Experimental investigation of solar-driven double ejector refrigeration system

Jedsada Visedmanee[a]*, Anan Pongtornkulpanich[a], Sakda Somkun[a] and Ananchai U-kaew[b]

[a]Thermal Energy Research Unit, School of Renewable Energy Technology (SERT), Naresuan University, Phitsanulok 65000, Thailand
[b]Department of Mechanical Engineering, Faculty of Engineering, Naresuan University, Phisanulok 65000, Thailand
Tel+ (66)055-963-180 Fax: + (66)055-963-182
***Corresponding author:** anh_tong2525@hotmail.com

Abstract

Basic single-stage ejector refrigeration system has been one of the attractive thermal refrigeration systems, because it works with solar assistance, resembles with a vapor compression refrigeration system, uses single pure refrigerant and easy to construct. However, the system performance, which is defined as coefficient of performance, COP, has been traditionally low. In order to promote this type of thermal refrigeration system as another choice in cooling market, the solar-driven double ejectors refrigeration system, in this research, has been developed from basic unit and fabricated to be experimentally tested. The computer simulation program of double ejectors refrigeration system has been developed to simulate various parameters such as optimum mass flow rate of entrained fluid, load at condenser, boiler, evaporator, ejector performance, COP and dimensions of ejector to be used for system design. Double ejector system, which differs from one ejector for single stage, uses two identical ejectors placed parallel in the system. Saturated boiling steam at 110^{o}C is used to primary vapor to drive ejectors and evaporator condition uses at temperature of 10^{o}C.From the comparison of experimental results between single and double ejector system, it was found that COP of double ejector system was 15% higher than single system.

Keyword: *solar refrigeration system, ejector system, double ejectors, coefficient of performance (COP)*

Nomenclature

$\dot{Q}$	= Heat transfer rate (kW)	ejc	= Ejector
COP	= Coefficient of performance	e	= Evaporator
ω	= Entrainment ratio	b	= Boiler
h	= Enthalpy (kJ/kg)	c	= Condenser
$\dot{m}$	= Mass flow rate (kg/s)	p	= Primary mass flow
W	= Work (kW)	s	= Secondary mass flow
Subscripts			
E	= Electric power		
G	= Generator		

1. Introduction

Ejector is utilized in several applications including refrigeration system to replace electrical energy in conventional refrigeration system by using solar thermal or low grade heat from industry sector resources. Conservation of the electric power as well as improvement in the performance of refrigeration system will be the significant benefits obtained from thermal refrigeration system which can compete with other refrigeration technologies of cooling market. There are two major types of thermal refrigeration system: absorption and ejector system. Absorption system yields higher performance or higher coefficient of performance (COP) than other thermal refrigeration systems. A comparison between absorption and ejector system reveals better performance of absorption system (COP_{abs} ~ 0.7-0.8, COP_{ejc} ~ 0.3-0.8) [1],however the absorption system is more complex in design and crystallization problem can occur at high temperature operation, because of the binary solution being used as working fluid. Whereas one single pure substance is used as a refrigerant in ejector system to avoid this problem. Furthermore, the configuration of ejector system is almost similar to conventional air conditioner or vapor compression system which results in easier design and construction.

Several previous research works have been done in many aspects of refrigeration system in order to improve the system performance such as design of ejector geometry, selection of working fluids, variation of operating condition as well as adding some devices, such as injector and pump to the ejector system [2]Ruangtrakoon, et al 2011[3] studied about the geometry of ejector by controlling temperature condition of evaporator and condenser at 75 ^{0}C, 110-150 ^{0}C respectively. Six nozzles throat diameters size from 1.4 to 2.6 mm was used in this test. An experimental result revealed that throat area of nozzle has a strong effect on ejector performance. Ma 2010[4]indicated that coefficient of performance (COP) was maximum when temperature of heat generator was 92°C and further increase in temperature had no effect on COP. In addition, the study of Huang et al 2006[5]and Meyer et al[6]found that the suitable temperature of heat generator was from 90 to 95 °C. Chunnanond and Aphornratana ,2004 [7]explained that the decreasing temperature of the steam generator can increase the entrainment duct and secondary flow rate and also result in the increase of COP. Sun 1999[8]described the results of available temperature of heat generation by using computer simulation program. The condition of temperature of heat generator, evaporator, and condenser were 80^{o}C to 90 ^{o}C, 5^{o}C and 35 ^{o}C respectively. It was found that temperatures above 90^{o}C were unable to further improve the COP.

From the previous literature reviews, we found that researchers emphasized on the development in performance of the single-stage ejector refrigeration system [2,9]. Some previous research works, suggested a significant concept for improvement in the performance of single-stage refrigeration system [2,9,7]. Chunnanond and Aphornratana [7] introduced that the decreasing primary fluid mass flow rate in interval of critical mode didn’t reduce the system performance, rather it can increase the system performance. Additionally, Bejan et al [10] conducted an experiment using three ejectors which were placed in parallel. Each ejector didn’t work at the same time. Operation of each ejector was dependent on condenser pressure, and also system efficiency was not good. However, installing ejector can be possible in practical system.

Therefore, from the aforementioned idea, by adding an ejector to single stage system, mass flow rate of primary fluid will be divided into two parts and each part of primary fluid will enter into each ejector. This leads to increase entrainment of secondary fluid. This hypothesis has not still been done so; the present study focuses on design and fabrication of double ejector refrigeration system and testing by utilizing solar energy which is renewable, clean, free, reduce fossil energy use and can be converted by solar collector to produce primary steam with required conditions. Refrigerating capacity studied was 2 Tons and water (R718b) was used as working fluid. Two ejectors has been designed with identical geometry and connected between heat generator and condenser as appeared in figure 1. The developed solar driven double ejector refrigeration system research can be an effective choice for application in industrial sector to save the cost of electricity used for refrigeration purpose and can compete with conventional refrigeration system in the market.

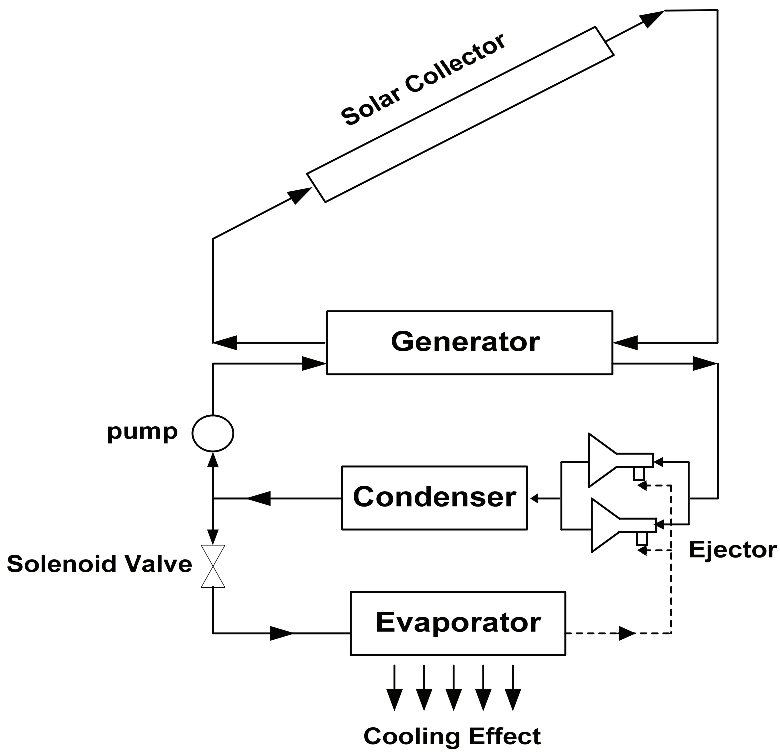


Figure 1 Solar-driven double ejector refrigeration system

2. Experimental equipment design and system operation

A schematic diagram of solar driven double ejector refrigeration system is shown in Figure 3. Design and test of solar driven double ejector refrigeration system have been performed. The system consists of following main components:

Evacuated heat pipe tube solar collector with area of 3.5 m^2 installed at the roof of the test room. The collector efficiency was determined according to ASHRAE93-77 standard and certified by SERT. FR(τα) and FRUL of solar collector were 0.81 and 2.55, respectively.

Heat generator, the immersion heater of 3 kW installed below the boiler tank as auxiliary heat source of the system to produce saturated steam at a pressure, temperature and mass flow rate of 143 kPa, 110 ^{0}C and 0.00065 kg/s respectively. This steam is a motive or primary fluid to enter nozzle of ejector.

Condenser, a spiral copper tube with length and diameter of 11 and 0.0158 m respectively installed inside the condenser tank in order to transfer heat (4.4 kW i.e. 2 Tons of refrigeration) from mix steam leaving diffuser of ejector to cooling tower by using 0.5 hp circulating pump.

Evaporator designed and installed between receiver tank and entrance of ejector by using a spiral copper tube length and diameter of 2 and 0.0158 m respectively in order to evaporate liquid under low pressure in evaporator tank and transfer heat capacity of 2.66 kW to storage tank.

Storage tank, provided with 20 liter capacity to accumulate water at 14 ^{0}C temperature.

Cooling Tower model REFRIGERATION MAN type CMB-10 to reject heat at condenser tank.

Circulation pumps, at four positions, each 0.5 hp capacity installed as shown in Figure 3.

Valves and measurement system, two needle valves with each size of ¾ inch installed between outlet streams of boiler and inlet stream of ejector, various valves and pressure gages for control of water mass flow rate including water level measurement as shown in Figure 3.

Before designing each system component, computer simulation program of solar driven double ejector refrigeration system, which was created by Pongtornkulpanich 2010 [12] has been developed to simulate various parameters such as optimum mass flow rate of entrained fluid, condenser pressure and temperature, loads at evaporator, boiler and condenser including entrainment ratio and COP of the system. These parameters have been used to design the details of each component. Simulation program has been written in Visual Basic version 6.0. A window of running program is displayed in Figure 2. The set of suitable operating conditions of ejector under test, used in calculations are given in table 1**.**

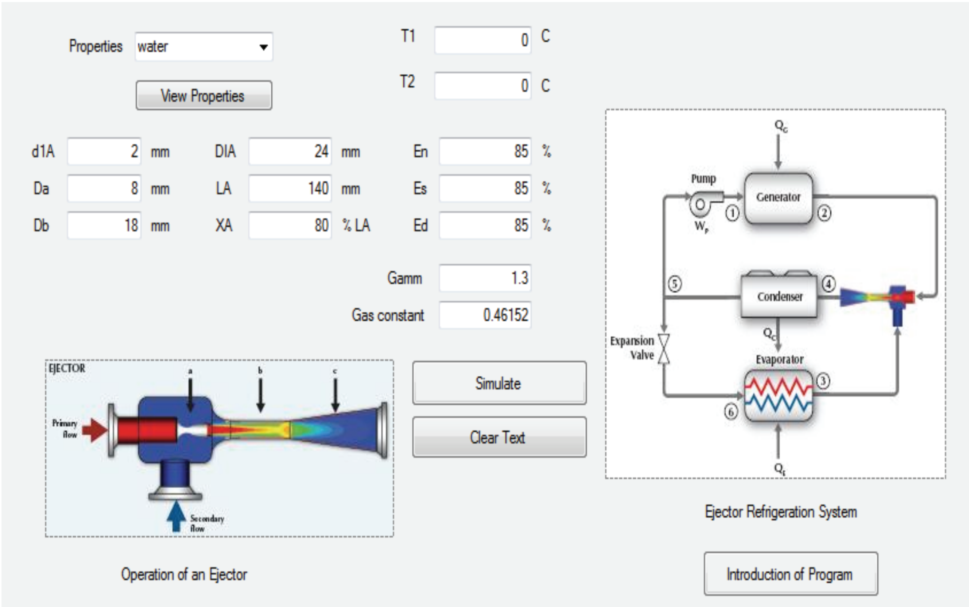


Figure 2 Form of simulation program to input parameters and simulate the results [12]

Table 1 Operating conditions

Operating condition	**Value**	**Unit**
Working fluid	Water	°C
Boiler (Generator) pressure	143	kPa
Boiler (Generator) temperature	110	°C
Evaporator pressure	1.22	kPa
Evaporator temperature	10	°C
Condenser pressure	5.6	kPa
Condenser temperature	35	°C
Mass flow rate of primary fluid	0.00065	kg/s
Mass flow rate of entrained fluid	0.00110	kg/s
Heat transfer rate of generator	4.4	kW

Design of every part of ejector in refrigeration system is very important and has effects on the system performance. Especially, throat area of primary nozzle and ejector to obtain double choking and the highest ejector performance is critical. In this study, simulation program of single-stage ejector refrigeration system has been upgraded and modified to be double ejector system.

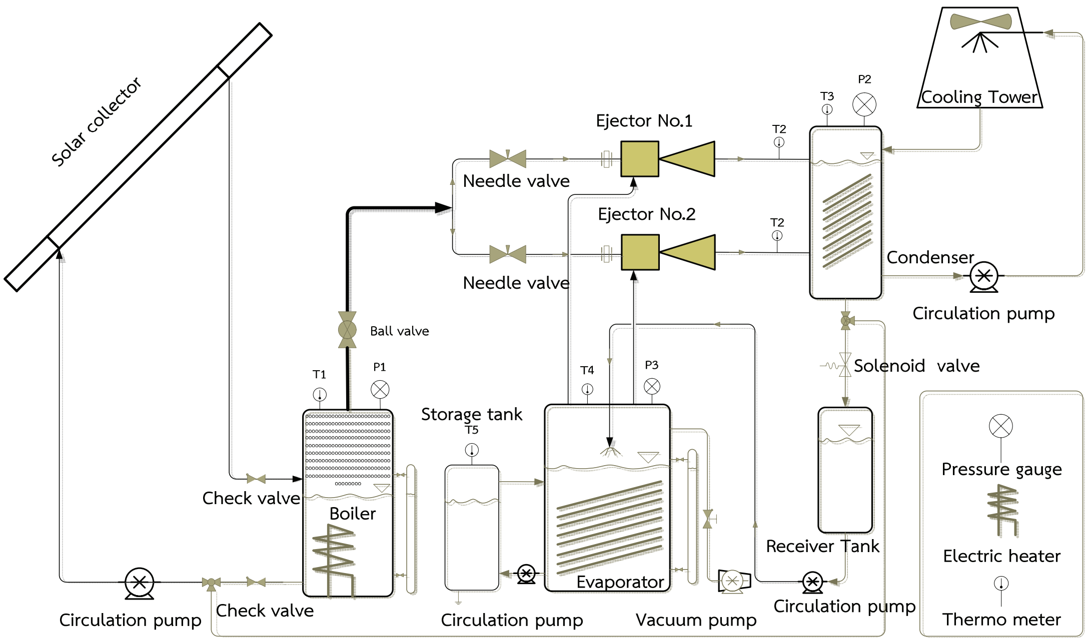


Figure 3 Schematic diagram of solar–driven double ejector refrigeration system

The following parameters as appeared in table 2 have been used as input in the developed program including all dimensions of ejector to obtain the suitable simulated results such as optimum mass flow rate of entrained fluid, optimum entrainment ratio or ejector performance and system performance, COP, etc. Furthermore, the specification design for suitable ejector in operating of system can be expressed as Table 2

Table 2 Ejector specifications

Specification of ejector	**Value**	**Unit**
Throat of nozzle (D_{1A})	2	mm
Exit diameter of nozzle (D_a)	8	mm
Inlet diameter of throat of ejector (D_b)	18	mm
Diameter inlet of mixing chamber (D_{LA})	24	mm
Length of mixing section (L_A)	100	mm
Mixing fluid distance (X_A)	80	%

In the ejector refrigeration system, ejector generates vapor compression effect replacing the compressor of electric refrigeration system by utilizing solar heat. System performance can be expressed in term of coefficient of performance COP_{ejc} as follows:

$$COP_{ejc} = \frac{\dot{Q}_e}{\dot{Q}_G + W_E} \quad (1)$$

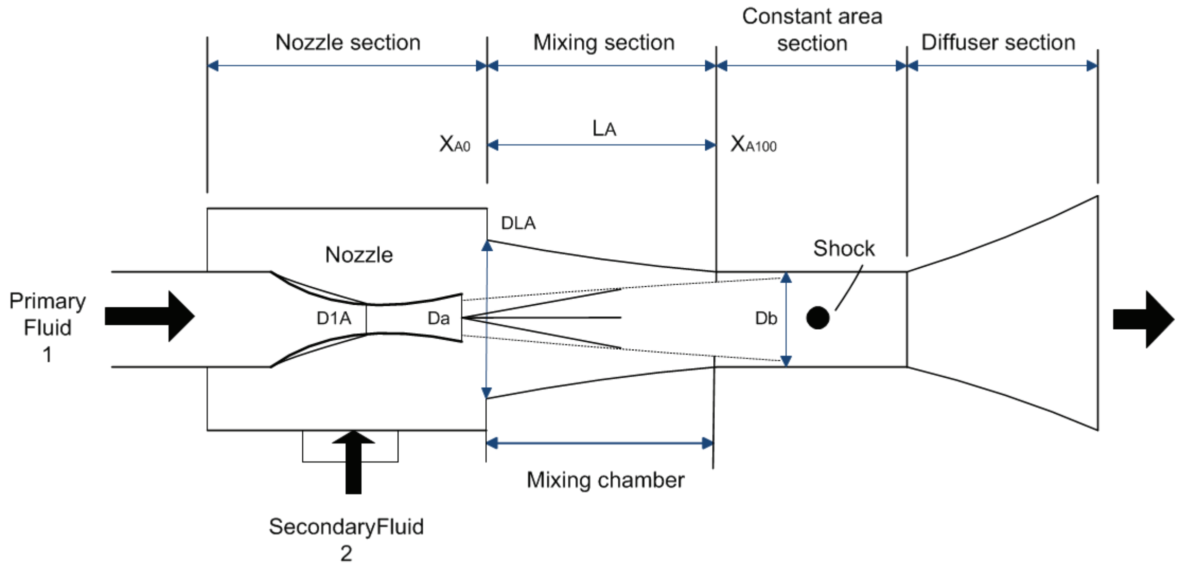


Figure 4 Parameters at different positions of ejector

Terms $\dot{Q}_e$ and $\dot{Q}_G$ expressed in the form of enthalpy difference and entrainment ratio, now system performance can also be written as

$$COP_{ejc} = \omega \frac{h_e - h_c}{h_b - h_c} \tag{2}$$

Ejector performance is measured in term of entrainment ratio, which is defined as the ratio of mass flow rate of secondary flow to primary flow as

$$\omega = \frac{\dot{m}_s}{\dot{m}_p} \tag{3}$$

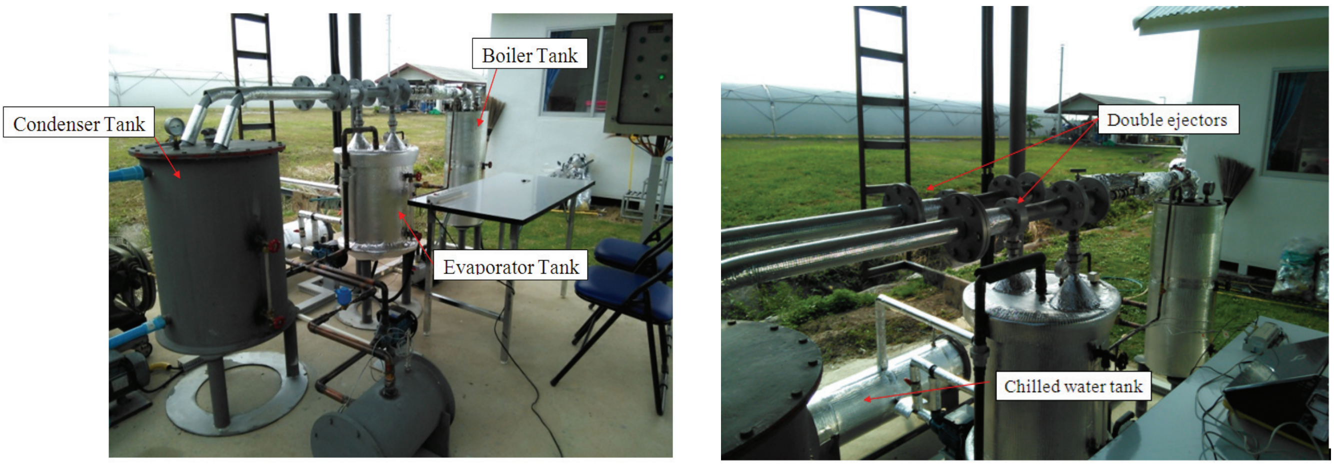
The main energy source being solar a term ‘solar fraction’ is used to explain the overall system efficiency. Solar fraction is defined as the fraction of the total thermal energy delivered to the chiller, which is supplied by the solar collector, over a period of 1 day.

$$\mathrm{SF} = \frac{\text{Solar energy used in the system}}{\text{Total thermal energy delivered to the chiller}} \tag{4}$$

The studied solar-driven double ejector refrigeration system, located adjacent to High temperature building in Energy Park, School of Renewable Energy Technology (SERT), Naresuan University, Thailand, has been shown in Figure 5. Figure 6 (a) and (b) shows various system components and double identical ejectors respectively. System was tested as single ejector by closing the needle valve for second ejector and as double ejector system by simultaneously opening the both needle valves allowing primary fluid to be divided into two streams. Testing for both single and double ejector systems was performed at the same conditions.
The experiment data was collected during the month of October 2014. Each system was tested for five times to ensure accuracy. All the equipment used for measuring different parameters was calibrated for accuracy with acceptable error percentage ranging from -1 to 1 before collecting data. For

temperature measurements to be used for evaluating COP of the system, standard deviation (SD) of 0.2 from the average temperature at any position was taken for accuracy. Data logger model WISCO AL 210, was used to measure the change of temperature in the intervals of 10 seconds, from 9:00 to 16:00. The data regarding saturation boiling pressure & temperature, evaporator pressure & temperature, condenser pressure &temperature, the change of water level (at boiler, condenser and evaporator tank) and electricity consumption of system was recorded to calculate the average value of entrainment ratio and Coefficient of Performance (COP).

Figure 5 Experimental solar-driven double ejector refrigeration system



(a) (b)

Figure 6 Multiple system components (a) and (b) double ejectors

As shown in Figure3, system operation starts from circulating water to roof-mounted solar collector and flows back to boiler, where if water temperature is not equal to 110°C (saturation boiling temperature of 110°C and pressure of 143 kPa), auxiliary heater will start to achieve desired conditions. Temperature in boiler is controlled by distributing signal from thermocouple through temperature controller to maintain boiler temperature at 110°C during the entire experiment. Water level in the boiler was controlled by 0.5 hp pump and a float valve. Saturated steam or motive fluid from boiler flows to each ejector and mass flow rate of motive steam was adjusted by needle valves to obtain designed value. After that, motive steam flows through nozzle and the secondary fluid at evaporator was entrained to mix with motive steam at the exit of nozzle. Mixed steam flows through the throat of ejector and diffuser, respectively and enters condenser. At condenser, water flowing in a spiral copper tube with diameter of 5/8 inch and length of 11 m rolls to reject heat from mixed steam to cooling tower. Vacuum conditions at condenser and evaporator were obtained by vacuum pump before starting experiment. Condenser and evaporator pressures were 6.2 and 2.2 kPa, respectively. Water from condenser output was separated into two parts: one part was pumped to solar collector and other allowed to flow through reducing valve towards evaporator tank. During system operation, various data such as temperature at desired positions was monitored on control box. The mass flow rate of primary and secondary vapor was determined by measuring the volume change of water in the boiler and evaporator tank, when the circulation pump was stopped for each cycle of experiment.

3. Results and Discussion

3.1 Performance of Solar-Driven Double Ejectors Refrigeration System

Experimental solar-driven double ejector refrigeration system was operated from 9:00 to 16:00 daily in October 2014. Monthly average solar radiation plotted with time is shown in Figure 7. Here average solar radiation is 703.8 W/m^2 and maximum solar radiation is between 12:00 and 13:00. Moreover average ambient temperature recorded is 33.4^{o}C. Performance of overall system is defined as solar fraction (SF) expressed as monthly average value at any time. As shown in Figure 8, performance of single and double ejector systems is compared and it can be seen that maximum and minimum value of single and double ejectors systems are 0.37 and 0.35 and 0.0038 and 0.015, respectively. Average monthly SF of single and double ejector systems is 0.2 and 0.18, respectively.

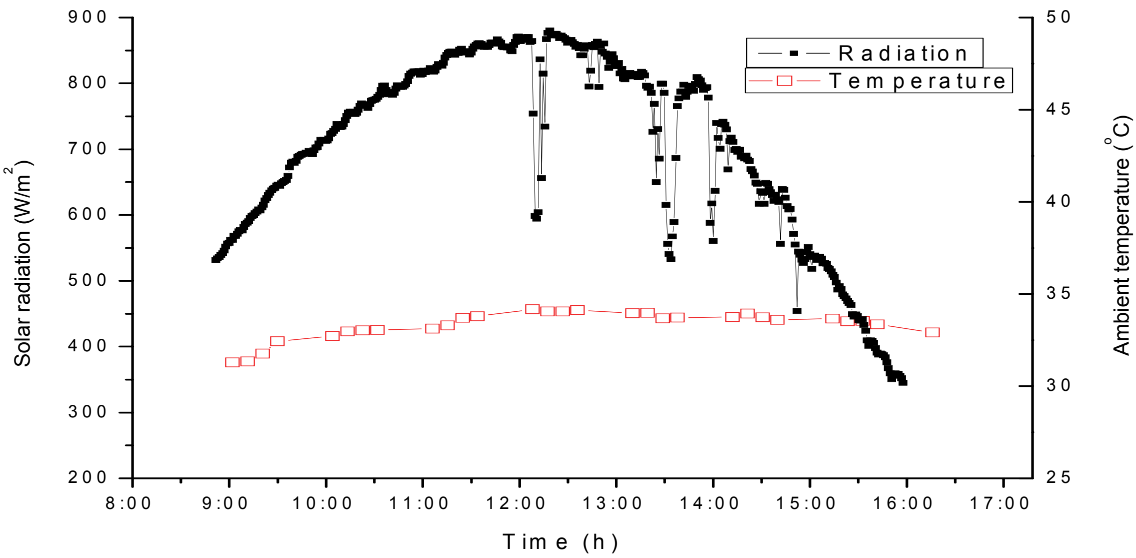


Figure 7 Relationship between monthly average solar radiation and ambient temperature and time

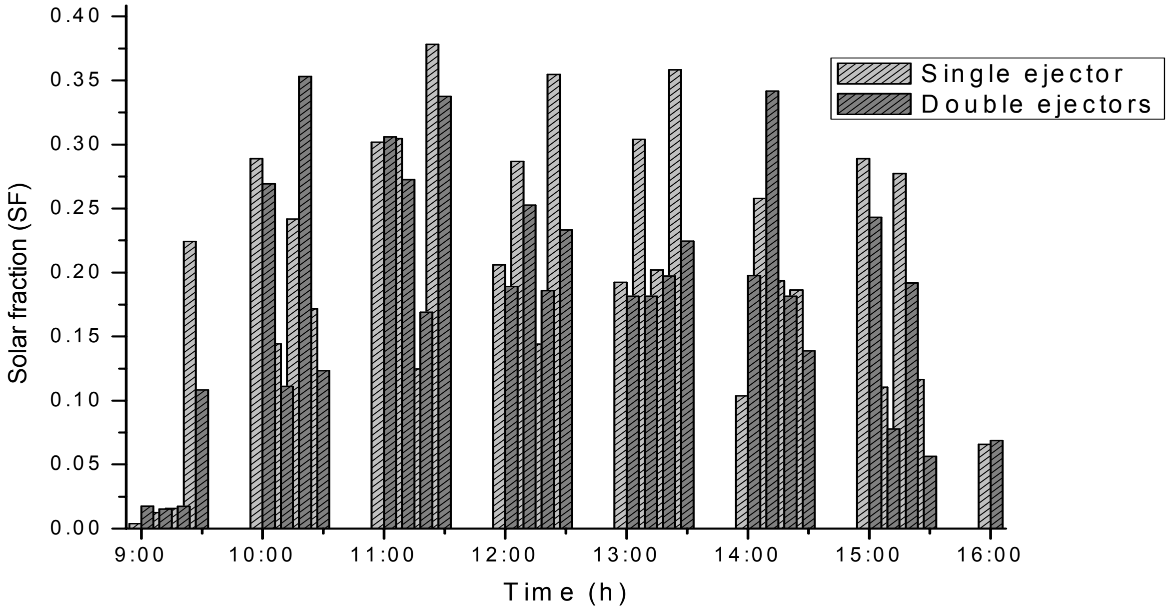


Figure 8 Hourly average solar fraction (SF) and time

As shown in figure 9, (during October 2014) the average solar fraction (SF) during clear sky and unclear sky for single and double ejector systems are 0.2 and 0.18, respectively and 0.08 and 0.07, respectively. Here SF of double ejector system for clear sky is 0.18, showing that solar energy used to drive the system was 18% and the rest 82% from electricity. For unclear sky, it can be explained in the same trend.

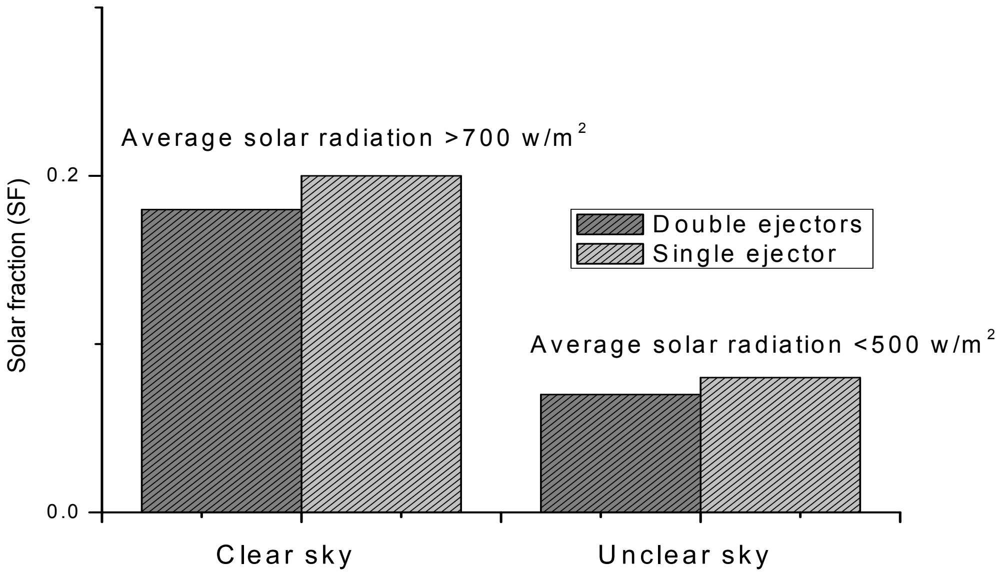


Figure 9 Monthly average solar fraction (SF)

3.2 Performance characteristics and comparison of refrigeration system

3.2.1 Effect of condenser pressure and temperature on entrainment ratio and COP

Figure 10 shows condenser pressure and temperature profile of single and double ejector refrigeration system. The results show that profile of both systems shows the same trend. It is found that condenser pressure appears to be constant throughout the operation in the range of studied time for both systems. In the first period of system operation, for single or double ejector system, secondary vapor from evaporator is entrained increasingly. This causes mixing temperature between motive vapor and secondary vapor to be lowered, which further results in the decreased condenser temperature. At longer time, condenser temperature tends to increase because the decrease of secondary vapor is entrained which leads to increase mixing vapor temperature. These results correspond to research work of Pollerberg [11]obtained through comparison between single and double ejector systems. It is found that condenser temperature of double ejector system yields higher than single one because mass of secondary vapor of double ejector system can be more entrained which results in the slight increase in condenser pressure. This causes condenser temperature to increase. Thus, design of double ejector refrigeration system should concern for released system heat to prevent back pressure occurrence. In the time period of 9:00 to 16:00, average condenser pressure of single and double ejectors systems are 6.2 and 6.8 kPa, respectively with an increase of 8.8%. In addition, average condenser temperature of single and double ejectors systems are 35.3 and 36^{o}C, respectively with an increase of 1.6%. This can be seen in Figure 10.

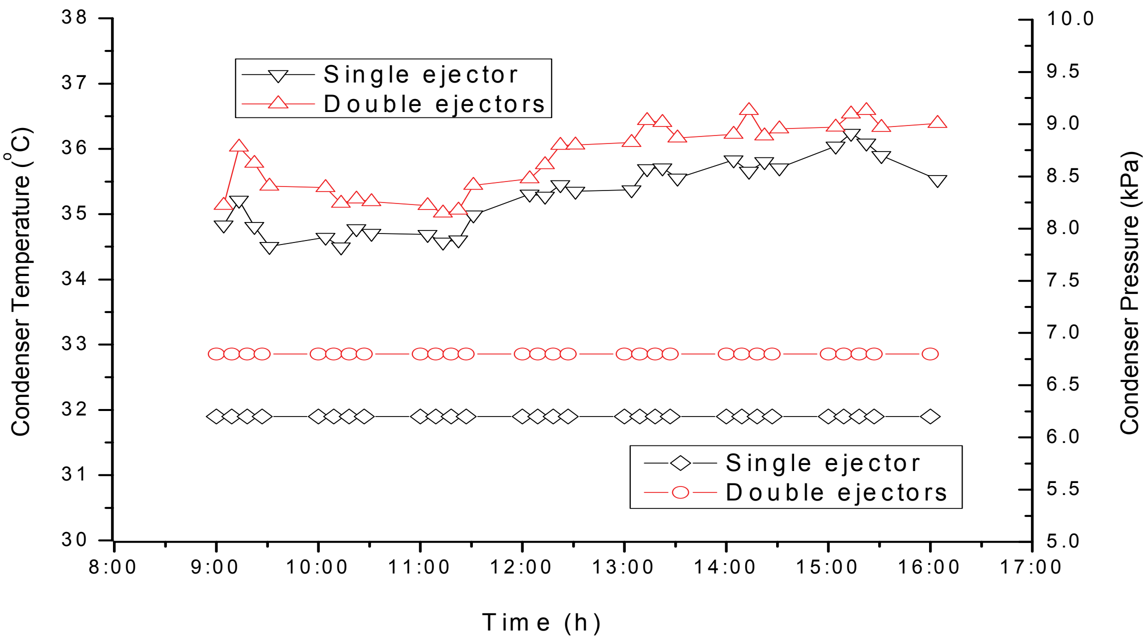


Figure 10 Condenser Pressure and temperature profile of single and double ejector system

3.2.2 Entrainment ratio (ω)

Figure 11 shows relationship of entrainment ratio and time, in comparison with single and double ejector refrigeration systems in time range of 9:00 to 16:00. Data was collected every 1 hr. For both single and double ejector systems, the entrainment ratio tends to increase in first period of time and decrease as operating time increases. Entrainment ratio is maximum at 11:00 am for single and double system with two main reasons. At that time, ejector can steadily work and chilled water temperature in tank is high so heat exchange between chilled water and sprayed water from condenser in the evaporator tank occurs well resulting in increased mass flow rate of secondary fluid and leads to increase entrainment ratio. After that time, vaporization of secondary fluid in evaporator tanks cannot occur easily, causing the trend of curve to decrease. For minimum case, the reason is just opposite. In addition, it was found that condenser temperature has a relationship with entrainment ratio, as condenser temperature decreases, mass flow rate of secondary fluid from evaporator is entrained increasingly which can be explained from Figure 10. Maximum and minimum of entrainment ratio of single and double ejector systems was 0.709 and 0.886, respectively and 0.354 and 0.472, respectively. The average entrainment ratio of single and double ejector systems was 0.58 and 0.69, respectively. From comparison we found that entrainment ratio of double ejector system is 15.2% higher than single ejector system.

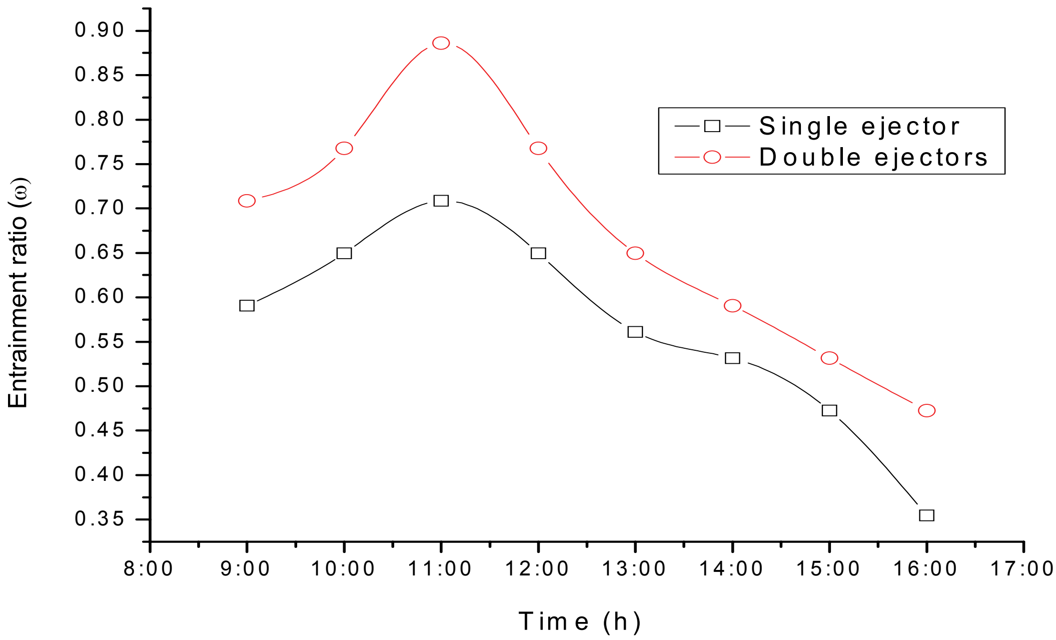


Figure 11 Comparison of entrainment ratio between single and double ejector systems during operational time period

3.2.3 Coefficient of Performance, (COP)

Comparison of COP between single and double ejector systems during operating time is shown in Figure 12. The result shows that COP of double ejector system is higher than that of single ejector system. The change of COP for two systems depends on that of entrainment ratio, COP increases with the increase in entrainment ratio. From the experiment results, it was found that maximum and minimum COP of single and double ejector systems were 0.74 and 0.93, respectively and 0.34 and 0.46, respectively. The average COP was 0.59 and 0.7 for single and double ejectors system, respectively. The increase in COP was 14.7%.

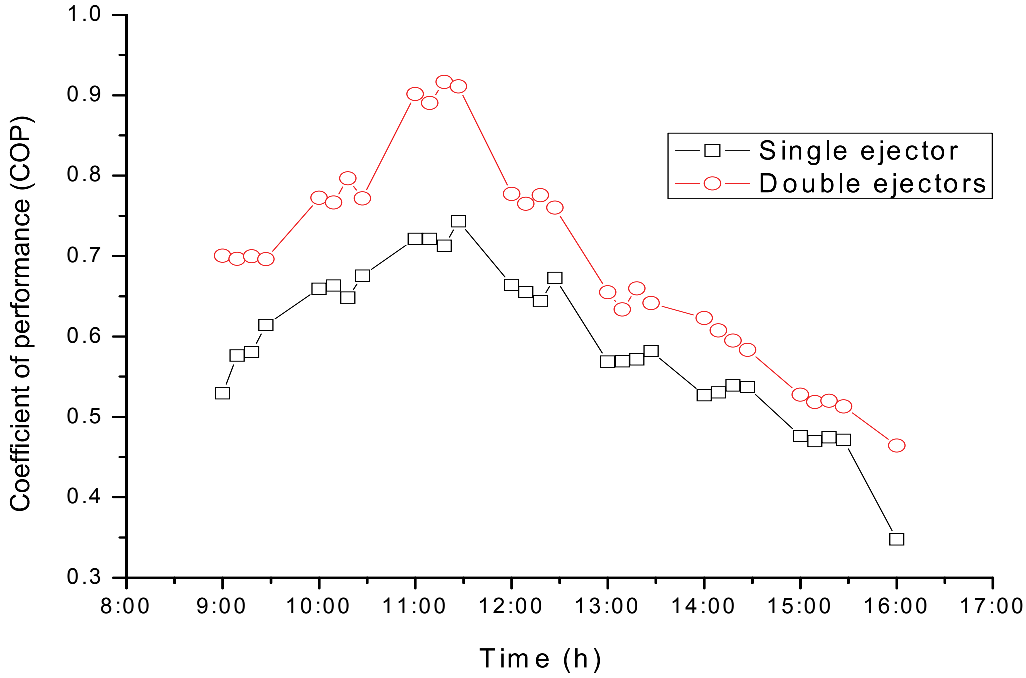


Figure 12 Comparison of COP between single and double ejector systems with time

3.2.4 Chilled water temperature

As shown in Figure 13, chilled water temperature is plotted with operating time for single and double ejector systems. Results show that chilled water temperature of double ejector system decreases rapidly if compared with single ejector system. Trend of curve for both systems shows that chilled water temperature of single and double ejectors system differs considerably after two hours of operating time. The maximum difference between chilled water temperatures of both systems is 2.5°C. After two hours, trend of curve is decreasing until the temperature becomes nearly constant around 13:00. From the experimental results, in the first period of operating time, entrainment ratio increases because water temperature within chilled water tank is high, heat transfer in evaporator tank occurs well, resulting in rapid vaporization of water (refrigerant). This indicates that secondary vapor is entrained well and causes chilled water temperature to dramatically decrease. The lowest chilled water temperature was recorded as 18.5°C. However, the chilled water temperature needs to be dropped below 18.5°C. This can be done by preventing the leakage in welded areas at different positions in the system. Additionally, pressure control sensor should be installed to maintain pressure value to be constant as per given condition. Problems determined in the fabricated prototype will be effective pathways to improve the next system in the future.

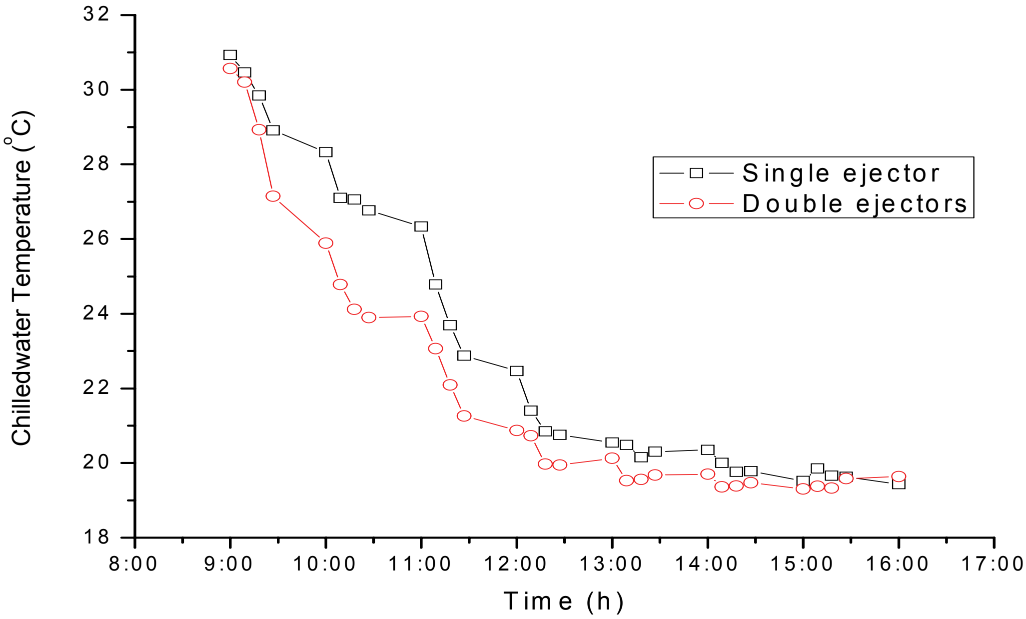


Figure 13 Comparison of chilled water temperature between single and double ejector systems with time

4. Conclusions

In order to improve solar ejector refrigeration system, solar-driven 2 ton double ejector refrigeration system has been designed and fabricated. Prototype testing of the system was performed under boiling saturation temperature at generator and evaporator temperature of 110 °C and 10°C, respectively. In addition, performance comparison of single ejector system and double ejector system was investigated in terms of solar fraction (SF). The result shows SF of double ejector system is higher than that of single system. The experiment results show that adding two identical ejectors in parallel to each other can increase the amount of entrained fluid resulting in increased entrainment ratio and COP. While condenser pressure and temperature of double ejector system increases slightly, this is worth when compared with the increase in COP.

However, cost of overall system is still higher (150,000 Thai Baht) because of some expensive components, such as ejector, solar collector and measuring devices. Due to this system cannot compete with conventional chiller. Effective efforts to bring system cost down will encourage use of this system during day time to save electricity used in conventional chiller. This research will be an option to introduce use of solar cooling system in the near future.

5. Acknowledgement

The author would like to thank you the National Research Council in Thailand (NRCT) for financial support and School of Renewable Energy Technology providing assistance during the research.

References

[1] Pongtornkulpanich, A., Thepa, S., Amornkitbamrung, M., Butcher, C. (2008): Experience with fully operational solar-driven 10-ton LiBr/H2O single-effect absorption cooling system in Thailand. Renewable Energy 33(5), 943-949.

[2] Chen, X., Omer, S., Worall, M., Riffat, S. (2013): Recent developments in ejector refrigeration technologies. Renewable and Sustainable Energy Reviews 19(0), 629-651.

[3] Ruangtrakoon, N., Aphornratana, S., Sriveerakul, T. (2011).: Experimental studies of a steam jet refrigeration cycle: Effect of the primary nozzle geometries to system performance. Experimental Thermal and Fluid Science 35(4), 676-683

[4] Ma, X., Zhang, W., Omer, S.A., Riffat, S.B. (2010): Experimental investigation of a novel steam ejector refrigerator suitable for solar energy applications. Applied Thermal Engineering 30(11–12), 1320-1325.

[5] Huang, B.J., Hu, S.S., Lee, S.H. (2006).: Development of an ejector cooling system with thermal pumping effect. International Journal of Refrigeration 29(3), 476-484

[6] Meyer, A.J., Harms, T.M., Dobson, R.T. (2009): Steam jet ejector cooling powered by waste or solar heat. Renewable Energy 34(1), 297-306.

[7] Chunnanond, K., Aphornratana, S. (2004): An experimental investigation of a steam ejector refrigerator: the analysis of the pressure profile along the ejector. Applied Thermal Engineering 24(2–3), 311-322.

[8] Sun, D.-W. (1999): Comparative study of the performance of an ejector refrigeration cycle operating with various refrigerants. Energy Conversion and Management 40(8), 873-884.

[9] Abdulateef, J.M., Sopian, K., Alghoul, M.A., Sulaiman, M.Y. (2009): Review on solar-driven ejector refrigeration technologies. Renewable and Sustainable Energy Reviews 13(6–7), 1338-1349.

[10] Bejan, A., Vargas, J.V.C., Sokolov, M. (1995): Optimal allocation of a heat-exchanger inventory in heat driven refrigerators. International Journal of Heat and Mass Transfer 38(16), 2997-3004.

[11] Pollerberg, C., Ali, A.H.H., Dötsch, C. (2008): Experimental study on the performance of a solar driven steam jet ejector chiller. Energy Conversion and Management 49(11), 3318-3325.

[12] Pongtornkulpanich, A. (2008): Complete research report entitled "Simulation program of solar driven double ejector refrigeration system" . National Research Council in Thailand (NRCT).