f.c_{pf}.(T_{inlet} - T_{outlet}) \tag{9}$$

Secondly, it can also be calculated by accounting for convective heat transfer through the following equation;

$$Q_j\ [W] = h_f.\pi.\mathrm{d}.\mathrm{L}_{seg}.\left(T_{w,j} - \left(\frac{T_{j-1}+T_j}{2}\right)\right) \qquad (j = 1, 2n) \tag{10}$$

In order to investigate the thermal behavior of GSHP system, all discussed equations (4-13) need to be solved simultaneously in the same network. They are coupled with each other using Engineering Equation Software (EES) which has thermo-physical databank for different types of working fluid and is one of the most useful environments for solving thermodynamic and heat transfer problems. Framework developed in EES for this study consists of more than 9000 variables and equations which are solved simultaneously.

3. 3. Validation of The developed numerical model

The accuracy of the developed framework is investigated by comparing against the results from the literature. Long term performance of a borehole with a single 1U tubes has been investigated by Aydin and Sisman (2015) [16]. By applying the same operating conditions presented by Aydin and Sisman (2015) [16], long-term performance of a single 1U borehole GHE is evaluated using the developed equations network framework. Figure 4 depicts that the results of the numerical model are in good agreement.

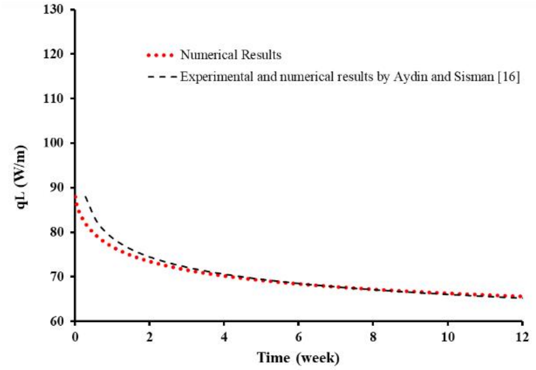


Figure 3: model validation

4. Numerical modelling of biomass waste heat storage and recovery process

4.1. Calculation of the biomass combustion plant

Here, the biomass fuel is Pine pellets for which the physical and chemical properties are listed in Table 1. Based on the ultimate analysis (dry ash free based), the chemical formula of the biomass fuel can be expressed as $\mathrm{CH_{0.89}O_{0.94}}$. Therefore, the stoichiometric combustion reaction is given by:

$$CH_{0.89}O_{0.94} + 1.0025 \cdot (O_2 + 3.76N_2) = CO_2 + 0.945H_2O + 3.7694N_2 \tag{11}$$

In practice combustion systems operate with excess air to ensure complete combustion and avoid formation of pollutants. The excess air coefficient is x_{air}, the chemical reaction becomes:

$$CH_{0.89}O_{0.94} + x_{air} \cdot 1.0025 \cdot \left(O_2 + 3.76N_2\right) = CO_2 + 0.945H_2O + 3.76N_2 + \left(x_{air} - 1\right) \cdot \left(O_2 + 3.76N_2\right) \qquad (12)$$

Table 1: Characteristics of Peach Stones [19]

Proximate analysis (received)	
Moisture (%)	7.1
Volatile (%)	75.6
Fixed Carbon (%)	15.9
Ash (%)	1.4
Ultimate analysis (dry ash free basis)	
C	46.39
H	5.97
O	47.64
Heating value dry fuel (MJ/kg)	15.8

Considering the operational parameters of the biomass boiler, taking that the excess air coefficient is 1.4, the boiler thermal efficiency is 0.65, and the flue gas heat loss percentage is 0.29 [20]. Therefore, the temperature and mass flow rate of flue gas were obtained under different boiler output powers by applying Eqs. (1-3). The results are summarized in Table 2.

Table 2: Mass flow rate and temperature of fuel gas

Boiler output power P (kW)	**Mass flow rate of fuel $\dot{m}_{fuel}$ (kg/s)**	**Mass flow rate of air $\dot{m}_{air}$ (kg/s)**	**Mass flow rate of flue gas $\dot{m}_{flue}$ (kg/s)**	**Temperature of flue gas T_f (kg/s)**
400	0.039	0.271	0.310	485.5
600	0.058	0.402	0.460	485.9
800	0.078	0.541	0.619	485.8
1000	0.097	0.676	0.773	485.9
1200	0.117	0.812	0.929	485.7

In the rest of this study, the boiler with 1000 kWt output is considered.

4.2. Waste heat storage process and analysis

Section 4.1 implied that in a biomass combustion system large amount of high temperature heat is wasted into the environment. This wasted high quality thermal energy can be used efficiently by supplying heating demands of buildings. The performance of a GSHP system can be significantly increased through waste heat recovery from the biomass thermal plant. In the considered biomass combustion plant, heat is wasted into the environment at 485.9 K and flow rate of 0.773 kg/s and the goal is to cool the flue gas to 300K. In this study, water is chosen as the coolant fluid and as shown in Fig. 1, storage temperature should not exceed 60oC. To ensure about this, controllers have been implemented.

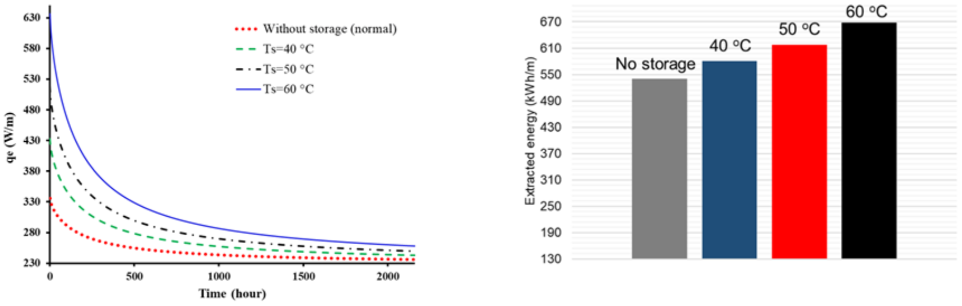
Operating conditions as well as boundary conditions given in Table 3 are applied to simulate storage process in the ground [8]. For the specific case study and based on the calculations presented in 4.1, to be able to cool exit waste heat temperature down to 300K, at least 4 units of GHEs are needed (n=4) which should be placed 7m apart from each other. Different case studies with various storage temperatures, flow rates, etc. can be investigated by using the framework presented in this work.

Table 3: Different properties of storage supplication area

Parameter	**Value**	**Definition**
r_i	0.014	Internal radius of PE pipe [m]
r_o	0.017	External radius of PE pipe [m]

L	50	Vertical length of U-tube GHE [m]
D	0.2	Major diameter of borehole GHE [m]
k_p	0.45	Thermal conductivity of PE [W/m.K]
k_s	1.8	Thermal conductivity of soil/ground [W/m.K]
m_f	0.355	Fluid flow rate in pipes [kg/s]
T_i	60	Average fluid inlet temperature [^{o}C]
T_g	18	Undisturbed ground temperature [^{o}C]
N	4	Number of needed U-tube GHEs
d	6	Distance between U-tube GHEs [m]
t_s	2160	Storage Time [hour]

Fig. 5 illustrates the total extracted heat transfer rate from the ground (q_e) by four borehole GHEs per unit length of borehole (W/m) in heating mode (in heating mode it is assumed that average T_{inlet} is about 1℃). For the current case study, the amount of heat extracted from the ground increases by 7.6%, 14.4% and 23.7% per unit length of the borehole when the storage temperature is 40℃, 50℃ and 60℃, respectively. These values are evaluated under the most critical working condition (3 months non-stop operation) and the real performance is better than the results given in Fig. 5 due to the intermittent operation of GSHP system.



(a)

(b)

Figure 4: Effects of storage process on thermal performance of GHEs (n=4)

5. Heat recovery performance and CO2 reduction

Results of this study show that a considerable amount of waste heat can be recovered and beneficially used for meeting the heating demands of buildings. In Fig. 6 the amount of recoverable waste heat of different biomass combustion plant with different installed capacity (0.5-10 MW) versus two different numbers of U-tube GHE (n=1 and 4) has been shown. Waste heat recovery ratio is the amount of recovered heat divided by the total wasted heat of the biomass plant.

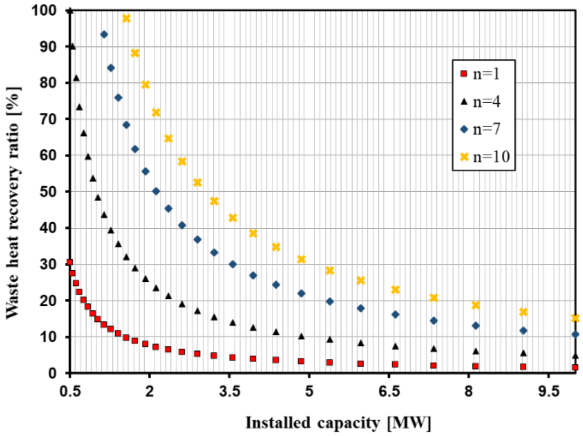


Figure 5: Possible waste heat recovery ratio versus biomass plant installed capacity and numbers of GHEs (T_s=60°C).

In almost all combustion systems a fraction of heat generated by burning fuel is wasted by flue gases to the atmosphere. Burning fossil fuels results in emission of CO2 and thus wasting thermal energy intensifies the emission of greenhouse gases. For those systems which burn biomass, waste of heat is essentially waste of renewable fuel and is therefore an environmental burden. The underground storage system introduced in this work offers an efficient way of storing a significant fraction of the heat that is normally wasted from the chimney. The preceding analyses showed that for the 1MW combustion system under investigation between 30% to 100% of the waste heat can be successfully recovered and delivered to buildings for space heating purposes. This range can be made even wider by implementing larger number of boreholes. Assuming an average recovery rate of 65%, it can be readily shown that the recovered heat saves emission of almost 1ton of CO2 per day, in comparison with the case of burning natural gas for supplying heat to the buildings. If the heat is to be supplied by biomass combustion approximately 700 kg of biomass should be burned per day. Clearly, higher storage capacities applied to bigger combustion plants will result in larger heat recovery and can further reduce the CO2 emissions and save biomass. It is essential to note that the calculations throughout this work were conservative and improvements in heat exchangers efficiency and the specifications of boreholes can readily increase the recovery rate. More details can be found in the recently research published by the authors [21].

6. conclusion

In this study, waste heat storage and recovery of thermal energy by using ground source heat pump were investigated. The source of waste heat was flue gases released by a combustion system. Results show that a considerable amount of waste heat can be recovered and beneficially used for meeting the heating demands of buildings. A case of 1000 kW biomass thermal plant generating 0.773 kg/s flue gas with temperature of 485.9 K was considered. The possibility of recovering waste heat was investigated numerically by developing a new modelling framework. A novel, fast, highly accurate and yet simple numerical modelling framework developed in EES environment could solve the complicated problems of GHEs modellings in a short time (generally in less than 20 seconds using one CPU). In this study, the framework developed in Engineering Equation Solver (EES) consists of more than 9000 variables and equations which are solved simultaneously. Equations' network is constructed based on an implicit modelling approach of the ground and empirical modelling of fluid flow inside U-tube ground heat exchangers (GHEs). All equations are coupled together and the influences of each parameter on the whole system performance can be investigated individually. The developed framework was validated by observing an excellent agreement between the numerical results and the existing experimental date.

Results showed that for this case 4 units of U-tube GHEs were needed. For 3 months continuous storage processes the average rate of heat storage in the ground (q_s) is 83.15, 75.77 and 70.40 W/m when the storage temperature is 60°C, 50°C and 40°C, respectively. Storage amount decreases as the time passes due to the thermal interactions between borehole and the surrounded soil.

After three months of heat storage, the stored heat is extracted and delivered to buildings for supplying heating demands through a GSHP system with the same application area (n=4). Referring to the results and for the considered biomass combustion plant, the amount of extracted heat from ground increases by 7.6%, 14.4% and 23.7% per unit length of the borehole corresponding to 40℃, 50℃ and 60℃ storage temperatures. Although different storage temperatures were investigated in this research, it is recommended to use 60℃ as storage temperature in which at least 23.7% more heat can be delivered to the buildings with the same application area. It was argued that the encountered temperatures are within the tolerance of existing commercial materials and thus the proposed system is practically viable.

In future studies, different subjects such as 3D modelling of application area, modelling of different GHE geometries including helical and slinky and intermittent modelling of GSHP system can be investigated through using the framework developed in this work.

Nomenclature

A	Peripheral area of pipe
$c_{p.flue}$	Specific heat capacity of flue gas
c_{pf}	Specific heat capacity of fluid
d	Distance between borehole
D	Major diameter of GHE
f	Friction factor
h_f	Heat transfer coefficient of fluid
k_s	Thermal conductivity of soil/ ground
k_p	Thermal conductivity of PE tube
k_f	Thermal conductivity of fluid
L	vertical length of U-tube GHE
LHV	Lower heating value of biomass fuel
$\dot{m}_{flue}$	Mass flow rate of flue gas
$\dot{m}_{fuel}$	Mass flow rate of biomass fuel
$(\dot{m}_{air})_s$	Air flow rate under stoichiometric conditions
m_f	Fluid flow rate in pipes
MW	Molar weight
N	Number of nodes
n	Number of GHE
$\dot{Q}$	HTR value
P	Biomass plant output
q	HTR per unit length
r_i	Inner radius of PE tube
r_o	Outer radius of PE tube
$\bar{T}_{ave}$	Average fluid temperature
T_0	Inlet air temperature
T_f	Flue gas temperature
T_s	Storage temperature
T_g	Undisturbed uniform ground temperature
t_s	Storage Time
η_f	Percentage of flue gas heat loss
η_t	Boiler thermal efficiency
u_d	Fluid velocity in pipes
x_{air}	Excess air coefficient
x	Distance between nodes
Nu	Nusselt number
Re	Reynolds number
ρ_f	Density of fluid
μ_f	Dynamic viscosity of fluid

Abbreviation

COP	Coefficient of Performance
GHE	Ground Heat Exchanger
GSHP	Ground Source Heat Pump
HTR	Heat Transfer Rate
PE	Polyethylene

4. References

[1] M. Esen, T. Yuksel. Experimental evaluation of using various renewable energy sources for heating a greenhouse. Energy and Buildings. 65 (2013) 340-51.

[2] V.K. Verma, S. Bram, J. De Ruyck. Small scale biomass heating systems: Standards, quality labelling and market driving factors – An EU outlook. Biomass and Bioenergy. 33 (2009) 1393-402.

[3] S.v.L. Jaap Koppejan. The Handbook of Biomass Combustion and Co-firing. Routledge. (2012).

[4] Q.X.Z. J.F. Zhang, H.C. Wang, Z.X. Zhang J.W. Zhou. Analysis on parameter optimization of flue gas heat recovery device. Journal of Chinese Society of Power Engineering. 30 (2010) 652-7.

[5] R. Saidur, J.U. Ahamed, H.H. Masjuki. Energy, exergy and economic analysis of industrial boilers. Energy Policy. 38 (2010) 2188-97.

[6] S.Z.W. Z.T. Xu, X.K Fan. The economy analysis of WFGD system without GGH and its environment impact. Power Protection of Environment. 21 (2005) 52-9.

[7] G.L. B.F Tchanche, A. Frangoudakis, G. Papadakis. Low-grade heat conversion into power using organic rankine cycles e a review of various applications. Renewable and Sustainable Energy Reviews. 15 (2011) 3963-79.

[8] B. Dehghan B. Performance assessment of ground source heat pump system integrated with micro gas turbine: Waste heat recovery. Energy Conversion and Management. 152 (2017) 328-41.

[9] HANDBOOK OF POLYETHYLENE PIPE. 2nd edition ed. Plastics Pipe Institute.

[10] X. Wang, M. Jin, W. Feng, G. Shu, H. Tian, Y. Liang. Cascade energy optimization for waste heat recovery in distributed energy systems. Applied Energy. 230 (2018) 679-95.

[11] S. Moser, J. Mayrhofer, R.-R. Schmidt, R. Tichler. Socioeconomic cost-benefit-analysis of seasonal heat storages in district heating systems with industrial waste heat integration. Energy. 160 (2018) 868-74.

[12] B. Dehghan, A. Sisman, M. Aydin. Parametric investigation of helical ground heat exchangers for heat pump applications. Energy and Buildings. 127 (2016) 999-1007.

[13] B. Dehghan B. Effectiveness of using spiral ground heat exchangers in ground source heat pump system of a building for district heating/cooling purposes: Comparison among different configurations. Applied Thermal Engineering. 130 (2018) 1489-506.

[14] B. Dehghan B. Thermal conductivity determination of ground by new modified two dimensional analytical models: Study cases. Renewable Energy. 118 (2018) 393-401.

[15] B. Dehghan B, E. Kukrer. A new 1D analytical model for investigating the long term heat transfer rate of a borehole ground heat exchanger by Green's function method. Renewable Energy. 108 (2017) 615-21.

[16] M. Aydın, A. Sisman. Experimental and computational investigation of multi U-tube boreholes. Applied Energy. 145 (2015) 163-71.

[17] J.P. Holman. Heat Transfer. McGraw-Hill. (2002).

[18] H.B. Madessa, B. Torger, P.F. Bye, A. Erlend. Parametric Study of a Vertically Configured Ground Source Heat Pump System. Energy Procedia. 111 (2017) 1040-9.

[19] M. Rabaçal, U. Fernandes, M. Costa. Combustion and emission characteristics of a domestic boiler fired with pellets of pine, industrial wood wastes and peach stones. Renewable Energy. 51 (2013) 220-6.

[20] J. Dias, M. Costa, J.L.T. Azevedo. Test of a small domestic boiler using different pellets. Biomass and Bioenergy. 27 (2004) 531-9.

[21] B. Dehghan B, L. Wang, M. Motta, N. Karimi. Modelling of waste heat recovery of a biomass combustion plant through ground source heat pumps- development of an efficient numerical framework. Applied Thermal Engineering. (2019) 114625.