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Performance analysis of solar thermal system for heating of a detached house in harsh cold region of Mongolia

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ABSTRACT

Ulaanbaatar is one of the top five cities with worst air quality because of the use of raw coal in the Ger District. The objective of this paper is to analyze the environmental significance of solar heating system with triple heat sources including the solar collector, coal stove, and electric heater for a simple detached house in the harsh cold and dry climate. A long-term measurement was conducted in a Ger district of Ulaanbaatar city, Mongolia. Based on the measurement of the solar thermal system for 8 months, from October 2015 to May 2016, it was found that the average collector efficiency was 49.8% and system efficiency was 37%. The study also reported monthly performance of the system. The dust deposition on the glass tubes of the evacuated tube solar collector considerably decreased the performance, especially during winter season.

1. Introduction

The overuse of organic fuel and acceleration of the greenhouse effect have resulted in negative environmental consequences like air and soil pollution. Even though scientists and engineers have enhanced energy production through the application of new environment-friendly technologies and modification of certain policies, raw coal is still widely used throughout the world. The World Health Organization has reported that the burning of raw coal for extracting thermal and electrical energy can have a significant negative effect on public health in big cities, particularly resulting in lung diseases in children [1,2].

Although electrification has widely spread, the use of raw coal for firing in small stoves in detached houses is still in practice, especially in the cold zones. Mongolia, with a population of slightly over 3 million, is one of the developing countries in a cold zone. About 45% of the total population lives in the capital city of Ulaanbaatar. Approximately 60% of total households in the city live in the Ger districts, where most of the residents have less income and dwell without proper sewage and district heating system [3]. Moreover, 98% of the households in Ger districts use raw coal for heating purpose. Due to the high usage of raw coal in the winter season (between November and March), Ulaanbaatar turns out to be one of the world's most polluted cities [4–6]. Thus, the Mongolian government is working on reducing air pollution along with many other international and national organizations such as The World Bank, Asian development bank, Japan international corporation agency, Mongolian Millennium Challenge Account, and Ministry of Nature and Environment [7,8].

Metropolitan air quality agency (MAQA), the Mongolian government and The World Bank are working as a group since 2007. The MAQA aims to decrease air pollution through the application of new technology for detached house heating and up-gradation of old coal stoves. In 2012, the MAQA replaced old coal stoves with 21 solar collector systems for heating purpose (not for hot water application) in 21 simple detached houses of Ger districts. The chosen houses were in different places of the city and followed the common house structure in Ger districts [9]. One of these solar thermal systems located in the highly polluted area (Tawan buudal, Chingeltei Ger district, Ulaanbaatar) was chosen for further observation and measurements.

Before the collector system was installed on the chosen house, the dwellers used to burn about 5 tons of raw coal for heating purpose every year (total cost to buy 1 ton of coal is approximately

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70$, 1$ = 2230 ₮). According to the World Bank consultant report of 2014 [10], each household in Ger district is estimated to use 5 tons of coal and 3 m^3 of fuel-wood for heating and cooking per year.

The chosen solar thermal system was under observation since 2013. In November 2014, our research group installed a few measurement devices to measure and estimate thermal gain and system efficiency of the solar collector. The system efficiency was measured over four months, i.e., 38.5% in December, 32.7% in January, 27.9% in February and 26.8% in March. It was found that the performance was lower than the predicted values on the basis of collector specification. Thus, it is required to identify the issues by measuring collector efficiency and system efficiency in real conditions during the heating period of September to May.

As mentioned above, cities having a cold climate like Ulaanbaatar face problems on how to effectively meet the heating requirements of thousands of detached houses. In order to select the most feasible system, heaters and heating systems such as electric heater, gas and district heating supply are economically and environmentally compared on the basis of certain conditions. However, the general public and the government do not consider solar thermal systems because of the huge investments involved and lack of sufficient studies on the application of such systems in cold regions.

Generally, the solar thermal collectors used for domestic hot water and space heating of detached houses include flat plate collector (FPC), water-in-glass evacuated tube collector (WIG-ETC), U-type evacuated tube collector (UT-ETC), and heat pipe evacuated tube collector (HP-ETC). In order to choose the suitable collector, it is necessary to consider the consumers' requirements, weather condition in a particular area, easiness of installation and maintenance, and the temperature produced. In Ulaanbaatar, the HP-ETC is preferred for detached house heating.

Many research works have compared the different types of solar collector in terms of their performance and thermal output. Studies have reported that the evacuated tube collector is more appropriate in cold and harsh regions compared to the FPC [11–14]. Michel Hayek et al. [15] carried out an experimental investigation on WIG-ETC and HP-ETC between November and January during the winter season. They concluded that the HP-ETC has better efficiency than the WIG-ETC. Other studies have also compared UT-ETC and HP-ETC [16–18]. Even though the efficiency of HP-ETC is less than that of UT-ETC due to the heat conversion factor, HP-ECT has many advantages for cold regions. For example, HP-ECT is free from the freezing issue, pump pressure drop and, most importantly, relatively easy for installation and maintenance.

Heat pipe technology is used in many fields such as ovens, electronic, electrical equipments, medicine, human body temperature control, manufacturing, and energy systems [19]. Heat pipes use high thermal conductance that transfers thermal energy by two-phase circulation of fluid and can be integrated easily with solar collectors [20]. Since 1970s, related research works have been conducted by many researchers [21–27].

Some researchers have focused on the enhancement of the efficiency and heat transfer of evacuated tube collectors, whereas others have improved its thermal performance using extra devices such as a reflector [28,29]. Some researchers have also explored specific applications of solar collector systems, for example, for cooling, industrial heat supply, and domestic hot water production [30–33]. However, Ayompe et al. [34] stated that the on-site thermal performance of evacuated tube solar collectors has not been well evaluated, especially in cold countries.

Sereeter Batmunkh et al. [35] studied the solar thermal system of a detached house in Ulaanbaatar between 1987 and 1988. A flat plate collector was used for air heating during the winter season between November and April, whereas for both air and water heating was used in the other months.

The objective of this study is to evaluate the operating efficiency and performance of the evacuated tube solar collectors in harsh cold areas of Mongolia while comparing the solar heating system with other heating devices such as coal stove, gas or electric heaters. Taro Mori et al. [36] mentioned that solar thermal collectors and solar hybrid systems combined with an electric heater are not so effective in cold regions. However, raw coal has been replaced with solar heating technologies to effectively solve the air pollution in Ulaanbaatar. Therefore, this study also investigates the solar thermal system used in Ulaanbaatar.

Hence, the first priority is to conduct a long-term measurement on the solar thermal system installed on a detached house in one of the Ger districts of Ulaanbaatar so as to analyze the performance of the solar system based on the actual data.

2. Measurement of solar thermal system

2.1. House for the measurement

A typical house situated in the Chingeltei Ger district, at longitude 106°54′E and latitude 47°57′N, was chosen for the study. Four people resided in this house of 56 m^2 area including kitchen (see Fig. 1). Based on the Mongolian standard MNS 5127: 2007, its heat loss coefficient was measured as 0.57 J/°C m^3 in 2014. Before the solar collector system was installed in 2012, a low-pressure stove connected to radiators was employed as a heater. The annual average fuel consumption of the low-pressure stove for house heating was 5 tons of raw coal. Additional information regarding the coal and the stove is shown in Table 1.

2.2. Installed solar thermal system

The installed solar collector system comprises four sections of heat pipe evacuated tubes. Each section has 30 glass tubes, which contain a heat pipe, a heat storage tank of 500 L in which auxiliary electric heater of 3 kW is set, solar circuit pipes, a pump, and a solar controller. The length of the solar circuit pipes to supply hot water is 11 m, of which 8 m are outside, and the return pipe length is of 14.5 m, of which 12 m are outside. The solar collector part was manufactured by Jiangsu Sun-rain Solar Energy Co., Ltd., and the mark is TZ58-1800-30. In 2007, it was also tested at the Fraunhofer Institute. Optical efficiency was 0.85, and the first and second order coefficients derived from the test were 1.771 and 0.0192,

Fig. 1. Overview of the measurement house.