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Energy and exergy analyses of an integrated solar heat pump system

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HIGHLIGHTS

- An integrated system is analysed using renewable energy source which can be used in textile industry.
- Energy losses and exergy destructions are calculated at all major components.
- Energy and exergy efficiencies of all subunits, subsystems and overall system are determined.
- A parametric study shows the effect of environment and operating conditions on efficiencies.
- Solar energy for heating in textile industry is efficient and environmentally friendly.

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ABSTRACT

An integrated solar and heat pump based system for industrial heating is developed in this study. The system comprises heat pump cycle for process heating water and solar energy for another industrial heating process. Comprehensive energy and exergy analyses are performed on the system. These analyses generated some compelling results as expected because of the use of green and environmentally friendly energy sources. The results show that the energy efficiency of the process is 58% while the exergy efficiency is 75%. Energetic COP of the heat pump cycle is 3.54 whereas the exergy efficiency is 42.5%. Moreover, the energetic COP of the system is 2.97 and the exergy efficiency of the system is 35.7%. In the parametric study, a different variation such as changing the temperature and pressure of the condenser also shows positive results.

1. Introduction

Energy is considered as the basic need in industrial processes around the world for economic development, better growth and modernization in the industrial sector. Modernization in industrial processes and their structures with the increasing usage of fossil fuels are causing new environmental problems [1]. The International Energy Agency claimed that, about 81% of energy is being provided by fossil fuels and this increasing demand of fossil fuels causes negative impact on environment in terms of acid rain, global warming and depletion of fossil resources. About 35% of world's total energy is used in industrial sectors [2]. One of the essential sectors of industrial heating is a process heating in which energy is transferred to the material for treatment. These materials include metal, plastic, cotton, rubber, textile, concrete, glass and ceramics [3].

The textile industry has a major role in the economies of many countries. This industry requires no large investment, but provides considerable amount of profit, especially in developing countries. Almost all of the major processes in textile industry require water heating systems and distribution. This heating involves the usage of fossil fuels which emit pollutants and large amount of carbon dioxide to the environment. In order to replace or minimize these traditional methods of heating, many researchers are looking towards renewable energy sources. Heating through renewable sources is a new mode of heating in industry, where heat is generated from renewable sources, instead of conventional electrical power (e.g. replacing a fossil fuel furnace/boiler using concentrated solar thermal or geothermal hot brine to transfer heat for desired output). The area of heating through renewable energy sources (RES) has received little awareness. On the other side a lot of work has been done to generate electricity by renewable sources [4]. This heating can be achieved by replacing fossil fuels through renewable energy sources as it has a large consumption of fossil fuel which is the area of concerned nowadays. The usage of solar, geothermal and biomass is therefore large for renewable energy heating and cooling (REHC) [5].

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One of the abundant renewable sources of heating is solar energy which is a well-known proven technology. It has zero negative effects on the environment compared to other conventional energy which gradually increase the earth average temperature and pollution. The earth's surface receives a daily solar dose of 10^8 kWh, which is equivalent to 500,000 billion oil barrels. This value is one thousand times any oil reserve known to human [6]. This availability makes solar energy less costly with no pollution. Solar thermal can be applied for used in heat pumps as space heating, space cooling and industrial process heating.

Numerous literature studies have discussed the utilization of solar thermal options in different applications. In their study, Calderoni et al. [7] studied solar thermal plants from economic point of view for process heat of the textile industry. They implemented solar thermal energy on three textile industries which have different textile processes. An industry which has a process of ironing clothes is suitable for using a medium temperature solar thermal system and temperature require to produce steam can easily be reached by solar thermal collectors. Moreover, results show that the solar thermal systems could provide better methods of heating systems economically in the textile processes.

Muneer et al. [8] constructed two different designs of water heating systems for dyeing purposes in the textile sector. These two designs have simple construction and low cost compared to thermosyphon heaters. The designs comprise plain and finned type heaters and three month data were collected for comparison. The data indicated that the solar fractions for plain and finned heaters were found to be 63% and 73%, respectively. Adel et al. [9] conducted a case study on the feasibility of using solar energy in textile dyeing. They proposed the two system in which the first can feed the dyeing process directly with hot water and the other can provide the boiler with hot water acting as a preheater. The first system is more economical than the second system and an environmental study confirmed that the solar system has less impact on the environment.

Lauterbach et al. [10] studied the potential use of solar heat in different industrial processes, particularly in Germany. Due to the low temperature requirement in the textile sector, about 25%–50% of heat demand could be fulfilled by solar thermal energy in the German textile sector. These numbers shows great potential of solar energy in industrial heating. Different integrated solar and heat pump systems were proposed and analysed by many researchers. Chow et al. [11] integrated the photovoltaic solar heat pump system as a sustainable alternative of electric/gas water heating system for building. In their numerical analysis they found out that heat pump with R-134a is capable of reaching average annual COP of around 6 with 12% PV efficiency. Quijera et al. [12] studied the exergy analysis of an integrated thermosolar and heat pump system for industrial processing of fish. The integration of a heat pump and solar energy improved their internal heat recovery and working together in parallel is more favourable than single.

Exergy, which is also called the availability, is a more proven tool to analyse energy systems thermodynamically. Exergy analysis is the use of energy and material resources effectively and has appeared as a significant method for system design and performance evaluation. Exergy is the useful amount of work produced by any system while interacting with reference-environment [13]. Exergy destruction and irreversibilities which is similar in a sense of loss during the process gives more realistic system losses than energy losses.

In this study, our focus is to integrate a renewable heat source with a conventional way of heating by heat pump which is used in low temperature heating processes such as in the textile industry. Moreover, the system in the present study is analysed exergetically which makes this system quite unique. Exergy destructions are calculated and evaluated for the process to determine how to improve it. Furthermore, a comprehensive performance assessment of the integrated system is conducted through parametric analysis to investigate the effects of changing environment and operating conditions on the system efficiencies.

2. System description

This integrated system comprises a solar system to raise the temperature of the heat transfer fluid (HTF), heat pump with heat recovery unit for industrial heating and different textile processes where hot water is used for dyeing, cleaning and ironing/pressing. Almost all of the processes need heating of liquid baths with different temperature ranges. For example, bleaching and dyeing require a temperature of around 60–90 °C, pressing needs 80–100 °C and a fixing process has a temperature demand of usually 160–180 °C. Usually hot water and hot air are used in these processes. During drying, a wet textile is passed through a drying mechanism. Different industries have different mechanisms for drying wet textiles. Most of them have heated cylinders from which a textile web is passed [14]. The cylinder is heated from inside by any heat source such as steam from boiler or hot air heated from heat pump. Ceylan et al. [15] investigated the use of a heat pump dryer experimentally for timber drying. Drying in the textile industry is an energy-intensive process after dyeing which uses large amounts of steam. Other processes in the textile industry are washing (cleaning), drying etc. which also require hot water for treatment, but here the energy utilization is not as much as drying. The above mentioned processes reveal the temperature limits in the textile industry and huge amounts of fuels and electricity consumed in such industries. Utilizing renewable sources along with conventional energy sources can reduce the overall energy cost, negative environmental impact and improve the system performance in terms of efficiency.

The system is illustrated in detail in Fig. 1. In order to have an efficient solar heating system, its working fluid should have a high critical temperature [16], so that more heat can be transferred from the solar system to the HTF. In the present analysis Therminol VP-1 is used as the HTF. In this cycle the temperature of HTF can be raised to 150 °C by the solar collector [17]. In Fig. 1, at point 1vp HTF enters into the solar collector and exit at point 2vp after heated by solar thermal. Now this heated heat transfer fluid is used as an input to the ironing process through steam. After the ironing process, the hot water goes to other process such as dyeing and cleaning where require temperature is around 60–90 °C. On the other side, a heat pump is also used for low temperature processes of cleaning and drying where the heat is carried through warm air. Air enters through a fan at point 2a which has a temperature of 39 °C and passes through a heat recovery unit. This air rejects heat in the evaporator where refrigerant enters at 4r and heated by this warm air. After the evaporator at point 4a air temperature falls to 12 °C and this cool air is preheated by the heat recovery before it goes to the condenser. After passing through heat recovery unit, air reaches the condenser of a heat pump where refrigerant enters at 2r with temperature 84 °C. In condenser, air is heated to a required temperature of 60 °C and after point 1a it reaches the supply fan by which it will proceed to textile processes. This warm air has several applications in the textile industry. It can be used for direct heating of water for washing. It is also used for low temperature drying of clothes with suitable humidity levels. Extra heating of textiles without maintaining humidity can degrade their quality. Heat pumps also have heat recovery units so that returned air is utilized to give heat to the evaporator. Moreover, a make-up water system is also installed which is also heated by solar energy. This make up