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Improvement of solar-electric compression refrigeration system through ejector-assisted vapour compression chiller for space conditioning in subtropical climate

K.F. Fong*, C.K. Lee, T.T. Chow

Building Energy and Environmental Technology Research Unit, School of Energy and Environment & Division of Building Science and Technology, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China

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ABSTRACT

In this study, improvement was made for the solar-electric compression refrigeration system by incorporating the ejector design to a conventional vapour compression chiller within the system. Through year-round dynamic simulation, the performances of the ejector-assisted vapour compression chiller (EAVCC) were evaluated under the intermittent and changing supply of solar energy in the subtropical climate. In addition, the effect of three common refrigerants, R22, R134a and R410A on the EAVCC was assessed and compared. It was found that the coefficient of performance of the chiller was increased and the total primary energy consumption of the system was decreased for all the three refrigerants, in which the degree of enhancement from R134a was the most significant. It was also noted that the effect of R410A on EAVCC was not apparent, and the overall system energy improvement was marginal. With appropriate ejector design and refrigerant selection of the solar-electric compression refrigeration system, the reduction potential of year-round primary energy consumption could be more than 5%. This would be certainly helpful in promoting the application of solar air-conditioning for building use in the subtropical climate.

1. Introduction

In the previous study [1], it was found that the solar-electric compression refrigeration system using a vapour compression chiller (VCC) would offer higher primary energy saving potential as compared to the solar-thermal ones. To enhance the performance of the solar-electric compression refrigeration, apart from the advancement of the photovoltaic (PV) technology and the development of building integrated PV [2], there is still room of improvement of chiller effectiveness. In fact, appropriate ejector design can be applied within a conventional vapour compression refrigeration cycle to increase the coefficient of performance *COP*. An ejector is a device used to entrain a low-pressure fluid with a high-pressure fluid for a specific purpose. Ejector design is one of the strategies to enhance the thermally driven refrigeration cycles [3], including those energized by the solar thermal gain [4]. Nevertheless, theoretical and experimental works were also made for directly incorporating the ejector into the electrically driven compression cycle and its *COP* improvement was studied [5,6]. Generally it was found that the effect of ejector design was positive, but it strongly depended on the evaporator and condenser temperatures of the refrigeration cycle [7,8], which is in turn related to the applications. In a refrigeration system for space conditioning in building, the cooling loading requirement would affect the evaporator temperature, while the heat rejection medium would influence the condenser temperature.

In this study, an ejector-assisted vapour compression chiller (EAVCC) was used in the solar-electric compression refrigeration system for a holistic evaluation in the changing loading and climatic conditions throughout a year. As there is coupling effect between the PV panels and the chiller in providing space conditioning under the changing year-round conditions, a thorough analysis of the electricity generation of the PV panels, the auxiliary supply from the power grid, and the possible amount of spill power was carried out in the studying period. This paper has the following arrangement: Section 2 describes the details of the ejector design and the EAVCC. Section 3 presents the dynamic simulation and evaluation for the solar-electric compression refrigeration system. Section 4 discusses the performances of the EAVCCs and the entire systems using different refrigerants. Section 5 is conclusion.

* Corresponding author. Tel.: +852 3442 8724; fax: +852 3442 9716.
E-mail address: bssquare@cityu.edu.hk (K.F. Fong).

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Nomenclature

COP	coefficient of performance
COP_r	*COP* ratio of EAVCC against VCC
d	diameter (m)
h	specific enthalpy (kJ kg^{-1})
m	refrigerant mass flow rate (kg s^{-1})
P	refrigerant pressure (kPa)
PE_{ch}	primary energy consumption of chiller (kWh)
PE_{sp}	spill primary energy to the grid (kWh)
PE_t	total primary energy consumption of the entire solar-electric compression refrigeration system (kWh)
Q	heat transfer rate (kWh)
Q_r	capacity ratio of EAVCC against VCC
SF	solar fraction
T	temperature (°C)
V	refrigerant velocity (m s^{-1})
W_{aux}	auxiliary electrical energy from power grid (kWh)
W_{ch}	electrical energy input to chiller compressor (kWh)
$W_{parasitic}$	electrical energy consumption of parasitic equipment (kWh)
W_{sol}	solar electric gain (kWh)
W_{sp}	spill energy to the grid (kWh)
x	refrigerant quality

Greek letters

η_e	electrical energy efficiency
η_n	isentropic efficiency for refrigerant flow through converging nozzle
ρ	refrigerant density (kg m^{-3})

Subscripts

cond	condenser or condenser outlet
ci	compressor inlet
cw	condenser water
d	diffuser
dis	compressor outlet
eo	ejector outlet
et	ejector tube
evap	evaporator
ew	chilled water
i	inlet
isen	isentropic process
n	nozzle
no	ejector nozzle
nop	primary refrigerant at ejector nozzle
nos	secondary refrigerant at ejector nozzle
o	outlet
r	refrigerant
suc	evaporator outlet

2. Ejector-assisted vapour compression chiller

2.1. Strategic location of ejector

The ejector incorporated into the vapour compression cycle should be designed in a strategic location, Bilir and Erosy [9] and Sarkar [10] investigated the one of the ejector-expansion refrigeration cycle and assured its effectiveness for the refrigeration cycle. In this study, the proposed strategic location of ejector was therefore adopted in the EAVCC, as shown in Fig. 1. The ejector was involved in a way to raise the gas refrigerant from the evaporator, such that the compressor power input would be reduced, and the enthalpy dissipation of expansion valve would also be decreased. It used the liquid refrigerant from the condenser as the primary flow, while the gas refrigerant from the evaporator as the secondary flow. The outlet gas refrigerant, with a pressure higher than the evaporator pressure, would be separated and fed into the compressor of the refrigeration cycle. The liquid refrigerant of the separator would then go through the expansion valve, and enter the evaporator for producing refrigeration effect.

2.2. Mathematical models of ejector and EAVCC

Fig. 2 shows a typical construction of ejector for this study. Based on the formulation of Sarkar [11], the states of the primary and secondary refrigerant flows at the ejector nozzle were given by:

$$h_{r,nop} = h_{r,cond} - \frac{V_{nop}^2}{2000} \tag{1}$$

$$h_{r,nos} = h_{r,suc} - \frac{V_{nos}^2}{2000} \tag{2}$$

where *V* is the refrigerant velocity calculated from:

$$V_{nop} = \frac{4m_{nop}}{\pi \rho_{nop} d_{no}^2} \tag{3}$$

$$V_{nos} = \frac{4m_{nos}}{\pi \rho_{nos}(d_{et}^2 - d_{no}^2)} \tag{4}$$

With the introduction of an isentropic efficiency for the refrigerant flow through a converging nozzle η_n,

$$h_{r,nop} = h_{r,cond} - \eta_n(h_{r,cond} - h_{r,nop,isen}) \tag{5}$$

$$h_{r,nos} = h_{r,suc} - \eta_n(h_{r,suc} - h_{r,nos,isen}) \tag{6}$$

The isentropic enthalpy drop for the primary and secondary refrigerant flows were calculated based on a given nozzle outlet pressure P_{no}. By applying momentum and energy balances inside the ejector tube,

$$V_{et} = \frac{m_{nop}V_{nop} + m_{nos}V_{nos}}{m_{nop} + m_{nos}} \tag{7}$$

$$h_{r,et} = \frac{m_{nop}h_{r,cond} + m_{nos}h_{r,suc}}{m_{nop} + m_{nos}} - \frac{V_{et}^2}{2000} \tag{8}$$

With the introduction of an isentropic efficiency for the refrigerant flow through a diverging diffuser η_d, between the ejector tube and the ejector outlet,

$$h_{r,ab} = h_{r,et} + \frac{h_{r,ab,isen} - h_{r,et}}{\eta_d} = \frac{m_{nop}h_{r,cond} + m_{nos}h_{r,suc}}{m_{nop} + m_{nos}} \tag{9}$$

Again, the isentropic enthalpy rise along the diffuser was determined according to a given P_{eo}. Based on the mass balance, the quality of the refrigerant at the ejector outlet was given by:

$$x_{eo} = \frac{m_{nop}}{m_{nop} + m_{nos}} \tag{10}$$

The models adopted by Lee [12] were applied for the condenser, the evaporator and the compressor. The parameters for the compressor were determined from the manufacturer's performance data [13] using a parameter estimation technique. A thermostatic expansion valve was used which would maintain a constant degree of superheat at the evaporator outlet. For given condenser and evaporator pressures, the performance of the ejector was found by solving Eqs. (1)–(10). For the entire EAVCC, the condenser and evaporator pressures were adjusted so that the degree of superheat at the evaporator outlet could be reached and that the refrigerant flow based on the ejector characteristics would match with that based on the compressor of the chiller.