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Evaluation of a novel integrated solar-borehole thermal energy storage system for residential high-rise building heating applications

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ABSTRACT

This study performs the design and performance analysis of a novel solar-borehole thermal energy storage system to supply a complete heating solution to a residential high-rise building located in Ontario, Canada. Building total heat demand is estimated based on user demand and ambient temperature, a solar-thermal collector system and a borehole thermal energy storage system (BTES) are designed to generate and store the energy. A 1+1D numerical code is developed to solve the heat transfer phenomenon in BTES and is coupled to the solar collector system. A time-dependent dynamic simulation is performed over a year with hourly weather data with a time-step of 10 minutes and the observations are recorded.

Keywords: solar-borehole heating, coaxial borehole heat exchanger, solar thermal building heating, seasonal energy storage.

NOMENCLATURE

Abbreviations	
BTES	*borehole thermal* energy storage system
TES	thermal energy storage
HTF	Heat Transfer Fluid

1. INTRODUCTION

Among the available thermal energy storage (TES) technologies, borehole thermal energy storage (BTES) integrated with a solar collector system is a viable alternative to satisfy the continuous heating/cooling requirement of the residential building throughout the entire year. Based on the solar energy availability pattern in Ontario, Canada which peaks in the summer when the heating demand is lower than in winter, Solar-BTES is a practical approach to overcome the mismatch between energy demand and supply.

The other advantage of this technique is that the heat capacity of the system can be expanded in the future depending on the growing building energy demand by drilling more boreholes and connecting them to the existing network. Several studies have been dedicated to the study of the functionality of BTES technology [1, 2]. Welsch et. al. [3] studied the different configuration of medium-deep BTES systems and evaluated the effects of key factors including depth (100-1000m), number of boreholes (7-37), and Center-Center distance (2.5-10m) between the boreholes. They stated that the larger BTES systems are more efficient with a high recovery rate of up to 83%. Rad et. al [4] also develop a system to evaluate the performance of the solar-BTES, consisting of 144 boreholes of 35m depth, for community energy supply in Canada called Drake Landing Solar Community (DLSC). They suggested an alternative design that can provide the total annual community thermal load of 2350GJ. Furthermore, the background research on the integration of solar thermal technology into BTES systems storage (e.g. [5-8]) indicates the significant potential for energy supply in the residential/industrial sector. While the potential of Solar-BTES is established, there have been very limited studies that deal with the hourly fluctuation in solar radiation as well as the ambient air temperature. Accordingly, this work presents an innovative full-scale dynamic numerical model that can capture the highly dynamic heat transfer behavior of the Solar-BTES system. In addition to solar thermal energy, the potential heat energy available in the exhaust of the building will be considered for the sustainable building heat energy supply. The schematics of the proposed system is presented in Fig. 1. The main

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components of the proposed system include a coaxial-borehole heat exchanger system (CBHE), a solar thermal collector system, a building heat recovery system, heat exchangers, and a heat pump.

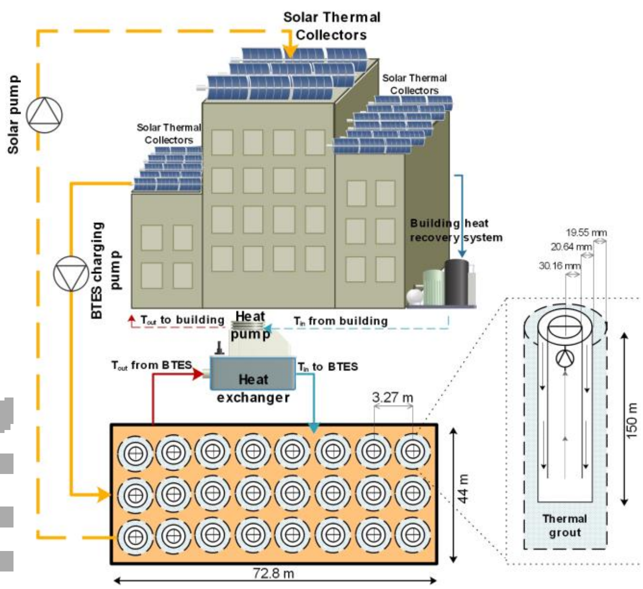

Fig.1. Schematics of the proposed system

1.1 Working principle

The operating strategy has two different cycles: injection and extraction. The injection cycle occurs during the sunshine hours when the available energy from solar collectors is more than the building's total heat demand at that instant of time. During this process, Heat Transfer Fluid (HTF) from the solar collectors is pumped to the BTES, while the outlet from the BTES is pumped back to the solar collectors. The heat transfer phenomenon between the ground and the HTF is responsible to increase the ground temperature during this cycle. During the extraction phase, higher temperature HTF from BTES exchanges heat energy with the HTF from the building. In addition, an exhaust heat recovery system is installed to capture the heat energy from the hot water coming out of the building.

2. METHODOLOGY

2.1 Development of the 1+1d model

The 1+1D numerical code solves the heat transfer mechanism between the ground and the HTF during both the injection and the extraction cycles [9]. The considered computational domain is axisymmetric and is composed of two solid mediums, namely the grout and the rock. Conduction within these solid zones is calculated using Eq. (1). Thermo-physical properties of the model can be found in Table 1.

$$\frac{\partial(\rho\, c_p T)}{\partial t} = \nabla \cdot (k \nabla T) \qquad (1)$$

The computational domain is bounded by insulated walls and the annular flow of the HTF. The insulation boundary condition is given as

$$\frac{\partial T_w}{\partial n} = 0 \qquad (2)$$

Where, T_w is the wall temperature and n is a displacement vector that is normal to the insulated walls. The convective boundary of the annular flow is expressed as

$$-k_{grout}\frac{\partial T_w}{\partial n} = h(T_w - T_{HTF}) \qquad (3)$$

here, h is the convective heat transfer coefficient of laminar flow in a concentric annulus. The HTF temperature, T_{htf}, decreases as the HTF loses heat to the ground, which can be calculated per unit area of the *pipe* by employing the first law of thermodynamics as

$$\Delta T_{HTF} = \frac{q_w}{(mc_p)_{HTF}} \qquad (4)$$

In this study, a semi-conjugate reduced-order 1+1D algorithm is developed to decrease the computational cost of the problem while monitoring the temperature change of HTF.

2.2 Solar efficiency

By employing the solar collector inlet (T_{in}), ambient air temperature (T_a), the global radiation incident on the tilted-surface of the solar collector (G), the energy efficiency of the solar collector can be obtained using Eq. (5). Here, the inlet temperature to the solar collector is also the outlet temperature from the BTES during the charging cycle.

$$\eta = 0.762 - 3.2787\left(\frac{T_{in}-T_a}{G}\right) - 0.0129\left(\frac{(T_{in}-T_a)^2}{G}\right) \qquad (5)$$

Solar collector efficiency is a function of solar irradiance, inlet, and ambient temperature. However, the mass-flowrate effect on collector efficiency is not accounted for in the analysis.

2.3 Total head demand for the building

The thermal storage system is designed to provide a total heating solution to the building. This includes thermal losses, the energy needed to heat fresh ambient air, and the energy required to supply the hot water demand of the building as shown in Eq. (6). Expressions used in calculating heat losses, fresh air demand, and hot water demand are Eq. (7), Eq. (8), and Eq. (9) respectively.

$$\dot{Q}_{total} = \left(\dot{Q}_{losses} + \dot{Q}_{fresh\ air} + \dot{Q}_{hot\ water}\right) \qquad (6)$$

$$\dot{Q}_{losses} = \left(\frac{A_{wall}}{R_{wall}} + \frac{A_{window}}{R_{window}} + \frac{A_{floor}}{R_{floor}} + \frac{A_{roof}}{R_{roof}}\right)\Delta T \quad (7)$$

$$\dot{Q}_{fresh\ air} = \dot{m}c_p\Delta T \quad (8)$$

$$\dot{Q}_{hot\ water} = \dot{m}c_p\Delta T \quad (9)$$

In the above equations, A and R represent the area and the R-value of insulation, and ΔT is the desired temperature change. Fresh air and hot water requirement for the building is determined from ASHRAE standard 90.1-2019 guidelines. The R-value of walls, roof, and the floor is considered as 4.75 K-m^2/W, and the R-value of 0.44 K-m^2/W is assumed for windows.

3. RESULTS AND DISCUSSION

3.1 Energy and power demand

The total power and energy demand of the building is calculated on an hourly basis based on the ambient temperature and the building load demand. Fig. 2 represents the weathering profile of the location and energy demand of the building calculated on an hourly basis. 25.2 TJ of total heat energy is needed to meet the annual building load, while the power demand ranges between 172 kW to 1640 kW.

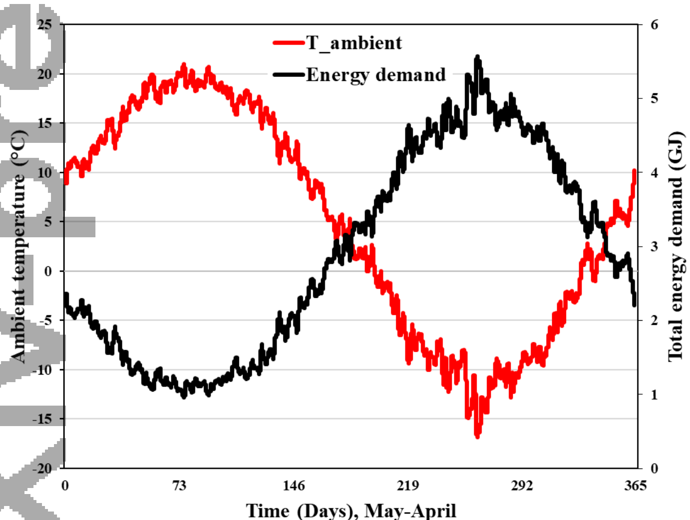

Fig 2. Hourly ambient temperature and hourly energy demand throughout the year

Based on the solar availability and the building load, the solar thermal system and the BTES are designed. The total required area of the solar collector is calculated as 10,534 m^2. The depth of each borehole considered is 150m, while 300 boreholes are considered in total with a Centre-Centre distance of 3.27m. State-of-the-art solar thermal collector technology available commercially is used in the analysis. The physical specifications of the solar thermal collector used are presented in Table 1.

Fig. 3 displays the efficiency of a thermal collector over the year. Efficiency is obtained higher in summer months as compared to winter months. Irradiance and ambient temperature are significant factors for this outcome.

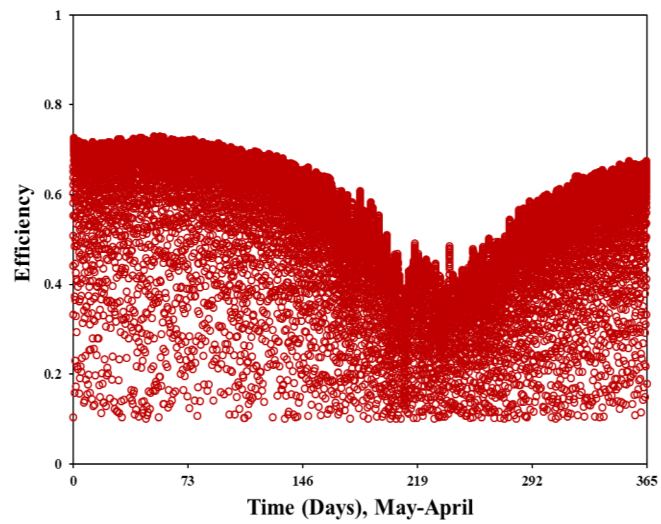

Fig 3. Efficiency of solar thermal collectors for a year

Total solar energy available from solar collectors is calculated as 34.5 TJ, while the average efficiency over a year during sunshine hours is calculated as 57%. 76% of total available solar energy is injected into the BTES system while the remaining solar energy is used directly by the building during sunshine hours.

Table 1. design and simulation parameters

Simulation Parameters – ground/grout				
S.N.	Item	Ground	Grout	unit
1	Density	2980	1800	kg/m^3
2	Thermal conductivity	2.4	1.0	W/m.K
3	Specific heat	840	1900	J/kg.K
S.N.	**Physical Specifications of Solar thermal collectors**			
1	Dimensions (L× W× H):	2 x 2.2 x 0.14		m
2	Aperture (gross) area	2.84 (4.4)		m^2

This stored energy is extracted during non-sun hours according to building demand. The analysis assumes that all the boreholes are in operation during both of the cycles. The flow rate is controlled in the boreholes to get the specified temperature difference between the inlet and outlet. Fig. 4 and Fig. 5 are the power and energy extracted from the system over the year. Here, total power and energy supply are the sums of power and energy from the BTES system and the direct solar use. It is worthwhile to mention that the building heat demand during the sunshine hours is directly supplied by the solar collector system without the involvement of BTES.

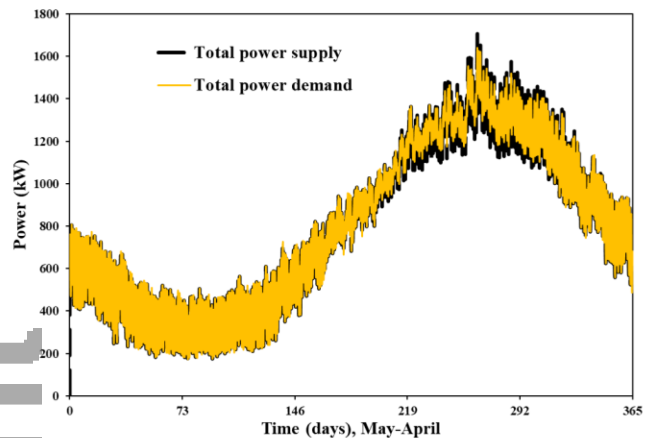

Fig. 4. Total power demand of the building and total power supply by the system

Point to point comparison of power and energy is made to make sure that the building load is supplied both in terms of power and energy in each hour of each day throughout the year. Results indicate that the designed solar-BTES system is capable of providing necessary power and energy to the building.

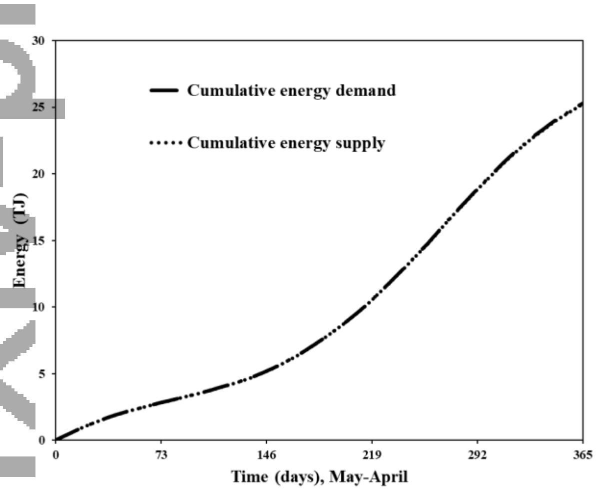

Fig. 5. Comparison of the energy demand of the building and energy supplied to the building.

4. CONCLUSION

In this study, a 1+1D numerical code is developed to solve the heat transfer phenomenon in the Co-axial Borehole Heat Exchanger system (CBHE). The code is extended to couple the heat transfer process in CBHE with energy generation from solar thermal collector and energy use form the building heating demand. The numerical model is dynamically simulated with time-steps of 10 minutes over a year with injection during sunshine-hours and extraction during non-sun hours.

Results indicate that to supply a total heating solution to a high-rise residential building located in Ontario, Canada with 826 total number of apartment units, 10,534 m2 of solar collector area is required. Besides, 300 co-axial boreholes with a depth of 150m are necessary to supply the desired energy and power to the building.

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REFERENCE

[1] Ghoreishi-Madiseh SA, Fahrettin Kuyuk A, Rodrigues de Brito MA, Baidya D, Torabigoodarzi Z, Safari AJE. Application of borehole thermal energy storage in waste heat recovery from diesel generators in remote cold climate locations. 2019;12:656.

[2] Ghoreishi-Madiseh SA, Sasmito AP, Hassani FP, Amiri L. Performance evaluation of large scale rock-pit seasonal thermal energy storage for application in underground mine ventilation. Applied Energy. 2017;185:1940-7.

[3] Welsch B, Ruehaak W, Schulte DO, Baer K, Sass IJIJoER. Characteristics of medium deep borehole thermal energy storage. 2016;40:1855-68.

[4] Rad FM, Fung AS, Rosen MAJEfSD. An integrated model for designing a solar community heating system with borehole thermal storage. 2017;36:6-15.

[5] Arabkoohsar A, Farzaneh-Gord M, Ghezelbash R, Koury RNJJotBSoMS, Engineering. Energy consumption pattern modification in greenhouses by a hybrid solar–geothermal heating system. 2017;39:631-43.

[6] Nilsson E, Rohdin PJRe. Performance evaluation of an industrial borehole thermal energy storage (BTES) project–Experiences from the first seven years of operation. 2019;143:1022-34.

[7] Rad FM, Fung AS. Solar community heating and cooling system with borehole thermal energy storage – Review of systems. Renewable and Sustainable Energy Reviews. 2016;60:1550-61.

[8] Elhashmi R, Hallinan KP, Chiasson ADJE. Low-energy opportunity for multi-family residences: A review and simulation-based study of a solar borehole thermal energy storage system. 2020:117870.

[9] R. Shah, A. London, Concentric Annular Ducts, in: Laminar Flow Forced Convection in Ducts, Academic Press, New York, 1978, Ch. XII, pp. 284-321.