Journal of Engineering and Applied Sciences 14 (20): 7709-7713, 2019
ISSN: 1816-949X
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Exergy Calculation Analysis of Differing Solar Collector Systems in Various Climate Conditions of Kazakhstan

[1]Yerzhan Belyaev, [1]Diaz Baiseitov [2]Murat Kunelbayev,
[1]Amantur Umarov and [1]Maxatbek Satymbekov
[1]Al-Farabi Kazakh National University, Almaty, Kazakhstan
[2]Institute Information and Computational Technologies CS MES RK, Almaty, Kazakhstan
murat7508@yandex.kz

Abstract: Calculations of exergy (heat loss) were carried out on different types of combined solar collectors and heat pump systems to determine the most appropriate version of the heating and hot water needs in Kazakhstan in harsh climatic conditions. To achieve this goal, a mathematical model was applied, representing a set of formulas for the sequential elementary calculation of temperature data from a solar heating system. An algorithm was developed to calculate the heat loss of both the solar collector system and the solar-assisted heat pump. The significance and importance of the achieved results is high, since, the developed and used algorithm allows detecting inefficient components of the solar heating system. In cold climatic conditions, the exterior performance of the solar collector ranges from 5-27%. Capacitor efficiency ranges between 9-15%. The least effective is the compressor, the exergy values of which vary within 10-88%.

Key words: Exergy, enthalpy, entropy, solar collector, solar assisted heat pump, calculate

INTRODUCTION

Solar power is gaining wide recognition as an alternative and renewable energy source of heat which can be widely used without a hazardous impact on the environment (Zhou *et al*., 2015; Ouyang *et al*., 2017). The principal component of a solar heating system is a flat-plate solar collector. Technical performance data of a flat-plate solar collector is not sufficient (Yuan *et al*., 2017a, b) to analyze the overall solar collector system efficiency, the reason being it does not account for internal losses. To address such internal losses, exergy analysis should be used along with consequential optimization of the solar heating system's operation. Flat-plate solar collectors alone have been previously studied from the perspective of their exergy and entropy (Sun *et al*., 2016; Yuan *et al*., 2016, 2017a, b). Bejan (1982) have elaborated on the exergy analysis of the flat-plate solar collector and found that the output of the solar collectors systems is influenced by inevitable heat transfer related losses. The research by Wang *et al*. (2015) compares the flat plate type and evacuated tube type collectors with regard to exergy. Exergy and energy-dispersive analysis of the flat-plate solar collector has been conducted in the research by Liu *et al*. (2014). The research by Xiang *et al*. (2018) has offered the exergy analysis of the flat-plate solar collector based on the assumption that the input temperature for the working liquid is equal to the ambient temperature. The present research describes the exergy (heat losses) calculation of different types of hybrid solar collector assisted heat pump systems in order to find the best version to serve heating and hot water supply demands under climatic conditions of Kazakhstan. The proposed model has been verified experimentally.

MATERIALS AND METHODS

Model: Household heating with fossil fuels is associated with large amounts of pollutant emissions. Moreover, as oil and gas reserves are limited (finite resources), the prospect of obtaining power by means of fossil fuels is thus, limited in the foreseeable future. Energy production will soon undergo change in the way it is generated and even today the preference is given to renewable sources such as solar and wind power.

The solar collector is one of the most popular renewable heat sources for today. However, in Kazakhstani continental climate conditions, it needs to be coupled with solar (assisted) heat pumps. Heat pumps use latent low grade (within the range from -20-30°C) thermal sources (typically found underground in the water, air, industrial and natural flows, ventilation air, shaft waters, etc) and transform them through a carnot thermodynamic

Corresponding Author: Murat Kunelbayev, Institute Information and Computational Technologies CS MES RK, Almaty, Kazakhstan, murat7508@yandex.kz

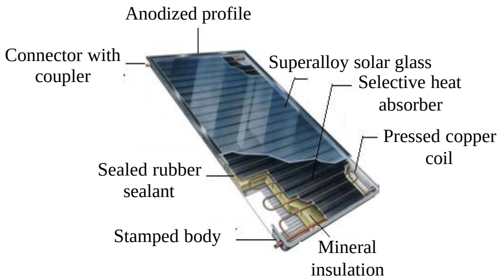

Fig. 1: Solar collector in section

cycle into a useful working temperature in the range from 30-80°C. By compressing the working body which is typically an antifreeze substance, saline solution or freon it usually consumes a definite amount of electric energy at the ratio of 1 kW per 3-5 kW to thermal power output (COP 3-5). Thermal pumps are a preferred, since, they do not emit combustion products and use only electricity which can be obtained from other renewable sources such as wind turbines or photoelectrical solar panels.

Physical problem statement: In this research of system have been considered:

- Conventional flat-plate solar collector system (produced by LLP “KunTech”)
- Solar collector assisted heat pump
- Solar collector assisted heat pump with direct expansion
- Cascaded solar collector assisted heat pump with direct expansion

Glazed solar collector with a square of 2.03 m^2 (2×1 m) is used as an evaporator (heat source) for coolants R407C and R134a. Inside the solar collector there is an aluminum sheet absorber with an aperture of 1.78 m^2. This is attached to the cooler’s copper tube with a cross-section of 18 mm filled with either circulating propylene glycol antifreeze substance (volume of 1.6 l) or freon under pressure. Solar collector evaporator (absorber) is covered with selective black coating for maximum solar radiation receipt (solar absorbtivity $\alpha_{AM\ 1.5}$) with minimal reflection ratio (thermal emisivity 82°C = 0.16). The absorber plate is located behind the glassed transparent surface with a width of 4 mm and an enclosed airspace (Fig. 1). The solar collector’s lower part is insulated with a 50 mm width mineral heat shield to prevent heat losses. The solar collector has been designed to gain the maximum heat from the solar radiation which constitutes 2, 0-2, 8 kWh annually per area of the collector at the latitudes of Kazakhstan.

During this experiment, a piston type sealed compressor filled with freon R407C was used. To avoid overloading and internal overheating, the compressor has been equipped with an automatic safety shut off relay. A plate soldered heat exchanger (condenser) with thermal load of 6, 9965 kW and mass rate of 0, 043 kg/sec was used. The coolant receiver and sight glass have been installed subsequent to the condenser, drier and flowmeter filter which are used for removing moisture content from the coolant. A thermal expansion valve regulates the coolant flow through the solar collector-evaporator. Upon conducting the experiments, the solar collector has been directed to the south at an angle of 45°C (latitude 54, 1 0N, longitude 71, 3 0E, Astana, Kazakhstan) to the horizon (Table 1 and Fig. 2).

- Solar collectors
- Automatic controller
- Heat exchange tank of accumulation and indirect heating
- Circulating pump
- Expansion tank
- Reserve electric heater (from 2-6 kW)
- Existing oven (electricity, fuel, gas)
- Hot water withdrawal
- Rreserve oven circuit
- Solar collector’s circuit
- Cold water supply

Mathematical model: Exergy analysis is widely applied for specifying the optimal operating mode of solar collector systems through defining the ineffectiveness of the system’s components. Exergy is the factor of the installation’s performance. Exergy analysis has been conducted with the following assumptions:

- All processes are stationary, i.e., time independent
- Asumed ignorance of potential, kinetic and chemical effects
- Mechanical ($\eta_{mechanical}$) and electric ($\eta_{electrical}$) efficiency (in some literature referred to as mechanical and electric COP) is supposed to be 0, 85
- Volumetric efficiency (in some literature referred to as volumetric thermal efficiency) is supposed to be 0, 8
- Compressor rate (N) is accepted as equal to 2900 rpm at 8, 4 cu m/h and 3500 rpm at 10,1 cu m/h
- Piston movement volume in the suction stroke end (V_{dis}) equals to 48, 06 cu cm/rev
- There are two solar collectors with a square of (A) 2 m^2 with minimal convective losses on the absorber plate
- Specific exergy (ex in kJ/kg) and total exergy factor (Ex in kW) are computed applying the following (Eq. 1-2)

Table 1: Technical specifications of the flat plate solar collector

Options	Magnitude
Total square	2.03 (m^2)
Absorber square	1.78 (m^2)
Aperture's square	1.78 (m^2)
Panel width with pipe fitting	1060 (mm)
Dimensions L×W×H (L Length, W Width, H Height)	2018×1018×100 (mm)
Weight	42.2 (kg)
Liquid volume	1.63 l
Maximal pressure	600 (kPa)
Heat exchanger flow	30-100 l/h per a collector
Connection	Flange joint with connected clutch
Casing	Glued aluminum profiles
Covering glass	Solar, 4 mm, impact resistant
Absorption factor	95%
Recommended working temperature	<100°C
Temperature of stagnation (1000 W/m^2, 30°C)	170, 5°C
Minimal power gain (Raulz 73)	525 kW*h/m^2 a year

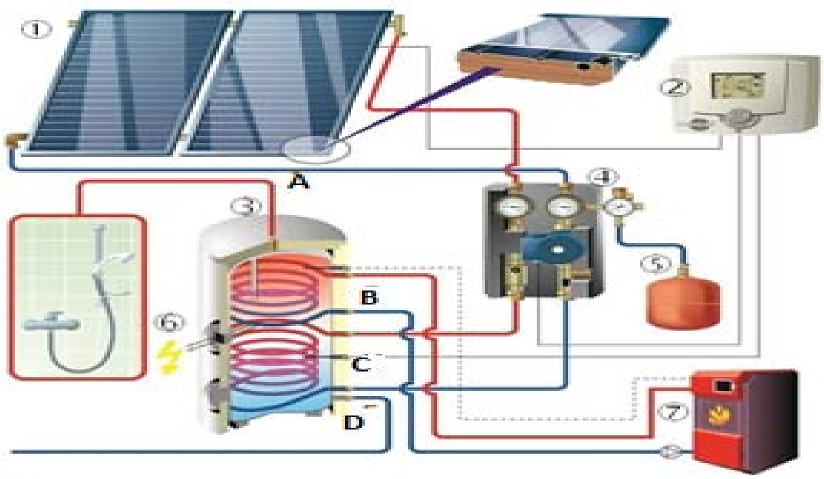

Fig. 2: Typical circuit of the solar system

$$\psi = (h-h_0)-T_0(s-s_0) \quad (1)$$

$$\dot{E}x = \dot{m}\psi \quad (2)$$

Compressor: Mass flow ($\dot{m}_r$) of coolant agents R407C and R134a, circulating in the systems equals to 0, 03429 kg/sec. The research (W_{comp}), executed by the compressor is defined as follows in compliance with Eq. 3-4:

$$\dot{W}_{comp} = \dot{m}_r(h_2-h_1) \quad (3)$$

$$\dot{W}_{comp.elec} = \frac{\dot{m}_r(h_2-h_1)}{\eta_{mechanical}\times\eta_{electrical}} \quad (4)$$

$$\dot{E}x_{dest}(comp) = \dot{m}_r(\psi_1-\psi_2)+\dot{W}_{comp.elec} \quad (5)$$

Exergy loss ($\dot{E}x_{desi(comp)}$) (11) and exergy efficiency (ε_{comp}) (Farahat *et al*., 2009) of compressors are computed according to Eq. 6-7:

$$\varepsilon_{comp} = \frac{\dot{E}x_2-\dot{E}x_1}{W_{comp.elec}} \quad (6)$$

Condenser: Exergy efficiency (ε_{cond}) of the condenser (soldered compact heat exchangers) is computed using Eq. 7:

$$\varepsilon_{con} = \frac{\Psi_2}{\Psi_1} \quad (7)$$

Expansion valve: Expansion process in the thermal regulating valve is almost isoenthalpic. Exergy efficiency ($\varepsilon_{(TEV)}$) is calculated according to Eq. 8 (Table 2).

$$\varepsilon_{TEV} = \frac{\psi_2}{\psi_1} \quad (8)$$

Evaporator (solar collector): Exergy efficiency ($\varepsilon_{(s.collector)}$) of the solar collector is defined according to Eq. 9:

Table 2: Exergy system computation for temperature 10°C

Component number	Temperature T(K)	Specific enthalpy h (kJ/kg)	Specific entropy S, (kJ/kg*K)	Specific exergy Ψ (kJ/kg)
At collector's inlet	301.65	418.55	1.7118	31.5740
At collector outlet	313.15	429.04	1.6899	47.8270
At inlet to accumulator tank	313.15	161.26	-	-
At output of accumulator tank/at circulating pump inlet	311.15	159.17	-	-
At circulation pump outlet	311.65	-	-	-
At radiator (thermal load) inlet	311.65	-	-	-
At radiator (thermal load) outlet	306.65	-	-	-
At accumulator tank outlet/at collector inlet	301.65	-	-	-

$$\varepsilon_{s.collector} = \frac{\dot{m}_r c[T_2 - T_1] - T_0 \ln\left(\frac{T_2}{T_1}\right)}{A\dot{I}\left[1 + \frac{1}{3}\left(\frac{T_0}{T_s}\right) - \frac{4}{3}\left(\frac{T_0}{T_s}\right)\right] + W_p} \quad (9)$$

Hereunder $\dot{I}$ is the process noninvertibility factor (kW). overall system total exergy loss of the system (Farahat *et al*., 2009):

$$\dot{E}x_{dest(system)} = \dot{E}x_{dest(comp)} + \dot{E}x_{dest(cond)} + \dot{E}x_{dest(exp.valve)} + \dot{E}x_{dest(s,collector)} \quad (10)$$

$$\varepsilon_{system} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \quad (11)$$

Thermal-physical properties in the modules have been specified applying the program REFPROP.

RESULTS AND DISCUSSION

Calculations have been conducted for Kazakhstan's climatic conditions (Astana city) at minimal average daily intensity of rates of solar radiation 200 W/m^2 and ambient temperature 10°C. The thermodynamic analysis in conformity with the second law in application to coolants R407C and R134a was carried out. Calculation outcomes are given in Table 2. Under cold climatic conditions the solar collector's exergy performance varies within 5-27%. Condensers efficiency changes between 9-15%. The least effective is a compressor, the exergy values of which vary within 10-88%.

Figure 3 shows the solar collector's exergy performance depending on the solar assisted heat pump and coolant type at different ambient temperature magnitudes. Proceeding from that it might be confirmed that the most effective system with minimal losses is the solar assisted heat pump with direct expansion using coolant agent R407C.

It has been confirmed that the most efficient system with minimal losses is a solar heat pump with direct expansion using cooling agent R407C. R407C-refrigerant is the most effective in terms of physical and chemical composition as well as the boiling point temperature is 42°C, so for, our climatic conditions it is convenient to use R407C-refrigerant.

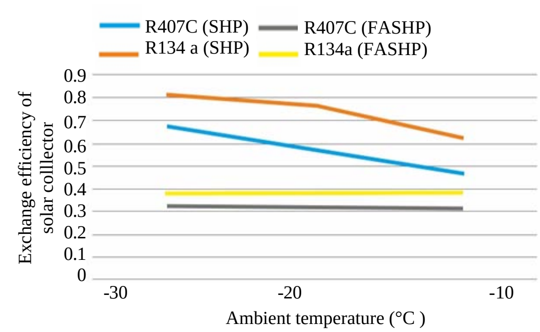

Fig. 3: Solar collector system exergy performance relation to the heat pump and coolant type

CONCLUSION

In this research, a new type of solar collector with a heat pump system has been developed. Experimental work has been carried out on the exergy efficiency of the solar collector. A mathematical model for exergy evaluation of the thermal performance of the solar collector system has been developed and investigated. The numerical calculations and thermodynamic analysis of the functioning of the solar collector system are carried out. By means of experimental work when considering the stability design of a solar collector system, exergy analysis is an important component for solar collectors which gives a more representative assessment of the efficiency and is a valuable method for assessing the possible configurations of these systems. This analysis is useful when considering not only solar collectors but also a complete system for identifying sources.

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