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Numerical modelling of photovoltaic thermal evaporator for heat pumps

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A numerical model is proposed in this paper to evaluate the energy performance parameters of photovoltaic-thermal hybrid evaporators. The energy performance parameters such as photovoltaic electrical efficiency, thermal efficiency of the evaporator, overall efficiency of photovoltaic-thermal evaporators, solar energy absorption ratio and evaporator heat gain were predicted for the meteorological conditions of Almaty city in Republic of Kazakhstan. R134a is selected as a working fluid in this work. The ambient temperature was simulated in the range between -20 ^oC and 30 ^oC with solar intensity in the range from 100 W/m^2 to 900 W/m^2. The wind velocity variations in the range between 0 and 10 m/s was also considered. The energy performance parameters under the influence of above three ambient parameters are discussed. The modelling results were also compared with experimental results reported in literature and found to be in good agreement with acceptable deviations.

Keywords*:* photovoltaic-thermal hybrid system, heat pumps, cold climates, Kazakhstan

INTRODUCTION

Probably the most important source of renewable energy is sun. Solar energy can be used as a low-grade heat source for heat pumps. Today direct expansion solar assisted heat pump (DXSAHP) system has been actively studied by many scientists of Western and East Asian countries to use in seawater desalination, domestic hot water, cottages heating and air conditioning, heating greenhouses, etc. However, in the CIS countries, including Kazakhstan, this system has not been paid any attention. With proper operation of DXSAHP system, it can achieve a high coefficient of performance as compared with heat pumps that power by geothermal, water and air. DXSAHP installation is inexpensive, it uses solar collectors, which regardless of weather conditions is able to accumulate sufficient energy and convert the solar radiation into heat.

The main objective of this paper is to increase the conversion efficiency of solar and ambient energy into heat, i.e. to increase coefficient of performance (COP). One of the ways to solve this problem is to integrate photovoltaic and thermal evaporator systems into one solar collector for generating electricity and heat simultaneously. The combination of photovoltaic and thermal evaporator (PV/T) systems in one module has the potential to reduce the use of materials and the required space [1]. Also, the hybrid system allows saving the aesthetic appearance of the building. In references [1-4] presented literature review of a photovoltaic-thermal hybrid system. The use of PV/T hybrid technology in conjunction with a solar assisted heat pump is presented in [5-7]. For example, in [5] a novel solar polygeneration system, which combines solar cooling, solar-assisted heat pump and photovoltaic/thermal collector technologies, is presented. The results showed a total energy efficiency of the PV/T is 0.49, a heat pump yearly COP is more than 4 and the adsorption chiller COP is 0.55. While in the paper [7] an experimental study on operation performance of PV/T solar heat pump air-conditioning system was conducted and its corresponding COP is 2.88. Experimental and numerical investigations of other type of hybrid PV/T solar collector were considered in [8-13]. In [8] a novel flat heat pipe design has been developed, where solar thermal collector with and without PV bonded directly to its surface. Performance study of solar water and space heating is discussed in papers [10-13]. In the present paper preliminary numerical results of thermal performance of hybrid PV/T solar collector used for DXSAHP under meteorological conditions of Kazakhstan is presented.

DESCRIPTION OF DIRECT EXPANSION SOLAR ASSISTED HEAT PUMP CYCLE

The detailed configuration of a direct expansion solar assisted heat pump and pressure-enthalpy diagram are shown in the Fig.1 and Fig.2, respectively. The DXSAHP consists of a R134 based hermetically sealed reciprocating

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compressor, a water cooled condenser, a liquid receiver, a sealed type refrigerant drier, a sight glass, a thermostatic expansion device and a glazed solar collector integrated with PV modules, which acts as an evaporator. The geometric characteristics of the hybrid PV/T system have been taken in accordance with the [14]. Dimensions of PV/T collector-evaporator is 1.01 m x 0.73 m. The PV/T collector-evaporator is a hybrid solar collector with solar cell encapsulation laminated on to the front surface of a thermal absorber plate [14]. Evaporator's copper tube has 6 m length with 7 mm outer diameter and 6 mm inner diameter. A glass cover and a thermal insulation layer are provided. The solar PV/T collector (evaporator) was tilted to an angle of about 45^o with respect to horizontal [14]. The system is oriented to face south to maximize the solar radiation incident on the collector (evaporator). Experiments will be conducted in Almaty (latitude of 43.25 ^{o}N, longitude of 76.91 ^{o}E). During the experiment the following parameters will be taken into account: solar radiation, ambient temperature and wind velocity. Kazakhstan is one of the leading countries in the Central Asian region with the average annual solar radiation potential. Annual duration of sunshine is 2200-3000 hours, and the estimated capacity of 1300-1700 kW per 1 m^2 per year, which exceeds that of Europe.

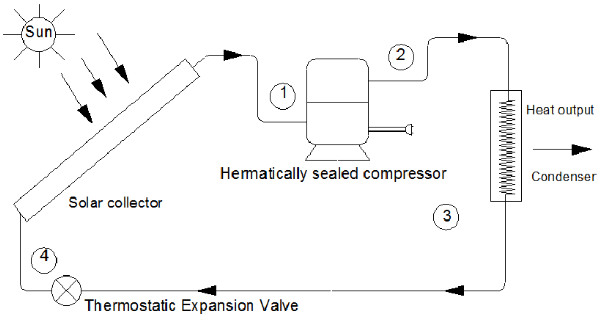


Fig.1. Schematic diagram of a direct expansion solar assisted heat pump

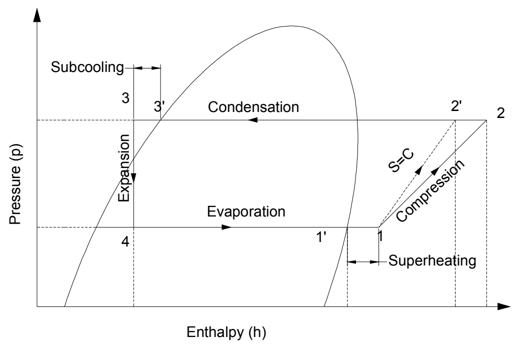


Fig.2. Pressure enthalpy representation of a direct expansion solar assisted heat pump

MATHEMATICAL MODEL

The thermal performance of the system was numerically evaluated according to a mathematical model [15]. Heat balance equation of the PV module is:

$$l_{pv}\rho_{pv}C_{pv}\frac{\partial T_{pv}}{\partial t}=G(\tau\beta)_{pv}-E+\alpha_{a-pv}\left(T_a-T_{pv}\right)+ \alpha_{r,a-pv}\left(T_{sky}-T_{pv}\right)+\frac{T_c-T_{pv}}{R_{pv-c}} \quad (1)$$

where l_{pv}, ρ_{pv} and C_{pv} are the effective thickness, density and specific heat of PV cells, respectively. Other terms in the right hand side of the equation (1) are described in detail in ref. [15]. Two-dimensional heat conduction equation of the thermal collector is given by the following formula:

$$m_cC_c\frac{\partial T_c}{\partial t}=G(\tau\beta)_c(1-\xi)A_c+\alpha_{a-c}(1-\xi)A_c(T_a-T_c)+ \alpha_{r,a-c}(1-\xi)A_c(T_{sky}-T_c)+\xi A_c\frac{T_{pv}-T_c}{R_{pv-c}}+A_c\frac{T_a-T_c}{R_b}+ \lambda_{c,y}l_{c,y}A_c\frac{\partial^2T_c}{\partial y^2}+\lambda_{c,z}l_{c,z}A_c\frac{\partial^2T_c}{\partial z^2} \quad (2)$$

where R_b is the thermal resistance between the back of the thermal collector and the ambient; $l_{c,y}$ and $l_{c,z}$ are the effective thicknesses along the Y direction and Z direction, respectively; and ξ is the PV cell coverage ratio [15].

METHOD OF SOLUTION

Finite-difference form of the equations (1)-(2) is based on the implicit scheme according to the [15].

$$l_{pv}\rho_{pv}C_{pv}\frac{T_{pv,j,k}^{n+1}-T_{pv,j,k}^{n}}{\Delta t}=G(\tau\beta)_{pv}-E+ \alpha_{a-pv}\left(T_a-T_{pv,j,k}^{n+1}\right)+ +\alpha_{r,a-pv}\left(T_{sky}-T_{pv,j,k}^{n+1}\right)+\frac{T_{c,j,k}^{n+1}-T_{pv,j,k}^{n+1}}{R_{pv-c}} \quad (3)$$

$$m_cC_c\frac{T_{c,j,k}^{n+1}-T_{c,j,k}^{n}}{\Delta t}=G(\tau\beta)_c(1-\xi)A_c+ \alpha_{a-c}(1-\xi)A_c\left(T_a-T_{c,j,k}^{n+1}\right)+ +\alpha_{r,a-c}(1-\xi)A_c\left(T_{sky}-T_{c,j,k}^{n+1}\right)+ \xi A_c\frac{T_{pv}-T_{c,j,k}^{n+1}}{R_{pv-c}}+A_c\frac{T_a-T_{c,j,k}^{n+1}}{R_b}+ +\lambda_{c,y}l_{c,y}A_c\frac{T_{c,j,k+1}^{n+1}+T_{c,j,k-1}^{n+1}-2T_{c,j,k}^{n+1}}{\Delta y^2}+ \lambda_{c,z}l_{c,z}A_c\frac{T_{c,j+1,k}^{n+1}+T_{c,j+1,k}^{n+1}-2T_{c,j,k}^{n+1}}{\Delta z^2} \quad (4)$$

where l_{pv}, ρ_{pv} and C_{pv} the effective thickness, density and specific heat of PV cells, respectively. As an input data solar irradiance, ambient temperature and physical constants were taken. For the hybrid PV/T absorber plate as the temperature boundary conditions during numerical implementation of the equation (4) zero first derivatives were adopted.

RESULTS AND DISCUSSION

Temperature variation of PV cells and solar collector were numerically estimated for climate conditions of Kazakhstan. In the present paper three cities of Kazakhstan were considered: Astana, Almaty and Oral. The corresponding ambient temperature and solar radiation were taken into account during the calculation.

The available solar radiation data for Astana, Almaty and Oral are presented in Fig.3.

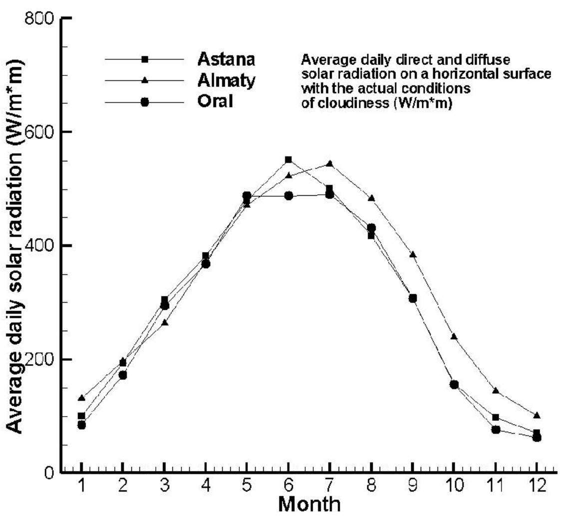
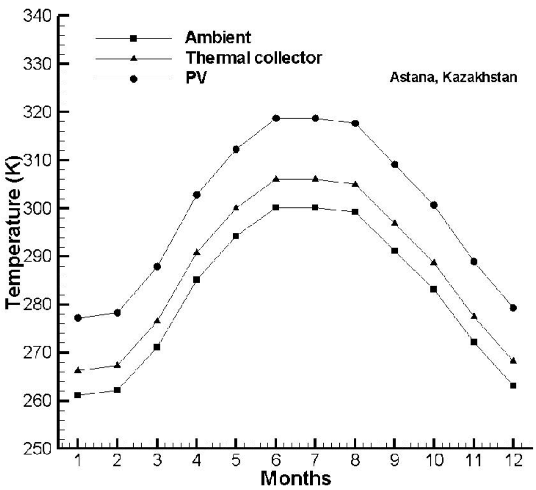
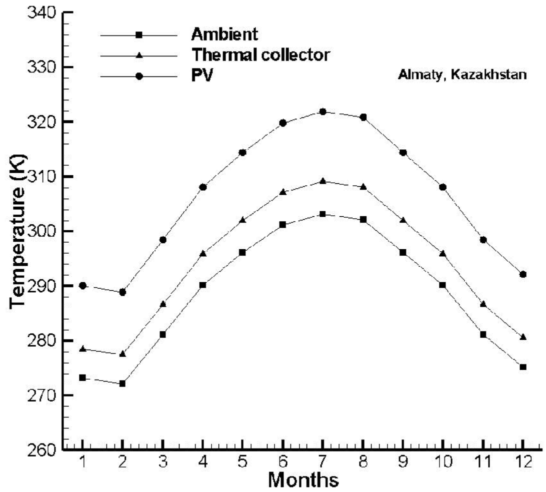


Fig.3. Solar radiation data





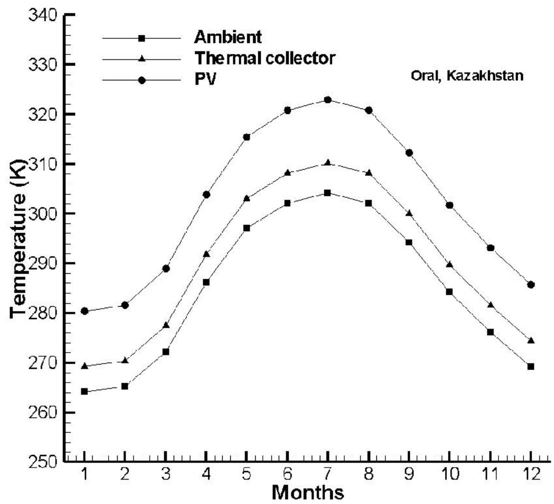


Fig.4. PV cell and thermal collector temperature variation by months

Fig.4 shows temperature variation of PV cells and solar collector depending of months. It can be seen from simulation results that the temperature of PV and thermal collector reach their maximum in the summer season. The trend is the same as the solar irradiation. Temperature difference of 3-20 K between PV cell and the thermal collector also can be observed.

Fig.5 and Fig.6 shows prediction of the heat gain by absorber plate and the output electricity by PV, respectively.

Both parameters generally increase with the solar irradiation. According to Fig.5 and Fig.6, the maximum value for Almaty city is achieved in the July months with heat indices of 5.55 kW and output electricity of around 1.0 kWh.

Thermal and PV efficiencies were assessed according to the solar energy input ratio (SEIR) parameter. In the calculations it was assumed that a solar collector area of 2 m^2, whereas the area of the photo elements covering the absorber plate is 1.7m^2. Solar energy input ratio for PV evaporator is presented in Fig.7 and Fig.8. The maximum value of SEIR thermal for Almaty city reaches 0.22 in May, whereas SEIR electrical is equal to 0.13 in August.

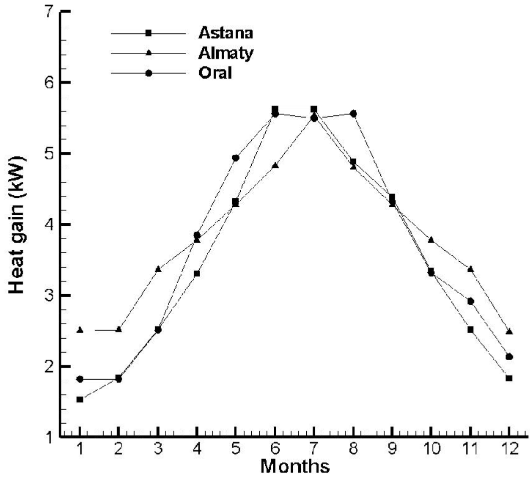


Fig.5. The heat gain of the evaporator

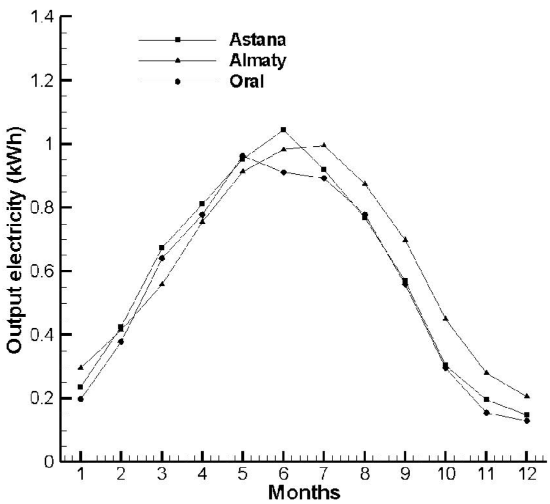


Fig.6. The output electricity of the PV evaporator

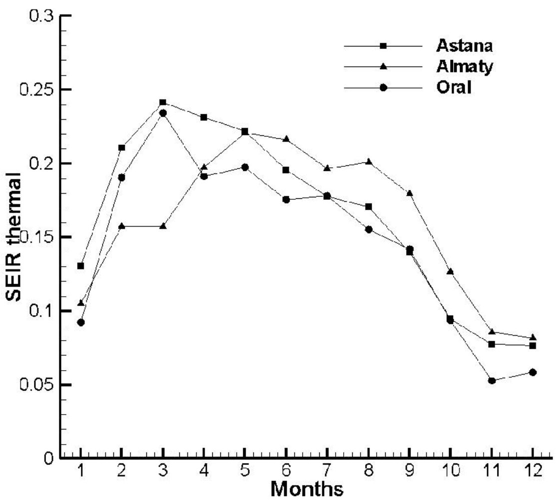


Fig.7. The SEIR thermal of the PV evaporator

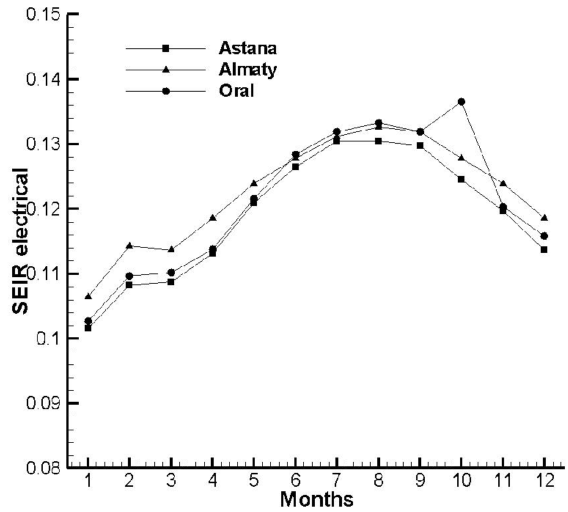


Fig.8. The SEIR electrical of the PV evaporator

CONCLUSION

Numerical modeling of photovoltaic thermal evaporator for heat pumps under meteorological conditions of Kazakhstan has been conducted. The predicted results are closer to the measured results reported in literature with acceptable deviations. Results are shown for currently available data for the total solar radiation on a horizontal surface with the actual conditions of cloudiness. In the future work it is planned to build an experimental setup of PV evaporator to integrate with direct expansion solar assisted heat pump system. Mathematical model and numerical algorithm accurately characterizes the thermal performance of the PV evaporator. In the future, the hydrodynamic calculation of the refrigerant flow in the tube of PV evaporator will be taken into account. Also daily solar radiation distribution for daily performance calculation will be considered.

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