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Investigation on performance of two-stage ejector in the steam ejector refrigeration by CFD simulation

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Abstract. The computational fluid dynamics (CFD) method is used to investigate the performance of the steam ejector in the refrigeration system. The modeled ejector in this study is a two-stage ejector (TSE) which is assumed to be 2D-axisymetric model. The shear-stress-transportation k-ω (k-ω-sst) model was applied as a turbulence model. In the simulation, the TSE is investigated by using the operating conditions from the previous work whose generator temperatures are between 100 ºC and 130 ºC and the evaporator temperatures are between 0 ºC and 15 ºC. Detailed explanation and comparison will be given to describe the performance and advantages of two-stage ejector over the single-stage ejector (SSE). Essential coefficients are specified in terms of entrainment ratio (Rm) and critical back pressure (CBP). From the simulations, the TSE provides higher entrainment ratio upto 77.2%, while, there is a marginal decrease in critical back pressure for maximum value of 21.9%. Results from this study are promising to enhance the COP of the future ejector refrigeration system. In addition, the CFD was found to be not only a sufficient tool in predicting ejector performances, but it also provides a better understanding of the flow and mixing processes within the ejector. Significant phenomena of the flow in the ejector, such as choke flow, mixing behavior, jet core effect and presence of the oblique shock can be explored.

1. Introduction

The first ejector refrigeration system was invented by Maurice Leblanc in 1910 [1]. Ejector refrigeration system is a system that uses heat to drive the system instead of mechanical energy from a compressor. Referring to the basic ejector refrigeration system show in "Figure 1", the system consists of 4 major components, which are the ejector, the boiler/ generator, the evaporator, and the condenser.

At present, the ejector refrigeration systems are several ways of improving the performance [2, 3], which is one of the Two-stage ejector (TSE). Its development geometric structure greatly effects on the performance improvement of a conventional single-stage ejector (SSE) [4, 5].

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 "Equation 1" and critical back pressure (CBP), consider a typical performance curve of a steam ejector as show in "Figure. 2". There are three operating regions distinguished by the critical back pressure [6].

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

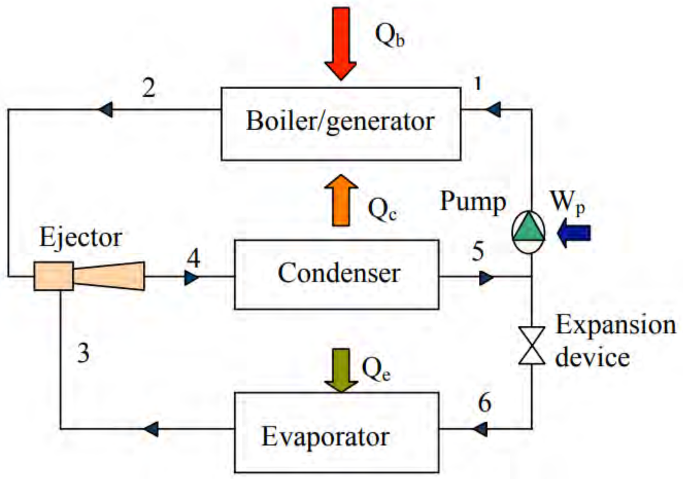


Figure 1. ejector refrigeration system

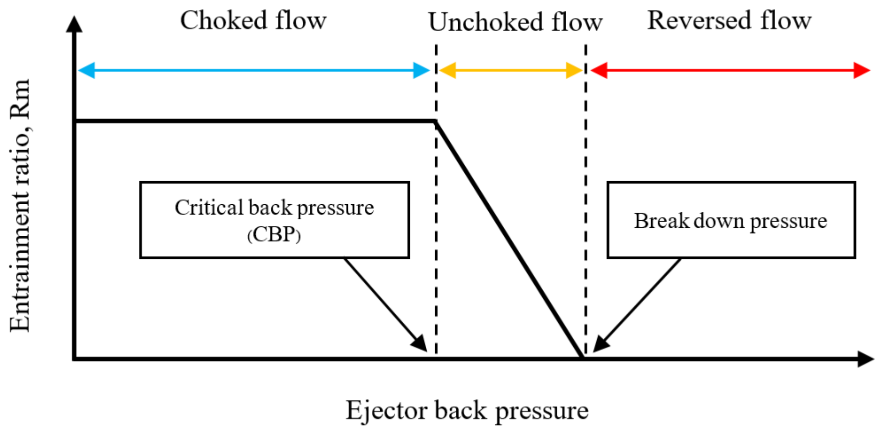


Figure 2. Performance characteristics of a steam ejector

This paper presents the results of a computational fluid dynamics (CFD) investigation on the performance of two-stage ejector in the steam ejector refrigeration compared with single-stage ejector, and significant phenomena of the flow in the ejector.

2. Computational setup

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:

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

Momentum equation:

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

Energy equation:

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

2.2 Single-stage ejector

Geometric structure of single-stage ejectors in the steam ejector refrigeration, the dimensions were designed by Ruangtrakoon [7]. The major parameters of the calculated domains are shown in Table. 1 and “Figure 3”.

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

2.3 Two-stage ejector

The flow phenomena in ejector two-stage 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.

The design concept of the proposed two-stage ejector compared with single-stage ejector. It’s all dimensions similar to the SSE, the parameters were designed by Suvarnakuta [8]. The dimensions of the calculated domains are shown in Table. 2.

Table 2. Parameters of the two-stage ejector [8]

Parameter	Value (mm)
Diameter of nozzle (d), mm	3.8
Diameter of entrance nozzle (D_1), mm	13.0
Nozzle area ratio [$(D_2/d)^2$], mm	20.0
Diameter of entrance mixing chamber (D_3), mm	34.0
Diameter of exit mixing chamber I (D_6), mm	26.1
Diameter of throat (D_4), mm	33.0
Diameter of exit subsonic diffuser (D_5), mm	60.0
Distance of mixing chamber I (L_1), mm	135.0
Distance of mixing chamber II (L_4), mm	66
Distance of throat ($L_2^{/}$), mm	72
Distance of subsonic diffuser (L_3), mm	242.0
Convergence angle of mixing chamber II (θ_{II}), Degree	4
Diameter of nozzle (d), mm	3.8
Diameter of entrance nozzle (D_1), mm	13.0
Nozzle area ratio [$(D_2/d)^2$], mm	20.0

* 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.

2.4 CFD model

The SSE and TSE geometry are modeled in 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. 3, the density of the working fluid is evaluated by using the ideal gas relationship while the calculation is progressing

All dimensions of the SSE and TSE calculation domain as shown in "Figure 4" and "Figure 5" respectively, 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.

Table 3. 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

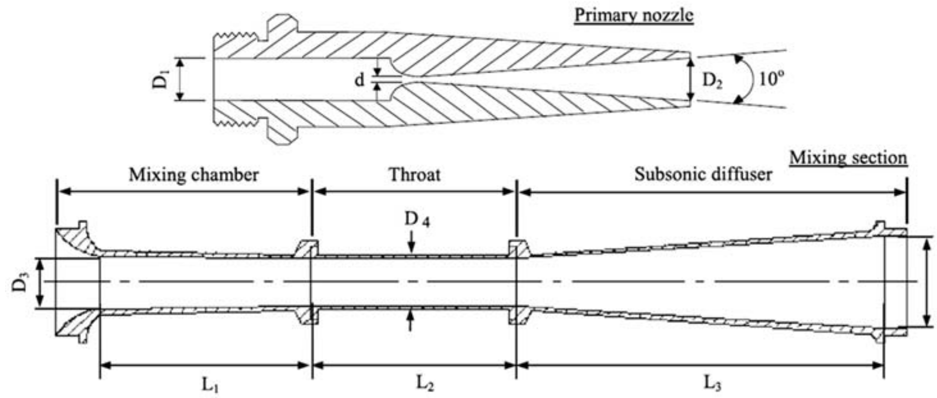


Figure 3. The single-stage ejector used in the research

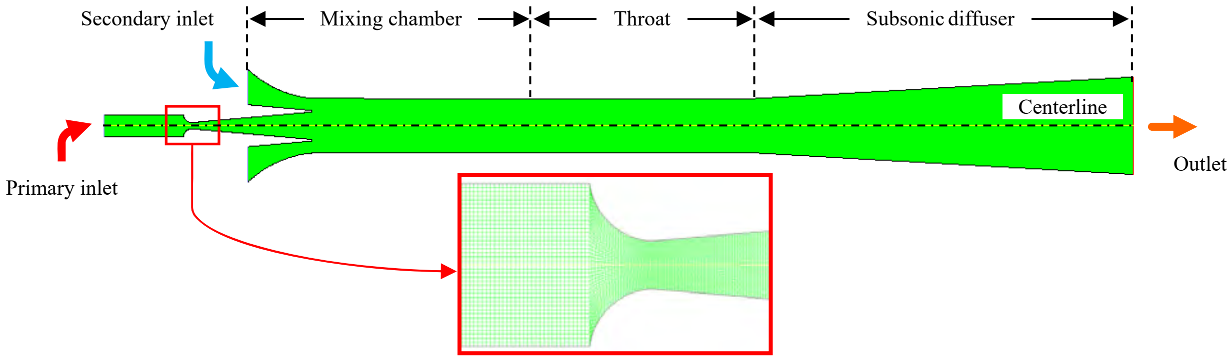


Figure 4. Geometry domain and grid structure of the single-stage ejector

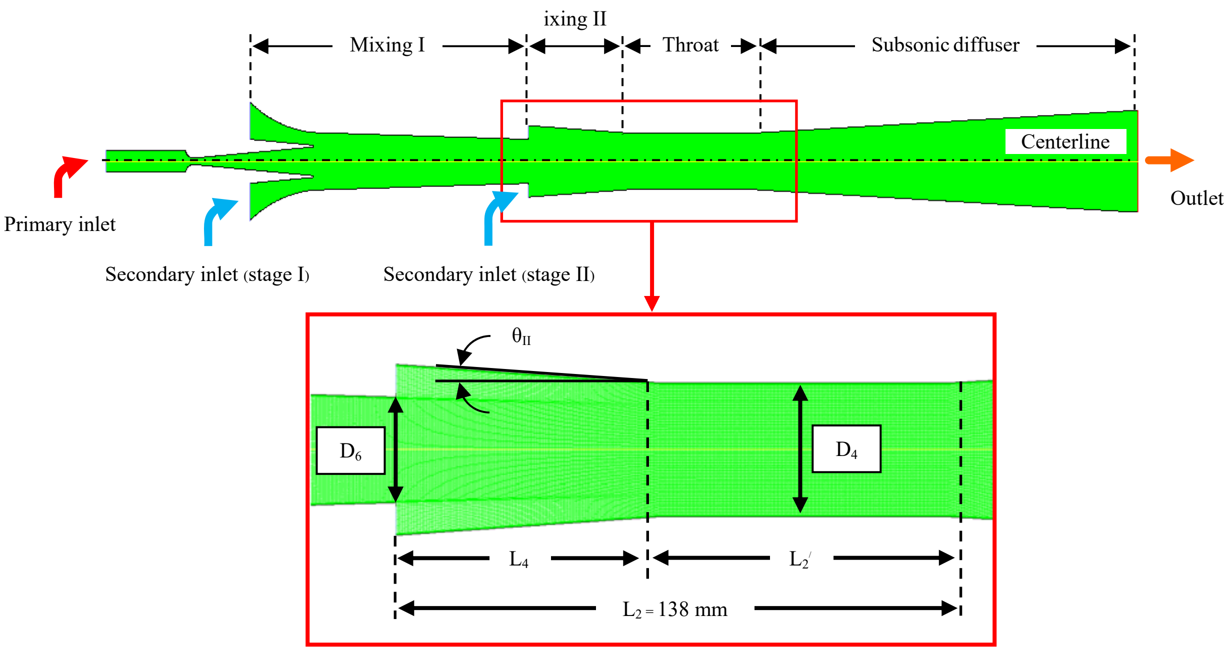


Figure 5. Geometry domain and grid structure of the two-stage ejector CFD

3. Results and discussions

The SSE 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 [7].

The TSE refrigeration system is investigation on performance of steam ejector refrigeration system using two-stage ejector 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% [8].

Comparison of CFD results between the secondary mass flow rate of SSE and TSE, under these operating conditions: area ratio (A_4/A_6) was 1.6, the length (L_4) was 2.0D_4, convergence angle (θ_{II}) was 4°, and generator temperature was between 100 °C and 130 °C, for the evaporator temperature at 0, 5, 10, and 15 °C are displayed in Figure 6 - 9, respectively. As as result, SSE had better induction of the secondary mass flow rate compared to TSE for each mixing chamber at the first stage ($\dot{m}_{s1}$) and mixing chamber at the second stage ($\dot{m}_{s2}$), but TSE could induce better for sum of mixing chambers ($\dot{m}_{s1} + \dot{m}_{s2}$). Moreover, in the mixing chamber of TSE, the secondary mass flow rate at the first stage was more than that at the second stage. However, decreasing evaporator temperature and increasing generator temperature caused the secondary mass flow rate at the second stage to be more than that at the first stage instead, as described in Figure 6.

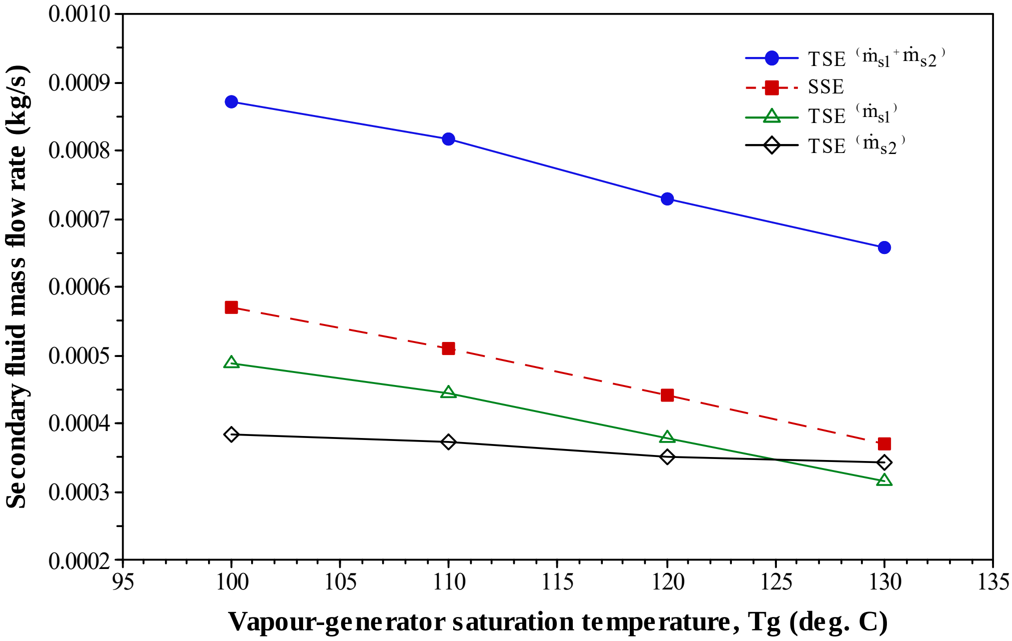


Figure 6. Secondary fluid mass flow rate of SSE and TSE at the evaporator temperature of 0 °C

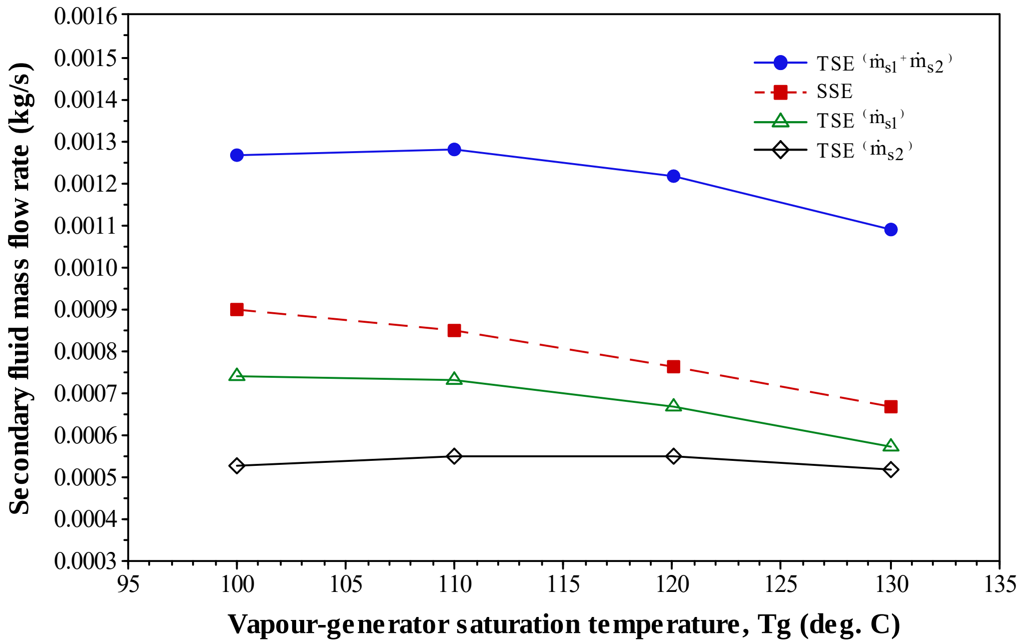


Figure 7. Secondary fluid mass flow rate of SSE and TSE at the evaporator temperature of 5 ºC

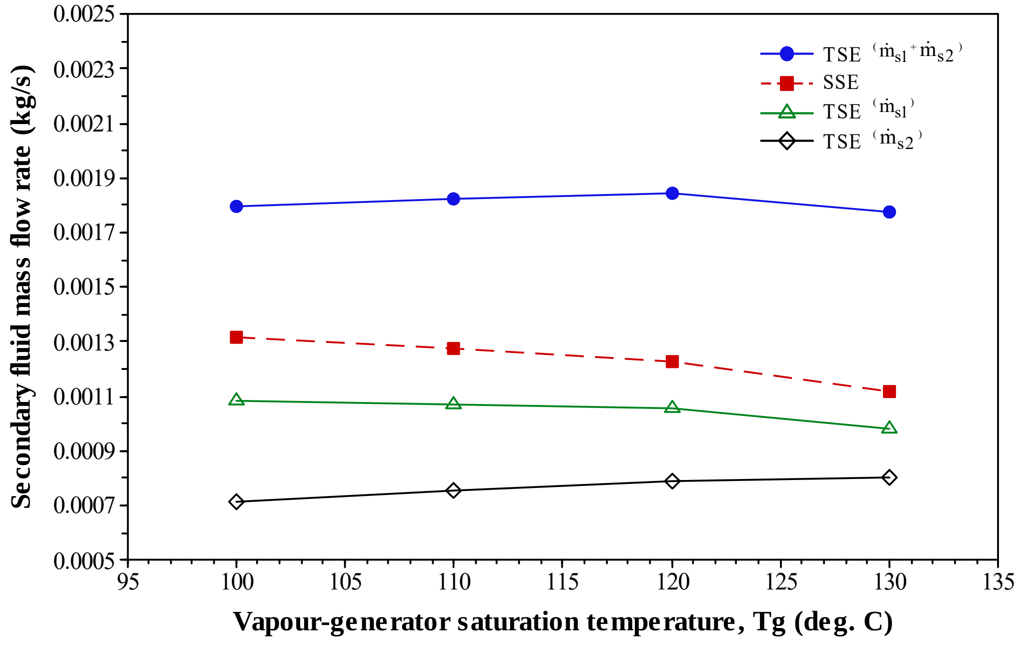


Figure 8. Secondary fluid mass flow rate of SSE and TSE at the evaporator temperature of 10 ºC

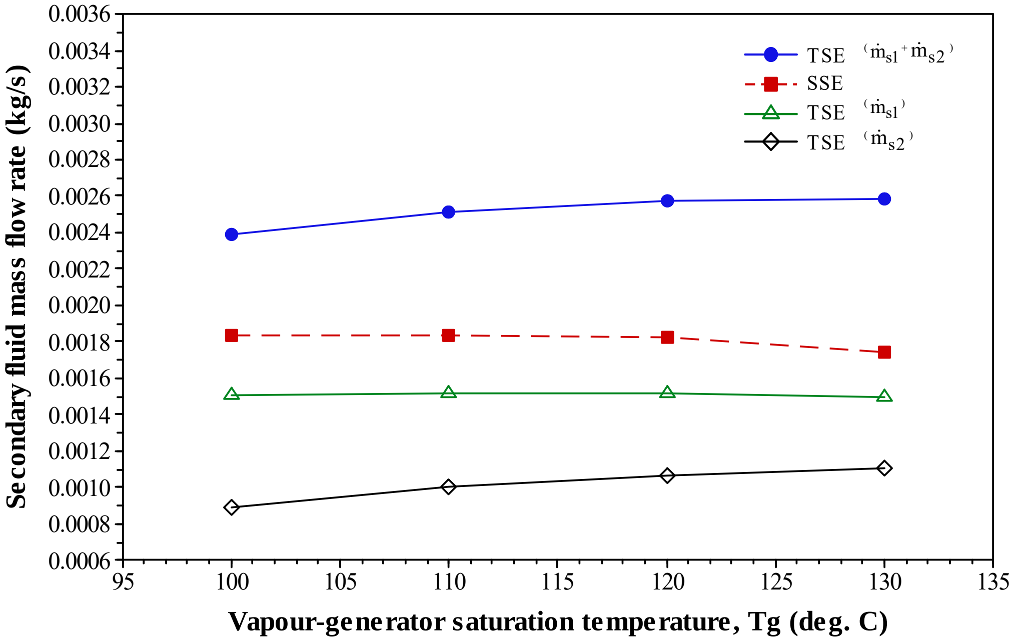
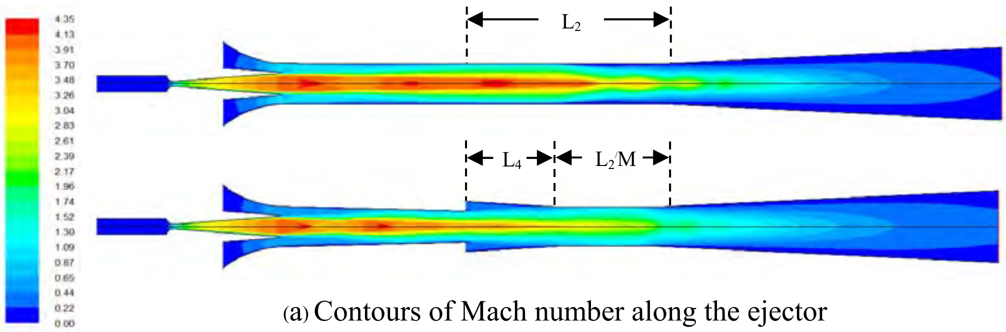
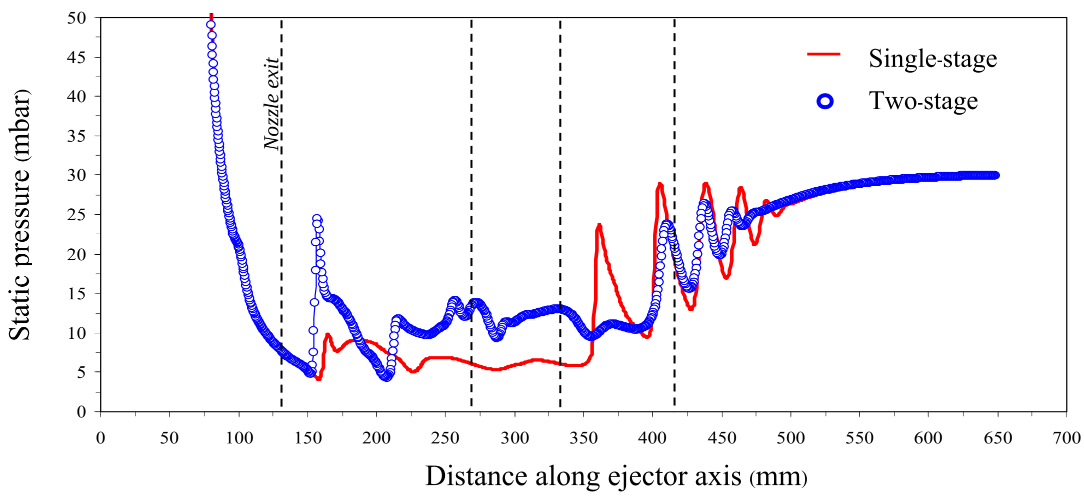


Figure 9. Secondary fluid mass flow rate of SSE and TSE at the evaporator temperature of 15 °C



(a) Contours of Mach number along the ejector



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

Figure 10. Comparison advantages of two-stage ejector and single-stage ejector

"Figure 10 (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

"Figure 10 (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.

Figure 11 compares the performance between SSE and TSE, the maximum Rm were equal to 1.000 and 1.307, and the maximum CBP were equal to 60.800 and 55.650 mbar, respectively. At the same working conditions, TSE gained higher Rm but lower CBP compared to SSE. Obviously, under high generator temperature, Rm of both SSE and TSE would reduce but CBP would increase, and for higher evaporator temperature, Rm and CBP of ejector would be higher as well.

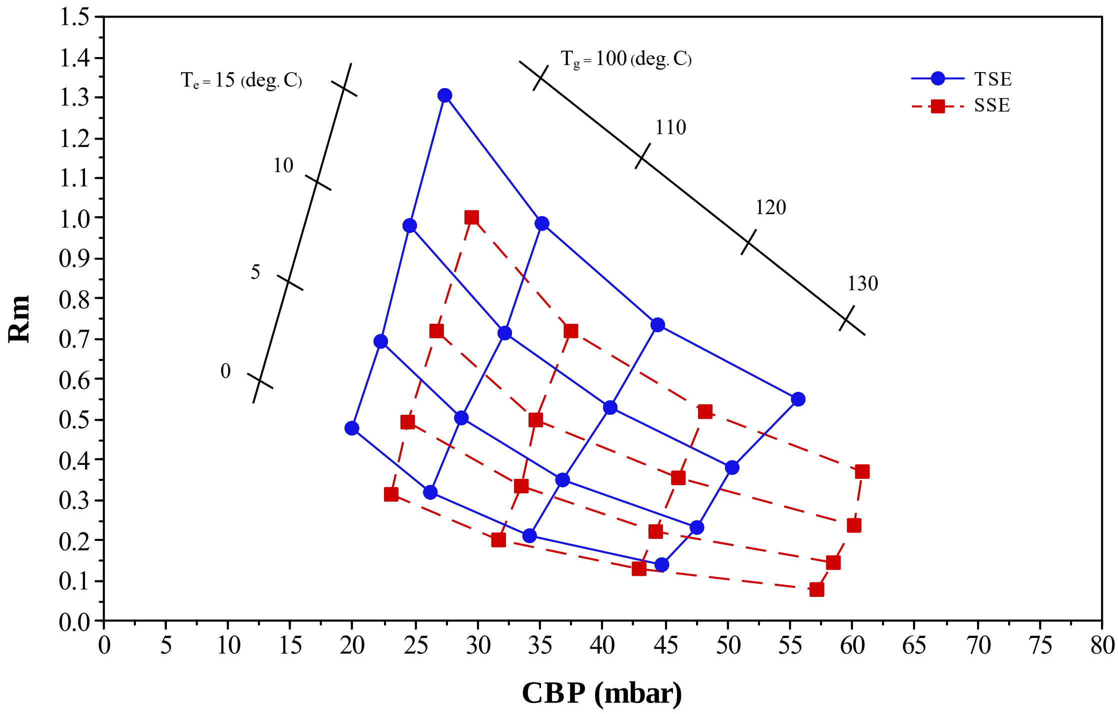


Figure 11. Performance characteristics of the steam ejector, effect of primary and secondary inlet temperature

4. Concluding Remarks

This paper proposes the design concept of two-stage ejector (TSE) and investigates its performance by the CFD simulations. In the simulation, the TSE performances were investigated by using the various-operating conditions in the steam ejector refrigeration system compared with single-stage ejector (SSE). For the geometry design of TSE, 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 provides higher entrainment ratio upto 77.2%, while, there is a marginal decrease in critical back pressure for maximum value of 21.9%. Overall, the TSE gives much better performance for entrainment ratio, but the critical back pressure is slightly lower.

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