ENERGY AND EXERGY ANALYSIS OF PEBBLE BED THERMAL ENERGY STORAGE SYSTEM FOR DIESEL ENGINE EXHAUST

Dheeraj Kishor JOHAR[1], Dilip SHARMA[2], Harekrishna YADAV[3], Satyanarayan PATEL[3*]

[1]*CMRB Govt. Polytechnic College, Sriganganagar, Rajasthan, India-335001*

[2]Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Jaipur, Rajasthan, India-302017

[3*]Affiliation [c]Department of Mechanical Engineering, Indian Institute of Technology Indore, Indore, Madhya Pradesh, India-453552

[*] Corresponding author: Email id: spatel@iiti.ac.in

In the present work, a pebble bed thermal energy storage (PBTES) system is developed to utilize the waste energy from engine exhaust. The developed PBTES is integrated with an electric dynamometer coupled stationary diesel engine for experimental investigation. The engine performance is compared with and without integration of the PBTES system. The 60-75% of energy can be stored in the fabricated system during the charging process at various load conditions. It is found that nearly 11-15% of engine fuel energy can be saved using this storage system considering the charging process. Heat recovery/discharging from PBTES shows that 6-8.5% of fuel primary energy can be saved. The system combined (engine+PBTES) efficiency varies from 11-38% at different load conditions. The highest exergy saved is obtained as 3.32% when a 3 kW load is applied. The developed system can be easily used for domestic or industrial use space heating or hot fluid requirements.

Keywords*: Thermal energy storage system; Pebble bed; Waste heat recovery; Diesel engine*

1. Introduction

Diesel engines are widely used for commercial, industrial and power generation applications. These engines convert nearly up to 35% of the fuel energy into practical work; however rest of the energy is lost into cooling, friction, exhaust gases and radiation [1, 2]. Out of these, nearly 30% of energy is carried away by exhaust gases [1, 2]. The energy available in exhaust gasses is wasted if not utilized properly; thus, efficient/effective use of waste energy is needed to improve engine overall efficiency/performance [3]. In this context, several studies reported engine exhaust energy onboard utilization to increase engine performance and emission reduction [4-6]. Moreover, the wasted heat can use for space heating, hot water/fluid, heating the air for various industrial processes [7, 8]. The exhaust/waste energy based cooling system is also developed with the help of a vapor absorption/adsorption system or desiccant dehumidifier [7, 8]. In this direction, many techniques such as mechanical & electric turbo compounding, Rankine cycle and Stirling cycle have also been suggested to recover heat from engine exhaust gases [9].

Further, thermoelectric modules are also used to convert engine waste heat to electricity [10-12]. However, the efficiency of such a system is lower because of a small figure of the merits of thermoelectric materials. Moreover, if thermal waste energy is directly used for space heating[3, 13], cooling, or trigeneration[3, 7, 13], then a large amount of fuel can be saved. Furthermore, it has been observed that the time mismatched, intermittent demand and availability are the major technical constraint for waste heat recovery implementation for these applications [14-17]. In order to overcome this problem, various researchers developed and studied thermal energy storage (TES) systems [18-22]. This is because TES allows storing excess energy for later rational use [23, 24]. In this direction, the most popular medium are phase change materials, fluid(water, air, oils), etc., considered for thermal energy storage during the charging process, which can be used later via discharging process [18]. In this regard, Gopal *et al.[25]* investigated energy and exergy analysis on phase change material-based TES system integrated with diesel engine exhaust [25]. Similarly, Mavridou *et al.* [26] show five different heat exchanger configurations for engine exhaust energy recovery. In the same way, several researchers have studied different types of TES systems integrated with the engine considering phase change materials, Oil, water, Zeolite based[14, 23, 25, 27].

Most of the previous work is focused on the packed bed integration with solar heating systems, which can be integrated with the engine. Kurklu *et al.[28]* used a rock-bed for solar energy storage and utilized it to warm a greenhouse (polyethylene tunnel). Moreover, Paul and Saini [29] studied two different packed beds for TES based on the wire mesh screen matrix and pebble bed. Furthermore, the operating parameter's effect on heat transfer, pressure drop characteristics, charging and discharging analysis in packed bed solar TES system is explored [30]. Hanchen *et al.* [27] developed a heat transfer model and experimental validation for a rock-based packed bed where the air is used as a heating/cooling medium. Finally, an extensive review of the packed bed solar energy TES system is discussed by Singh *et al.* [19]. Numerous reviews and analyses are available on the pebble bed sensible heat storage media for solar energy storage or other industrial waste energy storage (except engine waste energy) [2, 19-21, 29, 31-33]. However, few studies focus on integrating engine exhaust energy storage with a pebble bed system [32, 33]. Franklin et al.[2015] integrated a TES using alumina and stone pebble as storage media; however, the stone pabble size varies from 25 mm-75 mm[33]. Moreover, in the complete study, they have measured the temperature and discussed its variation; they completely ignored the efficiency of the system, fuel-saving or combined efficiency of TES and exergy analysis, etc. [33]. In another study, they considered fluid flow characteristics in the PBTES [32]. Hence, it is essential to look at the individual/combined efficiency, exergy and energy saving by such a system. The novel aim of this study is to develop a pebble bed thermal energy storage system and evaluate the performance (energy and exergy analysis) of PBTES system by integrating this with a small capacity (4.4 kW) stationary diesel engine.

2. Pebble Bed Thermal Energy Storage System

The Pebbles can store energy when they are heated in an insulated tank or bed. In this type of system, phase change does not occur during the energy storage and recovery process. Hence, this kind of heat storage is known as a sensible heat storage system. The heat storage capacity of pebble bed can be obtained by[20]:

$$Q = V\,\rho\,c_{p\,pebble}\,\Delta T_S\,(1-\varepsilon) = m_{pe}\,c_{p\,pebble}\,\Delta T_S\,(1-\varepsilon) \qquad (1)$$

$\Delta T_S = T_{max} - \Delta T_{min}$ is the temperature difference between the maximum and minimum temperatures of the thermal storage system.

In the present work, a cylindrical stainless steel tank with an inner diameter of 340 mm and a height of 420 mm is used as a pebbled bed as shown in Fig. 1. The pebbles of uniform size 14 mm are used as an energy storage medium. The pebbles are sieved to obtain a uniform size and the size of a pebble is measured by vernier caliper. The pebble measured/used properties are given in Tab. 1. The density of the pebble is measured by Archimedes's principle. The void fraction (ε) of the bed is calculated $\varepsilon = V_v/V_t$ where V_v is void volume and V_t is the total volume (including both void and solid). Other properties are taken from the literature.

Tab. 1: Properties of pebbles used for the analysis.

Pebble properties	Measured value
Pebble size [mm]	14
Void fraction [%]	37
Density [kg/m^3]	1700
Tank diameter to pebble size ratio	24
Specific heat capacity [kJ/kgK]	710
Thermal conductivity [W/mK]	1.83

A converging and diverging sections section was placed at the tank's top and bottom sides, as shown in Fig. 1. The diverging section was used to expand the exhaust gas for better heat transfer between exhaust gas and pebbles in the bed. However, the converging section was used at the top of the bed to smooth escape of exhaust gas. The storage tank was insulated with asbestos rope and glass wool to minimize any heat loss. A thin aluminum sheet was used to hold glass wool outside the tank. A small size sieve with a stand was used to support the pebbles or stop falling pebbles. The temperature was measured at various places using the K-type thermocouple.

3. Experimental Setup

In this work, a four-stroke, single-cylinder, air-cooled, stationary Kirloskar TAF1 Diesel Engine is employed. The engine is coupled with an electrical dynamometer, whereas the exhaust line is integrated with a PBTES, see Fig. 1. Specifications of the engine and dynamometer are given in Tab. 2. The schematic and photographic view of the experimental setup is presented in Fig. 1. A calibrated airbox and burette meter was used to measure air flow rate and fuel flow rate, respectively, in the engine. A detailed discussion on the engine, dynamometer specifications and parameters are previously reported [7, 13, 14, 23]. The exhaust gas flows in PBTES are also shown in Fig. 1. The exhaust gas and airflow direction are controlled during charging and recovery/discharging of TES pebble bed by four control valves.

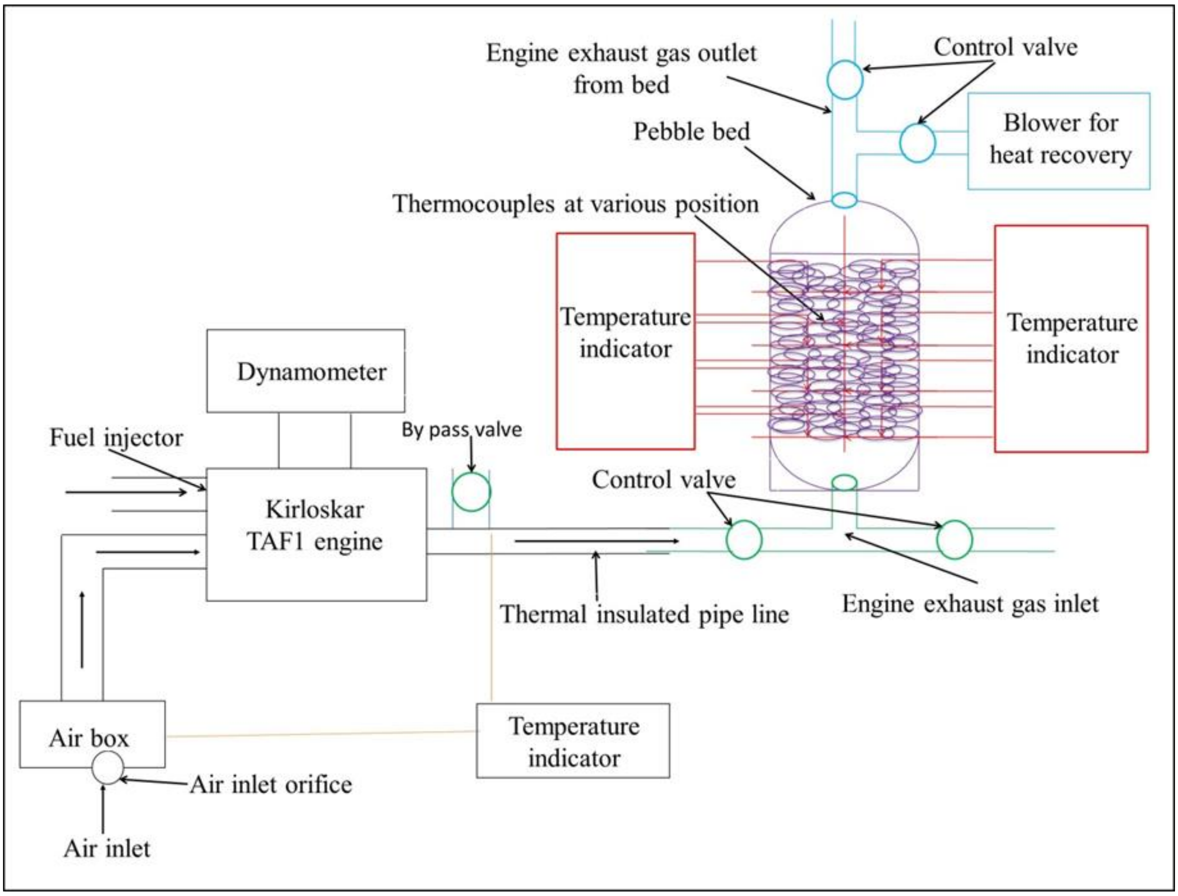

Fig. 1: Schematic of the experimental setup used in the present work. The engine is coupled with a dynamometer and the exhaust gas is passing in pebble bed.

These valves were fitted at the inlet and outlet of the PBTES tank. An air blower was used to recover heat from PBTES. The temperature was measured at different places with K-type (Cr/Al) thermocouples. Fifteen thermocouples were placed inside the PBTES tank at different palaces. The positions of the thermocouples are shown in Fig. 2. Three thermocouples were placed uniformly in 4 horizontal planes at different heights and one thermocouple at another 3 heights is set, as shown in Fig. 2.

Tab. 2: Specification of diesel engine and electric dynamometer.

Kirloskar TAF1 Diesel Engine		Electric dynamometer	
No. of cylinders	1	Model	KBM105
Bore × Stroke	87.5 × 110 mm^2	kVA	5
Compression Ratio	17.5 : 1	Voltage	230 V
Rated Output as per IS: 11170	4.4(6) kW(hp)	Current	21.7 A
Rated Speed	1500 rpm	Frequency	50 Hz
Fuel Tank Capacity	6.5 liters	PF	1.0

The distance between the two thermocouples was 8.5 cm and 5 cm for horizontal and vertical conditions, respectively (see Fig. 2). All thermocouples were connected with two eight-selector temperature indicators MULTISPAN MS-1208 temperature indicator. A separate six selector temperature indicator was used to measure the airbox temperature, engine exhaust, PBTES inlet, and outlet. The temperature reading of all thermocouples is noted down every 5 minutes during the experiment process. All thermocouples are calibrated with the standard method and ±1% variation is observed.

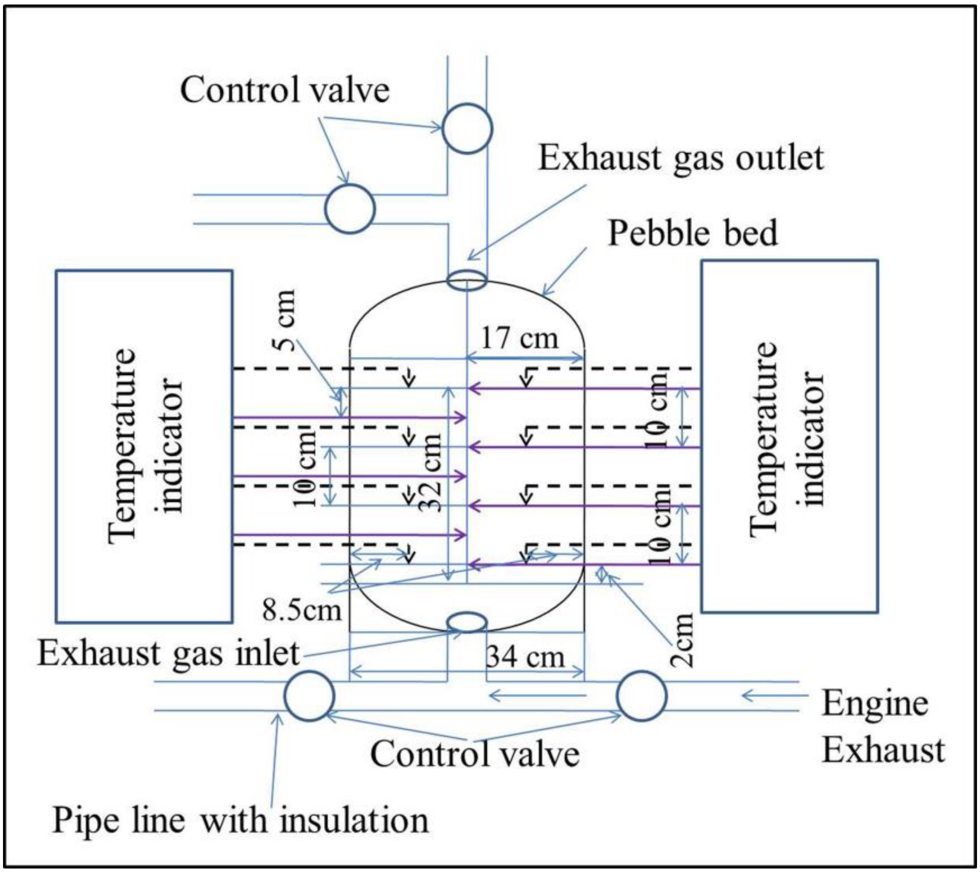

Fig. 2: A cross-section of the pebble bed showing thermocouples positions.

4. Methodology

The experiments were carried out at 1, 2 and 3 kW engine loads and compared with baseline case of no-load (0 kW). The whole experiment was performed in two stages: charging and discharging of the PBTES. The engine performance was obtained without integration of PBTES. Hence, the inlet control valve of PBTES was closed and the bypass valve was opened. The engine performance parameters were evaluated for brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) . After evaluating BTE at particular engine load, charging of PBTES was obtained by closing the bypass valve and opening the valve inlet to PBTES. In this case, the engine exhaust gases were allowed to flow through the pebble bed, as shown in Fig. 3(a). The engine parameters such as fuel flow rate, airflow rate and temperature at various locations were measured. These parameters were used to calculate the BTE of the engine during the charging process. The waste energy of exhaust gas is also stored in the PBTES during this process (charging, Fig. 3(a)). Then the engine was off to reach a steady state condition in PBTES. The measured temperature is used to see the temperature distribution over the pebble bed. It is further utilized to obtain the PBTES charging efficiency.

The discharging process is shown in Fig. 3(b), the engine is turned off and an air blower is used to airflow from the top of the PBTES. The valve arrangement and airflow are depicted in Fig. 3(b), where hot air is obtained at the bottom of PBTES system. The heat stored/recovered in the pebble bed during the charging/discharging is used to calculate charging and discharging efficiency. In order to estimate the performance of PBTES, the engine was operated at various loads. Further, the exergy concept has gained considerable interest because first law analysis is insufficient from an energy performance standpoint[34]. It is unable to provide sufficient information for the possible system imperfections. In this direction, various researchers also performed the exergy analysis on the thermal energy storage to find optimized performance[35-38]. Thus, to look in-depth analysis of the energy saved by PBTES, the exergy analysis was carried out for the steady flow steady-state condition. The exergy analysis is performed assuming that the change in potential, kinetic, electromagnetic and electrostatic exergy is negligible. For the exergy analysis, the atmospheric pressure and temperature (T_O) are taken as 1 atm and 40 °C (313 K), respectively, as the reference state condition.

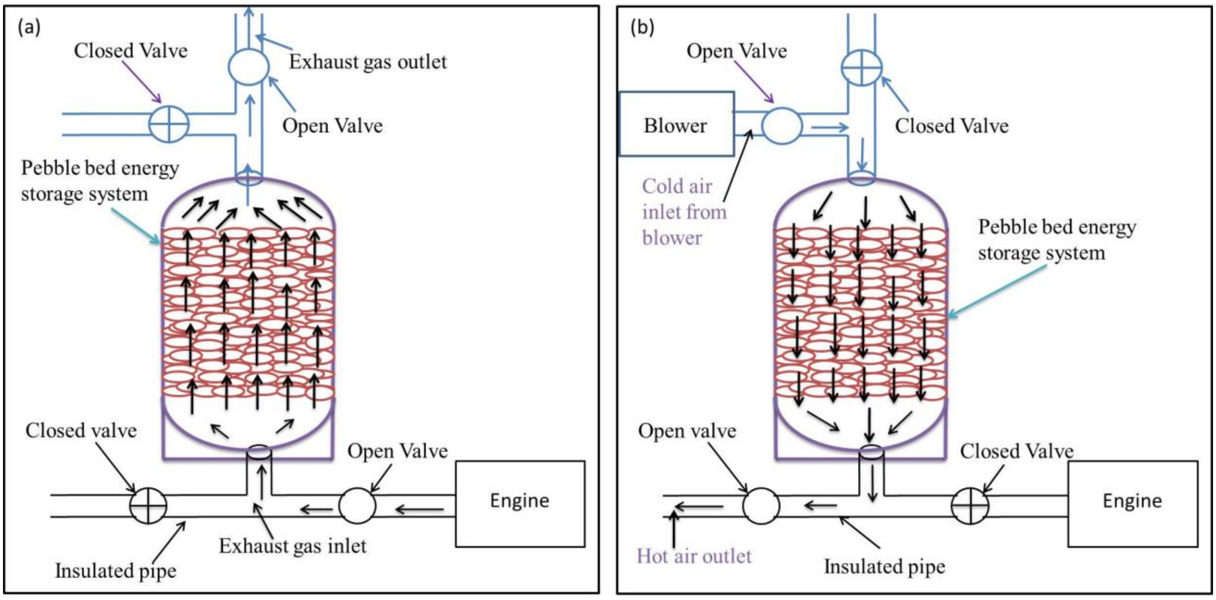

Fig. 3: (a) Charging and (b) discharging process of pebble bed thermal energy storage system.

Following simple thermodynamic relations were used to carry out exergy analysis[17, 23]. The input exergy of diesel engine (e_f) is calculated by [17]:

$$e_f = 1.04 Q_f \; [kW] \qquad (2)$$

where $Q_f = \dot{m}_f \times LCV$. However, exergy lost in exhaust gases ($e_{exhaust}$) is estimated as [23]:

$$e_{exhaust} = \dot{m}_{ex}[C_{p_{ex}}\{T_{eng.ex.gas} - T_{ambient}\} - T_O\{S_{eng.ex} - S_{ambient}\}][kW]$$

or

$$e_{exhaust} = \dot{m}_{ex}[C_{p_{ex}}\{T_{eng.ex.gas} - T_{ambient}\} - T_O(C_{p_{ex}}\int\frac{dT}{\mathrm{T}} - \mathrm{R}\ln\frac{\mathrm{Pout}}{Pin})] \; [kW] \; (3)$$

Moreover, exergy recovered (e_{PBTES}) by PBTES system can be obtained as [23]:

$$e_{PBTES} = \dot{m}_{ex} C_{p_{ex}}[\{T_{i\,PBTES} - T_{o\,PBESS}\} - \mathrm{T_o}\ln(\frac{T_{i\,PBTES}}{T_{o\,PBTES}})] \qquad (4)$$

Further, exergy charging rate ($e_{charging}$) can be calculated with the following expression:

$$e_{charging} = \frac{m_{pe}C_{p\,pebble}}{time}\left[\{T_{f\,pebble} - T_{i\,pebble}\} - T_o\,ln(\frac{T_{f\,Pebble}}{T_{i\,Pebble}})\right] \; kW \;\; (5)$$

The total exergy for combined storage and power (e_t) can be expressed as :

$$e_t = Electric\ output + e_{charging} \qquad (6)$$

Exergy efficiency (%) of diesel engine (only power):

$$\eta_{p\ exergy} = \frac{Electricoutput}{e_f} \times 100 \qquad (7)$$

Exergy efficiency (%) for combined storage and power:

$$\eta_{exergy\ CSP} = \frac{e_{tCSP}}{e_f} \times 100 \qquad (8)$$

Exergy saved:

$$e_{saved} = \frac{e_{charging}}{e_f} \qquad (9)$$

5. Results and Discussions

5.1. Engine performance analysis

Brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) are one of the most important parameters to evaluate engine performance. BTE defines as the ratio of brake power to heat supplied by fuel and BSFC can be obtained by the ratio of fuel consumption to brake power per unit hour. BTE versus applied load is shown in Fig. 4, with and without the integration of PBTES.

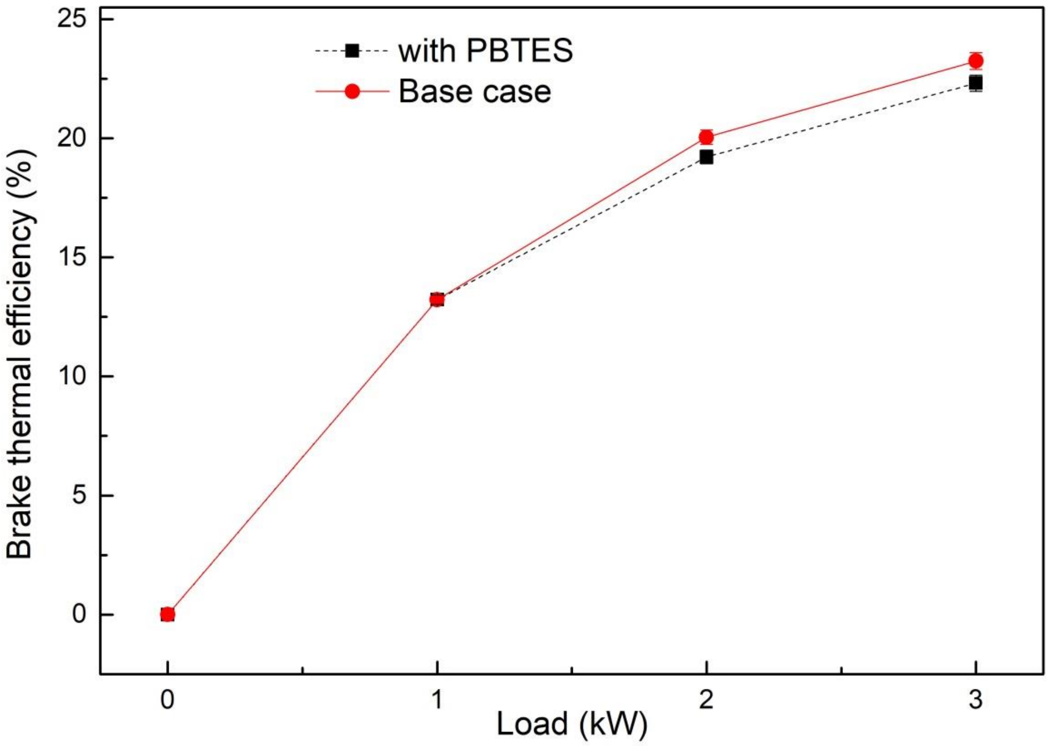

Fig 4: BTE with and without pebble bed thermal energy storage system at different loads.

Fig. 4 shows that BTE is increasing with an increase in applied load. This is the engine's general behavior where maximum BTE is obtained at 80% load. In this work, the 80% load capacity of the engine is equal to ~3.5 kW[3, 14]. However, due to losses in the fabricated PBTES system, we are limited to the maximum load of 3 kW. A slight decrease in BTE is obtained with the integration of PBTES system at 3 kW. The variation in the BTE can be the effect of back pressure arising due to PBTES [13, 39]. However, the change in BTE is small with PBTES; hence, it can be assumed that it doesn't significantly affect the engine performance.

5.2. Charging and heat loss analysis of PBTES

The temperature profile inside the pebble bed at a load of 3 kW is shown in Fig. 5. A similar curve was obtained at other loads (not shown here). At a lower load, the temperature of exhaust gases was low; hence, only the values of temperatures were different at a particular time. It shows that the saturation temperature of PBTES is a function of the bed height. The saturation time is larger for the longer bed height (at 27 and 32 cm). However, at the bed's lower height (2 and 7 cm), the exhaust gas temperature reached a constant temperature of ~425 °C after 15-30 minutes. Fig. 5 presents temperature distribution during the charging of PBTES. After charging, the temperature difference between PBTES system and the ambient was very high. Hence, due to this temperature difference, there was heat loss from PBTES system.

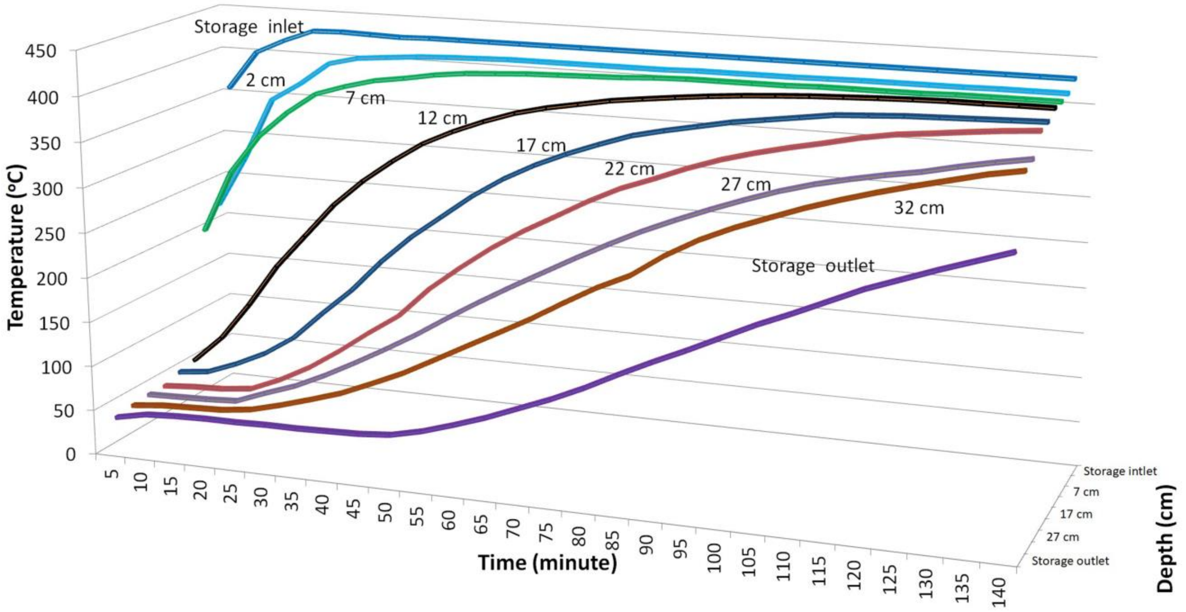

Fig. 5: Temperature distribution in the pebble bed at different heights and time intervals under a 3 kW load during the charging period [40].

Fig. 6 depicted heat loss versus time at a different height in PBTES. It shows that the pebble layer's temperature at the height of 2 cm from the bottom and 32 cm height had the highest temperature decline in the first two hours. This was because lower and upper portions of the pebble bed are exposed to open space (diverging and converging sections). After a span of 2 hours, heat losses were reduced due to upper and lower pebble layers' temperature stability. The middle layer of the pebble bed has a constant slope of temperature drop. If the engine is operated at a higher load, exhaust gas temperatures are more, which means a large amount of heat can be stored. However, a large amount of heat is also lost by PBTES in a short time due to very high temperatures. Thus, good insulation is required to obtain maximum energy storage, whereas it increases the cost of setup.

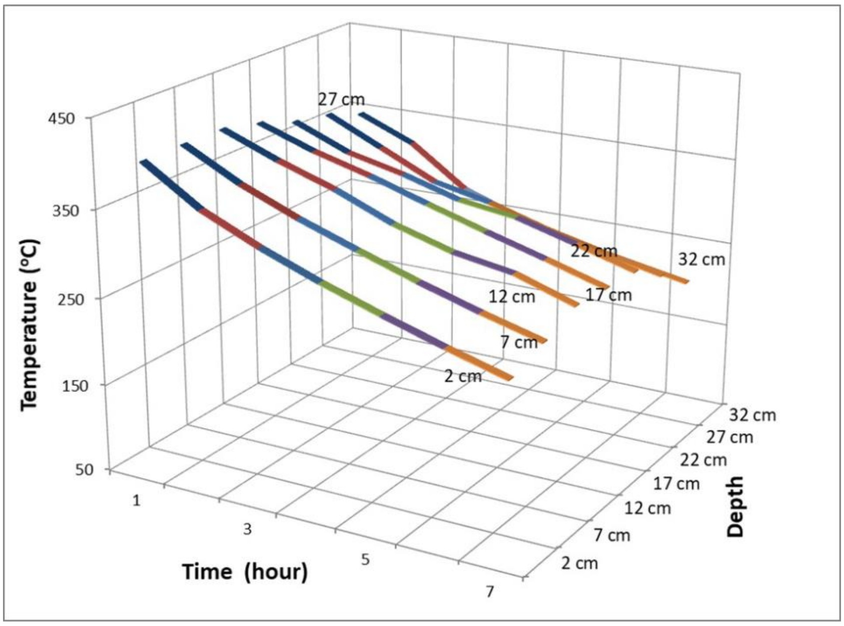

Fig. 6: Temperature decline (heat loss) from the pebble bed after charging at 3 kW load [40].

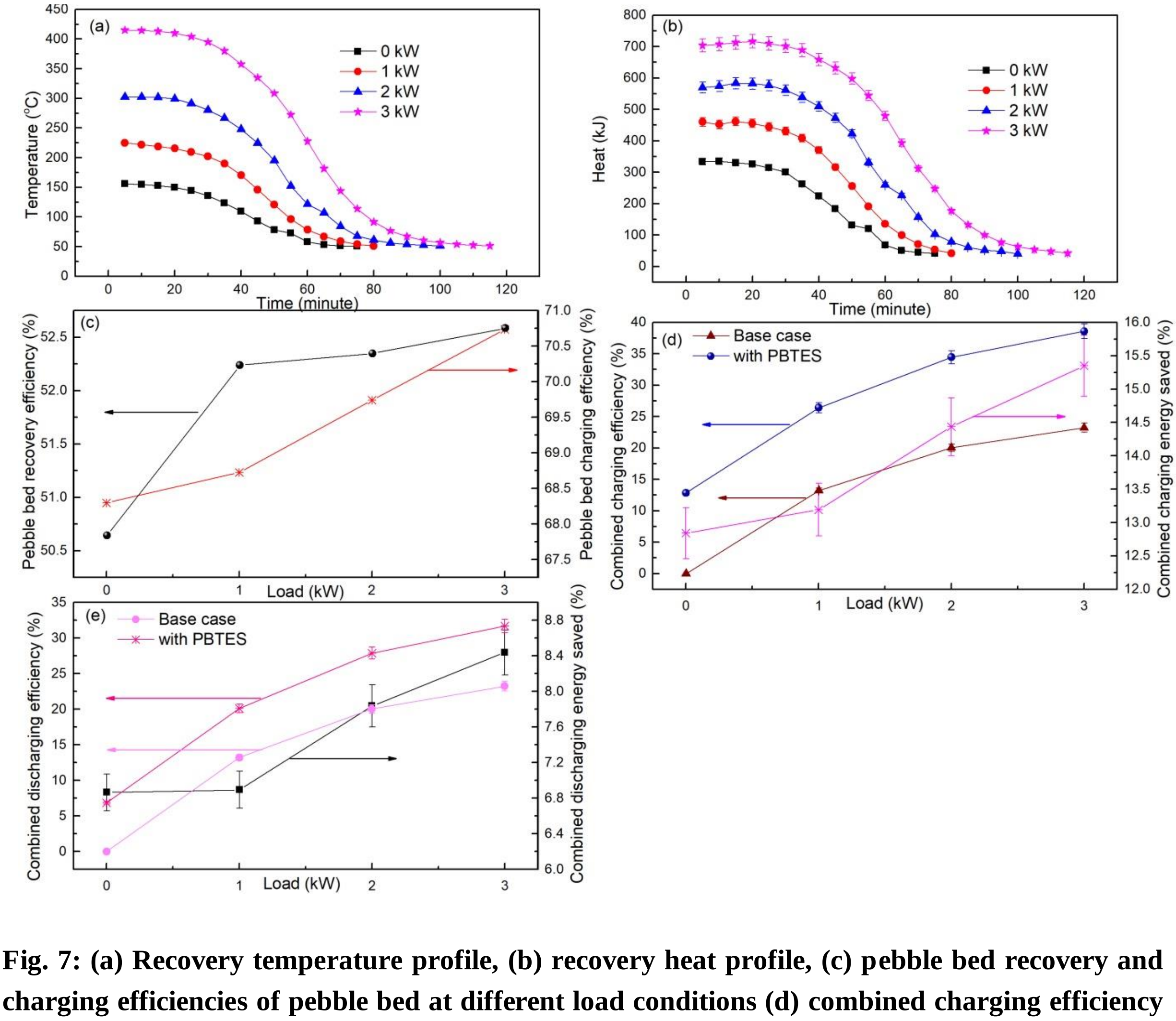

Fig. 7: (a) Recovery temperature profile, (b) recovery heat profile, (c) pebble bed recovery and charging efficiencies of pebble bed at different load conditions (d) combined charging efficiency and energy saved at various loads according to heat stored in pebble bed during charging (e) Combined discharging efficiency and energy saved at various loads according to heat recovered by pebble bed [40].

5.3. Heat recovery analysis of PBTES

In the discharging or heat recovery process, the engine is turned off and the air was blown through the PBTES with the help of a blower (Fig. 3). Temperature and heat recovery profiles were plotted for every 5 minutes interval and are depicted in Figs. 7(a) and (b), respectively. The discharging is measured immediately after the engine is turned off. It is found that when the load is 1 kW, the heat available for recovery is less because of the lesser temperature of pebble bed. However, large energy recovery is available if the engine runs at a maximum load of 3 kW. At 3 kW load, more time is required to extract the heat than in lower load or no-load condition, as shown in Figs. 7(a) and (b). This is because at 3 kW maximum inlet temperature in PBTES was ~425 °C, whereas it was 160 °C at no load.

5.4. Energy saving analysis by pebble bed

5.4.1 Charging and recovery efficiency

Pebble bed charging and recovery efficiency as a function of load are depicted in Fig. 7(c). The charging efficiency can be calculated by the ratio of energy stored in the tank to the actual energy supplied during the charging process. Similarly, the recovery or discharging efficiency can be estimated by the heat ratio recovered to the total heat stored in the pebble bed during charging. It is observed that the charging efficiency increases with increasing load and achieved a maximum value of ~60-74% at the highest tested loads. However, the maximum recovery efficiency is obtained as ~52.5% at maximum load. It suggests that about half of the stored energy is lost from the fabricated PBTES. Hence, one can look for perfect insulation materials to avoid heat loss from the pebble bed. However, as said earlier, it will increase the cost of the system. Therefore, in the present work, cheap insulation materials are used to see the possibility of integrating PBTES with the engine instead of maximizing the energy storage capacity of the system.

5.4.2 Percentage energy saved and combined efficiency

The percentage of energy saved is a direct measure of the overall efficiency improvement of the system. It is related to saving fuel power (energy needed over and above to produce an equal amount of energy saved by introducing the storage system) and combined efficiency is the integrated system's efficiency. The percentage of combined charging and discharging energy saved, combined charging and discharging efficiency at different loads are given in Figs. 7(d) and (e). The combined charging efficiency is obtained considering the ratio of heat stored in the PBTESS during charging to fuel energy input with engine efficiency. However, the combined discharging efficiency is calculated by adding engine efficiency and the ratio of the amount of heat recovered during discharging by PBTES to fuel energy input. The percentage of energy saving of an integrated system varies from 11% to 15%. Fig. 7(d) also gives the saved combined charging energy as a ratio of heat stored in the pebble bed during the charging process to fuel energy. Fig. 7(e) provides the combined discharging energy-saving with a ratio of heat recovered during discharging to fuel energy. The actual energy saved is significantly less as compared to stored energy. This is due to heat loss from PBTES and thermodynamic limitations. It is seen from the diagram that the engine efficiency of the integrated system is increased by 16% at 3 kW and it becomes 38% according to heat stored in the pebble bed during the charging process.

5.5. Exergy analysis

The Eq.s presented in section 4 are used to calculate the exergy analysis and the results are presented in Tab. 3. It shows that as the load varies from 0 to 3 kW, the input exergy to the diesel also increases 5.765 to 14 kW. The exergy efficiency of the combined (engine+PBTES) system is found as 1.31% (at no load) and 24.75% (at 3 kW), corresponding exergy saved is obtained as1.31% (at no load) and 3.32% (at 3 kW). This is due to the fact that at a higher load (i.e. 3 kW), the temperature of the exhaust is higher. The results show the maximum exergy saving is 3.32%; however, the energy saving efficiency is 15% at 3 kW.

Tab. 3: Values of various parameters of exergy analysis at different load conditions

S.No	Parameters	0 kW	1 kW	2 kW	3 kW
1	The input exergy to the diesel engine (e_f) [kW]	5.765	7.87	10.845	4.000
2	Electric output [kW]	0	1	2	3
3	Exergy recovered (e_{PBTES}) [kW]	0.0896	0.1549	0.2922	0.446
4	Exergy charging rate (e_{charging}) [kW]	0.076	0.147	0.269	0.466
5	Total exergy for combined power and storage (e_t) [kW]	0.076	1.147	2.269	3.466
6	Exergy efficiency in % for the diesel engine ($\eta_{p\ exergy}$)	-	12.70	18.44	21.42
7	Exergy efficiency in % for combined storage and power ($\eta_{exergy\ CSP}$)	1.31	14.57	20.92	24.75
8	Percentage exergy saved (e_{saved})	1.31	1.86	2.48	3.32

6. Conclusions

The pebble bed thermal energy storage (PBTES) system is developed and successfully integrated with an air-cooled stationary diesel engine. The experimental investigation is carried out at different loads of 0, 1, 2 and 3 kW, and the following conclusions were drawn:

1. There was no significant impact of back pressure on the engine due to the integration of PBTES.
2. The charging efficiency of PBTES approaches nearly 60%-74% at different load conditions. It is observed that with an increase in the load, the charging efficiency of the PBTEs is increased.
3. When the engine was integrated with PBTES, 11–15% of the total heat energy of the fuel is saved.
4. The combined efficiency of the integrated system varied from 10 - 38% at different load conditions.
5. The highest exergy saved is obtained as 3.32% at a load of 3 kW.

Nomenclature

BSFC-brake specific fuel consumption [kg/kWh]
BTE-brake thermal efficiency [%]

$C_{p\,pebble}$ -heat capacity of pebble [J/kgK]
$C_{p_{ex}}$ - specific heat of exhaust gases [J/kgK],
LCV -lower caloric value of fuel [kJ/kg]
$\dot{m}_f$ -mass flow rate of fuel [kg/s]
PBTES-pebble bed thermal energy storage
TESS-thermal energy storage system
m_{pe} -mass of pebble [kg]
$\dot{m}_{ex}$ - mass flow rate of exhaust gases [kg/s]
$T_{eng.ex.gas}$ - engine exhaust gas temperature [°C]
$T_{ambient}$ - ambient temperature [°C].
$T_{i\,PBTES}$ -input temperature in PBTES [°C]
$T_{o\,PBESS}$ - output temperature of PBTES [°C].
$T_{f\,pebble}$ - final temperature of pebble [°C]
$T_{i\,pebble}$ - intial temperature of pebble [°C]
V -volume of bed [m^3]
ρ - density of pebbles [kg/m^3]
ε - porosity of the pebble bed

References

[1] Hoang, A.T., Waste heat recovery from diesel engines based on Organic Rankine Cycle, *Applied Energy*, *231*. (2018), pp. 138-166, DOI No. https://doi.org/10.1016/j.apenergy.2018.09.022

[2] Jadhao, J.,D. Thombare, Review on exhaust gas heat recovery for IC engine, *International Journal of Engineering and Innovative Technology (IJEIT)*, *2*. (2013), 12

[3] Goyal, R., *et al.*, Performance and emission analysis of CI engine operated micro-trigeneration system for power, heating and space cooling, *Applied Thermal Engineering*, *75*. (2015), pp. 817-825

[4] Gatts, T., *et al.*, An experimental investigation of H2 emissions of a 2004 heavy-duty diesel engine supplemented with H2, *International Journal of Hydrogen Energy*, *35*. (2010), 20, pp. 11349-11356

[5] Tartakovsky, L.,M. Sheintuch, Fuel reforming in internal combustion engines, *Progress in Energy and Combustion Science*, *67*. (2018), pp. 88-114

[6] Thawko, A., *et al.*, Particle emissions of direct injection internal combustion engine fed with a hydrogen-rich reformate, *International Journal of Hydrogen Energy*, *44*. (2019), 52, pp. 28342-28356

[7] Goyal, R., *et al.*, An experimental investigation of CI engine operated micro-cogeneration system for power and space cooling, *Energy Conversion and Management*, *89*. (2015), pp. 63-70

[8] Hatami, M., *et al.*, Experimental and numerical analysis of the optimized finned-tube heat exchanger for OM314 diesel exhaust exergy recovery, *Energy Conversion and Management*, *97*. (2015), pp. 26-41

[9] Hountalas, D., *et al.*, Study of available exhaust gas heat recovery technologies for HD diesel engine applications, *International Journal of Alternative Propulsion*, *1*. (2007), 2-3, pp. 228-249

[10] Choi, Y., *et al.*, Waste heat recovery of diesel engine using porous medium-assisted thermoelectric generator equipped with customized thermoelectric modules, *Energy Conversion and Management*, *197*. (2019), p. 111902

[11] Kim, T.Y., *et al.*, Waste heat recovery of a diesel engine using a thermoelectric generator equipped with customized thermoelectric modules, *Energy Conversion and Management*, *124*. (2016), pp. 280-286

[12] Kim, T.Y., *et al.*, Energy harvesting performance of hexagonal shaped thermoelectric generator for passenger vehicle applications: An experimental approach, *Energy Conversion and Management*, *160*. (2018), pp. 14-21

[13] Johar, D.K., *et al.*, Comparative studies on micro cogeneration, micro cogeneration with thermal energy storage and micro trigeneration with thermal energy storage system using same power plant, *Energy Conversion and Management*, *220*. (2020), p. 113082
[14] Johar, D.K., *et al.*, Experimental investigation on latent heat thermal energy storage system for stationary CI engine exhaust, *Applied Thermal Engineering*, *104*. (2016), pp. 64-73
[15] Pandiyarajan, V., *et al.*, Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system, *Applied energy*, *88*. (2011), 1, pp. 77-87
[16] Al-Abidi, A.A., *et al.*, Numerical study of PCM solidification in a triplex tube heat exchanger with internal and external fins, *International journal of heat and mass transfer*, *61*. (2013), pp. 684-695
[17] Pandiyarajan, V., *et al.*, Second law analysis of a diesel engine waste heat recovery with a combined sensible and latent heat storage system, *Energy policy*, *39*. (2011), 10, pp. 6011-6020
[18] Zhang, H., *et al.*, Thermal energy storage: Recent developments and practical aspects, *Progress in Energy and Combustion Science*, *53*. (2016), pp. 1-40
[19] Singh, H., *et al.*, A review on packed bed solar energy storage systems, *Renewable and Sustainable Energy Reviews*, *14*. (2010), 3, pp. 1059-1069
[20] Kedida, D.K., *et al.*, Performance of a Pebble Bed Thermal Storage Integrated with Concentrating Parabolic Solar Collector for Cooking, *Journal of Renewable Energy*, *2019*. (2019), p. 4238549, DOI No. 10.1155/2019/4238549
[21] Sarbu, I.,C. Sebarchievici, A comprehensive review of thermal energy storage, *Sustainability*, *10*. (2018), 1, p. 191
[22] Mawire, A.,S.H. Taole, A comparison of experimental thermal stratification parameters for an oil/pebble-bed thermal energy storage (TES) system during charging, *Applied Energy*, *88*. (2011), 12, pp. 4766-4778
[23] Johar, D.K., *et al.*, Experimental investigation and exergy analysis on thermal storage integrated micro-cogeneration system, *Energy Conversion and Management*, *131*. (2017), pp. 127-134
[24] Medrano, M., *et al.*, Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems, *Applied energy*, *86*. (2009), 10, pp. 2047-2055
[25] GOPAL, N., *et al.*, Thermodynamic analysis of a diesel engine integrated with a PCM based energy storage system, *International Journal of Thermodynamics*, *13*. (2010), 1, pp. 15-21
[26] Mavridou, S., *et al.*, Comparative design study of a diesel exhaust gas heat exchanger for truck applications with conventional and state of the art heat transfer enhancements, *Applied Thermal Engineering*, *30*. (2010), 8-9, pp. 935-947
[27] Hänchen, M., *et al.*, High-temperature thermal storage using a packed bed of rocks–heat transfer analysis and experimental validation, *Applied Thermal Engineering*, *31*. (2011), 10, pp. 1798-1806
[28] Kürklü, A., *et al.*, A study on the solar energy storing rock-bed to heat a polyethylene tunnel type greenhouse, *Renewable Energy*, *28*. (2003), 5, pp. 683-697
[29] Paul, B.,J. Saini, Optimization of bed parameters for packed bed solar energy collection system, *Renewable Energy*, *29*. (2004), 11, pp. 1863-1876
[30] Singh, R., *et al.*, Nusselt number and friction factor correlations for packed bed solar energy storage system having large sized elements of different shapes, *Solar energy*, *80*. (2006), 7, pp. 760-771
[31] Gautam, A.,R.P. Saini, A review on technical, applications and economic aspect of packed bed solar thermal energy storage system, *Journal of Energy Storage*, *27*. (2020), p. 101046, DOI No. https://doi.org/10.1016/j.est.2019.101046
[32] Franklin, S.B., *et al.*, Experimental Investigation on the Heat Transfer in fluid flow through Porous media in Pebble Bed Heat Exchanger, *International Journal of Applied Engineering Research*, *10*. (2015), 50, pp. 905-916
[33] Franklin, M.S.B.,K. Ramesh, Experimental Investigation on Heat Recovery from Diesel Engine Exhaust Using Pebble Bed Heat Exchanger and Thermal Energy Storage System, *International Journal of Applied Engineering Research*, *10*. (2015), 16, pp. 37090-37098

[34] Terzi, R., *Application of exergy analysis to energy systems*, in: *Application of Exergy*, (Ed., Editor^Editors), Intech open: London, UK. 2018.
[35] Xu, Y., *et al.*, Exergy analysis and optimization of charging–discharging processes of latent heat thermal energy storage system with three phase change materials, *Solar energy*, *123*. (2016), pp. 206-216
[36] Rismanchi, B., *et al.*, Energy, exergy and environmental analysis of cold thermal energy storage (CTES) systems, *Renewable and sustainable energy reviews*, *16*. (2012), 8, pp. 5741-5746
[37] Rahimi, M., *et al.*, Energy and exergy analysis of an experimentally examined latent heat thermal energy storage system, *Renewable Energy*, *147*. (2020), pp. 1845-1860
[38] Song, H.-j., *et al.*, Exergy analysis and parameter optimization of heat pipe receiver with integrated latent heat thermal energy storage for space station in charging process, *Applied Thermal Engineering*, *119*. (2017), pp. 304-311
[39] Johar, D.K., *et al.*, Experimental investigation of thermal storage integrated micro trigeneration system, *Energy Conversion and Management*, *146*. (2017), pp. 87-95
[40] Patel, Satyanarayan, Pebble Bed Heat Recovery and Storage System, *LAP Lambert Academic Publishing* , (2018), pp.1-108.

Submitted: 28.06.2021.
Revised: 16.02.2022.
Accepted: 16.03.2022.