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CFD Investigation on Performance of Two-Stage Ejector in the Ejector Refrigeration System

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Abstract

The aim of this paper is to investigate the performance of steam ejector refrigeration system using two-stage ejector (TSE) by using computational fluid dynamics (CFD) approach. In this study, 2D-axisymetric model was used. The shear-stress-transportation k-ω (k-ω-sst) model was applied as a turbulence model. The design concept of the proposed two-stage ejector can be classified into two types which are annular primary, and annular secondary at the second stage. In the simulation, the TSE type annular secondary at the second stage in refrigeration system is investigated by using the operating conditions from the previous work whose generator temperature of 110 °C and the evaporator temperature of 10 °C. Detailed explanation and comparison will be given to describe the performance and advantages of two-stage ejector and single-stage ejector (SSE). Essential coefficients obtained in the present study were specified in terms of entrainment ratio (Rm) and critical back pressure (CBP). From the simulations, the annular secondary at the second stage ejector, the entrainment ratio can be increased for 42.8%, while, there was a marginal decrease in critical back pressure for 7.4%. Results from this study is promising enhance the COP of the future ejector refrigeration system.

Keywords: two-stage ejector, steam ejector refrigeration, CFD investigation

1. Introduction

Various ejector refrigeration systems are described with the associated studies, and categorized as conventional ejector refrigeration system, combined refrigeration systems, advanced ejector refrigeration systems/Multi-components ejector refrigeration system (MERS) [1, 2]. The MERS geometric structure greatly affects its performance, such as two-stage ejector. The design concept of the proposed two-stage ejector can be classified into two types which are annular primary at the second stage was first invented by Grazzini et al., simulation results show high ejector compression ratio with a very compact geometrical configuration but low entrainment [3, 4] and annular secondary at the second stage, Its effects on the performance improvement of a conventional single-stage ejector [5, 6]. For refrigeration applications, the most two significant parameters used to describe the performance of an ejector were specified in terms of entrainment ratio (Rm) is defined as “Eq. 1” and critical back pressure (CBP), consider a typical performance curve of a steam ejector as show in “Fig. 1”. There are three operating regions distinguished by the critical back pressure. [7]

This paper presents the results of a computational fluid dynamics (CFD) investigation on the performance of two-stage ejector (TSE) in the steam ejector refrigeration compared with single-stage ejector (SSE).

$$Rm = \frac{\text{mass of secondary flow}}{\text{mass of primary flow}} = \frac{\dot{m}_s}{\dot{m}_p} \quad (1)$$

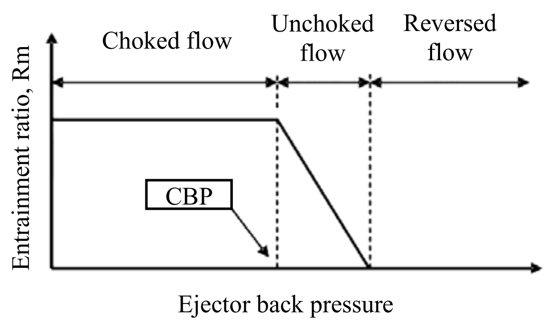

Fig. 1 Performance characteristics of a steam ejector

2. Computational methodology

2.1 Governing equations

The flow field in the ejector analysis is based on the well-knowns, conservation equation such as mass, momentum and energy. Generally compressible axis symmetric Navier-Stokes equation are suitable for the analysis of variable density flows. The governing equations are given below.

Continuity equation:

$$\frac{\partial P}{\partial T} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (2)$$

Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_i u_j + P\delta_{ij} - \tau_{ji}\right] = 0 \quad (3)$$

Energy equation:

$$\frac{\partial(\rho e_o)}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_j u_o + u_j P + q_j - u_i \tau_{ij}\right] = 0 \quad (4)$$

2.2 Single-stage ejector

Geometric structure of single-stage ejectors in the steam ejector refrigeration, the dimensions were designed by Ruangtrakoon [8]. The major parameters of the calculated domains are shown in "Fig. 2" and Table. 1.

The commercial software Gambit 2.3 and FLUENT 6.3 were used at the grid generator and the CFD solver, respectively. Two-dimensional (2-D) axisymmetric model is used as suggested by Pianthong et al. [9]. The shearstress-transportation k-ω (k-ω-sst) turbulence viscosity model which provided more accurate results [10] was used. The properties of water vapour are shown in Table. 2, the density of the working fluid is evaluated by using the ideal gas relationship while the calculation is progressing.

Table. 1 Parameters of the single-stage ejector [8]

Parameter	Value (mm)
Diameter of nozzle (d)	3.8
Diameter of entrance nozzle (D_1)	13.0
Nozzle area ratio $[(D_2/d)^2]$	20.0
Diameter of entrance mixing chamber (D_3)	34.0
Diameter of throat (D_4)	33.0
Diameter of exit subsonic diffuser (D_5)	60.0
Distance of mixing chamber (L_1)	135.0
Distance of throat (L_2)	138.0
Distance of subsonic diffuser (L_3)	242.0

Table. 2 Properties working fluid (water vapour) use in the CFD simulation

Properties	Value
Viscosity, μ (kg/m s)	1.34×10^{-5}
Thermal conductivity, k (W/m k)	0.0261
Specific heat capacity, C_p (J/kg K)	2014.00
Molecular weight, M (kg/kmol)	18.01534

All dimensions of the calculation domain as shown in "Fig. 3", the grids were made of 55,000 structured quadrilateral elements. To investigate the effects of geometry on the flow of the steam ejector, a grid refinement (increasing grid numbers to around 80,000) was performed. After refining the grid elements, the solutions of the models with the order of 40,000 elements and 80,000 elements were found no different.

2.3 Two-stage ejector type annular secondary at second stage

The flow phenomena in ejector are very complicated. At the high pressure steam, known as "a primary fluid", expands and accelerates through the primary nozzle, it fans out with supersonic speed to create a very low pressure region at the nozzle exit plane subsequently in the mixing chamber. This means "a secondary fluid" can be entrained into the mixing chamber. This mixing causes the primary flow to be retarded whilst secondary flow is accelerated. By the end of the mixing chamber, the two streams are completely mixed. Therefore, it is designed with an ejector mixing chamber geometries at the second stage; increase a fluid mix two steam.

Present the design concept of the proposed two-stage ejector, type which annular secondary at the second stage compared with single-stage ejector. It's all dimensions similar to the SSE, unless the distance of throat (L_2), the length of L_2 decreases according to the length of L_4, this length is call as L_2', which the total length (L_4+L_2') is 138 mm.

This paper is focuses to investigate the performance of two-stage ejector type annular secondary, mixing chamber geometries at the second stage, the effects of the mixing chamber geometries in three-effect parameter systems, A_6, L_4, and θ_{II}, as shown in "Fig. 4".

The dimensions of the geometry domain are shown in "Fig. 4". The grids were made up of 70,000 structured quadrilateral elements. The grid independence was tested to guarantee the reliability and accuracy of the simulation.

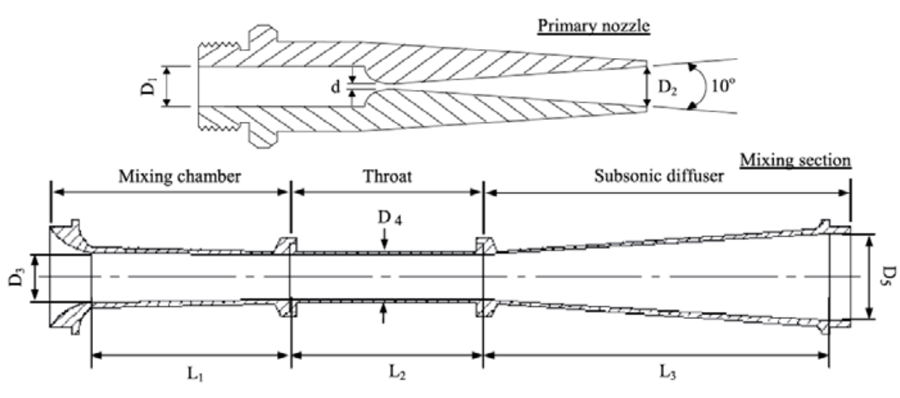

Fig. 2 The single-stage ejector used in the research study [8]

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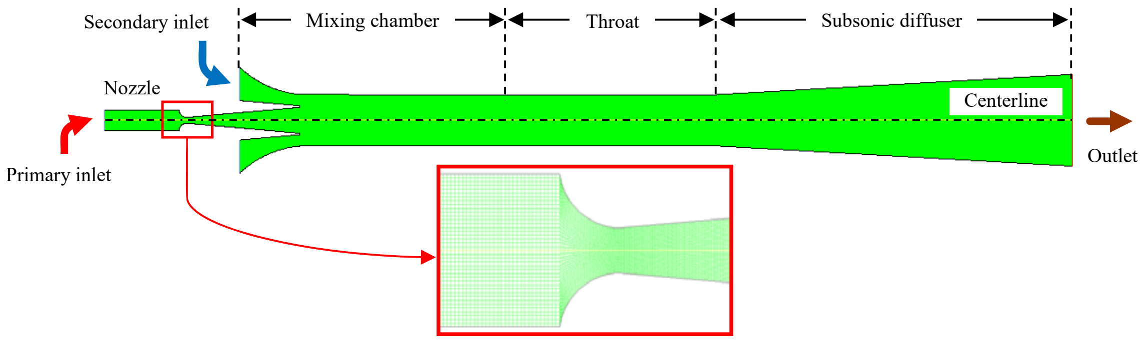

Fig. 3 Geometry domain and grid structure of the single-stage ejector CFD model

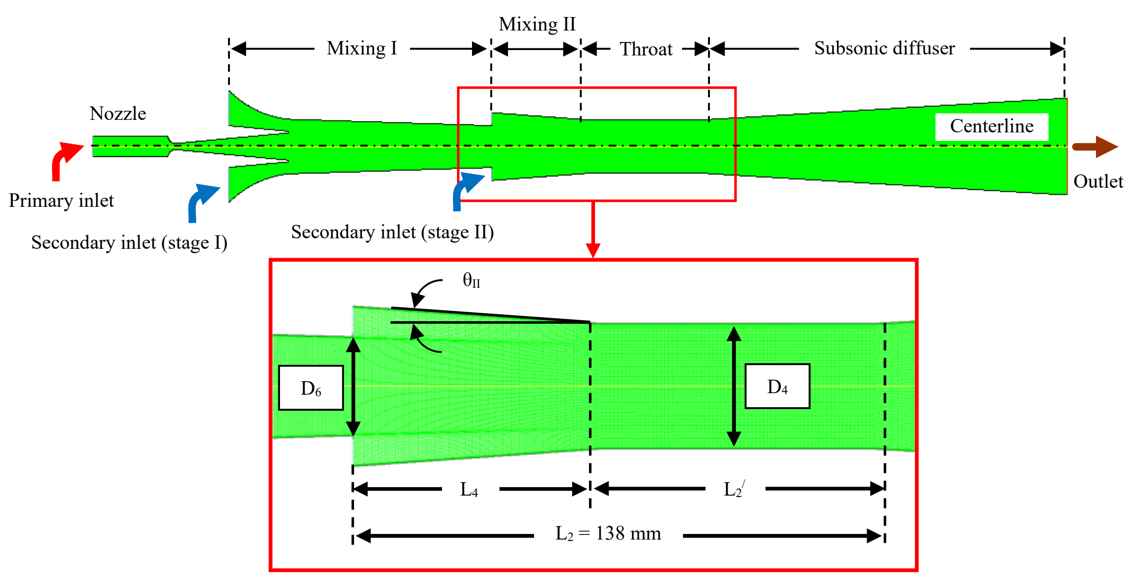

Fig. 4 Geometry domain and grid structure of the two-stage ejector type annular secondary at second stage CFD model

3. Results and discussion

In the simulation, ejector refrigeration system is investigated by using the operating conditions from the previous work whose generator temperature (T_g) of 110 °C and the evaporator temperature (T_e) of 10 °C. The best single-stage ejector, at maximum cooling load of 3000 W, the room temperature of 24.2 °C was obtained. The entrainment ratio of single-stage ejector is 0.50, and the COP was raised to maximum value at 0.45 [8].

The geometries in three-effect parameter systems design of TSE, the effects of the area ratio (A_4/A_6) in the mixing chamber geometries at the second stage on the entrainment ratio shows in "Fig. 5". The TSE by using the operating conditions from the previous work whose generator temperature of 110 °C and the evaporator temperature of 10 °C, there are fixed the mixing chamber geometries at the second stage, length (L_4) is 1.0D_4 and convergence angle (θ_{II}) is 10°. After reaching it, maximum entrainment ratio (Rm) is 0.665, at the area ratio (A_4/A_6) is 1.6 and 1.7.

The effects of the length (L_4) in the mixing chamber geometries at the second stage on the entrainment ratio shows in "Fig. 6". The TSE by using the operating conditions from the previous work whose generator temperature of 110 °C and the evaporator temperature of 10 °C, there are fixed the mixing chamber geometries at the second stage, the effects of the area ratio (A_4/A_6) is 1.6, and convergence angle (θ_{II}) is 10°. After reaching it, maximum entrainment ratio (Rm) is 0.694, the length are $1.6 \leq L_4/D_4 \leq 2.0$.

The effects of convergence angle (θ_{II}) in the mixing chamber geometries at the second stage on the entrainment ratio shows in "Fig. 7". The TSE by using the operating conditions from the previous work whose generator temperature of 110 °C and the evaporator temperature of 10 °C, there are fixed the mixing chamber geometries at the second stage, the area ratio (A_4/A_6) is 1.6, and length (L_4) is 2.0D_4. After reaching it, maximum entrainment ratio (Rm) is 0.714, at convergence angle (θ_{II}) is 4°.

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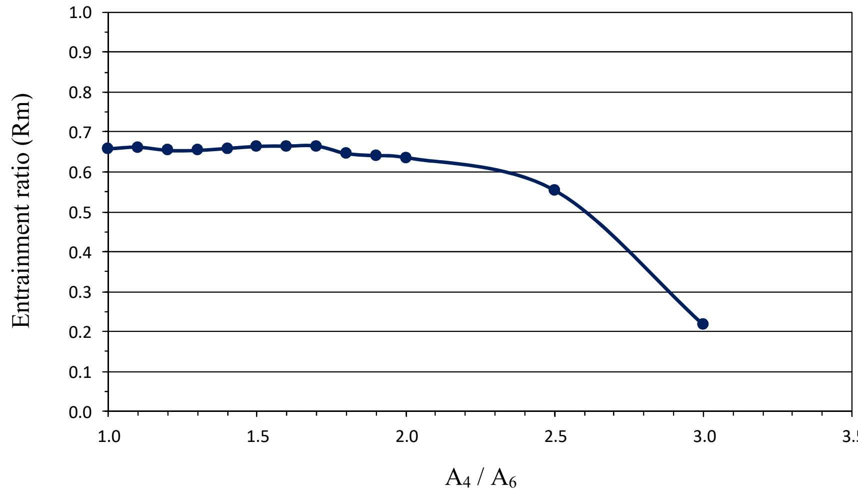

Fig. 5 Effect of the area ratio (A_4 / A_6) in the mixing chamber geometries the second stage on the entrainment ratio

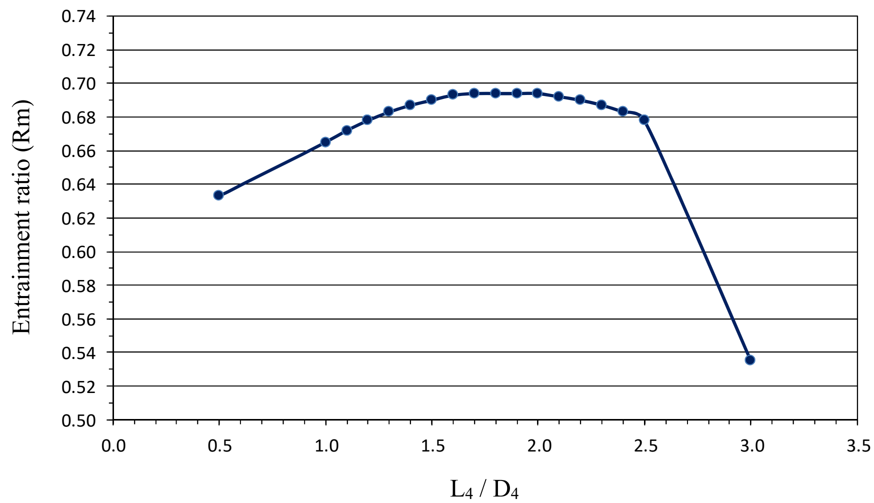

Fig. 6 Effect of length (L_4) in the mixing chamber geometries the second stage on the entrainment ratio

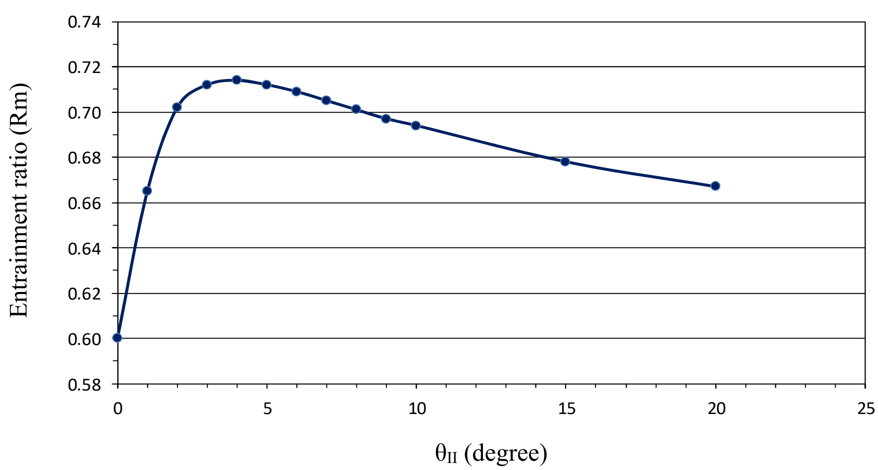

Fig. 7 Effect of convergence angle (θ_{II}) in the mixing chamber geometries the second stage on the entrainment ratio

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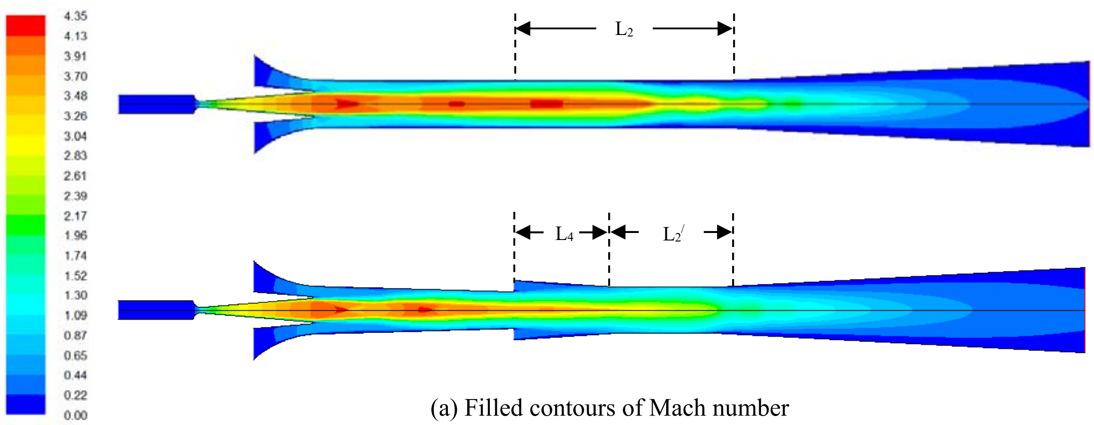
The simulation results show that, investigation on performance of steam ejector refrigeration system using two-stage ejector type annular secondary at the second stage in term of entrainment ratio (Rm), at the area ratio (A_4/A_6) is 1.6, the length (L_4) is 2.0D_4 and convergence angle (θ_{II}) is 4°, the maximum of entrainment ratio (Rm) is 0.714. It's compared with the single-stage ejector, can be increased for 42.8%.

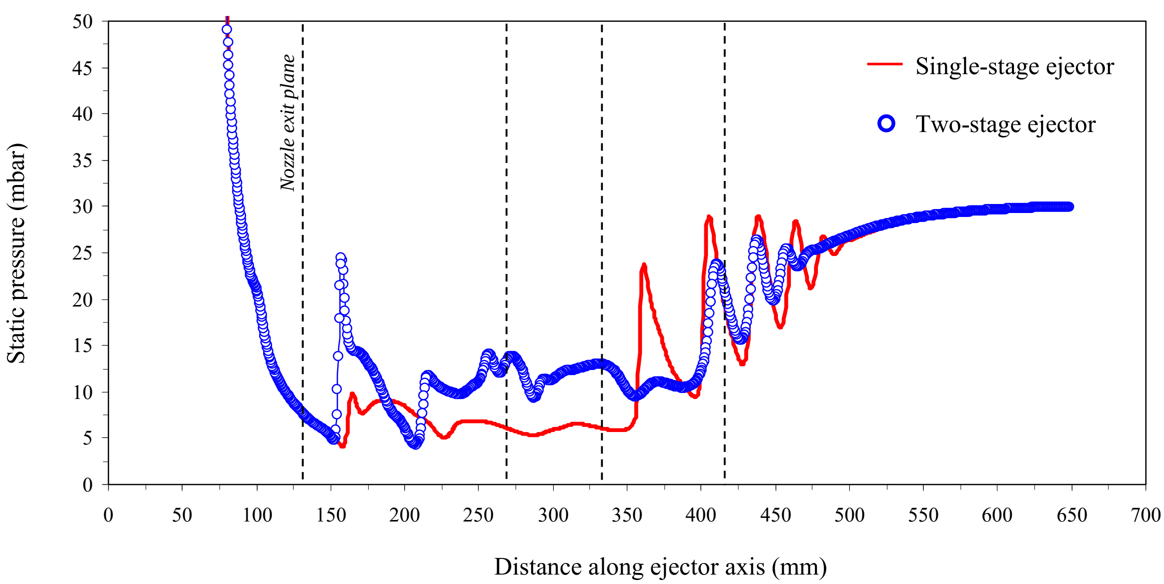
"Fig. 8(a)" shows the contours of Mach number of the ejector simultaneously with along the ejector, its comparison single-stage ejector and two-stage ejector. The generator temperature, evaporator, and condenser were fixed at the corresponding saturated temperature of 110 °C, 10 °C, and 24.1 °C (30 mbar), respectively. The single-stage ejector, a larger jet core mixing chamber inlet diameter moves with slightly greater speed and hence higher momentum. Two-stage ejector, the secondary fluid better mixing causes the smaller

"Fig. 8(b)" shows the static pressure profiles along the axis of both ejector. The two-stage ejector has a lower static pressure in the throat (L_2') allowing more secondary flow to be induced. However, in the diverging section, the recovery of the static pressure of the single-stage ejector is better resulting in higher critical back pressure.

Comparison of CFD results between the single-stage ejector and two-stage ejector are listed in Table. 3. The two-stage ejector type annular secondary at the second stage using the operating conditions from the previous work whose generator temperature of 110 °C and the evaporator temperature of 10 °C gives the best performance in term entrainment ratio being 0.714. It increases the entrainment ratio comparing to the single-stage ejector for 42.8%. But its critical back pressure is decreased by 7.4%, when compare with that of the single-stage ejector.



(a) Filled contours of Mach number



(b) Static pressure distribution along the centerline of the ejector

Fig. 8 Comparison advantages of two-stage ejector and single-stage ejector

Table. 3 Comparison of ejector performance between two-stage ejector and single-stage ejector

Generator temp. (°C)	Evaporator temp. (°C)	Entrainment ratio (Rm)			Critical back pressure, CBP (mbar)		
		Two-stage	Single-stage	Increase (%)	Two-stage	Single-stage	Decrease (%)
110	10	0.714	0.500	42.8	32.07 (25.2 °C)	34.64 (26.5 °C)	7.4
120	10	0.527	0.352	49.7	40.54 (29.2 °C)	44.44 (30.8 °C)	8.7
130	10	0.378	0.238	58.8	50.33 (33.0 °C)	59.45 (36.0°C)	15.3
110	0	0.320	0.200	60.0	26.13 (21.8 °C)	31.69 (25.0°C)	17.5
110	5	0.503	0.333	51.1	28.62 (23.3 °C)	33.43 (25.9 °C)	14.4

4. Conclusions

This paper proposes the design concept of two-stage ejector (TSE) type annular secondary at the second stage. In the simulation, the TSE performances are investigated by using the various-operating conditions in the steam ejector refrigeration system compared with single-stage ejector (SSE). The geometry design of TSE, at the area ratio (A_4/A_6) is 1.6, the length (L_4) is 2.0D_4 and convergence angle (θ_{II}) is 4°. The TSE gives much better performance for entrainment ratio, but the critical back pressure is slightly lower.

In this study, the authors expect that the information provided will contribute to the idea of improvement on performance of the TSE in actual refrigeration application.

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