Design and modeling of innovative solar ejector air conditioners and chillers operating with low-boiling working fluids

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Abstract

This paper provides the design and modeling of various solar ejector chillers and air conditioners operating with low-boiling working fluids. The paper presents a theoretical analysis of the solar ejector air conditioner (SEAC) and shows effect of operating conditions on the ejector and ejector system performance. The results of performance simulation of autonomous ejector air conditioner are given. Unified serially produced heat exchangers and components are used in this SEAC that ensures its high adaptability to existing refrigeration techniques and low estimated production cost.

1. Introduction

Solar ejector cooling machines (ECMs) operating with low-boiling working fluids can provide refrigeration for air-conditioning, space-cooling and food storage in the range of evaporating temperatures from 12°C to –10°C. These systems can be driven by conventional single-glazed flat plate solar collectors with selective surface and vacuum tube solar collectors, which can be most economical for ECM by a proper choice of optimum generating temperature [1].

Ejector cycle has several advantages over other heat-driven refrigeration cycles, including low temperature heat supply, simplicity in design and operation, possibility of sub-zero operation, high reliability and low installation cost. These make the ECMs more attractive than other heat-driven refrigeration machines [2].

The main objective of this R&D is to create innovative high-performance solar ejector air conditioners and chillers intended for commercial application in different domestic and industrial cooling, refrigeration and air-conditioning systems, and which meet modern requirements of efficiency, reliability, and level of automation, as well as ecological and economical standards.

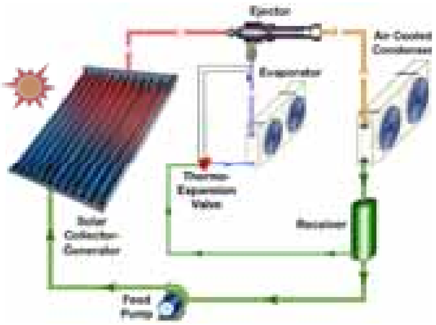

Fig. 1. Design of solar ejector air conditioner with direct heating.

2. Solar ejector air conditioners and chillers

Solar-powered refrigeration for air-conditioning or space-cooling is very attractive, since cooling loads and the availability of solar radiation are generally in phase. A solar ejector air conditioning system consists of a solar collector and a heat driven ECM. Solar collector transforms solar radiation into thermal energy, which then is used to operate the ECM.

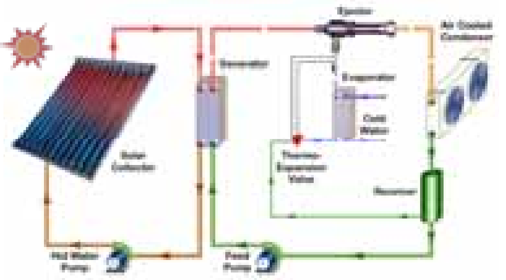

Fig. 2. Design of solar ejector air conditioner with closed-loop mode for circulating heating medium.

The main feature of solar ECM is the solar collector and heating mode of the generator. Figs. 1-3 show the three different methods for heating the generator. Fig. 1 presents the design of solar ejector air conditioner (SEAC) with direct heating, that is the surface of the generator is the absorbing plate of the solar collector; Fig. 2 shows the design of SEAC with closed-loop mode for circulating heating medium in which generating heat is supplied by intermediate heat-transfer liquid – usually water, that is heated in solar collector. Fig. 3 shows open-loop mode for heating water that first is used to cool the condenser to reduce the condensing temperature and raise the efficiency of ejector chiller [3].

The process of a continuously operating SEAC shown in Fig.2 is characterized by the points 1-9 illustrated in Fig. 4, which represents a diagram of an ejector cooling cycle with the following working principle. Refrigerant is heated and vaporized in the generator by solar thermal energy Q_g at relatively high pressure P_g. This motive vapor, with a mass flow rate $\dot{m}_p$, flows through the primary nozzle of the ejector. At the exit of the nozzle, the accelerated flow becomes supersonic, which produces a low-pressure region at its exit. Hence, vapor, at low pressure P_e, with a flow rate of $\dot{m}_e$, is induced from the evaporator into the ejector. Primary and secondary fluids are mixed in the mixing section of the ejector and then undergo a pressure recovery process in the diffuser section. The combined stream flows to the condenser where it is condensed into liquid at intermediate pressure P_c. The heat of condensation Q_c is rejected to the environment. Some of the condensate is returned to the solar-powered generator via an electrically driven feed pump, consuming mechanical power W_{mech}, whilst the remainder expands as it flows through a valve before returning to the evaporator, where it re-evaporates to produce the necessary cooling effect Q_e.

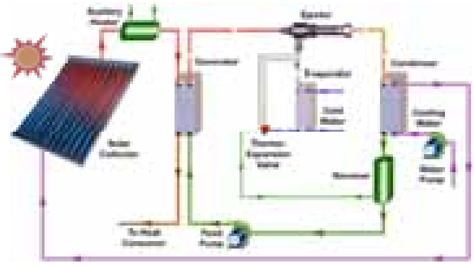

Fig. 3. Design of solar ejector air conditioner with open-loop mode for heating medium.

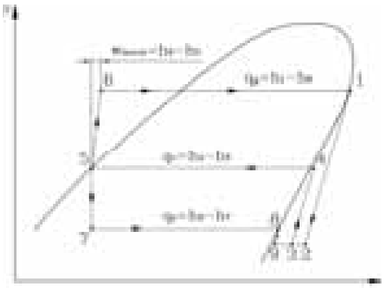

Fig. 4. Diagram of thermodynamic cycle of ECM.

3. Analysis of ejector design and ejector cooling cycle performance

The supersonic ejector is the key component in the ejector cooling cycle. Fig. 5 illustrates the structure of supersonic ejector with conical-cylindrical mixing chamber. The ejector assembly can be divided into four main parts: a nozzle, a suction chamber, a mixing chamber, and a diffuser.

Operating conditions of an ejector are specified by operating pressures P_e, P_c, P_g, expansion pressure ratio $E = P_g/P_e$ and compression pressure ratio $C = P_c/P_e$.

The performance of an ejector is measured by its entrainment ratio ω, which is defined as: $\omega = \dot{m}_e / \dot{m}_p$. The design of an ejector flow profile with conical-cylindrical mixing chamber is specified by area ratio $\alpha = A_3/A_t$, converging angle γ at mixing chamber entrance, and the area ratio $\beta = A_2/A_3$.

The performance of the ECM is usually expressed by a single *COP*, which is the ratio of the useful cooling effect produced in the evaporator over the gross energy input into the cycle. But it should be taken into account that the ECM usually utilizes a mechanical feed pump, and, consequently, an input of some amount of mechanical power W_{mech} in addition to low-grade heat energy Q_g. Therefore, from thermodynamic and economic points of view, the efficiency of ECM can be correctly characterized by using both COP_{therm} and the actual specific power consumption of mechanical feed pump w_{mech} [3,4]. They are defined respectively as:

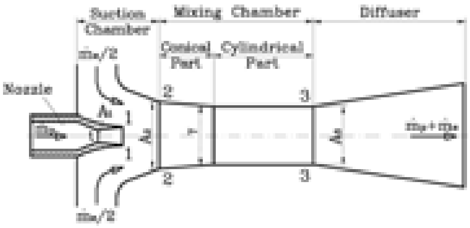

Fig.5. Structure of supersonic ejector.

$$COP_{therm} = \frac{Q_e}{Q_g} = \omega \frac{q_e}{q_g}, \quad (1)$$

$$w_{mech} = \frac{W_{mech}}{Q_e} = \frac{v_5 (P_g - P_c)}{\eta_{pump} \omega \, q_e}. \quad (2)$$

where v_5 and η_{pump} are specific volume of intake refrigerant and feed pump coefficient of efficiency, respectively; $(P_g - P_c)$ is the generating and condensing pressure difference, kPa.

Analysis of Equations (1) and (2) shows that characteristics COP_{therm} and w_{mech} strongly depend on the operating conditions, the efficiency of the ejector used and the thermodynamic properties of the refrigerant used.

The evaluation of performances of various refrigerants shows that the environmentally friendly low-pressure working fluids R600, R600a, R245fa and R245ca offer the best performance combinations and at present are the most suitable for application in ejector chillers, air conditioners and refrigerators [4,5].

4. Solar ejector cooling cycle performance simulation

In this study, we selected vacuum tube solar collector which steady-state energy collection efficiency is calculated as follows: $\eta_{sc} = 0.8 - 2.0(T_i - T_a)$, where I_T is the incident solar radiation on tilted surface of the collector (W/m^2); T_i and T_a are the collector inlet and the ambient temperatures (°C), respectively. The overall efficiency COP_o of SEAC is the product of the two particular coefficients: $COP_o = COP_{therm} \times \eta_{sc}$.

The selection of generating temperature T_g is especially important for SEAC as it affects not only the COP_{therm} of the ECM, but also the solar collector efficiency η_{sc}. Since increasing of T_g increases the COP_{therm} but decreases the η_{sc}, the theoretical optimal T_g corresponds to a maximum COP_o that is also will be determined in the present study [1].

In the current study environmentally friendly refrigerant R600 (butane) with normal boiling temperature T_b=-0.5°C was selected as a promising working fluid for ECM [4,5].

In order to predict the ejector refrigeration cycle performance characteristics, a computer simulation program based on the improved 1-D theory of ejector has been developed [6]. This program predicts the performance of the ejector and ECM and provides optimum ejector design data for a system. The program was used to calculate and compare the performances of the ejector with conical-cylindrical mixing chamber and ECM, using R600 and operating over a wide range of the T_g = 80–130°C, at T_c = 28, 32, 36 and 40°C and T_e = 8°C for air conditioning or space-cooling purposes.

The results of the analysis are shown in Figs. 6, 7, 8, 9, that illustrate the variations of theoretical A_3/A_t, ω, COP_{therm} and w_{mech}, with generating temperatures T_g at different critical condensing temperatures T_c for evaporating temperature T_e = 8°C. The area ratio A_3/A_t represents the design of the ejector. It is seen that the area ratio A_3/A_t increases with increasing T_g and decreasing T_c. The ω and COP_{therm} of the ECM also has the same trend. The characteristic w_{mech} decreases with both decreasing T_c and decreasing T_g.

Fig. 10 shows variation of solar collector efficiency η_{sc} with generating temperature T_g, and Fig. 11 shows the variation of overall COP_o with T_g for T_e = 8°C at T_c = 28, 32, 36 and 40°C. Each curve on Fig. 11 has a broad peak, which corresponds to the theoretical optimum of generating temperature T_g. The optimum COP_o decreases with increasing T_c. For a higher performance efficiency of solar collector η_{sc} the rated T_g can be chosen at temperatures about 10 to 15°C lower than the corresponding theoretical optimum values of T_g with only very little effect on COP_o [1].

For specified operating conditions T_e = 8°C and T_c = 36°C maximum $COP_o = 0.215$, $\eta_{sc} = 0.51$ at value of T_g = 120°C. But rated optimum of T_g has been chosen 15°C lower – that is 105°C with $\eta_{sc} = 0.54$ and $COP_o = 0.209$ which is 3% smaller than maximum COP_o.

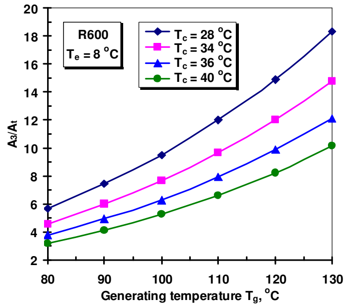

Fig. 6. The variations of A_3/A_t with T_g at different T_c.

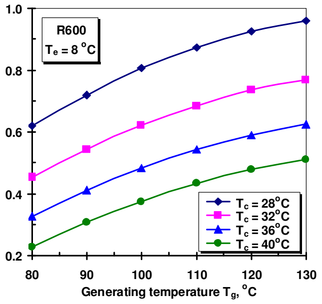

Fig. 7. The variations of ω with T_g at different T_c.

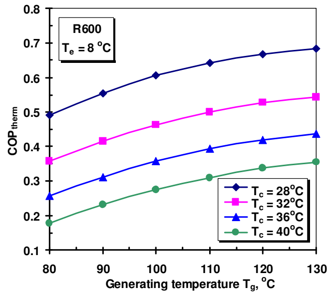

Fig. 8. The variations of COP_{therm} with T_g at different T_c.

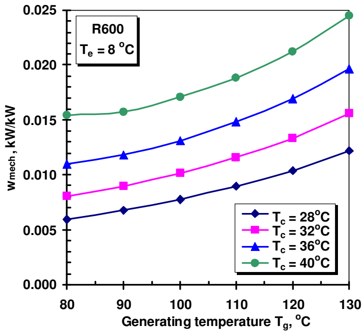

Fig. 9. The variations of w_{mech} with T_g at different T_c.

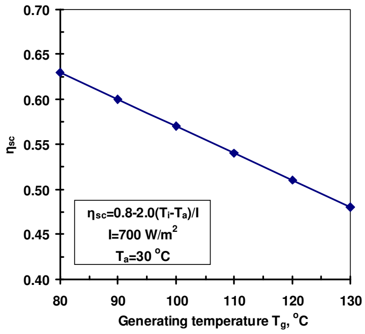

Fig. 10. The variation of solar collector efficiency η_{sc} with T_g.

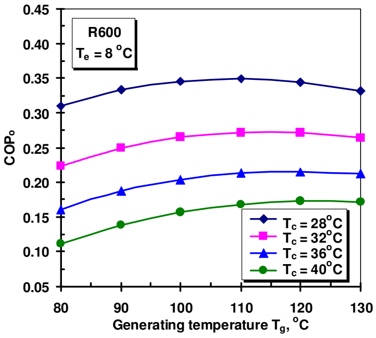

Fig. 11. The variations of overall COP_o with T_g at different T_c.

For these operating conditions from Figs 6, 7, 8 and 9 follows that the design $A_3/A_t = 7.12$, $\omega = 0.51$, $COP_{therm} = 0.38$, and actual specific power consumption of mechanical feed pump $w_{mech} = 0.014$ kW/kW. At these conditions feed pump should be able to overcome design pressure difference $\Delta P = P_g - P_c = 13.4$bar.

5. Design of autonomous ejector chillers and air conditioners

A conventional ECM usually requires an electrically driven feed pump which is the only component in the ejector cycle that has moving parts and therefore determines the reliability, leakproofness, and lifetime of the whole system. Utilization of thermally driven feed pumps allows a cooling effect obtained by using only heat energy. That makes the ECM independent from the source of electric power, i.e., autonomous [7].

Novel autonomous air conditioners and chillers using non-conventional thermo-gravity feeders are proposed and designed [7].

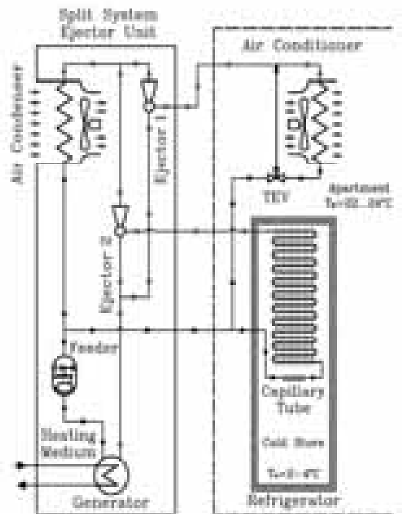

Fig. 12. Diagram of autonomous ejector split system intended for simultaneous air conditioning and refrigeration.

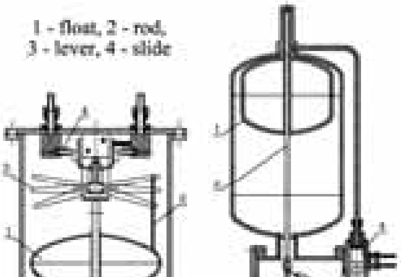

Fig. 13. Different constructions of automatic float-type thermo-gravity feeders.

Fig. 12 shows a diagram of an autonomous heat-driven split ejector system with two ejectors operating in parallel. This system is intended for simultaneous air conditioning and refrigeration.

Fig. 13 illustrates two different constructions of automatic float-type thermo-gravity feeders, which can be used in various small-capacity ejector chillers, air conditioners and refrigerators.

The operating principle of the proposed thermo-gravity feeders is as follows. A float-type feeder is located at the intermediate level between the condenser and generator and is connected to them by vapor and liquid lines. Gravity transports the primary fluid from the condenser to the generator via the feeder in two stages. The first stage is the filling of the feeder, and second stage is the evacuation of the liquid refrigerant from it. The process of automatic control is realized by a slide that opens and closes equalizing vapor lines in turns. The slide position depends on the liquid level in the feeder and is controlled by a float. Proposed thermo-gravity feeders are simple and reliable, and much less expensive than conventional mechanical feed pumps.

Instead of using a conventional electrically driven feed pump for ECM, using a thermally activated pump that converts thermal energy into mechanical energy to drive a mechanical feed pump is very attractive [7].

Fig. 14 shows the diagram of an autonomous ejector air conditioner, that uses a thermally actuated piston feed pump driven by a piston engine, utilizing high-pressure vapor produced in the generator. The application of such a heat-operated feed pump in the different ejector cycles provides an increase in both the reliability and the life expectancy of the whole system.

In this case, the efficiency of autonomous ECM could be correctly characterized by using only a single COP_{therm}

$$COP_{therm} = \frac{Q_e}{Q_g} = \frac{Q_e}{Q_{g1} + Q_{g2}}\,, \tag{3}$$

where Q_{g1} and Q_{g2} are heat consumption for actuating ejector and thermo-pump, respectively.

Fig. 15 shows the construction of the experimental heat driven piston feed pump, and Fig. 16 presents a photograph of it. The design of the thermo-pump is simple and reliable, and it is thought to be less expensive than a conventional electro-mechanical feed pump [7].

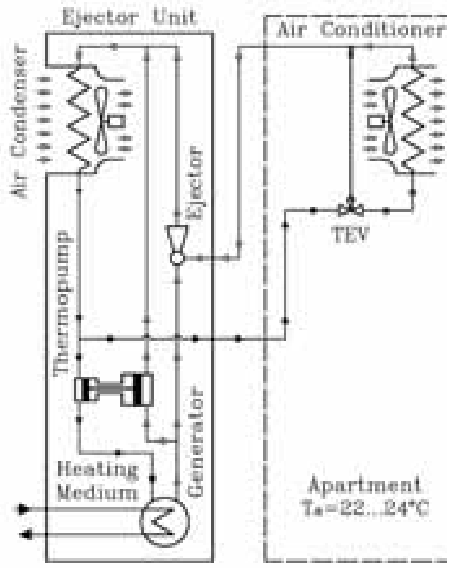

Fig. 14. Diagram of autonomous ejector air conditioner.

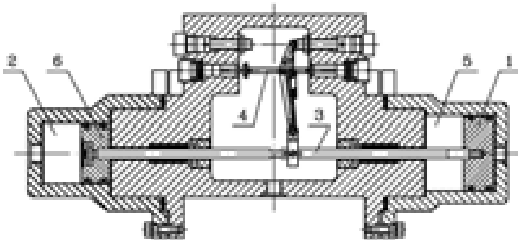

Fig. 15. Construction of heat driven piston feed pump: 1 – piston engine, 2 – piston pump, 3 – rod, 4 – slide-link mechanism, 5, 6 – pistons.

Fig. 16. Photograph of the heat driven piston feed pump.

6. Performance simulation of autonomous ejector air conditioner

Figs. 17, 18 and 19 illustrate the influence of the operating conditions T_g and T_c on the generating heat consumptions Q_{g1}, Q_{g2} and $Q_g = Q_{g1}+Q_{g2}$ for autonomous SEAC with cooling capacity Q_e = 5kW at T_e = 8°C utilizing thermally actuated feed pump with coefficient of efficiency $\eta_{tp} = 0.5$. It is seen from Figs. 17 and 18, that Q_{g1} decreases with increasing T_g and decreasing T_c, and Q_{g2} is increasing with increasing both T_g and T_c. Figs. 19 and 20 represent the influence of the operating conditions T_g and T_c on Q_g and COP_{therm} of autonomous ejector refrigeration machine, respectively.

Comparative analysis of two series of curves presented in Fig. 19 and Fig. 20 shows that all curves of the first series have minimum values at different generating temperatures T_g which are coincident with T_g corresponding to the maximum values of the second series of curves in Fig. 20. Thereby obviously the maximum COP_{therm} corresponds to minimum of total generating heat load Q_g.

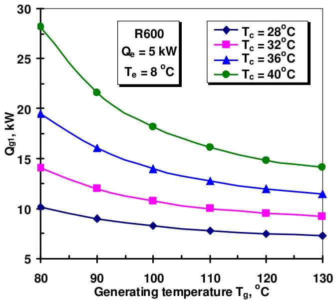

Fig. 17. Influence of T_g and T_c on Q_{g1} for actuating of ejector.

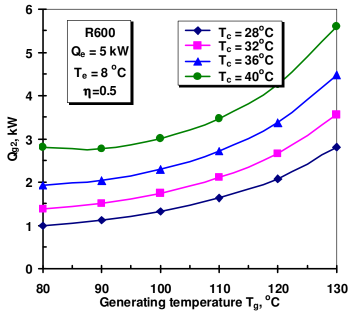

Fig. 18. Influence of T_g and T_c on Q_{g2} for actuating of thermo-pump.

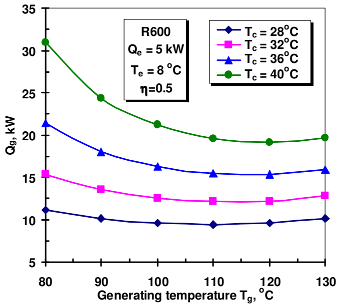

Fig. 19. Influence of T_g and T_c on total generator heat load Q_g.

For specified operating conditions T_e = 8°C and T_c = 36°C the minimum value of Q_g = 15.31kW and the maximum of COP_{therm} equals 0.33 at the value of T_g = 120°C. Fig. 21 shows the variation of overall COP_o with T_g for T_e = 8°C at T_c = 28, 32, 36 and 40°C. Each curve in Fig. 21 has a maximum value, which corresponds to the theoretical optimum value of T_g. The optimum COP_o decreases with increasing T_c.

Since all curves in Fig. 21 have broad peaks (like in Fig. 11) the rated T_g for a higher solar collector efficiency η_{sc} can also be chosen at lower temperatures than the corresponding maximum values with only very little effect on COP_o. For specified operating conditions T_e = 8°C and T_c = 36°C, maximum COP_o = 0.176, η_{sc} = 0.54 at value of T_g = 110°C. But rated T_g has been chosen 95°C corresponding to η_{sc} = 0.58 and COP_o = 0.171 which is 2.9% smaller than maximum COP_o. For these operating conditions from Figs. 6, 7 and 8 follows that design A_3/A_t = 5.32, ω= 0.45 and COP_{therm} = 0.33. At these conditions feed pump should be able to overcome design value of pressure difference $\Delta P = P_g - P_c$= 10.5 bar.

On the basis of the obtained results, an autonomous ejector unit with air cooled condenser is designed in packaged type that is the most suitable for mass production (see Fig. 22). Unified serially produced heat exchangers and components are used in this ECM that ensures its high adaptability to existing refrigeration techniques and low estimated production cost.

The design performance characteristics of autonomous SEAC using R600 are listed in Table 1. The portion of generating heat to drive such well-designed thermally actuated feed pumps usually is within limits of 10-14% of total generating heat load. The main application of the proposed autonomous chillers and air conditioners is a decentralized use in rural areas, which have no standard electric grid power service [3].

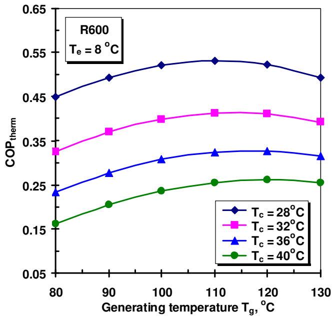

Fig. 20. Influence of T_g and T_c on COP_{therm} of autonomous SEAC.

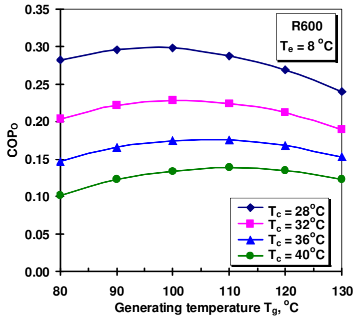

Fig. 21. Influence of T_g and T_c on COP_o of autonomous SEAC.

Fig. 22. Exterior view of autonomous ejector unit.

Table 1. Performance characteristics of autonomous SEAC

Parameter	Value
Cooling capacity, Q_e	5 kW
Evaporating temperature, T_e	8 °C
Condensing temperature, T_c	36 °C
Generating temperature, T_g	95 °C
Pressure difference, P_g-P_c	10.44 bar
Entrainment ratio, ω	0.45
Thermo-pump coefficient of efficiency, η_{tp}	0.5
Total generator heat load, Q_g	17.0 kW
Portion of generating heat for actuating of thermo-pump, Q_{g2}/Q_g	12.4%
Condenser heat load, Q_c	22.0 kW
Rated $COP_{therm} = Q_e/Q_g$	0.29
Solar collector efficiency, η_{sc}	0.63
Rated $COP_o = COP_{therm} \times \eta_{sc}$	0.183

7. Conclusion

The most important findings drawn from this study are as follows:

- Various innovative multipurpose ejector chillers and air conditioners are designed in a packaged type that is the most suitable for mass production. Unified serially produced heat exchangers and components are used in these ECMs ensuring their high adaptability to existing refrigeration techniques and their low production cost.

- The application of simple and reliable thermo-gravity feeders and thermally actuated feed pumps in the innovative ejector chillers, air conditioners, and refrigerators allows increases in the reliability and life time of the whole system and a cooling effect obtained by utilizing only thermal energy.

- The advanced ejector chillers and air conditioners are suitable alternatives to water-LiBr absorption systems, especially when cooling capacities up to 100-200 kW are required.

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The chapter on air-conditioning equipment design makes use of the concept of enthalpy potential involving simulta- neous heat and mass transfer. Examples on air transmission include the static regain method of duct designing which leads to a balanced air-distribution system. Chapter 23 adequately fills the need to provide essential information on the elec- trical aspects of the control of refrigeration and air-conditioning equipment.Â Chapter 9 on Evaporators includes many illustrative examples for simulation and design of flooded and direct-expansion chillers which include pressure drop calculations and use of Slipcevic correlations for tubes with roughened surfaces. Application of innovative ejector chillers and air conditioners operating with low boiling refrigerants in trigeneration systems. Louvain-la-Neuve: International Seminar on ejector/jet-pump technology and application.Google Scholar. Plesset, M. (1949). The dynamics of cavitation bubbles.Â Readdressing working fluid selection with a view to designing a variable geometry ejector. International Journal of Low Carbon Technologies, 10, 1â€“11.Google Scholar. Wang, F., Shen, S., & Li, D. (2015). Evaluation on environment friendly refrigerants with similar normal boiling points in ejector refrigeration system. Heat and Mass Transfer, 51(7), 965â€“972.CrossRefGoogle Scholar. Wegener, P., & Mack, L. (1958). Aspects related to their design, operation, theoretical and experimental approaches employed, analysis of the complex interacting phenomena taking place within the device, and performance are highlighted. Conventional and improved ejector refrigeration cycles are discussed.Â Ejector-based systems, which are thermally activated, provide a potentially promising solution, particularly for moderate heating or cooling applications, refrigeration and air conditioning.Â Progress in the mathematical modeling of ejectors was updated by He et al. [4] in this respect.Â When they operate with compressible fluids, they are referred to as supersonic ejectors and the primary stream is expanded to choked state in a converging-divergent supersonic nozzle.