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Techno-economic evaluation of a ventilation system assisted with exhaust air heat recovery, electrical heater and solar energy

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ABSTRACT

The energy consumed to condition fresh air is considerable, particularly for the buildings such as cinema, theatre or gymnasium saloons. The aim of the present study is to design a ventilation system assisted with exhaust air heat recovery unit, electrical heater and stored solar energy, then to make an economical analysis based on life cycle cost (LCC) to find out its payback period. The system is able to recover thermal energy of exhaust air, store solar energy during the sunlight period and utilize it in the period between 17:00 and 24:00 h. The transient behaviour of the system is simulated by the TRNSYS 16 software for winter period from 1st of November to 31st of March for Izmir city of Turkey. The obtained results show that the suggested ventilation system reduces energy consumption by 86% compared to the conventional ventilation system in which an electrical heater is used. The payback period of the suggested system is found to be 5 years and 8 months which is a promising result in favour of the solar energy usage in building ventilation systems.

1. Introduction

Many people live, work, study or spend their leisure time in buildings having heating, ventilation and air conditioning (HVAC) system that provides hot/cold, fresh, and clean indoor air at proper temperature and humidity levels. In this manner, the ventilation process plays an important role on improving indoor air quality. If fresh air could not be supplied into the buildings, harmful pollutants such as CO_2 accumulate in indoor spaces. Fresh air cannot be supplied to the building directly, in general. An HVAC system should heat or cool fresh air first, and then supplies it into the indoor space to prevent destroying of indoor thermal comfort. Due to its costly operation, some energy saving strategies can be established for heating or cooling processes of fresh outdoor air. Nowadays, the usage of heat recovery and energy storage is an effective trend. Due to limited fossil fuel resources and their hazardous environmental impacts, utilization of renewable energy resources becomes one of the most important research areas for HVAC systems in recent decades. Solar energy is a reliable and convenient energy resource; however, the variability and discontinuity of solar radiation cause serious difficulties on its applicability. Thermal energy storage systems have been developed to overcome the problem of solar radiation discontinuity. Thermal energy storage systems can store solar energy during peak periods to utilize it during the lower solar radiation or solar off periods. Solar energy can be stored by sensible, latent or chemical storage systems. Among them, the sensible energy storage may be the simplest and the most convenient choice for practical applications.

Studies on the use of thermal sensible energy storage for an HVAC system can be found in the related literature. The storage medium is mostly water, natural soil, special soils (i.e. gravel, grit or sand) or a combination of these materials. Solar energy is stored in these media and used later on. Literature survey shows that seasonal thermal storage is preferred in the most of studies. Ozyogurtcu [1] showed that the use of solar assisted ventilation system with heat recovery unit reduces considerably ventilation energy consumption compared with conventional ventilation system in which only an electrical heater operates. Kroll and Ziegler [2] investigated the use of ground heat storage and evacuated tube solar collectors for meeting the annual heating demand of family-sized houses. In their seasonal storage system study, soil is used as a storage material. They found that the system with a ground heat storage and high quality evacuated tube collector is able to supply an essential part of heat demand of a family-sized houses. Simons and Firth [3] performed a study on life cycle assessment of a 100% solar fraction thermal supply to a European apartment building by using water-based seasonal sensible heat storage. They compared 100% solar heating system recently installed in a Swiss apartment building with five alternative heating systems on the basis of life cycle assessment. Terziotti et al. [4] studied on the modelling seasonal solar thermal energy storage (SSTES) in a large urban residential building using the software called TRNSYS 16. Their seasonal solar

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thermal energy storage system used two closed fluid (water) loops. One loop ran through solar collectors to heat the fluid, then into coils inside the storage medium. Fehrm et al. [5] studied on exhaust air heat recovery units in buildings. They investigated systems use exhaust air as a source of heat for the appliances. Yumrutaş and Ünsal [6] performed an energy analysis and modelling of a solar assisted house heating system with a heat pump and an underground energy storage tank. Results of their study indicated that an operational time span of 5–7 years would be necessary before the system could attain an annually periodic operating condition. Calise et al. [7] performed a study on transient analysis and energy optimization of solar heating and cooling systems in various configurations. The simulation model was developed by using the TRNSYS software, and included the analysis of the dynamic behaviour of the building in which the solar heating and cooling systems were supposed to be installed. The obtained results of the study analyzed on monthly and weekly basis were encouraging. Ortiz et al. [8] modelled a solar-assisted HVAC system with thermal storage for the Mechanical Engineering Department building of the University of New Mexico in order to predict performance and optimize control parameters. They found that the solar assist could account meet for over 90% of the total heating requirements, if certain energy conservation strategies are adopted. Further information on the utilization of heat of exhaust air and solar energy in the buildings for heating purpose can be found in Refs. [9–11].

For economic analysis of HVAC system, the study of Kizilkan et al. [12] on thermoeconomic optimization of a LiBr absorption refrigeration system can be mentioned. The thermoeconomic optimization study was performed in order to determine the optimum operating temperatures and parameters of a LiBr absorption refrigeration system. Ahmadi et al. [13] performed a study on the exergo-environmental analysis of an integrated organic Rankine cycle for trigeneration system. Environmental impact assessment, energy and exergy analyses were carried for a trigeneration system consists of a gas turbine cycle, an organic Rankine cycle, a single-effect absorption chiller and a domestic water heater. Further information on thermo-economic analysis of different systems such as polygeneration systems, central air conditioners and power plants can be found in Refs. [14–16].

The aim of the present study is to suggest a ventilation system assisted by solar energy, heat recovery unit, and an auxiliary electrical heater. The application areas of the proposed system are theatres, cinemas, gymnasium saloons, shopping centres and other spaces which require high rate of fresh air due to peak occupation time between 17:00 and 24:00 h. The hourly energy analysis of the suggested system and traditional system, operating only with an electrical heater, is performed by using TRNSYS 16 software for winter period from 1st of November to 31st of March for Izmir city of Turkey. The total energy consumption for both systems is determined and then compared for the considered period. The obtained results are presented and discussed via graphics. Furthermore, the initial investment and maintenance costs of both traditional and suggested systems are determined based on the prices in Turkish HVAC market available in 2013 in order to perform an economical analysis for both systems. The aim of economical analysis is to find out payback period of the suggested system.

Based on the above literature survey, it is observed that no study on the use of both heat of exhaust air and stored solar energy for heating of fresh air for ventilation purpose in the buildings was performed. The proposed system is an innovative system which can reduce the energy consumptions in the buildings, considerably. Furthermore, the energy and economical evaluations are performed for this innovated system to investigate applicability of the system, practically. Hence, the results of the present study are new and original.

2. The traditional and proposed innovative ventilation systems

Both the traditional and suggested ventilation systems are analyzed in the present study. The main components of traditional ventilation system are supply and return fans, an electrical heater and a simple automation system as shown in Fig. 1(a). The main components of the suggested system are supply and return fans, an electrical heater, a heat recovery unit and a solar energy storage system as shown in Fig. 1(b). The solar energy storage system mainly consists of an evacuated tube solar collector, a sensible heat storage tank with heating coil and circulation pumps. There are two separate loops in the solar energy system. In the first loop, water circulates between solar collector and sensible storage tank by a circulation pump named as pump #1. In the second loop, the water is circulated between tank and heating coil by another circulation pump named as pump #2. Solar collector is used to increase the water temperature. The water at high temperature enters to the sensible storage tank and transfers heat of circulated water to the storage tank water. Then, the water leaves storage tank at lower temperature. It enters to the pump #1 and becomes pressurized to be circulated in the loop #1. The control of pump #1 is done by a differential temperature controller. It receives average temperature of the water storage tank and outlet temperature of the solar collector. If the temperature inside the storage tank is greater than the solar collector outlet temperature, a signal is sent to pump #1 for stopping. When sun rises, the solar collector outlet temperature becomes greater than the temperature of storage tank, operated at night period. During sunset, the collector outlet temperature becomes less than the storage tank temperature. Hence, a signal is sent to pump #1 to stop circulation. By this way, the temperature of storage tank increases during the sun light period. Our observation showed that the temperature of water at outlet of solar collector may exceed 100 °C in warm days during winter period. That is why a temperature controller is adapted to the system for controlling outlet water temperature of solar collector for safety reason. If the temperature of solar collector exceeds 90 °C, the pump #1 stops the water circulation.

The operation of loop #2 is arranged by a time controller. It operates from 17:00 to 24:00 h which is the operation period of the ventilation system. At 17:00 h, the time controller sends a signal to pump #2 and water is circulated through loop #2. The pressurized water leaves the pump #2 and enters to the storage tank. Then, the water leaves storage tank at higher temperature and flows towards heating coil. Heat is transferred from the hot water that leaves the storage tank to the air via the heating coil. On the other hand, fresh air, which should be supplied to the space, is preheated by the heat recovery unit. The temperature of fresh air is increased by the energy of exhaust air. Then, the fresh air is passed through the coil heat exchanger connected to the solar energy storage system. Finally, the fresh air flows towards the electrical heater. If the fresh air temperature is less than 22 °C, the electrical heater automatically operates and increases the fresh air temperature to 22 °C. After 24:00 h, the supply and return fans are switched off automatically. By this way, the solar energy stored in the storage tank during day period is used to heat fresh air required from 17:00 to 24:00 h. The study is performed at air flow rate of 1000 m^3/h. The solar collector, storage tank, heat recovery unit and heating coil are the main components of the proposed system. For the studied systems, the optimal design of heat recovery unit and heating coil is performed by HVAC manufacturers. The commercial programs developed by manufacturers are used to determine the optimal design of heat recovery unit and coils for the given operational conditions. Based on the specified air flow rate, double core aluminium plate type heat recovery unit, each has size of 500 mm × 500 mm × 500 mm and pressure drop of 100 Pa, is chosen as the optimal design for