Integration of Packed-bed Thermal Energy Storage in Solar Heat System for a Food Industry

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Abstract

Thermal energy storage (TES) is a key technology to increase efficiency of solar energy in industrial applications. Especially, packed-bed TES systems filled with low cost and sustainable sensible thermal energy storage materials (STESMs) decrease the energy cost and provide green industries by increasing use of solar energy. In this study, integration of packed-bed TES system filled with new sustainable and low cost STESMs developed from demolition wastes in a solar heat industrial process (SHIP) was simulated. Potato crisp production process was selected as a case study. Results showed that packed-bed TES system integrated with solar plant could provide 39.2 % saving in fossil fuel consumption of potato crisp production process.

Keywords: Demolition waste, packed-bed, solar heat industrial applications, thermal energy storage.

1.Introduction

Total energy consumption in the world was 9717 Mtoe in 2019 and industry is the largest energy-consuming sector in the world with 37 % share (IEA, 2019a). Industrial energy systems are mainly based on fossil fuels that causes serious environmental problems mainly air pollution and global warming. One-fifth of the 33 Gt global CO_2 emissions were released to nature by industry in 2019 (IEA, 2019b). World leaders from 130 countries have committed to "keeping the rise in global mean temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels." according to Paris agreement in 2017 (UNFCCC, 2015). Renewable energy sources can play an important role in industries to meet long-term climate and other sustainability goals.

Using renewable energy in industrial applications can reduce dependency on fossil fuels, decrease production cost and increase competitiveness in global market. Solar energy is one of the most abundant and eco-friendly renewable source, especially for processes up to 200°C (Koçak et al. 2020). Although, solar heat industrial applications are expected to reduce fuel cost and CO_2 emissions, there are only 741 industrial heat solar plants (SHIP) in the world that supply approximately 567 MW_{th} heat for industrial processes (IEA, 2019c). The current industrial solar use is less than 1% of the worldwide installed solar capacity (IEA, 2019c). Today, solar thermal applications are mainly used in residential, hospitals, shopping malls etc in building sector.

Only drawback is intermittency of solar energy, which necessitates using it with a suitable TES technology (Koçak et al. 2020). TES is a key technology to increase efficiency of solar energy in industrial applications (Koçak et al. 2020). The integration of TES systems using eco-innovative storage materials can increase energy efficiency and sustainability of solar heat industrial applications. Using storage materials based on wastes for energy saving complies with circular economy that is one of the main blocks of European Union Green Deal.

Recent studies focus on reducing fossil fuel consumption in industrial application by integrating TES system in solar heat industrial applications. Packed-bed TES systems filled with cheap and high energy density packing materials are preferable options for industrial applications due to their low cost and high storage capacity (Khare et al., 2013; Alonso et al., 2016; Koçak et al. 2020). Experimental data from lab-scale and pilot scale packed bed TES systems are crucial for potential large scale TES systems in industrial applications. Besides, mathematical models can be used to estimate storage performance and optimum design parameters (Buscemi et al. 2018,

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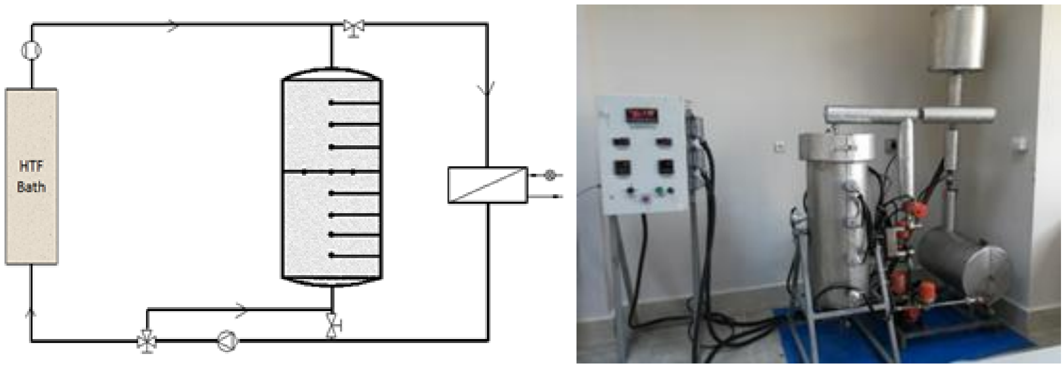
Cardenas et al. 2019, Singh et al. 2019). In our previous studies (Koçak and Paksoy, 2019; 2020; Koçak et al. 2020), new eco-innovative STESM was developed from demolition waste and its performance was evaluated in a lab-scale packed-bed TES system in the temperature range of 130 °C – 180 °C.

In this study, a scaled-up simulation study was carried out for a potato crisp production process based on the findings from lab-scale packed-bed TES system filled with new STESM developed from demolition wastes. Economic and environmental impacts were evaluated.

2.Materials and methodology

2.1 Lab-scale TES system

Laboratory scale packed bed TES system was built based on the scheme given in Fig. 1a. The real system given in Fig. 1b consists of a cylindrical storage tank with a height of 0.9 m and diameter of 0.3 m, oil bath, flow meters, oil pump, 2-way and 3-way valves, heat exchanger, heating coil and thermocouples.



(a) **(b)**

Fig. 1: Lab-scale packed-bed TES system

In lab-scale TES system design, packing material developed from demolition waste and Therminol 66 as HTF were used. STESM developed from demolition waste is a potential low-cost STESM for industrial solar applications up to 750°C (Koçak and Paksoy, 2019). Therminol 66 was selected as HTF due to its operation capability in medium temperature range. Lab-scale packed-bed TES system properties are listed in Table 1 (Koçak and Paksoy, 2020). Thermal energy storage experiments were carried out in fluid temperature range of 80 - 180 °C for charging and fluid flow rate from 50 kgh^{-1} to 750 kgh^{-1}. At the optimum operating conditions, system energy efficiency reached to 65%.

Tab. 1: Properties of industrial scale TES system

Parameter	Value	Unit
Height of storage tank; h_{tank}	0.9	m
Diameter of storage tank; D_{tank} (m)	0.3	m
Inlet temperature range; T_{in}	80-180	°C
Bed void fraction, ε	0.39	-
Diameter of solid; D_s	0.01	M
Fluid flow rate; ṁ	50-750	kgh^{-1}
Charging temperature; T_{charge}	240	°C
Discharging temperature; $T_{discharge}$	180	°C
Density of solid; ρs ,	2855	kgm^{-3}
Specific heat of solid, Cp_s	1450	$Jkg^{-1}C^{-1}$
Density of HTF; ρ_f	889 @ 180 °C	kgm^{-3}
Specific heat of HTF; Cp_f	2120 @180 °C	$Jkg^{-1}C^{-1}$
Maximum System Energy Efficiency, η_{sys}	65	%

2.2. Potato frying crisp process as a case study

Based on data obtained from lab-scale TES system, integration of large scale TES system in an industrial plant was investigated. For this purpose, a potato crisp frying process was selected as case study. Economic and environmental impacts of TES systems in potato crisp process were evaluated through 3 case studies given below.

2.2.1 Case 1: Current energy system

Current energy system of potato frying process studied previously by Wu et al (2012, 2013) was taken as the reference system. In the process shown in Fig. 2, raw potatoes are fed to the fryer at a flow rate of 1.0 kgs^{-1} to produce crisp potatoes at a flow rate of 0.28 kgs^{-1}. Hot sunflower oil at a range of 170-190 °C is circulated through the fryer. At the exit of the fryer, fresh sunflower oil is added to make up for the loss during frying. Combined oil at approximately 155 °C is sent to the heat exchanger. Combustion products flow through the heat exchanger to heat oil coming from fryer. After heat exchange, hot oil at approximately at 173 °C is returned to the fryer.

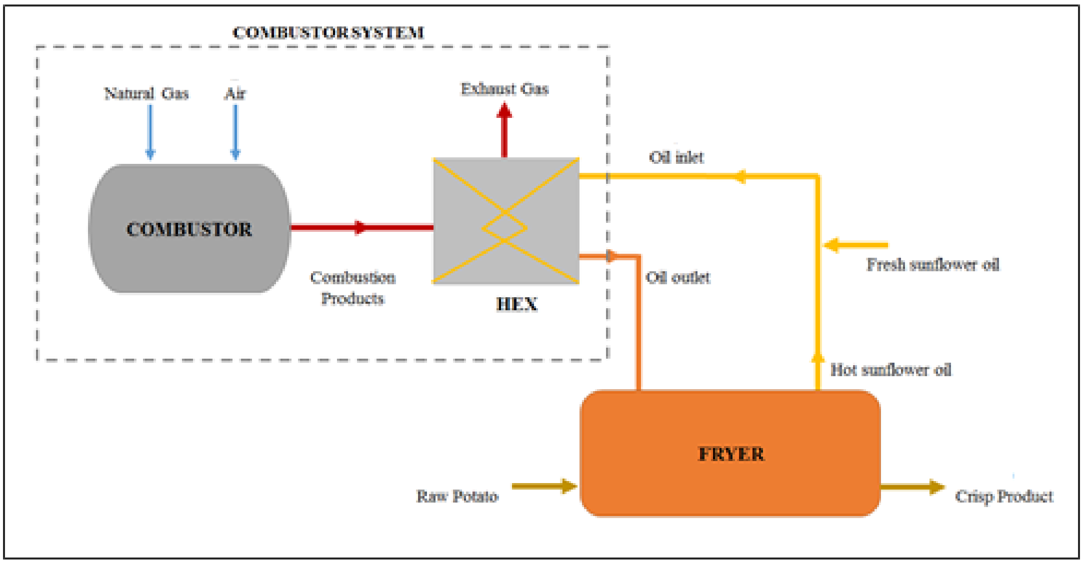


Fig.2: Energy supply diagram for case 1

2.2.2 Case 2: Integration of solar plant in potato crisp frying process

In case 2, solar energy integration in potato crisp production process was simulated as an alternative energy source. It was assumed that industrial plant is located in Adana, Turkey. According to data from Turkish Meteorological Service, average daily hours of sunshine are 7.5 hours in Adana (www.mgm.gov.tr). Solitem PTC4000 parabolic trough collector was selected as suitable collector type due to the process temperature range up to 250 °C and high efficiency (up to 75%). Considering annual average direct normal irradiation (DNI) value for Adana is 1900 $kWhm^{-2}$ per year, the gross collector area needed for potato crisp process was found as 5870 m^2 (Koçak, 2020).

2.2.3 Case 3: Integration of TES system in potato crisp frying process

In case 3, integration of packed-bed TES system with solar heat in potato crisp production process was evaluated as an alternative energy source. In TES system design, packing material developed from demolition waste and Therminol 66 as HTF were used. Industrial scale TES system properties are listed in Tab. 2 based on the data from lab-scale system.

Working principle of industrial scale packed-bed TES system is same with the lab-scale storage system. During the charging step, hot HTF enters top of the storage tank. Storage media absorbs heat from the hot HTF and HTF leaves from bottom of the tank. During the discharging step, cold HTF coming from HEX enters through bottom of the storage tank and hot packing materials release heat to the HTF. As a result, hot HTF leaves from top of the tank to provide heat to the process.

Tab. 2: Properties of industrial scale TES system

Parameter	Value	Unit
Bed void fraction, ε	0.39	-
Energy System Efficiency, η_{sys}	65	%
Charging temperature, T_{charge}	240	°C
Discharging temperature, $T_{discharge}$	180	°C
Density of solid, ρs	2855	kgm^{-3}
Specific heat of solid, Cp_s	1450	$Jkg^{-1}C^{-1}$
Density of HTF, ρ_f	840 @ 240 °C	kgm^{-3}
Specific heat of HTF; Cp_f	2340 @240 °C	$Jkg^{-1}C^{-1}$
Mass of components of system, m_{comp}	13	ton
Specific heat of components of system, Cp_{comp}	460	$Jkg^{-1}C^{-1}$

3.Results and discussion

Average energy requirement to increase frying oil temperature from 155 °C to 173 °C is 2650 kW. Energy requirement for process is supplied from a natural gas combustion system with an efficiency of 84%. Therefore, the combustor should have an average energy capacity of 3150 kW (Wu et al. 2012; 2013).

It was assumed that potato crisp frying process is working for 24 hours per day and 5 days per week. Considering working period, annual heat consumption for potato frying crisp process is 16.7 GW.

In case 2, 5870 m^2 solar plant was integrated in potato crisp frying process. The diagram of the solar system is shown in Fig. 3. Therminol 66 is selected as HTF due to its operation capability for medium temperature range. A shell and tube heat exchanger (HEX) with 90 % efficiency is used in the system to transfer heat from Therminol 66 to frying oil. Combustor system is still available in frying process as an axillary heater to provide heat when solar energy is not available or not enough.

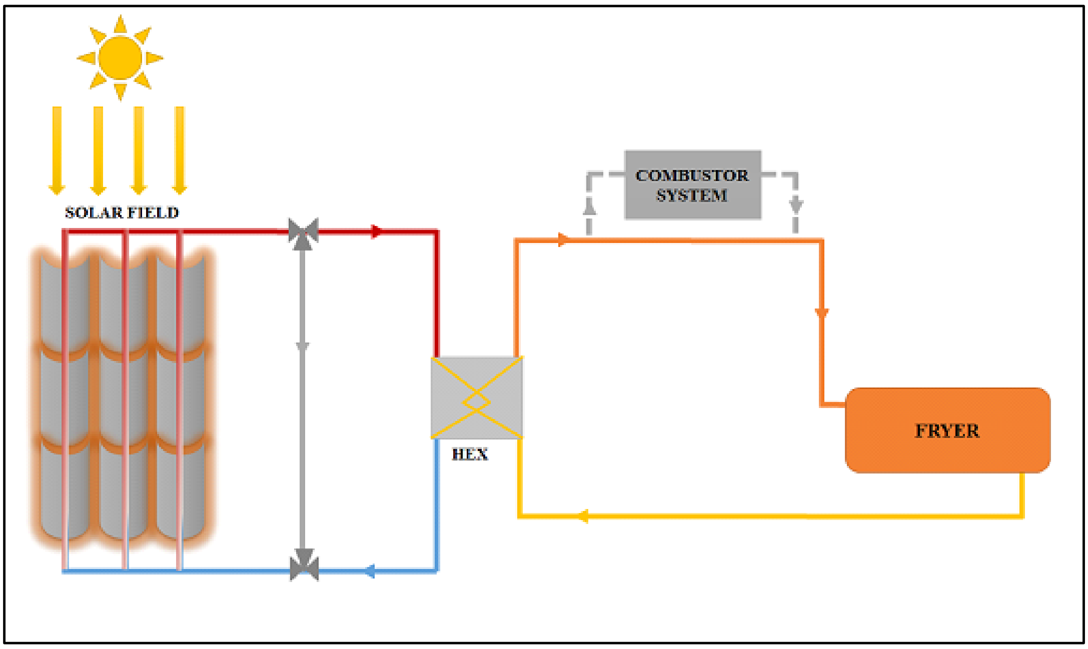


Fig. 3: Energy flow diagram for case 2

Although potato crisp frying process is shut down during weekends, solar system is operated 7 days per week. 7.85 GWh energy can be provided from 5870 m^2 PTC4000 solar field by operating 360 days per year with 1900 kWh/m^2 of DNI and average 7.5 hours of sunshine. 5.15 GWh of the available solar energy can only be provided for the process heating (Koçak, 2020). This is 29.8 % of annual total heat consumption of potato frying crisp process. The rest of 2.7 GWh can be stored in packed bed to be used later.

In case 3, packed-bed TES system was integrated into potato crisp frying process to increase efficiency of solar system. Fig.4 gives flow diagram for solar heat and TES integration in potato crisp process.

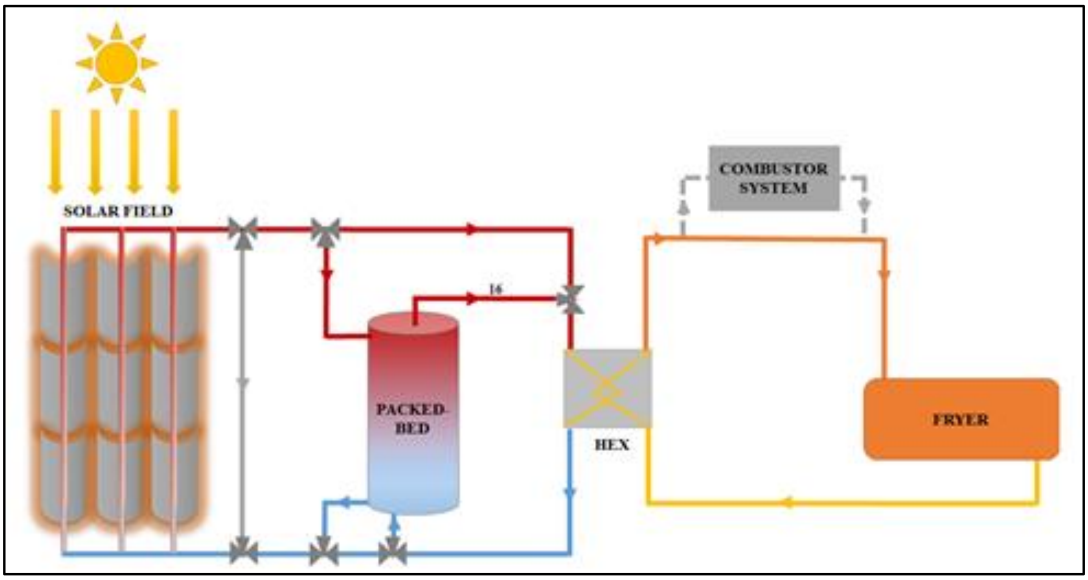


Fig. 4: Energy flow diagram for case s3

Maximum energy (E_{max}) that can be stored in the packed-bed system is the sum of energy stored in solid phase, fluid phase and other components of the system such as tank walls, filters etc. E_{max} can be calculated using Eq. 1 (IEA-ECES, 2018). According to Eq. 1, storage volume (V_{tank}) of 200 m^3 is needed to store annual excess heat of 2.7 GWh.

$$E_{max} = \int_{T_{in}}^{T_{out}} [V_{tank}(\varepsilon \rho_f(T) Cp_f(T) + (1-\varepsilon)\rho_s Cp_s) + m_{comp} Cp_{comp}] dT \quad \text{(eq. 1)}$$

Efficiency, the ratio of discharged energy (E_D) to charged energy (E_C), is calculated with Eq. 2 (Bruch et al. 2017)

$$\eta_E = \frac{E_D}{E_C} \quad \text{(eq. 2)}$$

Efficiency of packed bed storage system is assumed to be 65 % basd the experimental results of the lab-scale system (Koçak and Paksoy, 2020). Packed-bed storage system with this efficiency can provide 1.75 GWh energy per year. 90% of 1.75 GWh energy can be utilized by HEX. Hence, 1.58 GWh energy from TES system can be used for process heating.

As a result, packed-bed TES system with a volume of 200 m^3 increased the solar energy efficiency from 29.8 % to 39.2 %. This leads to reduction of total annual energy supply from combustor system from 11.7 GWh to 10.1 GWh.

Economic and environmental impacts of the TES system in this industrial application were evaluated for the case studies and shown in Tab. 2. Potato frying process analyzed as case study consumes 16.7 GWh energy per year for fryer oil heating. In this energy system used currently, process heat demand is totally provided from combustion system burning natural gas. According to natural gas provider company BOTAŞ, industrial natural gas price per unit consumption is 0.20 €/ m^3 for 2021. As a result, annual natural gas consumption price of case 1 is 380000 Euro excluding tax. Besides high energy cost, natural gas burning causes high amount of greenhouse gas emissions. According to EPA, CO_2 emission factor for natural gas combustion is 1.92 kg $CO_2 m^{-3}$. As a result, greenhouse gas emissions released to nature is 3650 tons.

5.0 GWh of process heat demand is supplied from Solitem PTC4000 solar field that has 5870 m^2 gross collector area. This provides 29.8% saving in both annual energy price and CO_2 emissions. Annual energy cost decreases from 380000 € to 267000 € and CO_2 emissions decreases from 3650 ton CO_2 per year to 2650 ton CO_2 per year.

Thermal energy storage systems increase the efficiency of solar systems by storing surplus solar heat. In case 3, energy efficiency reaches to 39.2 % by integrating 200 m^3 volume packed-bed TES system. Totally, 6.58 GWh energy can be provided from solar system. This energy represents CO_2 emissions reduction of 1430 tons per year. Besides, 148700 € saved per year.

Tab. 3: Economic and environmental impacts of case studies

Parameters	Case 1	Case 2	Case 3	Unit
Process Energy Demand	16.7	16.7	16.7	GWh
Energy supplied from combustor	16.7	11.7	10.1	GWh
Energy supplied from solar field	-	5.0	5.0	GWh
Energy supplied from TES	-	-	1.58	GWh
Natural gas consumption amount	1900800	1334150	1156430	m^3/year
Natural gas consumption cost	380000	267000	231300	€/year
Cost saving	-	113000	148700	€/year
CO_2 emissions	3650	2560	2220	ton CO_2/year
Saving	-	29.8	39.2	%

4.Conclusion

Thermal energy storage systems increase the efficiency of solar systems by storing surplus solar heat. Sustainability aspects of STESM make TES systems more favorable and allow using energy according to circular economy principles. In the case study given here, energy efficiency of solar system was increased from 29.8 % to 39.2 % by integrating packed-bed TES system filled with STESMs developed from demolition waste. Natural gas consumption and hence CO_2 emissions were also reduced. Also, valorization of demolition waste as STESM is a sustainable approach in reducing fossil fuel consumption of industrial applications and avoiding the use of natural resources as packing material.

5.Acknowledgments

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