Applied Energy 185 (2017) 172–182

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimisation and financial analysis of an organic Rankine cycle cooling system driven by facade integrated solar collectors

Dan Wu, Lu Aye *, Tuan Ngo, Priyan Mendis

Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, The University of Melbourne, Vic 3010, Australia

HIGHLIGHTS

- A novel solar cooling system was developed for office buildings.
- The system uses solar energy collected at the façade to cool the building.
- The net present value of the electricity saving was maximised for the optimisation.
- The unit cost of cooling of optimised system is \$0.24 per kWh_r of cooling effect.

ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form 5 October 2016
Accepted 23 October 2016

Keywords:
Solar energy
Organic Rankine cycle
Refrigeration
Optimisation

ABSTRACT

The use of a solar cooling system has the potential to reduce the amount of energy required for cooling buildings. One of the most important methods of improving energy efficiency in buildings is by carefully designing building façades. A façade integrated evacuated tube collector (ETC)-organic Rankine cycle (ORC)-vapour compression cycle (VCC) was applied in this study. To optimise the design parameters of ORC, a steady-state semi-empirical model was developed in Engineering Equation Solver (EES). The optimum number of plates in each heat exchanger is obtained by maximising the net present value (NPV) of electricity savings. The financial performance of the optimised system was assessed through a unit cooling cost (UCC) analysis. It was found that the UCC of the optimised facade integrated ETC-ORC-VCC system is \$0.24 per kWh_r of cooling effect.

1. Introduction

Currently, air-conditioners are normally powered by electricity [1]. Most electricity is generated by coal in Australia, which is the single largest contributor to GHG emissions (199.5 Mt of CO_2 or 36.9% of national GHG emissions in 2007) [2]. Meanwhile, the working fluids applied in conventional chillers have negative impacts on the environment and high GHG emission factors [3].

In general, cooling dominant localities receive abundant solar radiation and the availability of this radiation matches the cooling demand. In other words, the building's cooling load is in phase with the solar radiation. Therefore, the use of solar energy to drive space cooling systems is an attractive and logical approach for reducing the peak electricity demand in hot sunny climates. Solar cooling encompasses a wide variety of cooling technologies driven by either photovoltaic (PV) modules or solar thermal collectors. Cooling can be achieved through solar electrical, thermal cooling process and thermal mechanical. Among these, the solar organic Rankine cycle (ORC) cooling system has been proven to be the most technically and financially feasible solar cooling technology in façade integration applications [4].

Solar ORC cooling systems were investigated widely in the 1970s and 1980s. However, this research area did not attract much attention over the past two decades until the recent development of the ORC cooling system and the introduction of environmentally friendly working fluids. Prigmore and Barber [5] conducted an experimental study on a solar ORC cooling system to produce 10.55 kWr cooling effect or 1 kW of electricity for residential use. In this system, R113 and R22 were employed for the ORC and VCC chiller, respectively. They concluded that the overall coefficient of performance (COP) of the solar ORC cooling system under off-design conditions can surpass the overall COP of the solar absorption cycle. Wang et al. [6] developed a prototype cooling system with a separate ORC and VCC chiller, with working fluids R245fa and R134a, respectively. A scroll compressor was used to

* Corresponding author.
E-mail address: lua@unimelb.edu.au (L. Aye).

http://dx.doi.org/10.1016/j.apenergy.2016.10.071
0306-2619/

Nomenclature

Symbols		*Subscripts*	
A	area (m^2)	*aux*	auxiliary heater
ALCC	annualised life cycle cost (\$ yr^{-1})	*col*	collector
C	cost (\$)	*cont*	control system
d	real discount rate (–)	*gen*	generator
D	nominal discount rate (–)	*eng*	engineering and installation
E	energy (kW h)	*ev*	evaporator
IC	initial cost (\$)	*ex*	exhaust
LCC	life cycle cost (\$ yr^{-1})	exp	expander
MC	maintenance cost (\$)	*hxc*	heat exchanger
OC	operating cost (\$)	*pp*	pump
P_a	present worth factor (–)	*pip*	pipe
UCC	unit cooling cost (\$ kW hr^{-1})	*ta*	tank
$\dot{W}$	power (kW)		

achieve 5 kWr cooling capacity and 0.5 COP. Demierre et al. [7] also built a prototype solar-driven ORC heat pump for both heating and cooling with R134a. In this prototype, a radial in-flow turbine and a centrifugal compressor were directly coupled. Bu et al. [8] developed an ice maker driven by a solar ORC-VCC system with R123 as the most suitable working fluid. The optimal evaporating and condensing temperature were also identified to achieve maximum overall system efficiency. Hu et al. [9] developed a thermodynamic model to study the effect of evaporating temperature, condensing temperature and working fluid types on an ORC-VCC system. As one of the most important components, ORC has been studied comprehensively in terms of both theory and experiment [10–15]. Meanwhile, several studies focused on ORC optimisation. Quoilin et al. [16] used a single-objective function to optimise a high temperature ORC. The specific investment cost was selected as the objective function. They found that a thermo-economic optimisation can lead to different outcomes compared with a pure thermodynamic optimisation. Sun et al. [17] optimised the exergy efficiency and the system net power output of an ORC for ocean thermal energy conversion in order to select the most suitable working fluid, and evaporating and condensing temperatures. Wang et al. [18] developed a float-point coding scheme based on the genetic algorithm optimisation method to optimise a solar driven regenerative ORC. They used the daily average efficiency as the objective function and minimised the turbine inlet pressure, pinch temperature difference and approach temperature difference. They also studied the effects of the key thermodynamic parameters on the system's performance. Pierobon et al. [19] aimed to find the optimal design for medium size ORCs by employing multi-objective optimisation with the genetic algorithm as the optimiser. Three objective functions were considered: thermal efficiency, the total volume and the net present value of the system. The working fluid, turbine inlet temperature and pressure, condensing temperature, pinch points and mass flow rate were selected as optimisation variables. Liu et al. [20] developed a generic model of a scroll expander in MATLAB/Simulink for a waste heat recovery ORC. The model takes into account the geometric characteristics of the expander, and this geometry can be optimised to avoid under- or over-expansion for any given operating conditions or fluids. Freeman et al. [13] maximised solar ORC electrical power generation by optimising the working fluid, selecting a solar collector module and utilising a recuperator. However, none of these studies considered the optimal design parameters for ORC in cooling generation applications. Meanwhile, the effects of the façade integrated ETCs on the ORC system also have not been considered.

Therefore, the aim of this study is to optimise the heat exchanger area of an ORC to minimise the unit cooling cost (UCC) of the façade integrated ETC-ORC-VCC cooling system. Unlike other previous studies that mainly focused on the optimisation of operating conditions rather than the system design, this paper tends to study the effect of each heat exchange area on the net present value (NPV) of the ORC system.

2. System description and initial design

The solar cooling system comprises four main components: ETCs, ORCs, water-cooled VCC chillers and electric generators. ETCs coupled with the building facade are known as façade integrated ETCs. To maximise the installation areas, ETC modules are also placed on the building rooftop. In addition, several water pumps and buffer tanks are used to obtain the required constant heat transfer fluid flow rate. Gas-fired auxiliary heaters are required to ensure that the heat source for the ORC maintains a constant temperature. The schematic diagram of the proposed system is illustrated in Fig. 1. Hot fluid is supplied to the ORC when useful energy is gained. The super-heated organic working fluid vapour drives the expander, which produces shaft power, and this subsequently drives either the compressor of the vapour compression chiller or the generator for electricity generation. To avoid the conversion losses from the electric motor, the expander of the ORC and the compressor of the vapour compression chiller are directly coupled. A continuous variable transmission device is used to split the power generated from the ORC between the electric generator and VCC chiller. The excess ORC output energy can be used for electricity generation and supplied back to the electricity grid. The generated electricity combined with grid electricity drives the conventional cooling system. The efficiency of ORC is in the order of 10% and the compressor COP of the scroll type vapour compression chiller is typically 4 or even higher. The widely used refrigerant R134a is used as the working fluid for both the power cycle and cooling cycle. In the simulated model, cooling towers are excluded because they were assumed to maintain a constant cooling water temperature by varying their fan speeds. It should be noted that the proposed system is a formulated concept i.e. there was no prototype. Although the integrated system has not been fully validated through experimental work, the individual components (ETCs, evaporator, condenser, recuperator and vapour compression cycle) are well established and operational. In a previous study by Wu [4], the optimum places for installation and design of façade integrated ETC modules are determined by testing different slopes of rooftop ETC modules, as well as a different number of modules in series/parallel under various orientations to achieve the maximum energy gain. The optimum design