

Simulation of Solar Assisted Absorption Cooling and Electricity Generation along with Thermal Storage

Faezeh Mosallat, Eric L. Bibeau, Tarek El Mekkawy

Abstract—Parabolic solar trough systems have seen limited deployments in cold northern climates as they are more suitable for electricity production in southern latitudes. A numerical dynamic model is developed to simulate troughs installed in cold climates and validated using a parabolic solar trough facility in Winnipeg. The model is developed in Simulink and will be utilized to simulate a tri-generation system for heating, cooling and electricity generation in remote northern communities. The main objective of this simulation is to obtain operational data of solar troughs in cold climates and use the model to determine ways to improve the economics and address cold weather issues.

In this paper the validated Simulink model is applied to simulate a solar assisted absorption cooling system along with electricity generation using Organic Rankine Cycle (ORC) and thermal storage. A control strategy is employed to distribute the heated oil from solar collectors among the above three systems considering the temperature requirements. This modelling provides dynamic performance results using measured meteorological data recorded every minute at the solar facility location. The purpose of this modeling approach is to accurately predict system performance at each time step considering the solar radiation fluctuations due to passing clouds. Optimization of the controller in cold temperatures is another goal of the simulation to for example minimize heat losses in winter when energy demand is high and solar resources are low.

The solar absorption cooling is modeled to use the generated heat from the solar trough system and provide cooling in summer for a greenhouse which is located next to the solar field.

The results of the simulation are presented for a summer day in Winnipeg which includes comparison of performance parameters of the absorption cooling and ORC systems at different heat transfer fluid (HTF) temperatures.

Keywords—Absorption cooling, parabolic solar trough, remote community, organic Rankine cycle.

I. INTRODUCTION

ROOM air conditioning systems based on vapor compression chillers have negative environmental impacts. This leads to increasing interest in efficient cooling technologies powered by renewable energy such as solar assisted absorption cooling which is the most commercially developed amongst the solar cooling technologies [1]. Five types of solar cooling systems are compared for Hong Kong in [2], solar mechanical compression refrigeration, solar electric compression refrigeration, solar absorption refrigeration, solar adsorption refrigeration and solar desiccant cooling. The

highest energy saving potential was found to be associated with the solar electric compression and solar absorption refrigeration. A review of solar-powered single effect absorption cooling systems is presented in [3]. It was concluded that the operation cost of absorption systems is lower than the compression cooling systems since 1) they have no moving part and 2) only three main types of electrical equipment are involved in the absorption cooling cycle: pump, condenser fan and cooling coil fan. Hence, they can become competitive in long term operation. Citterio et al. [4] studied a solar cooling system with and without oil storage tank. Solar electric cooling of an office building is compared with solar thermal cooling in [5]. The first one uses solar PV to power a compression chiller and the second one uses solar flat panel collectors and an absorption chiller. A solar-driven absorption cooling system is presented in [6] which is modeled and installed. Evacuated tube collectors are used to provide thermal energy.

Unlike most of the works which focus on using solar flat panels or evacuated tubes for cooling only purposes, this paper presents a solar absorption cooling along with organic Rankine cycle (ORC) electricity generation and latent heat thermal storage tank using parabolic trough solar technology which is the lowest cost, high temperature solar collector technology available today [7]. ORC power plants are mostly used for solar electricity generation. They are simple, flexible, and suitable for small scale applications (<5 MW) [8]. The most common uses are solar power generation, geothermal, and remote power. An organic fluid is used as the working fluid instead of water in traditional Rankine cycle. A latent heat thermal storage tank is used which contains phase change material to store heat for periods with low or no solar irradiance.

II. SYSTEM DESCRIPTION

The proposed system consists of an absorption cooling, ORC and thermal storage tank. Thermal oil 59 is used as the heat transfer fluid (HTF) of the solar trough system. Fig. 1 represents the system layout.

The ORC is considered as the first user of thermal energy generated from the solar collectors since it operates at high temperatures. The heated thermal oil from the solar troughs goes to a thermal storage tank after it exchanged heat with ORC. The absorption cooling system is the third user and gains its required thermal energy by exchanging heat between the thermal oil and water. The heated water is used in the absorption cycle to provide the required heat for the refrigerant evaporation in the generator.

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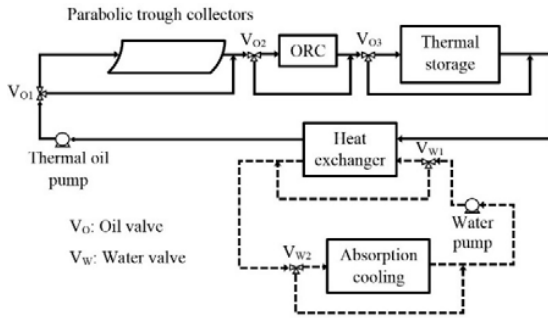


Fig. 1 Solar cooling and power generation layout (solid lines show thermal oil path and dashed lines show water path)

A three way valve is considered for each of the heat transfer/generation blocks which enables them to be bypassed based on the control system decisions.

III. CONTROL STRATEGY

Proper distribution of the oil through the three users should be done based on the temperature requirements of each system. A control strategy is designed to perform this task. The control approach is basically applied to the three way valves to determine the flow rate and path for each heat transfer/generation device. The key parameters for the control decisions are presented in Table I.

TABLE I
KEY PARAMETERS WHICH DETERMINE THE CONTROL DECISIONS

Symbol	Definition and unit
P_{ref_solar}	Solar normal irradiance (W/m^2)
$T_{out_collector}$	Thermal oil outlet temperature from solar collectors ($^{\circ}C$)
T_{outORC}	Thermal oil temperature after exiting the ORC ($^{\circ}C$)
$T_{storage}$	Storage tank temperature ($^{\circ}C$)
$T_{outdoor}$	Ambient temperature ($^{\circ}C$)

Each of the valves V_{O1} to V_{O3} and V_{W1} and V_{W2} in Fig. 1 are connected to a controller which sends them a command based on the value of control parameters presented in Table I. For example for the first user which is the ORC, if the $T_{out_collector}$ is greater than or equal to the set temperature of the ORC the controller allows the valve to send the thermal oil to the heat exchanger in which the oil thermal energy will be transferred to the cycle working fluid. Otherwise, the valve will lead the oil through the bypass.

IV. SIMULATION METHOD

A. Parabolic Solar Trough System

The first step to start the system simulation is to calculate how much thermal energy is available at each time step by calculating the thermal oil outlet temperature during the system operation. The fluid temperature is obtained using energy balance equations for the absorber pipe which consists of a non-evacuated glass envelope to reduce heat loss. Fig. 2 shows the heat fluxes through different sections of the absorber pipe.

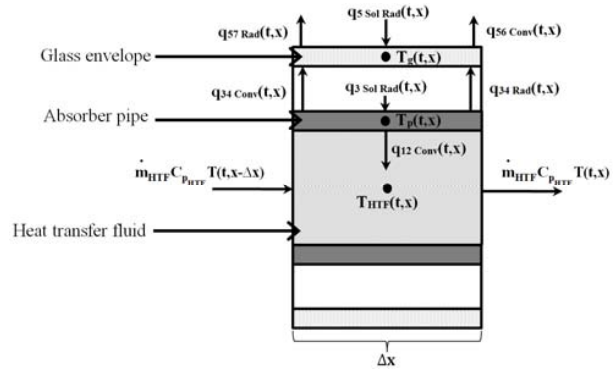


Fig. 2 Energy balance for the receiver tube of solar trough

TABLE II
DEFINITION OF HEAT FLUX TERMS USED IN FIG. 2, (3)-(5)

Heat flux (kW/m)	Heat transfer mode	Heat transfer path	
		From	To
$q'_{12,conv}$	Convection	Inner absorber pipe surface	Heat transfer fluid
$q'_{34,conv}$	Convection	Outer absorber pipe surface	Inner glass envelope surface
$q'_{56,conv}$	Convection	Outer glass envelope surface	Ambient
$q'_{34,rad}$	Radiation	Outer absorber pipe surface	Inner glass envelope surface
$q'_{57,rad}$	Radiation	Outer glass envelope surface	Sky
$q'_{5,SolAbs}$	Solar irradiation absorption	Incident solar irradiation	Outer glass envelope surface
$q'_{3,SolAbs}$	Solar irradiation absorption	Incident solar irradiation	Outer absorber pipe surface

The energy balance equations are written as (1) to (3). Table II presents the heat flux definitions shown in Fig. 2 and (3)-(5). The heat fluxes are calculated using equations presented by [9]:

$$q'_{net,g} = m_g c_{p_g} \partial T_g / \partial t. \quad (1)$$

$$q'_{net,p} = m_p c_{p_p} \partial T_p / \partial t. \quad (2)$$

$$q'_{12,conv} - \dot{m}_{HTF} c_{p_{HTF}} (\partial T_{HTF} / \partial x) = m_{HTF} c_{p_{HTF}} \partial T_{HTF} / \partial t. \quad (3)$$

where \dot{m} is the mass flow rate (kg/s), m is mass (kg/m), c_p is specific heat (kJ/kg.K) and T is temperature ($^{\circ}C$). The subscripts g , p and HTF are associated with glass envelope, absorber pipe and heat transfer fluid respectively. The terms $q'_{net,g}$ and $q'_{net,p}$ are determined by (4) and (5).

$$q'_{net,g} = q'_{5,SolAbs} + q'_{34,rad} + q'_{34,conv} - q'_{56,conv} - q'_{57,rad}. \quad (4)$$

$$q'_{net,p} = q'_{3,SolAbs} - q'_{34,conv} - q'_{34,rad} - q'_{12,conv}. \quad (5)$$

The solar absorption into the glass envelope $q'_{5,SolAbs}$ is considered as a heat flux and since the glass envelope is thin with small absorption coefficient, this assumption introduces minimal error. The solar absorption by the absorber pipe $q'_{3,SolAbs}$ can also be considered as heat flux as it occurs close

to the surface. Convection heat transfer between the HTF and the absorber $q'_{12,conv}$ is calculated considering both laminar and turbulent flows. The Gnielinski correlation is used to find Nusselt number for turbulent flow in the absorber tube. The glass envelope loses heat to the environment by convection $q'_{56,conv}$ which is calculated in both no wind and wind cases. The Nusselt number can be evaluated by Churchill and Chu correlation when there is no wind and Zhukauskas correlation to account for wind.

The heat transfer model is developed in MATLAB and Simulink using finite difference method. The heat fluxes in Table II are calculated for each section of the absorber pipe and the outlet temperature of the HTF, the pipe wall and the glass envelop temperatures are computed at each time step of 1 second. The model also includes the passive mode which simulates the solar system during night time or whenever the pump is off.

B. Organic Rankine Cycle

The organic Rankine cycle is modeled using Thermolib which is a simulation toolbox for design and development of thermodynamic systems in MATLAB and Simulink. The organic fluid of R245fa is chosen as the working fluid for the cycle. A heat exchanger is used to transfer the heat from the solar thermal oil to the R245fa. The key parameters that affect the efficiency of the Rankine cycle is the working fluid inlet temperature and pressure to the turbine and the turbine pressure ratio.

C. Thermal Storage Tank

A latent heat storage tank is considered to store thermal energy using phase change material (PCM). The storage tank is a shell and tube tank with the PCM in the shell and the thermal oil in the tubes. Fig. 3 shows the schematic of the tank.

The heated thermal oil goes through the inner tubes which separate the oil from the Erythritol that has filled up the outer space. When the hot oil enters the inner tubes it exchanges heat with the Erythritol which results in the solid Erythritol melting. This is the way that thermal energy is stored as latent heat and once the cold oil circulates through the tubes, it absorbs the heat from Erythritol and causes solidification.

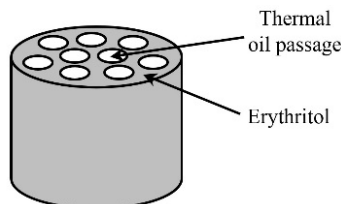


Fig. 3 Shell and tube thermal storage tank

A MATLAB code is developed to solve the energy equation for thermal oil and Erythritol.

D. Absorption Cooling

The absorption cooling cycle consists of 5 main components which are shown in Fig. 4. A solution of LiBr

refrigerant and water is considered as the working fluid of cooling cycle.

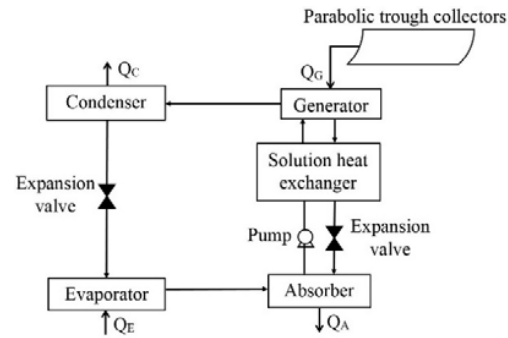


Fig. 4 Solar assisted absorption cooling cycle

The LiBr and water solution absorbs heat from the heated thermal oil in the generator and evaporates. It then goes to the condenser where it releases heat and returns to liquid phase which passes through an expansion valve and enters the evaporator at low pressure. The refrigerant will evaporate by removing heat from its surrounding where the cooling effect is required. The refrigerant vapor then enters the absorber where it will be absorbed by water and pumped back to the generator. The solution heat exchanger improves the process efficiency by heating the refrigerant solution before entering the generator using the heated water which is separated from the LiBr.

The cycle is modeled in Simulink by considering each component as a control volume. For each component the mass and energy conservation and heat transfer equations are considered between the streams of the flow.

V. RESULTS AND DISCUSSION

The considered parameters for evaluating the system performance include the absorption cooling coefficient of performance (COP), the solar coefficient of performance (COP_s), the ORC efficiency (η_{ORC}) and the ORC solar efficiency (η_{ORC-s}). The parameters are defined by (6) to (9).

$$COP = Q_e / Q_g \quad (6)$$

$$COP_s = \eta_s COP \quad (7)$$

$$\eta_{ORC} = W_{net} / Q_{in} \quad (8)$$

$$\eta_{ORC-s} = \eta_s \eta_{ORC} \quad (9)$$

where Q_g is the input energy to the generator, Q_e is the cooling effect produced in the evaporator, W_{net} is the generated power by the ORC, Q_{in} is the input thermal energy to the Rankine cycle and η_s is the solar efficiency of each system and it is defined as:

$$\eta_s = Q_{used} / Q_{sol} \quad (10)$$

Q_{used} is the amount of solar energy used by each user and Q_{sol} is the total incident solar energy on the collector aperture area.

The numerical code is written in MATLAB to solve the system equations and compute the values of COP and η . The MATLAB code is linked to the Simulink model. The outlet temperature of the solar trough collectors is considered at 5 different set points of 100°C, 120°C, 150°C, 170°C and 200°C and the effect of this is studied on the cooling and power generation performance. The simulation is performed using 1 minute meteorological data measured in Winnipeg (49.9° N, 97.14° W). Figs. 5 and 6 show the effect of the collectors outlet temperature on Q_g and W_{net} for a summer day in July 2013 from sunrise to sunset.

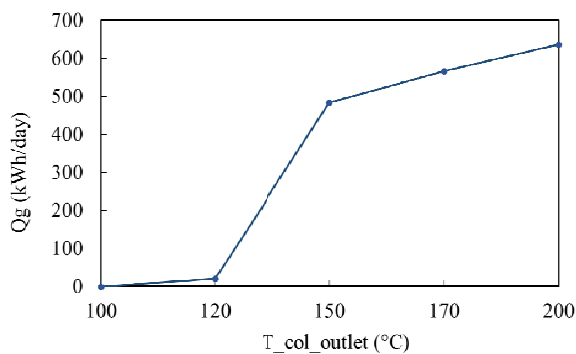


Fig. 5 Effect of solar collector outlet temperature on the input energy to the absorption cooling system generator

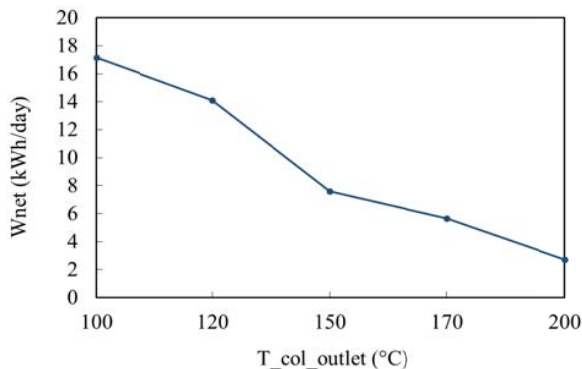


Fig. 6 Effect of solar collector outlet temperature on the generated power by the organic Rankine cycle

At lower temperatures most of thermal energy goes to the ORC since it is the first user and its outlet temperature is not suitable to be used for cooling. As the temperature increases the thermal energy distribution starts. The COP and ORC efficiency increases with temperature as shown in Figs 7 and 8.

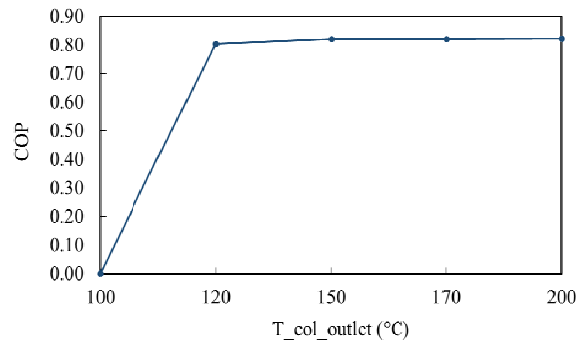


Fig. 7 Effect of solar collector outlet temperature on the absorption cooling coefficient of performance (COP)

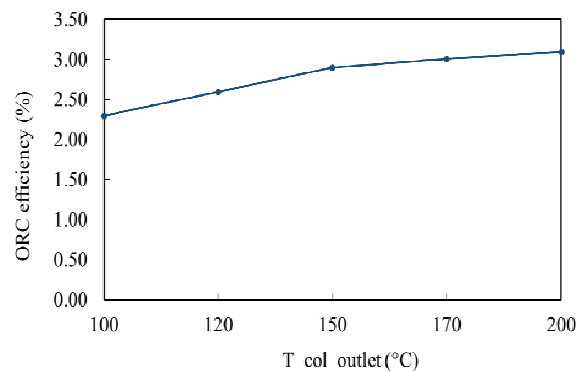


Fig. 8 Effect of solar collector outlet temperature on the organic Rankine cycle efficiency

At 100°C the COP is zero since the cooling effect is zero and all the thermal energy is used by the ORC. The total efficiency of solar cooling and power generation are calculated by (7) and (9) which describe the contribution of the total solar energy received by the collector aperture area in the generated cooling effect and electricity. The comparison of the two parameters is presented in Fig. 9.

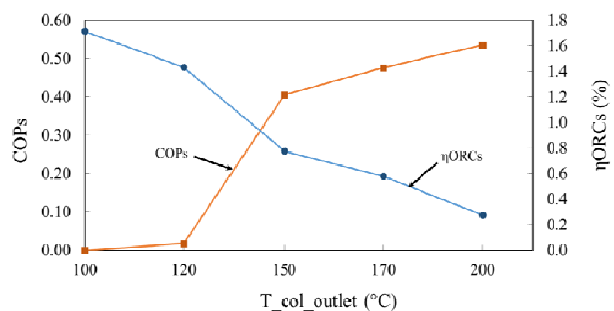


Fig. 9 Comparison of solar coefficient of performance of absorption cooling and solar efficiency of the organic Rankine cycle

Fig. 9 is a useful guide for the controller to make a decision on sending the hot oil to either the cooling or ORC system based on the oil temperature and the performance parameter of the system at this temperature. However, this decision should also be a function of other variables such as the cooling and

electricity load at each time and the cost function of electricity and cooling during a day which vary based on peak periods.

VI. CONCLUSION

A numerical model of an existing concentrated solar trough facility is developed and validated using the experimental data obtained from the facility for the heating only operation. The model uses meteorological data collected at the same location of solar system. The validated model is used to simulate a solar assisted cooling and power generation system. The performance parameters of both systems are compared for different heat transfer fluid temperatures. By adding a cost function for electricity and cooling and also considering the performance of each system at various temperatures, control decisions can be made to minimize the cost considering the best possible performance situation. This is important in remote off-grid communities where the cost of energy is higher due to high price of fossil fuels.

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