Ministry of Education and Science of Ukraine

ODESSA NATIONAL ACADEMY OF FOOD TECHNOLOGIES

International Competition of
Student Scientific Works

BLACK SEA SCIENCE 2018

PROCEEDINGS

April, 4, 2018

ODESSA, ONAFT 2018

Ministry of Education and Science of Ukraine

Odessa National Academy of Food Technologies

International Competition of Student Scientific Works

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Proceedings

April 4, 2018

Odessa, ONAFT 2018

Міністерство освіти і науки України

Одеська національна академія харчових технологій

Міжнародний конкурс студентських наукових робіт

BLACK SEA SCIENCE 2018

Матеріали

4 квітня 2018 року

Одеса, ОНАХТ 2018

UDC 001(262.5):378.4.091.27(08)
BBC 421D221
B64

Black Sea Science 2018: Proceedings of the International Competition of Student Scientific Works, April 4, 2018, Odessa / Odessa National Academy of Food Technologies; B. Yegorov, M. Mardar (editors-in-chief.) [*et al.*]. – Odessa: ONAFT, 2018. – 827 p.

Proceedings of International Competition of Student Scientific Works «Black Sea Science 2018» contain the works of winners of the competition.

The author of the work is responsible for the accuracy of the information.

ISBN 978-966-289-181-2 Odessa National Academy of Food Technologies

УДК 001(262.5):378.4.091.27(08)
ББК 421D221
В64

Black Sea Science 2018: Матеріали Міжнародного конкурсу студентських наукових робіт, 4 квітня 2018 р., Одеса / Одеська національна академія харчових технологій; Б. В. Єгоров, М. Р. Мардар (відп. ред.) [та ін.]. – Одеса: ОНАХТ, 2018. – 827 с.

Збірник включає матеріали робіт переможців Міжнародного конкурсу студентських наукових робіт «Black Sea Science 2018».

За достовірність інформації відповідає автор публікації.

ISBN 978-966-289-181-2 Одеська національна академія харчових технологій

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A NOVEL TWO-STAGE EJECTOR REFRIGERATOR WITH MIXED REFRIGERANTS

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The energy consumption is ramping up in recent decades. Therefore, it was very important to recover and utilize the low-grade energy, such as the solar energy, the geothermal energy and low-temperature waste heat discharged to the environment. The ejector system has a good prospect in this area due to its obvious advantages :simple structure, without moving part and available for heat sources in different temperature levels, as well as long life-span. Nevertheless, the coefficient of performance of the ejector system is relatively low, so the technology to optimize the ejector refrigeration cycle has been hot topics. In this report, a novel two-stage ejector system with mixed refrigerants was proposed to improve the efficiency of the ejector system. A separator was used to divide the working fluid to high boiling point fluid and low boiling point fluid. The performance of the new system was calculated and compared with other ejector systems. It was suggested that the novel system had a higher COP than other ejector refrigeration systems. Furthermore, it could operate at a higher condensation temperature. When the condensation temperature continued to rise above 50℃, the new system could still be reliable and the COP was about 0.1

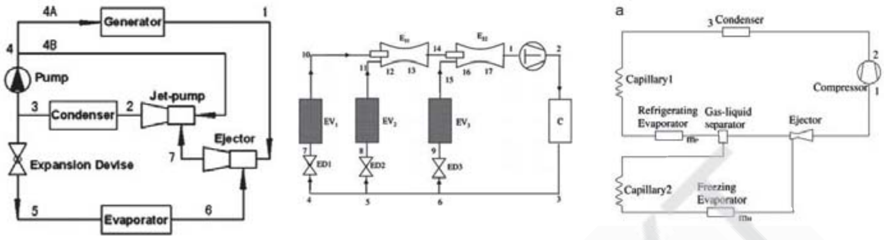
1. Introduction

With the rapiddevelopmentof the modern society, increasing of the population and improving living standardshavecaused a great demand of the energy [1-3], although the extent of this growth is offset by acceleratinggains in energy efficiency. According to the predicting of the BPenergy outlook, the liquid fuelconsumption of the world will beyond 100Mb/d by 2035 [4]. As a result, the production of manypetroleum exporting countiesare ramping upsharply.Nevertheless, there area lot of low-grade energy beingdischarged to the surroundings directly, and it is a greatwaste of energy. Generally, the low-grade energy concerns about solar energy, geothermal energy and low-temperature waste heat exist in the industrial world extensively [5, 6]. People have realized that exploitingthe low-grade energy is very important to achievea sustainable developmentsocietysomany regulations or the laws are introduced to lead theway [7]. Most of the low-grade energy cannot be utilized by the conventional power machines efficiently [8]. In the refrigeration field, the ejector systems providea promising way of producing cooling effect or heat by recoveringwaste heat from industrial process and automobile or using renewable energy [9, 10], such as solar radiation and geothermal energy, which makes such systems particularly attractive in this energy-conscious era.

The ejector refrigeration system has been studied since the mid-1950s.The systemhas some apparent advantages, such as the simplicity in constructionor the structure, installation and maintenance [11-13]. Furthermore, the ejector system isa very good choicebecause it can use some environmental-friendly working fluidsconsideration thatmany serious environmental problems had been caused during the utilization of the energyin the past decades [14]. In this system, the most important componentis the ejector, which isa device that increases the pressure of one stream, designatedby secondary or entrained stream,and obtainsthe middle pressure mixed flow [15, 16]. Duringworking process there is no need to use either mechanicalequipmentor devices with moving parts. The parameter that characterizes the ejector performance is the “entrainment ratio”,and it is defined by the mass ratio between the secondary fluidand the primary fluid [17]. Due to relatively low coefficient of performance (COP)for the conventional ejector systems, many novelejector systemswereproposed to improve the efficiency.Yu *et al*. [18] improved the ejector system by introducing a liquid-vapor jet pumpbetween the condenser and the ejector, as shownin Fig.1 (a). It was believed the new system wouldincrease the entrained ratio by decreasingthe backpressure of the ejector. Kairouani*et al*. [19] proposed a new ejector refrigeration cyclewithmulti-evaporatoroperating in different pressure and temperature levels,as shown in Fig.1 (b).Others researchers combined the ejector system with other kind of refrigeration systems, such as the compression refrigeration systemsand the absorptionrefrigeration systems. Liu *et al*.[20] proposed a new cycle that coupled the compression refrigeration cycle and ejector refrigeration cycle,as shownin Fig.1(c). The energy consumption analysis revealedthat the energy consumption was reduced. Yu*etal*[21] presented a new autocascade refrigeration cycle with an ejector. The ejector was used to recover the heatand to increase the pressure of the compressorinlet.

From the above-mentioned contents,it could be found that the current improving method was attachingnew componentsor new cycleswith the ejector system.

However, the system may still work in a narrow temperature range, despite the potential improving of the efficiency. In some applicationarea, the temperature difference between the heat source and the evaporator could be very large, such as the storage of deep-sea fishesby the engine waste heat. Employing theseejector systems may be not suitable.



(a) (b) (c)

Fig.1. Some ejector refrigeration cycles proposed in the literatures.6

In this work, a novel two-stage ejector refrigerator with mixed refrigerants was proposed to improve the heat utilization efficiency, and to enlarge the temperature scopeof the ejector system.In the new system, both the mass flow rate and the heat loadweredecreased for each stage cycle, and thereforethe COP of the system increased.The new system has a good prospect using in the recovery of the wasteheat, as well as other low-grade energy.

2. The novel two-stage ejector system

2.1 Cycle description

The novel two-stage ejector refrigerator with mixed refrigerants was showed in Figure 2.It consisted of two sub-ejector systems,the low-pressure stage system and high-pressure stage system.The working fluidgenerated from the low-pressure stage generator and entrained the secondary flow coming from the evaporator in the low-pressure stage ejector. The mixed fluid was condensed by the low-pressure stage condenser, which connected a vapor-liquid separator.The fluid after the separator was divided into the vapor phase and the liquidphase.The liquid phase was pumped out of the separator at the bottom, and then flowedinto the low-pressure stage generator. After absorbingthe heat,it entered the low-pressure stage ejector as the primary fluid.The vapor phase was entrained by the high-pressure ejector.Part of the mixed fluid after the condenser in the high-pressurestage was throttled and enteredinto the low-pressure evaporator.

When the mixed working fluid was used in the system, the operating process was a little different. The high boiling point working fluid was absorbed by the low-pressure stage generator to become a high-pressure gas, and functionedas the primary flow to entrain the low boiling point refrigerant coming from the evaporator. Afterwards, the mixed working fluid was condensed and separated in the low-pressure condenser and the separator. The liquid from the outlet of high-pressure condenser was divided into two ways. One of them was pumped by the high-pressure stage pump into the high-pressure stage generator, becoming a high-pressure vapor.

The other was throttled to the evaporator pressure.

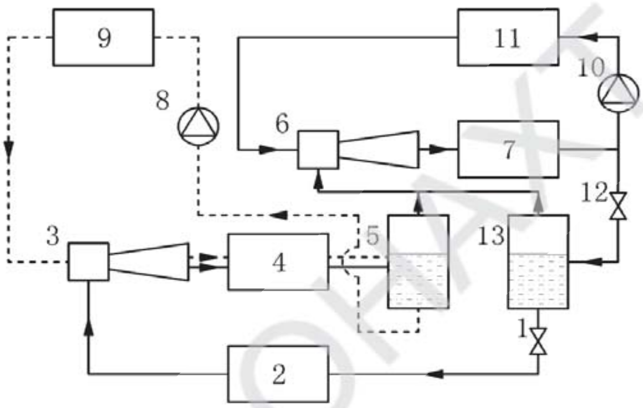


Fig. 2. The two-stage ejector system: 1,12. throttle; 2. evaporator; 3. low-pressure stage ejector; 4. low-pressure stage condenser; 5,13. gas-liquid separator; 6. high-pressure stage ejector; 7. high-pressure stage condenser; 8. low-pressure stage pump; 9. low-pressure stage generator; 10. high-pressure stage pump; 11. high-pressure stage generator

2.2 Refrigerants selection

The working fluid used in this system could be a non-azeotropicmixture of two or more refrigerants.In order to illustrate the advantages of this system, this paper chose R245fa as a high boiling point refrigerant and R600a as a low boiling point refrigerant.The coefficient of performance (COP) of the system was presented in the followingparts.

3. Themathematical modelfor the system

A mathematical model was developed to analyze the performance of new cycle. To simplify the model, some basic assumptions were made in this paper.

(1) The whole system workedin a steady state.

(2) Pressure drops and energyloss along the pipelines were neglected.

(3) The refrigerantsat the outletofcondenser, generatorsand evaporator wereinthe saturate state.

(4) The high boiling point refrigerant was completely condensed in condenser and the low boiling point refrigerant remained inthe vapor state.

(5) The vapor out of the separator is pure low boiling point refrigerant and the liquid out of the separator is pure high boiling point refrigerant.

(6) The enthalpy didn't change during the throttle process.

During the throttling process,according to the assumption 6, the enthalpy of the refrigerant could be evaluated by:

$$h_{1,in} = h_{1,out} \tag{1}$$

For the evaporator, the cooling capacity was calculated from the Eqs. (4) to (6)based onthe energy balance law:

$$m_{2,in} = m_{2,out} \tag{2}$$

$$m_{2,in} h_{2,in} + Q_E = m_{2,out} h_{2,out} \, (Q_E > 0) \tag{3}$$

$$h_{2,in} = h_{1,out} \tag{4}$$

The refrigerant absorbed the heat from both generator of two stages, and the heat could be calculated by the enthalpy increase of the refrigerant, that is:

$$m_{9,in} h_{9,in} + Q_{LG} = m_{9,out} h_{9,out} \, (Q_{LG} > 0) \tag{5}$$

$$m_{11,in} h_{11,in} + Q_{HG} = m_{11,out} h_{11,out} \, (Q_{HG} > 0) \tag{6}$$

When the refrigerant mixed in the low-pressure ejector,the energy and the mass were conversation during the process,and they could be presented as:

$$m_{3,p} + m_{3,s} = m_{3,out} \tag{7}$$

$$m_{3,p} h_{3,p} + m_{3,s} h_{3,s} = m_{3,out} h_{3,out} \tag{8}$$

The heat load of the low-pressure condenser could be determinedby:

$$m_{4,in} h_{4,in} + Q_{LC} = m_{4,out} h_{4,out} \, (Q_{LC} < 0) \tag{9}$$

Inthe separator, the mixed fluids were divided into high boiling point refrigerant and low boiling point refrigerant. The following equations were available:

$$m_{5,in} = m_{HBP} + m_{LBP} \tag{10}$$

$$m_{5,in}h_{5,in} = m_{HBP}h_{LBP} + m_{LBP}h_{LBP} \tag{11}$$

The governing equations of the high-pressure stage ejector could be obtained in the similar way:

$$m_{6,p} + m_{6,s} = m_{6,out} \tag{12}$$

$$m_{6,p}h_{6,p} + m_{6,s}h_{6,s} = m_{6,out}h_{6,out} \tag{13}$$

The energy balance equationwasgiven for the high-pressure stage condenser:

$$m_{7,in}h_{7,in} + Q_{HC} = m_{7,out}h_{7,out}\,(Q_{HC} < 0) \tag{14}$$

The refrigerant was pressurized by the pump, and some work was consumed during the process. Therefore, the pump work could be determined by for the low-pressure stage pumpand the high-pressure stage pump:

$$m_{8,in}h_{8,in} + W_{LP} = m_{8,out}h_{8,out}\,(W_{LP} > 0) \tag{15}$$

$$m_{10,in}h_{10,in} + W_{HP} = m_{10,out}h_{10,out}\,(W_{HP} > 0) \tag{16}$$

Consequently, the overall coefficient of performance (COP) of the system couldbe derived from above equations:

$$COP = \frac{Q_E}{Q_{LG} + Q_{HG} + W_{LP} + W_{HP}} \tag{17}$$

In Eqs.(18), the work of the pump was very small when compared with the heat loadsof the condensers. If the pump workwas neglected, then the equation above couldbe simplified as:

$$COP = \frac{Q_E}{Q_{LG} + Q_{HG}} \tag{18}$$

4. Analysis results and discussions

4.1 The effect of condensation temperature to the system performance

The COP of the new ejectorsystem wasshowedin Fig.3 when the evaporation temperature was 5°Cand the high pressure stage generator and the low pressure stage generator were both 100°C. The condensationtemperature was the dew point temperature of the refrigerantsin the high pressure stage condenser or the low pressure stage condenser. It couldbe observed that with the increase of the condensation temperature, the coefficient of performance of the system decreased continuously when kept theevaporation temperature and generation temperaturethe same. When the condensation temperature was above 50°C, the refrigerator still operatedreliably with a coefficient of performance around 0.1. In practical applications, when the condensationtemperature was higher than 50°C, the COP of other ejector refrigeration systems werevery lowand evenimpossible to work.

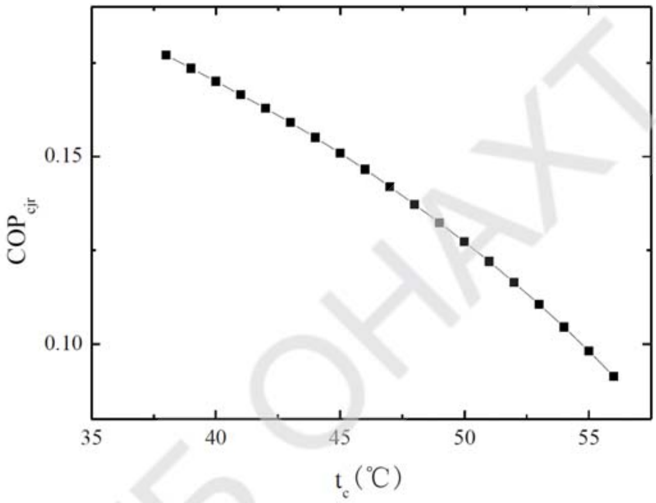


Fig. 3. The COP changed with condensation temperature

4.2 The comparison between new ejector system and single stage system

In order to compare the performance of two-stage ejector refrigeration system and single-stage ejector refrigeration system withdifferent condensation temperatures, the performance of the three systemswere calculated. As shown in Figure 4, both the COPsof three systems decreasedas the condensation temperature increased. When the condensation temperature was 38°C, the COP of the two-stage ejectorrefrigeration system was similar to that of the single-stage ejector refrigeration system using R245fa as the refrigerant, which was much larger than the single-stage ejector refrigeration system using R600a as the refrigerant. When the condensation temperature was higher than 50°C, the COP of the single-stage ejector refrigeration system using R245fa or R600a as the refrigerant is obviously reduced, while the COP reduction of the two-stage ejector refrigeration system with mixed refrigerants was relatively insignificant.

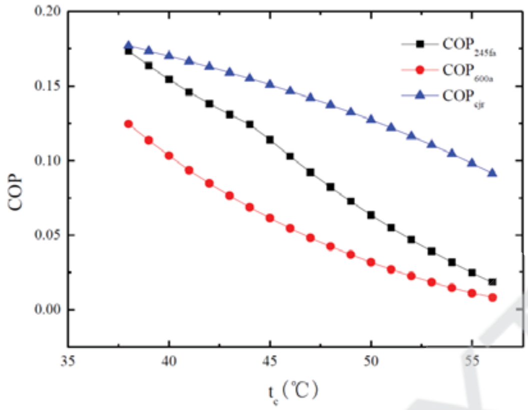


Fig. 4. The comparison between new ejector system and single stage system

4.3 The comparison between new ejector system and two-stage system

The comparison of the COP between the novel two-stage ejector refrigeration system with mixed refrigerants andthe two-stage ejector refrigeration system when the refrigerants were R600a andR245fa was showed in the Figure 5.It could be found that when the condensation temperature was below 40℃, the COP of the new systemwas less than that of two-stage ejector system used R600a. However, with the increase of condensation temperature, theperformance of the new system wasobviously better than the two-stage system with single refrigerant.

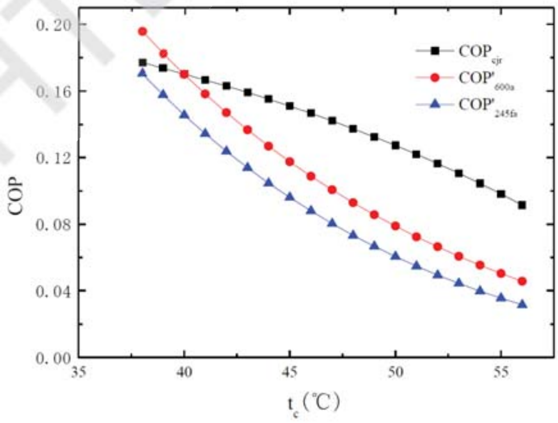


Fig. 5. The comparison between new ejector system and single stage system

In order to better illustrate the advantages of the new system, the relatively evaluation ratios of the COP for the new system were calculated and showed in Fig.6. From Fig.6, it was obvious that the overall COP of the system was significantly improved when using the proposed novel two-stage ejector refrigeration system with mixed refrigerants.

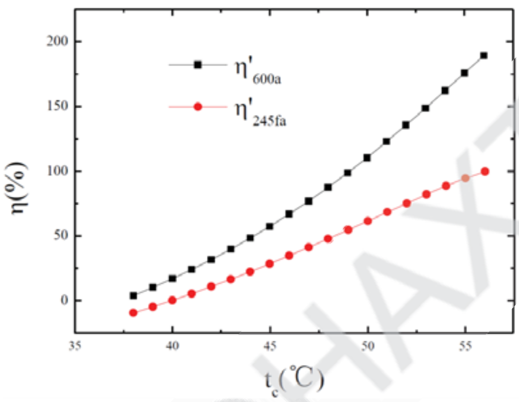


Fig.6. The evaluation ratios of the COP when compared with two-stage systems

5. Conclusions

In this paper, a novel two-stage ejector system with mixed refrigerant was proposed to improve the energy efficiency.A separator was used to divide the mixed refrigerant intolow boiling point components and high boiling components.This paper calculated and analyzed the COP of the systems in different conditions, and the main conclusions were:

1) It was suggested that the COPsof the two-stage ejector refrigeration system with mixed refrigerants were considerably higher than thoseof other ejector refrigeration systems under most calculation conditions.

2) When the condensation temperature of ejector refrigeration system was high, single-stage ejector refrigeration system was extremely inefficient and could not be practically used.In this working condition, the proposed two-stage ejector refrigeration system with mixed refrigerants couldwork normally. When the condensation temperature continued to rise above 50℃, the new system could still be reliable and the COP was about 0.1.

To sum up, the new systemhadvery good prospect to recover the waste-heat. Itcouldbedrivenby a heat source with two different temperaturelevels.

Besides, it couldbe operated at a higher condensation temperature, and hada higher COP than other ejector refrigeration systems.

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Наукове видання

Міжнародний конкурс студентських наукових робіт

BLACK SEA SCIENCE 2018

Матеріали

Верстка – Н.М. Ковальчук

Формат 60x84/16. Гарнітура Times New Roman.
Умовно-друк. арк. 48,07. Тираж 300. Замовлення № 0518-105.

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Свідоцтво суб'єкта видавничої справи
ДК № 4392 від 20.08.2012 р.