



Experimental investigation on solar-powered ejector refrigeration system integrated with different concentrators

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Abstract

The objective of the work is to analyse and to improve the efficiency of solar-powered ejector refrigeration system integrated with flat-plate collector and Scheffler concentrator. The Scheffler concentrator of 2.7 m² and flat-plate collector of 5 m² collecting area are coupled with the storage tank of 15 l capacity. The developed system was designed for a potential replacement of conventional 1-ton room air conditioner with much reduced electrical energy consumption. The system was built based on two key subsystems namely ‘Scheffler concentrator-based vapour system’ and ‘ejector-based cooling system’. The pilot effort showed promising results with the probability of energy-saving potential as near 70 to 80% over conventional air conditioners.

Keywords Solar energy · Solar cooling · Green energy · Renewable energy · Pollution reduction

Introduction

All across the world, air conditioning systems are considered to be electrical energy guzzlers as not only they demand high electrical energy per unit but also their run hours are quite long usually on an average 8–10 h continuous in most cases. Besides, the use of such systems peaks mostly in high-temperature ambience when it is the worst period for electrical load demand. World over there are ongoing efforts to reduce the electrical consumption of such systems by developing high-efficiency drives to substitute conventional electrical drives as the most case they use high kW induction motors. The utilization of solar energy for refrigeration or cooling

application becomes more attention in the last few years due to the use of low-grade renewable energy. Most popular solar refrigeration systems are absorption and adsorption machines. On the contrary, more attention focused on solar ejector refrigeration system because of the low operating cost and simplicity. The concepts developed in the present work uses a multi-disciplinary approach to save energy in air cooling applications using the thermal energy from solar.

However, the ejector refrigeration system has lower performance than previous technologies which motivates to do more research. Many numbers of research are conducted to improve the performance solar ejector refrigeration system. Many studies reveal that the solar ejector cooling system with evacuated tube collector has more coefficient of performance (COP) than flat-plate collector (Bellos and Tzivanidis 2017; Elbel and Lawrence 2016; Sumeru et al. 2012; Chua et al. 2010). The overall performance of the solar ejector refrigeration system is depending on solar collector efficiency and performance of the ejector sub-cycle (Chunnonond and Aphornratana 2004). Therefore, it is necessary to pay attention to improving the performance of the solar collector and the ejector refrigeration system. Huang et al. (2001) examined the performance of solar ejector refrigeration system using different collectors namely specially designed flat-plate collector with 10 cm air insulation, conventional flat-plate collector and vacuum tube solar collector. The results showed that proper selection of the collector with optimum generator temperature could provide higher performance. Ersoy et al. (2007)

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reported that the efficiency of the evacuated tube ejector cooling system depends on the ambient condition, solar radiation and generator temperature. Pridasawas and Lundqvist (2004) conducted energy and exergy analysis in the solar ejector cooling system. They reported that the major losses of 51% and 16% have occurred at the location of solar collector and ejector system respectively. Besagni et al. (2016) reported that the constant rate of generator temperature has been affected by solar irradiation intensity value. At high ambient temperatures, the ejector needs more power than the power supplied by the solar collector. Also, the generator temperature from 120 °C to 140 °C provides better COP with critical flow conditions. Zhengshu Dai et al. (2012) studied the ejector refrigeration system without a pump. Experiments were conducted to analyse the performance of the solar operated ejector-based system with the refrigeration capacity of 1.5 kW, evaporation temperature as 15 °C, condensation temperature as 45 °C and a generator temperature as 80 °C. The effect of evaporation, condensation and generation temperatures on the performance of ejector was evaluated. However, the performance of the tested ejector was found to be unsatisfactory. Jagveer et al. (2014) analysed solar operated ejector system at the steady-state condition. Ejector-based refrigeration cycle that used natural working fluids gave a good performance with reduced environmental influence compared to environmental affecting gases like CFCs and HFCs. The research paper gave an outcome for one ejector dimension where refrigerant was R11. The power source for the system was 2 kW solar panel used with solar heater kit. Effects of different controlling parameters such as evaporator temperature, generator temperature, condenser temperature that affected the ejector system's performance were discussed in the work by Nayak and Mandal (2014). They concluded that the COP of the ejector refrigeration system depended on the ejector's configuration and evaporator's operating temperature, condenser and generator temperature. The behaviour of entrainment ratio was analysed by Zheng et al. (2012) when R718, HFC134a and R290 were used as working fluid. It was observed that the entrainment ratio of R290 was the highest over a range of operating conditions, and that of HFC134a of middle value, and the R718's was the lowest. It was found that within the operating range of the experimentation, the entrainment ratio increased as the generator and evaporator temperature of the system increased and decreased with the increase of the condenser temperature. It was noticed that condenser temperature had a large effect on the ejector system more than temperatures of generator and evaporator. The project work by Bonafoni and Capata (2015) showed that heat recovered from 1400 cc Diesel engine exhaust gases was able to vaporize working fluid of a small (< 10 kW) organic refrigeration system. The objective was to have a compact system to make it useful for transport applications such as ships and cars. Water and refrigerant fluids R134a and

R245fa were the three fluids studied. The two refrigerants were found to be superior to water. Thereafter, a design procedure was formulated to model heat exchanger and a steady-state structural and thermal analysis was carried out. By using commercial software, temperature effects of the thermal stress on the material of the helically coiled tube were investigated. Selvaraju (2003) studied the effects of operating parameters on entrainment ratio and critical ejector area ratio. Refrigerants considered being environment-friendly such as R134a, R152a, R290, R600a and R717 were investigated for comparing their performance with ejector. Refrigerants, R134a among the tested ones, was found to have a higher critical entrainment ratio with better performance. The main ejector geometry parameters for the ejector cycle using R134a with a cooling capacity of 2 kW were designed by Yan and Cai (2012). They studied optimum area ratios experimentally by increasing the design area ratios using replaceable nozzles with the main body. The entrainment ratio, cooling capacity and COP were evaluated, and the observed results indicated that the optimum area ratios were in between 3.69 and 4.76. These values were lesser than those in other studies. Experiments showed that with fixed area ratio, the effect of the ejector area ratio on the ejector performance mainly depended on the operating conditions. Subsequently, the effects of primary flow pressures, on the ejector system performance, were evaluated. Butrymowicz et al. (2010) developed a way for ejector analysis using the performance curve of the installation and performance curve for the ejector. The interception of two curves gave the operating point of the system. The model was formed for an ejector-based air-conditioning cycle. It consisted of the characteristics of the ejector and thermodynamic performance of the system. The performance of the ejector could be assessed by numerical modelling or by experimental studies. Scheffler (2006) explained the design of Scheffler reflectors, helps to study the constructional details and working of Scheffler throughout the year irrespective of seasons. Rakeshsharma et al. (2006) developed an experimental procedure for paraboloid concentrator with cavity receiver and employed in the field. To evaluate the performance of paraboloid solar thermal concentrator, a characteristics equation was developed using extensive experimental work. Kinjavdekar et al. (2010) proposed and devised a testing method for comparison of the performance of different types of concentrators on a common platform. This helped in the design and performance prediction of concentrator as well as a complete system. The method consisted of two tests namely optical (focus test) and thermal performance test. They deployed the focus test to a Scheffler concentrator. The test quantified the focus size, the total solar radiations, distribution of radiations and concentration ratio. This data was useful in the choice of material and design of receiver shape. Patil et al. (2011) performed an experimental analysis on 8 m² Scheffler reflector. It had one large drum of

20 l of capacity which served the purpose of the storage tank and absorber tube both. Collector's performance analysis showed that efficiency and average power in terms of water boiling test were 21.61%, 1.30 kW respectively at average beam radiations of 742 W/m^2 . The water temperature was achieved up to $98 \text{ }^\circ\text{C}$ in the storage tank on a clear day of operation and ambient temperature between $28 \text{ }^\circ\text{C}$ and $31 \text{ }^\circ\text{C}$. Daffe and Shinde (2012) conducted a performance evaluation of 16 m^2 Scheffler reflector for 2 bar pressure and $110 \text{ }^\circ\text{C}$ temperature for cooking application. The Scheffler was used with mild steel absorber plate having 18 cm diameter and 2.5 cm thick. Solar radiations in a day were found to vary between 620 W/m^2 and 937 W/m^2 . Absorber plate temperature was recorded between $138 \text{ }^\circ\text{C}$ and $235 \text{ }^\circ\text{C}$, while at the outlet of boiler, the maximum steam temperature achieved was $107 \text{ }^\circ\text{C}$. It was noticed that with an increase in radiations, instantaneous efficiency dropped. The overall efficiency obtained was 57.41% which was higher than the parabolic trough system. It was concluded that for applications such as water heating, low temperature and pressure applications of steam in process industries, Scheffler concentrator systems could be useful. Ajay Chandak et al. (2009) designed and experimented for the production of distilled water using multi-stage evaporation. In the first stage at 8 bar pressure, two Scheffler concentrators of 16 m^2 each were used for generating steam. The pressure was then lowered to 1 bar in four steps. The total yield obtained for the whole project was 2.3 times higher than single-stage distillation. The temperature drop was designed to $25 \text{ }^\circ\text{C}$ in each stage.

The detailed literature survey reveals that the performance of an ejector refrigeration system could be increased by imparting the improved solar collector design. Also, no attempt has been made for the integration of different solar collectors on improving the heat source to the ejector system and this leads to increase the generator temperature. The present work is intended to analyse the solar-powered ejector refrigeration system integrated with the flat-plate collector and the Scheffler concentrator. The Scheffler concentrator of 2.7 m^2 and flat-plate collector of 5 m^2 collecting area are coupled with the storage tank of 15 l capacity. The developed system is designed for a potential replacement of conventional 1-ton room air conditioner with much reduced electrical energy consumption.

Experimental investigation

The general working layout of solar ejector refrigeration system integrated with flat-plate and Scheffler collector is shown in Fig. 1. The water from the storage tank was entered into the integrated flat-plate collector and Scheffler concentrator system and becomes super-heated steam at the end. This steam has been temporarily in the storage tank. The thermal oil has

been used to transfer heat from the steam storage tank to heat exchanger or vapour generator. The refrigeration system consists of two loops namely power loop and refrigeration loop. In the power loop, the low-grade heat is used to generate super-heated vapour from primary flow (refrigerant) in the generator at high pressure. It necessary that the streamflow enters into the ejector should be in super-heated condition for the prevention of formation of liquid droplets in the primary nozzle (Eldakamawy et al. 2017). The high-pressure super-heated primary flow from the generator enters into the ejector and accelerated in the nozzle and thus produces a vacuum which in turn sucks the vapour (secondary flow-refrigerant) from the evaporator. These two fluids are mixed in the chamber and enter into a diffuser where the flow is decelerated and pressure is recovered. Then, this mixed fluid enters into the condenser where heat rejection takes place with the environment, and thus, condensation takes place. A portion of liquid refrigerant is pumped back to the generator for the completion of the power loop. The remaining liquid refrigerant enters the expansion valve where the reduction of pressure and temperature takes place with partial vaporization. The mixture liquid and vapour refrigerant enter into the evaporator and produce required refrigeration effect by absorbing heat from the given source. The vapour from the evaporator enters to ejector for the completion of the refrigerant loop. The heat source required in the power loop is compensated by the solar power by the concentration of all incident radiation to produce the required heat in the generator. Figure 1b represents the total thermodynamic cycle of the system in pressure-enthalpy diagram. A typical 1-ton capacity air conditioner was considered in the work as a target for bringing down the energy consumption substantially. Out of several types and shapes of solar concentrators, Scheffler concentrator was chosen as most appropriate for medium temperature steam between 130 and $150 \text{ }^\circ\text{C}$. The system was designed with saturated vapour at 1 bar pressure to be supplied to a heat exchanger where hot steam gives up its heat to the refrigerant converting it from a liquid state to vapour state. A small size Scheffler concentrator of 2.7 m^2 is conventionally used for water heating; however, this development has made it useful for medium temperature steam generation. Initial experimentation showed that a stand-alone Scheffler of 2.7 m^2 size may not satisfy the requirement, and hence, the integration of Scheffler and flat-plate collector was proposed. The proposed system consists of a typical flat-plate collector and Scheffler collector with the collecting area on 5 m^2 and 2.7 m^2 respectively. These collectors are connected in series to produce steam at the required rate and then stored in the tank of 15 l capacity. The steam made a pass through the generator or heat exchanger for the conversion of liquid refrigerant into vapour refrigerant, and then, the cycle is completed. The refrigeration system using CFC and HCFC refrigerant causes adverse effect on the layer of ozone, and hence, HFC family of refrigerant is

extensively used as their replacement. The refrigerant used for the subject research work was R134a, tetrafluoroethane (CF₃CH₂F). The specifications of the collector and the properties of refrigerant R134a are listed in Tables 1 and 2 respectively. It is also widely used in new vehicle’s air conditioning system. It is safe to use as it is non-corrosive, non-toxic and non-flammable and hence considered a good choice.

Performance evaluation

Ejector design

The proposed ejector in the system is shown in Fig. 1. It consists of a nozzle section, mixing section, throat section and diffuser section. There are two inlets and one outlet in the ejector system namely primary stream flow inlet (state point 1), secondary stream flow inlet (state point 7), and one outlet for mixed streamflow (state point 4). The primary flow from the generator enters into ejector through the motive nozzle where the pressure of the fluid flow decreases to very low pressure (state point 2). Simultaneously, the secondary flow enters the ejector through the suction nozzle and the pressure gets reduced to (state point 2). These two streams are mixed in the mixing chamber and enter to the throat section. In the proposed design, it is assumed that the pressure levels in the mixing section and in the throat-section are at the same level. Then, the mixed streams are entered into the diffuser section and the pressure of the streams is increased to level 4 (state point 4). The ejector analysed in this work has different geometry characteristics and it is shown in Fig. 2. The thermodynamics design of the ejector system has been developed based on the research output of Bellos and Tzivanidis (2017) and Haghparast et al. (2018). The following assumptions are made for designing the ejector system.

The flow of streams is at steady-state conditions and it is assumed to be a one-dimensional homogeneous equilibrium flow.

There is no heat transfer between the ejector and the environment.

Table 2 Properties of refrigerant, R-134a

Property	Value
Boiling point	− 25 °C
Density	1362 kg/m ³ (liquid) 5.593 kg/m ³ (vapour)
Enthalpy	69.23 kJ/kg (liquid) 283.43 kJ/kg (vapour)
Critical temperature	101.1 °C

The mixing of streams is at a constant pressure level. The velocity of streams is ignored at the inlet and at the outlet of the ejector.

The energy balance in the mixing section can be arrived by the assessment of the mass flow rate of primary flow m_g , the mass flow rate of secondary flow m_e , enthalpy of primary flow h_1 at the inlet of the ejector, enthalpy of secondary flow h_7 at the inlet of the ejector and the enthalpy of the mixed stream h_3 at the mixing chamber. The energy balance in the mixing chamber is given in Eq. (1):

$$(m_g + m_e)h_3 = m_g h_1 + m_e h_7 \tag{1}$$

The law of conservation of momentum at the mixing section of the ejector is given by Eq. (2): where the velocity of primary flow, secondary flow and mixed streamflow is denoted by V_g , V_e and V_m respectively.

$$m_g V_g + m_e V_e = (m_g + m_e) V_m \tag{2}$$

The isentropic nozzle efficiency η_{Nozzle} at exit is defined as the ratio between actual kinetic energy to isentropic kinetic energy and this can be written as:

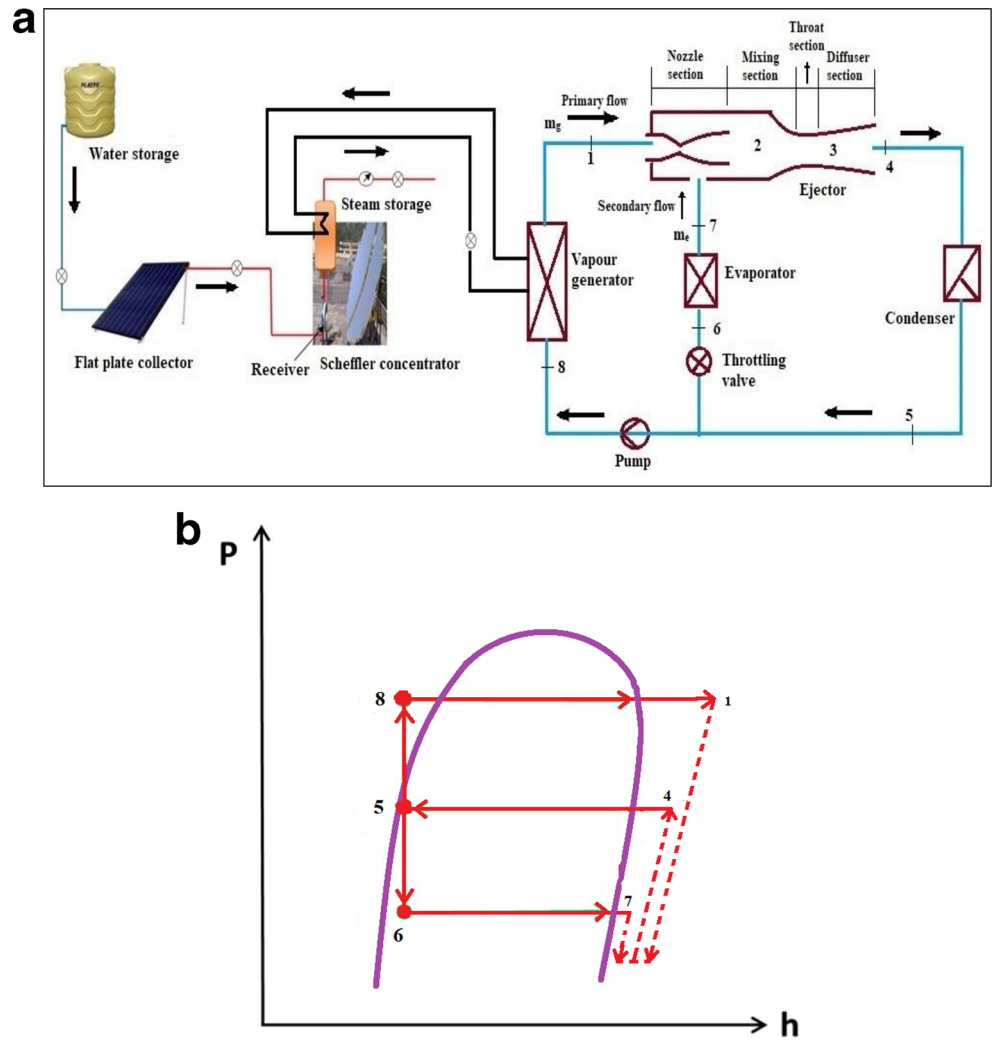
$$\eta_{\text{Nozzle}} = \frac{h_1 - h_2}{h_1 - h_{2,s}} \tag{3}$$

where h_1 and h_2 are the enthalpy of streamflow at nozzle inlet and outlet respectively and the isentropic enthalpy of the stream at the exit of the nozzle is denoted by $h_{2,s}$. By

Table 1 Specifications of Scheffler collector and flat-plate collector

Scheffler collector	Flat-plate collector
Reflector area, 2.7 m ²	Absorber area, 1.91 × 0.975 m ²
Aperture area, 2.5 m ²	9 Riser tubes of copper with outside dia-12 mm, inside dia-9 mm
Concentration ratio, 17	Insulation glass wool with 5 mm thickness
Mirror reflectivity, 80%	Dimensions: $L = 2.015$ m, $W = 1.035$ m, $H = 0.096$ m
Cylindrical Receiver:	
Diameter, 450 mm	
Length, 50 mm	

Fig. 1 a Experimental layout. b Thermodynamic cycle in pressure-enthalpy diagram



considering the adiabatic and no work conditions of the horizontally positioned nozzle, the velocity of the stream at the outlet of the nozzle V_g can be found by Eq. (4).

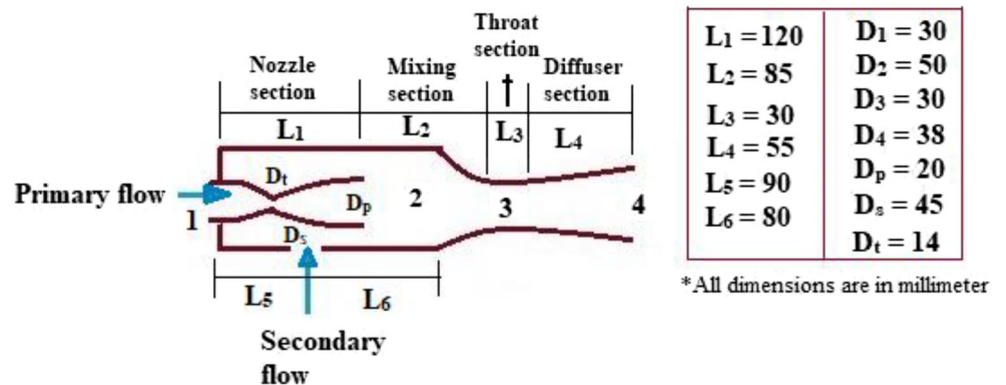
$$V_g = \sqrt{2(h_1 - h_2)} = \sqrt{2\eta_{\text{Nozzle}}(h_1 - h_{2,s})} \tag{4}$$

Similarly, the isentropic diffuser efficiency η_{Diffuser} is defined as

$$\eta_{\text{Diffuser}} = \frac{h_{4,s} - h_3}{h_4 - h_3} \tag{5}$$

where h_3 and h_4 are the enthalpy of streamflow at diffuser inlet and outlet respectively and the isentropic enthalpy of the

Fig. 2 Ejector geometry



stream at the exit of the diffuser is denoted by $h_{4,s}$. By considering the adiabatic and no work conditions of the horizontally positioned nozzle, the velocity of the stream at the outlet of the diffuser V_g can be found by Eq. (6).

$$V_g = \sqrt{2(h_4 - h_3)} = \sqrt{2 \left(\frac{1}{\eta_{\text{Diffuser}}} \right) (h_{4,s} - h_3)} \quad (6)$$

The entrainment ratio or mass ratio ω is the ratio between the mass flow rate of secondary flow m_e , and the mass flow rate of primary flow m_g :

$$\omega = \frac{m_e}{m_g} \quad (7)$$

The product of the isentropic efficiency of the nozzle (η_{Nozzle}), the isentropic efficiency of diffuser (η_{Diffuser}) and the mixing efficiency (η_{mixing}) is referred to as isentropic efficiency of the ejector, η_{ejector} . Based on the literature studies (Wang et al. 2009; Liu and Groll 2013), the nozzle, diffuser and mixing efficiency considered for this study are 90%, 85% and 85% respectively.

$$\eta_{\text{ejector}} = \eta_{\text{Diffuser}} \times \eta_{\text{Nozzle}} \times \eta_{\text{mixing}} \quad (8)$$

The ratio between the condenser pressure p_c and the evaporator pressure p_e is referred to as compression ratio r_p of the ejector.

$$r_p = \frac{p_c}{p_e} \quad (9)$$

The performance of the ejector cooling system can be assessed by the coefficient of performance (COP); it is the ratio between the cooling effect (Q_e) and the total energy input ($Q_g + W_p$), where Q_e is the cooling effect or the amount of heat absorbed by the refrigerant in the evaporator, Q_g is the amount of heat given by the generator and W_p is the pump work.

$$\text{COP} = \frac{Q_e}{Q_g + W_p} \quad (10)$$

In general, the liquid pump work is very low and thus it is neglected.

$$\text{COP} = \frac{Q_e}{Q_g} = \frac{m_e(h_7 - h_6)}{m_g(h_1 - h_8)} \quad (11)$$

Solar collector performance

The performance of the solar collector array can be assessed by the solar collector efficiency (η_c); it is the ratio between useful heat gain, Q_u and the total solar incident radiation ($A_c \cdot I$). In addition, the solar collector efficiency can be expressed

by the Bliss coefficient ($F_R(\tau\alpha)$) and the heat loss coefficient ($F_R U_L$); it is given in Eq. (12). The average temperature between the fluid inlet and the fluid outlet from the collector or absorber tube is referred by T_a and the ambient temperature is referred to as T_∞ .

$$\eta_c = \frac{Q_u}{A_c I} = F_R(\tau\alpha) - F_R U_L \left(\frac{T_a - T_\infty}{I} \right) \quad (12)$$

The values of bliss coefficient and heat loss coefficient are referred from the previous studies and are listed in Table 3.

Results and discussion

The overall performance of the system can be analysed by measuring the temperature and pressure of the working fluid at different locations. The temperatures are measured by direct contact T-type thermocouples with calibrated accuracy $\pm 3^\circ\text{C}$. The measurements of pressure are done by pressure transducers with an accuracy of $\pm 0.3\%$. The Coriolis mass flowmeter was used to measure the mass flow rate of the primary flow and the secondary flow of the refrigerant with an accuracy of $\pm 0.03\%$. The electricity consumption of the components was measured by AC watt transducers with an accuracy of $\pm 0.25\%$. All the experimental data are recorded after reaching stable conditions by using a data acquisition device with an interval of 10 s. The experiments are conducted with the variation in the entrainment ratio, set values of evaporator temperature and the variation in the pressure ratio. The overall performance of the system can be analysed by the evaluation of solar collector efficiency and the COP of the ejector refrigeration system.

Performance of the solar collector

In the present system, there are two solar concentrators are used namely flat-plate collector and the Scheffler concentrator, both are connected in series and the outcoming steam from the collectors are used to heat the oil which is circulated between the steam collector and the vapour generator or heat exchanger. The solar collecting efficiency is purely depending on the solar irradiation value at the test location. The solar intensity values are recorded by the Pyranometer with the calibrated accuracy $\pm 0.3\%$. The experiments were conducted in the City Pune, India, during April 7–11, 2018. The direct beam radiation value and ambient temperature on a typical day is shown in Fig. 3. It is seen that the maximum values of solar intensity are recorded in the during 11:45 h–13:45 h with the range of $698\text{--}614 \text{ W m}^{-2}$; during this time, the instantaneous solar collector efficiency will be maximum and thus produces higher useful heat gain and higher generator temperature. Average ambient conditions on test day are about 37°C temperature, wind velocity 1.67 m/s.

Table 3 Bliss coefficient and heat loss coefficient

Solar collector type	Bliss coefficient, $F_R(\tau\alpha)$	Heat loss coefficient, $F_R U_L, W / (m^2 K)$	Reference
Flat-plate collector, single glass cover	0.8	0.5	Fléchon et al. (1999)
Scheffler concentrating collector	0.7	2.5	Henning (2004)

In addition to the study, the comparative performance analysis has been carried out between the stand-alone Scheffler concentrator system and the integrated solar collecting system by the estimation of the steam generation rate and the thermal efficiency of the systems. The experimental results of the thermal efficiency of the collectors and the steam generation rates are presented in Figs. 4 and 5 respectively. It is seen that the stand-alone Scheffler system had low thermal efficiency and low steam generation rate than an integrated system. Due limited focal area, the Scheffler system produces the steam about 0.9 kg h^{-1} at 1 bar pressure with the thermal efficiency of 36.19%, whereas the integrated system produces the steam about 1.6 kg h^{-1} with the thermal efficiency of 41.64% at the same pressure. The results are in good agreement with the studies made by Chen et al. (2014) and Gil and Kasperski (2015). The similar trend has been noted for all remaining pressure range. It was clearly noted that the integrated system has the capacity to boost the thermal efficiency by 4 to 5% and the steam generation rate by 0.5 to 0.7 kg h^{-1} . This performance was adequate to achieve the required generator temperature.

Performance of solar-powered ejector cooling system

The performance of the solar-powered ejector cooling system with integrated solar collectors was analysed by the variation

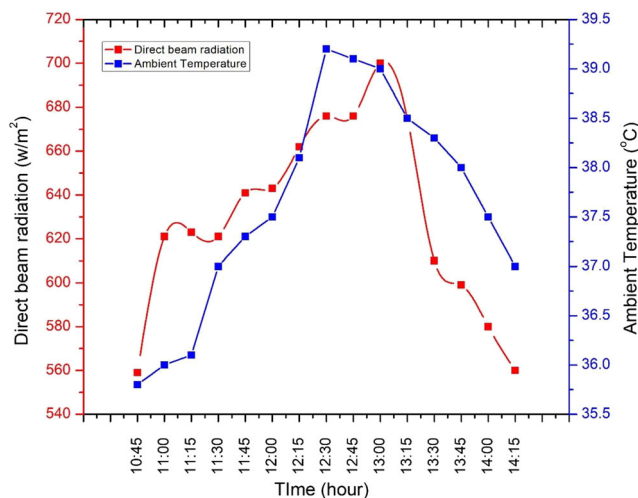


Fig. 3 Direct beam radiation and ambient temperature

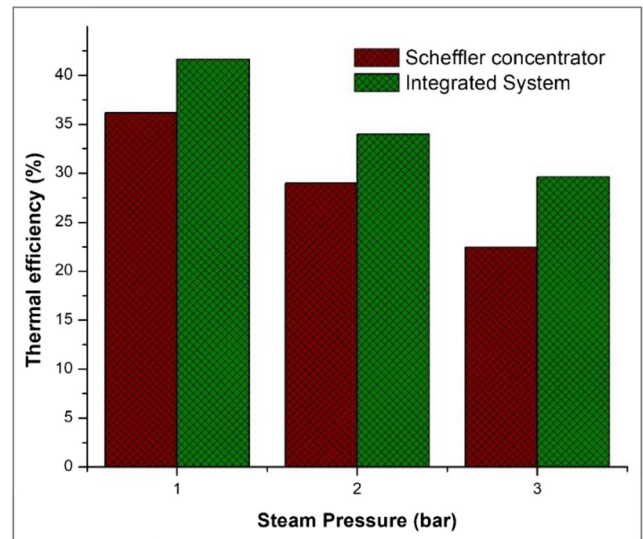


Fig. 4 Thermal efficiency of the collectors

in the set values of the entrainment ratio, pressure ratio, evaporator temperature and the condenser temperature.

Figure 6 illustrates the effect of entrainment ratio on the performance of the ejector cooling system. It is seen that the COP of the system increases with increase in entrainment ratio which results in an increase of evaporator pressure. The entrainment ratio is defined as the ratio between the mass flow rate of the secondary flow and the primary flow. It is obvious that the increase of entrainment ratio leads to admit higher rate of the secondary flow into the ejector which in turn increases the evaporation rate and thus the COP of the system increased. In the present system, the entrainment ratio was increased from 0.24 to 0.27, and this was greatly influenced by the rise of system COP from 0.207 to 0.257. The existence of optimum entrainment ratio also been stated in references Wu et al. (2014), Fu et al. (2016) and Li et al. (2014).

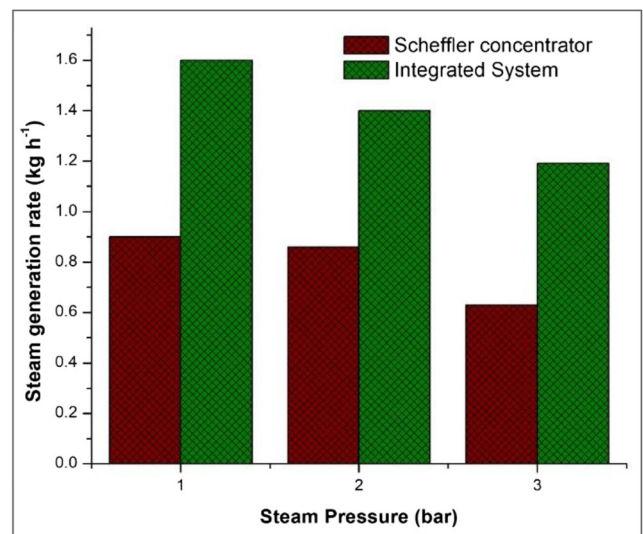


Fig. 5 Steam generation rate of the collectors

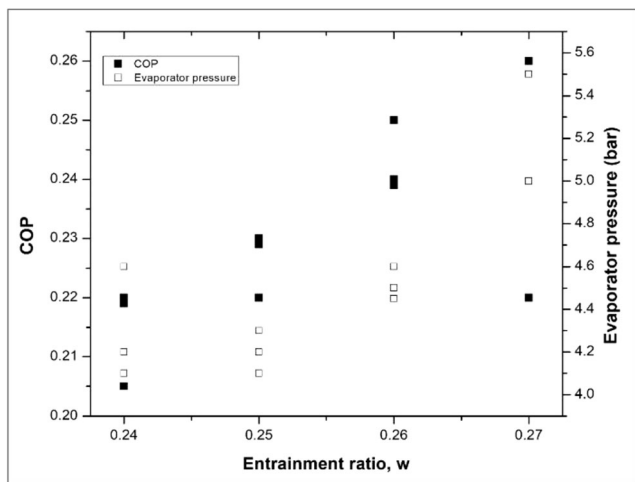


Fig. 6 Effect of entrainment ratio

The variations in the generator temperature have greatly influenced the performance of the ejector cooling system. It is seen from Fig. 7 that the increase in generator temperature results in an increase in entrainment ratio and COP. Due to the integration of solar collectors with the ejector cooling system, the steam temperature increased to 195 °C. The steam traps are provided to control the generator temperature between 65 °C and 85 °C. It is noticed that the increased temperature leads to an increase in the pressure and the enthalpy of the primary flow which in turn produces the better COP and the higher entrainment ratio. It has been noticed that the COP of the system increases parallelly from 0.27 to 0.365 with the varied range of generator temperature from 65 °C to 85 °C. The increase in generator temperature beyond this point is not advisable due to the critical temperature of the refrigerant R134a, and also, it results in more energy losses due to higher pressure and velocity gradient in the ejector at a given evaporator temperature ($T_e = 10$ °C) and condenser temperature ($T_c = 45$ °C). The average ambient temperature during this test was measured as 30 °C.

The effect of variations in the evaporator temperature on the system performance is shown in Fig. 8. It is evident that the system COP increases from 0.22 to 0.37 with an increase in evaporator temperature and the entrainment ratio from 0.22

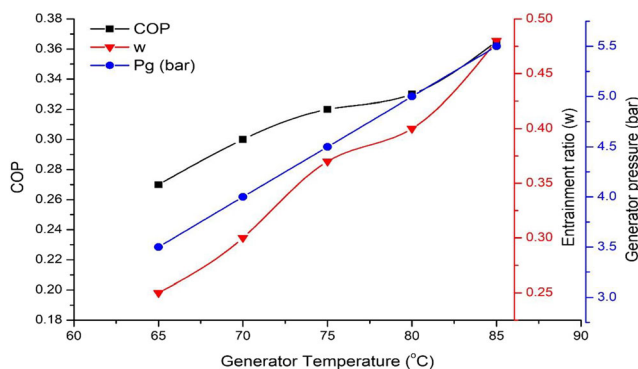


Fig. 7 Effect of generator temperature

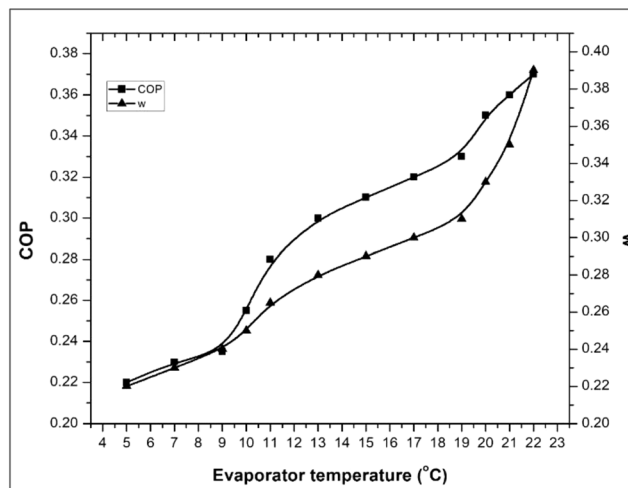


Fig. 8 Effect of evaporator temperature

to 0.39. The increase rate of COP was high during the rise of evaporator temperature from 4 °C to 11 °C, and then, the slow rate of increase was observed until 22 °C. This is due to the higher amount of secondary flow entry in the nozzle which produces higher energy and exergy losses in the ejector system. It is noted that for given evaporator temperatures, every ejector in a particular configuration has an optimum generator temperature at which the maximum COP could be obtained (Hamzaoui et al. 2018; Haghparast et al. 2018). The entire test was conducted at the fixed operating conditions; the performance of the system is evaluated based on the following conditions; the primary mass flow rate 0.22 kg/s, the generator temperature $T_g = 85$ °C and the condenser temperature $T_c = 45$ °C. The average solar intensity value 550 W m^{-2} , average ambient conditions on test day, is about 37 °C temperature, wind velocity 1.67 m/s.

Figure 9 shows the effect of condenser temperature variations on the performance of solar-powered ejector cooling

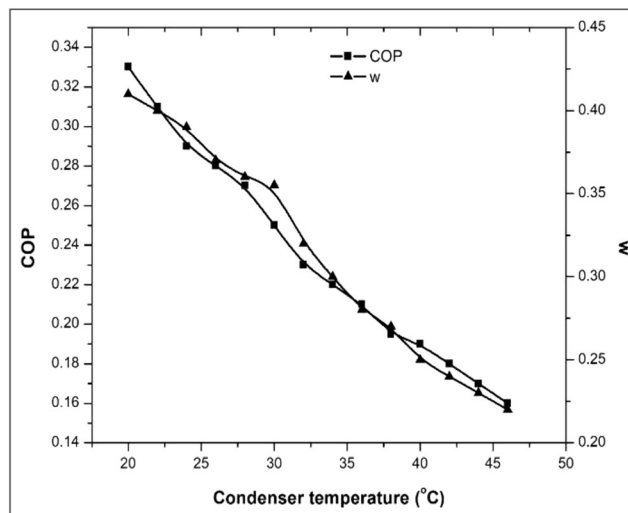


Fig. 9 Effect of condenser temperature

Table 4 Power consumption pattern

Power consumption	Ejector-based refrigeration system	Conventional VCR system
Compressor	0.3 kW	2 kW
Evaporator fan	0.08 kW	0.5 kW
Condenser fan	0.045 kW	0.4 kW
Miscellaneous	0.01 kW	0.01 kW
Total	0.435 kW	2.91 kW

system. It is seen that the COP and the entrainment ratio of the system decrease with increase in the condenser temperature. As per the Carnot refrigerator theorem, the COP of the system increased when the hot reservoir temperature is low and the cold reservoir temperature is high. In agreement with the statement, the condenser temperature should be maintained as low as possible and the evaporator temperature should be maintained as high as possible to reach the high COP of the system (Besagni and Inzoli 2017; Zhang et al. 2018). The present system was developed to produce higher generator temperature by the integration of solar collectors namely flat-plate collector and Scheffler collector which in turn increases the evaporation rate in the ejector and thus higher COP of the system was achieved.

Table 4 shows the power consumption pattern between the solar-powered ejector refrigeration system and the conventional vapour compression refrigeration system. It is seen that the power consumption of each component in the ejector system was very low compared to the vapour compression system. On the other side, the COP of the ejector system was very low at 0.22 compared to the COP of conventional vapour compression refrigeration (VCR) system 0.7. The only way to enhance the COP of the system without change in the power consumption is by redesigning of the ejector system and also by redesigning of the evaporator and condenser with increased the area of exchange.

Conclusions

The effect of integration of solar collectors on the performance of solar-powered ejector system was analysed. The experiments were conducted by the variation of fixed values of the entrainment ratio, the generator temperature, the evaporator temperature and the condenser temperature. The major conclusion is as follows:

- The integration of solar collectors namely Scheffler concentrator of 2.7 m² and the flat-plate collector of 5 m² produces the higher generator temperature closer to 200 °C.
- The COP of the system was increased from 0.22 to 0.47 by the effect of increased generator temperature from 65 to 85 °C.

- If the entrainment ratio increases, the system COP increased considerably.
- The system COP increases with the increase in the evaporator temperature and decreases with an increase in the condenser temperature.
- The total power consumption of the developed system almost 85% lower than the conventional VCR system at the rated capacity of 1 TR.
- The COP of the developed system is much lower than the conventional VCR system of the same capacity. The only way to enhance the COP of the system without change in the power consumption is by redesigning of the ejector system and also by redesigning the evaporator and condenser system with increased the area of exchange.
- Future work is planned to focus on the redesign of the ejector, evaporator and condenser and also the relocation of heat exchanger for the purpose of enhancing the heat transfer and the COP. This is essential to make the system compact and its potential commercialization.

Authors' contributions Conceptualization: Yuvarajan and Beemkumar; methodology: Yuvarajan and Beemkumar; formal analysis and investigation: Ganesan and Elangovan; writing—original draft preparation: Yuvarajan and Beemkumar; and writing—review and editing: Ganesan and Elangovan.

Data availability The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Authors are attested that this paper has not been published elsewhere, the work has not been submitted simultaneously for publication elsewhere and the results presented in this work are true and not manipulated.

Consent to participate All the individual participants involved in the study have received informed consent.

Consent to publish The participant has consented to the submission of the study to the journal.

References

- Bellos E, Tzivanidis C (2017) Optimum design of a solar ejector refrigeration system for various operating scenarios. *Energy Convers Manag* 154:11–24. <https://doi.org/10.1016/j.enconman.2017.10.057>
- Besagni G, Inzoli F (2017) Computational fluid-dynamics modeling of supersonic ejectors: screening of turbulence modeling approaches. *Appl Therm Eng* 117:122–144
- Besagni G, Mereu R, Inzoli F (2016) Ejector refrigeration: a comprehensive review. *Renew Sust Energ Rev* 53:373–407
- Bonafoni G, Capata R (2015) Proposed design procedure of a helical coil heat exchanger for an ORC energy recovery system for vehicular application. *Mechanics, Materials Science & Engineering Journal, Magnolithe*. <https://doi.org/10.13140/RG.2.1.2503.5282>
- Butrymowicz D, Bergander MJ, Smierciew K, Karwacki J (2010) Ejector-based air conditioner utilizing natural refrigerants. International Refrigeration and air conditioning conference at Purdue, pp 1–8
- Chandak A, Somani SK, Dubey D (2009) Design, development and testing of multieffect distiller/evaporator using Scheffler solar concentrators. *J Eng Sci Technol* 4(3):315–321
- Chen J, Havtun H, Palm B (2014) Screening of working fluids for the ejector refrigeration system. *Int J Refrig* 47(0):1–14. <https://doi.org/10.1016/j.ijrefrig.2014.07.016>
- Chua KJ, Chou S, Yang WM (2010) Advances in heat pump systems: a review. *Appl Energy* 87(12):3611–3624
- Chunnanond K, Aphornratana S (2004) Ejectors : applications in refrigeration technology. *Renew Sust Energ Rev* 8:129–155
- Dafle VR, Shinde NN (2012) Design, development & performance evaluation of concentrating monoaxial Scheffler technology for water heating and low temperature industrial steam application. *Int J Eng Res Appl* 2(6):848–852
- Dai Z, He Y, Huang Y, Tang L, Chen G (2012) Ejector performance of a pump-less ejector refrigeration system driven by solar thermal energy. International Refrigeration and Air Conditioning Conference at Purdue, pp 1–9
- Elbel S, Lawrence N (2016) Review of recent developments in advanced ejector technology. *Int J Refrig* 62:1–18
- Eldakamawy MH, Sorin MV, Brouillette M (2017) Energy and exergy investigation of ejector refrigeration systems using retrograde refrigerants. *Int J Refrig* 78:176–192. <https://doi.org/10.1016/j.ijrefrig.2017.02.031>
- Ersoy HK, Yalcin S, Yapici R, Ozgoren M (2007) Performance of a solar ejector cooling system in the southern region of Turkey. *Appl Energy* 84:971–983
- Fléchon J, Lazzarin R, Spinner B, Dicko M, Charters W, Kleinmeier H, Hammad MA (1999) Guild to solar refrigerators for remote areas and warm countries. International Institute of Refrigeration (IIR), Paris
- Fu W, Li Y, Liu Z, Wu H, Wu T (2016) Numerical study for the influences of primary nozzle on steam ejector performance. *Appl Therm Eng* 106:1148–1156
- Gil B, Kasperski J (2015) Efficiency analysis of alternative refrigerants for ejector cooling cycles. *Energy Convers Manag* 94:12–18
- Haghighparast P, Sorin MV, Nesreddine H (2018) The impact of internal ejector working characteristics and geometry on the performance of a refrigeration cycle. *Energy* 162:728–743. <https://doi.org/10.1016/j.energy.2018.08.017>
- Hamzaoui M, Nesreddine H, Aidoun Z, Balistrrou M (2018) Experimental study of a low grade heat driven ejector cooling system using the working fluid R245fa. *Int J Refrig* 86:388–400. <https://doi.org/10.1016/j.ijrefrig.2017.11.018>
- Henning H-M (2004) Solar-assisted air-conditioning in buildings, a handbook for planners. Springer-Verlag, Wien
- Huang BJ, Petrenko VA, Samofatov IY, Shchetinina NA (2001) Collector selection for solar ejector cooling system. *Sol Energy* 71: 269–274
- Jagveer Kumar D, Gupta T (2014) A solar powered air conditioning system for daytime offices based on ejector cycle: an alternate of conventional air conditioning systems. *IJESRT* 3(8):635–639
- Kinjavdekar CA, Muley VP, Kedare SB, Nayak JK (2010) A test procedure for determining optical characteristics of a dish concentrator and its implementation on a Scheffler dish. *Solar Energy Soc India* 20(1 & 2):13–24
- Li H, Cao F, Bu X, Wang L, Wang X (2014) Performance characteristics of R1234yf ejector expansion refrigeration cycle. *Appl Energy* 121: 96–103
- Liu F, Groll EA (2013) Study of ejector efficiencies in refrigeration cycles. *Appl Therm Eng* 52(2):360–370
- Nayak B, Mandal BK (2014) Effect of generator, condenser and evaporator temperature on the performance of Ejector Refrigeration System (ERS). *J Basic Appl Eng Res* 1:4–9
- Patil RJ, Awari GK, Singh MP (2011) Experimental analysis of Scheffler reflector water heater. *Therm Sci* 15(3):599–604
- Pridasawas W, Lundqvist P (2004) An exergy analysis of a solar-driven ejector refrigeration system. *Sol Energy* 76:369–379
- Rakeshsharma V, Bhosale SJ, Kedare SB, Nayak JK (2006) Field tests of the performance of paraboloid solar concentrator-ARUN160 at Latur. Proceedings of AER2006 - National Conference on Advances in Energy Research, Indian Institute of Technology - Bombay, December 4-5, p 182–187
- Scheffler W (2006) Introduction to the revolutionary design of scheffler reflectors. International Conference on Solar cookers, Granada, Spain
- Selvaraju AM (2003) Analysis of an ejector with environment friendly refrigerants. *Appl Thermal Eng* 43(9):915–921
- Sumeru K, Nasution H, Ani FN (2012) A review on two-phase ejector as an expansion device in vapor compression refrigeration cycle. *Renew Sust Energ Rev* 16(7):4927–4937
- Wang J, Dai Y, Sun Z (2009) A theoretical study on a novel combined power and ejector refrigeration cycle. *Int J Refrig* 32(6):1186–1194
- Wu H, Liu Z, Han B, Li Y (2014) Numerical investigation of the influences of mixing chamber geometries on steam ejector performance. *Desalination* 353:15–20
- Yan J, Cai W (2012) Area ratio effects to the performance of air-cooled ejector refrigeration cycle with R134a. *Energy Convers Manag* 53(1):240–246
- Zhang H, Wang L, Jia L, Wang X (2018) Assessment and prediction of component efficiencies in supersonic ejector with friction losses. *Appl Therm Eng* 129:618–627. <https://doi.org/10.1016/j.applthermaleng.2017.10.054>
- Zheng HF, Liang YH, Huang LY (2012) Analysis of entrainment ratio about solar ejector refrigerant system. *Energy Procedia* 16(Part A): 516–521