CHAPTER VII

PERFORMANCE OF THE EJECTOR: EFFECTS OF OPERATING CONDITIONS

This chapter provides the investigation's results of the influences of operating conditions on the performance characteristics of the R141b ejector. From Chapter V, the validations of the CFD results of the R141b ejector model with the actual values obtained from the experiment were satisfied. This chapter, therefore, will only present the CFD investigation's results of the influences of interested parameters on the performance characteristic of the ejector. The performances of the experimental R141b ejector were evaluated in terms of the mass entrainment ratio (Rm) and the critical back pressure (P_C). The other flow information such as, the change in the static pressure distribution along the axis of the ejector and the change in contours of mach number, regarding the change of the operating conditions and the variation in the ejector's geometry, were used to explain how the performance of the ejector was altered.

The parameters of the ejector's operating conditions including the variation of the upstream and the downstream operating conditions are listed below.

- Vapour-generator saturation temperature (the primary fluid)
- Evaporator saturation temperature (the secondary fluid)
- Condenser saturation pressure (the back pressure)

In addition, it is expected that using the simulated Computational Fluid Dynamics (CFD) ejector models, the detail analyses of the results leads to a better understanding and the flow and mixing behavior which cause the change in ejector performance can be described clearly.

The investigations of the effects of operating pressures were carried out over a variety of upstream and downstream operating conditions. During the simulation, vapour-generator saturation temperature or the “upstream of the primary fluid” was ranged from 90 to 120^{o}C. The evaporator saturation temperature was considered as the “upstream of the secondary fluid”, and it was varied in the range of 0 to 10^{o}C. Lastly, the condenser saturation temperature, the “downstream of the ejector”, was varied from 25 to 45^{o}C. To avoid any unwanted influences from other parameters, the studies were done with a fixed geometry model as shown in Figure 4.2. The modeled ejector was constructed from primary nozzle no.1, mixing chamber no.1, throat section no.3 and the subsonic diffuser The primary nozzle exit plane was fixed at NXP = 30 mm.

7.1 Effect of Downstream Conditions (the condenser saturation pressure)

Figure 7.1 represents the calculated entrainment ratio when upstream and downstream conditions of the ejector were varied. Similar to the performance characteristics curve of typical steam ejector as shown in Chapter I, Figure 2.5, at each setting of vapour-generator and evaporator condition, the operation of the R141b ejector can be categorized into 3 regions, the choked flow, the un-choked flow and the reversed flow of secondary fluid. The ejector entrains the same amount of secondary fluid when it operates under critical condenser pressure. If the ejector operates beyond the critical point, the entrainment rate drops with an increasing of downstream pressure. If the condenser saturation pressure is further increased to the point called breakdown pressure, the secondary fluid cannot be induced into the ejector.

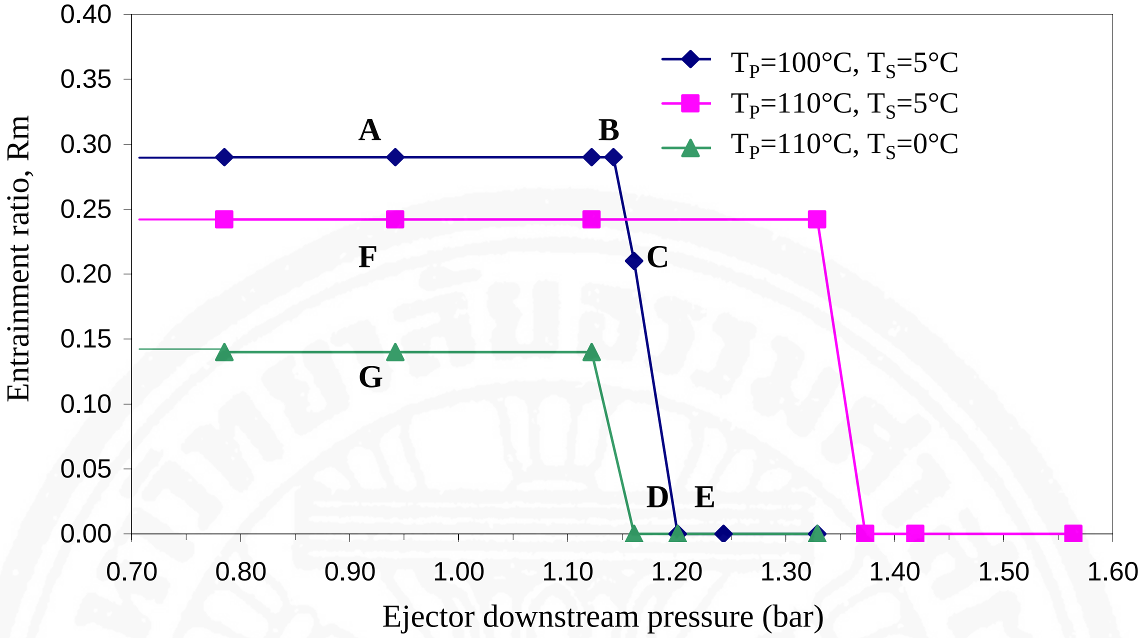
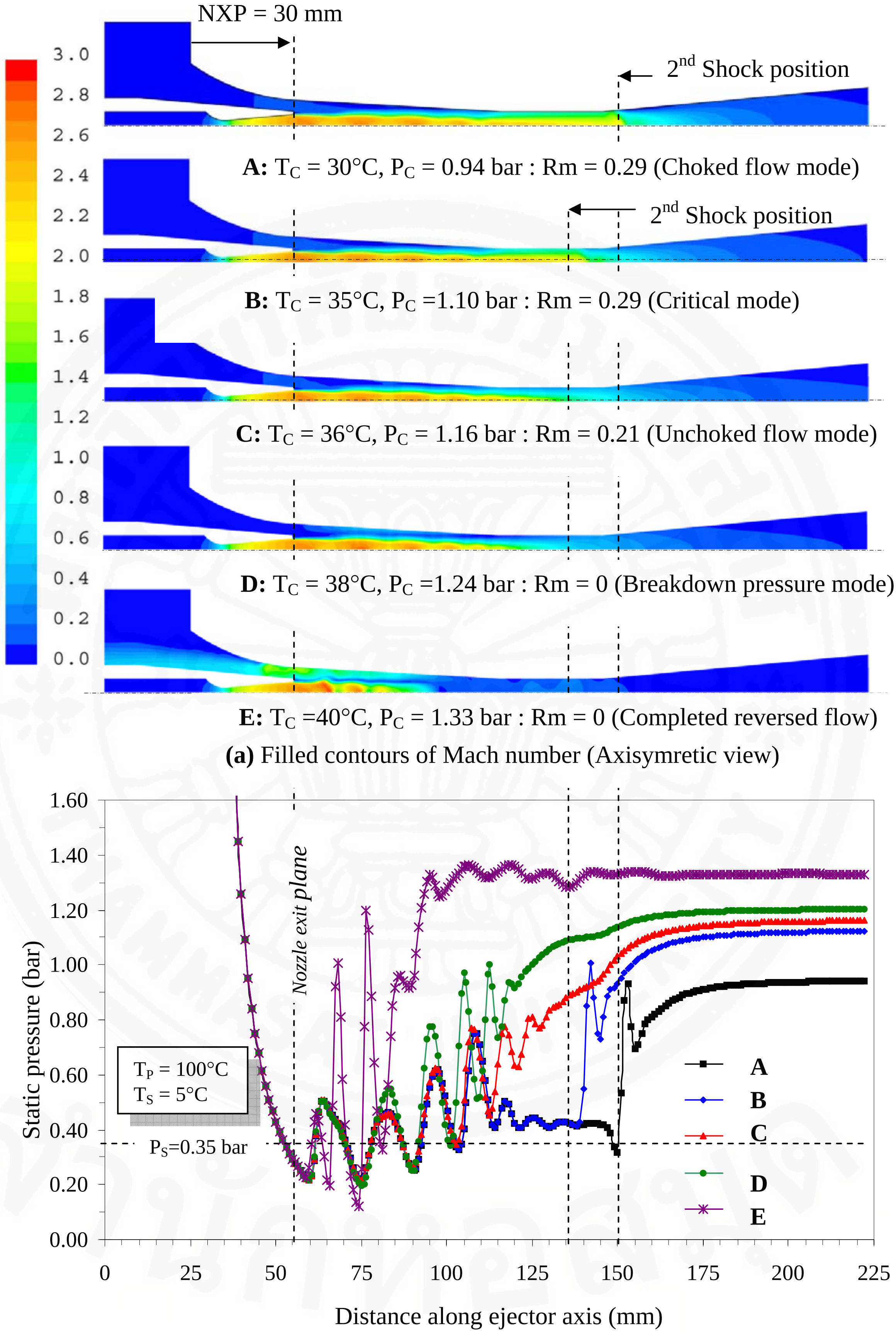


Figure 7.1 Performance characteristics of an R141b ejector, effect of operating conditions.

Considering filled contours of Mach number and path lines display simultaneously with static pressure profiles along the centerline of the R141b ejector, as shown in Figure 7.2a and 7.2b, it was found that, increasing downstream pressure from point **A** to **E** caused the shocking position to move upstream into the ejector throat. However, when back pressure does not exceed the critical point or within the choked flow region (**A** and **B**), the shock will not affect the mixing behavior of the two streams. Flow structures in front of a shocking position are shown unchanged and the size of the primary jet core remained constant and independent from downstream conditions. It was thought, that during this choke flow region, the effective areas were always forced to appear within the constant area throat section, since, the entrainment ratio remained constant. This proved the existence of the choking phenomenon.

When a downstream pressure increased higher than the critical point (**C**, **D** and **E**), the second series of oblique shocks, as given the description in Chapter VI, was forced to move further upstream and combine with the first series of oblique shocks to form a single



(a) Filled contours of Mach number (Axisymretic view)

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

Figure 7.2 Effect of downstream operating conditions on the flow in the R141b ejector (All operating points, **A**, **B**, **C**, **D** and **E**, correspond to those shown in Figure 7.1).

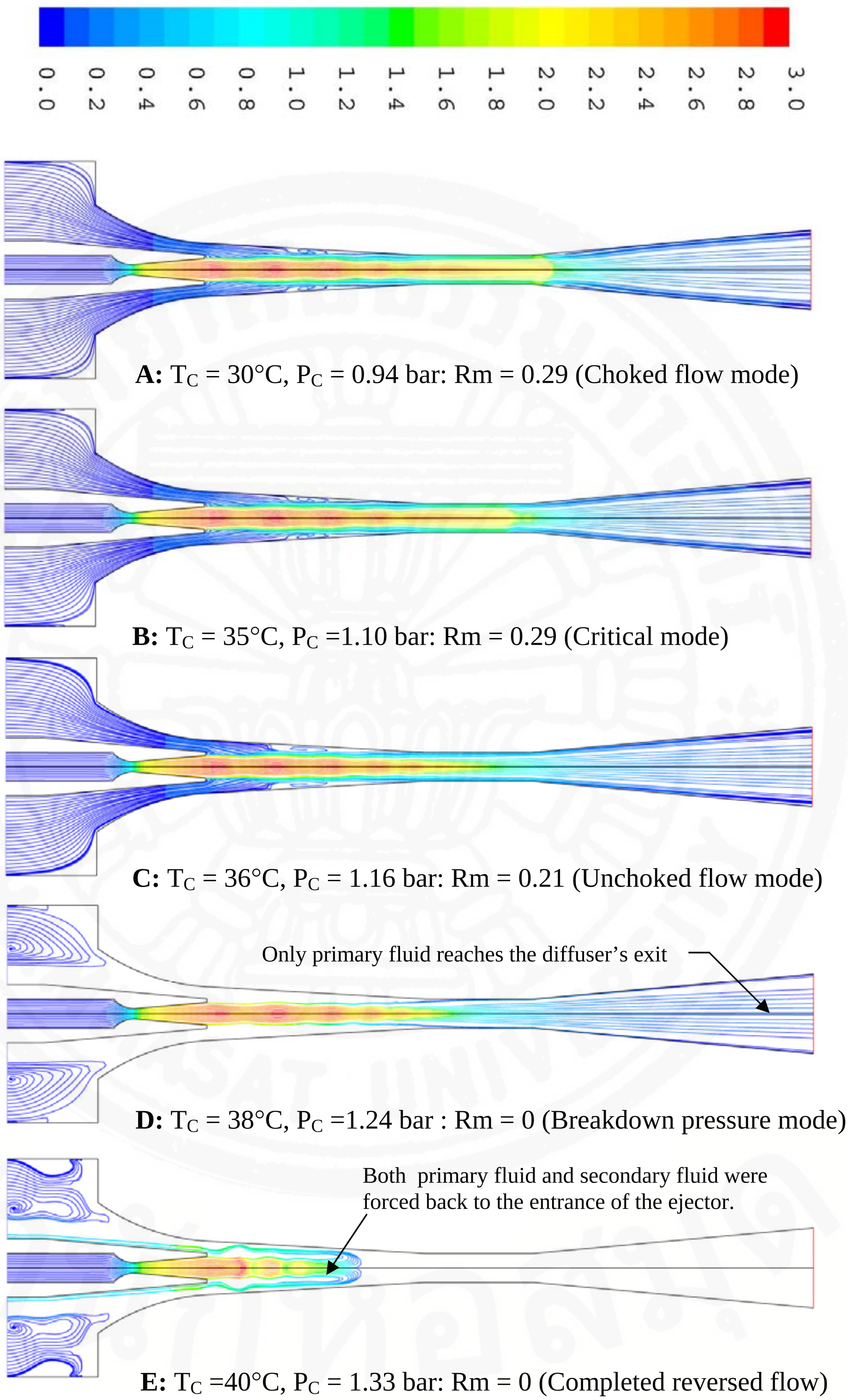


Figure 7.3 Path lines colored by Mach number of the flow in R141b ejector (corresponding to Figure 7.2).

series of oblique shocks. This movement of the second series of oblique shocks caused the secondary fluid to be no longer choked in the constant throat section, and hence, disturbed the entrainment process. The variation in the entrainment ratio under the unchoked flow region resulted from the variation in position of the effective area happening in the convergent mixing chamber. This can be investigated from the lowering of an entrained fluid speed and hence, the increasing of static pressure before shock. It should be noted that the size and the momentum of the jet core was independent from the variation of the downstream pressure.

Figure 7.3 illustrates path line displays colored by Mach number in which the flow directions of both the primary fluid and secondary fluid can be visualized (corresponding to the contours of Mach number in Figure 7.2). It was shown that, when back pressure does not exceed the critical point (**A** and **B**), the flow direction upstream of the shock position is the same. At the unchoked flow mode (**C**), the flow direction upstream of the shocking position was disturbed, hence, caused difficulties in entraining the secondary fluid. If the back pressure was increased to reach the breakdown pressure at point **D**, only the primary fluid was allowed to flow to the diffuser's end of the ejector. Thus, the entrainment ratio is zero at point **D**. At point **E**, where the back pressure exceeds the breakdown pressure, the flow direction shows that both the primary fluid and secondary fluid were forced to reverse to the entrance of the ejector.

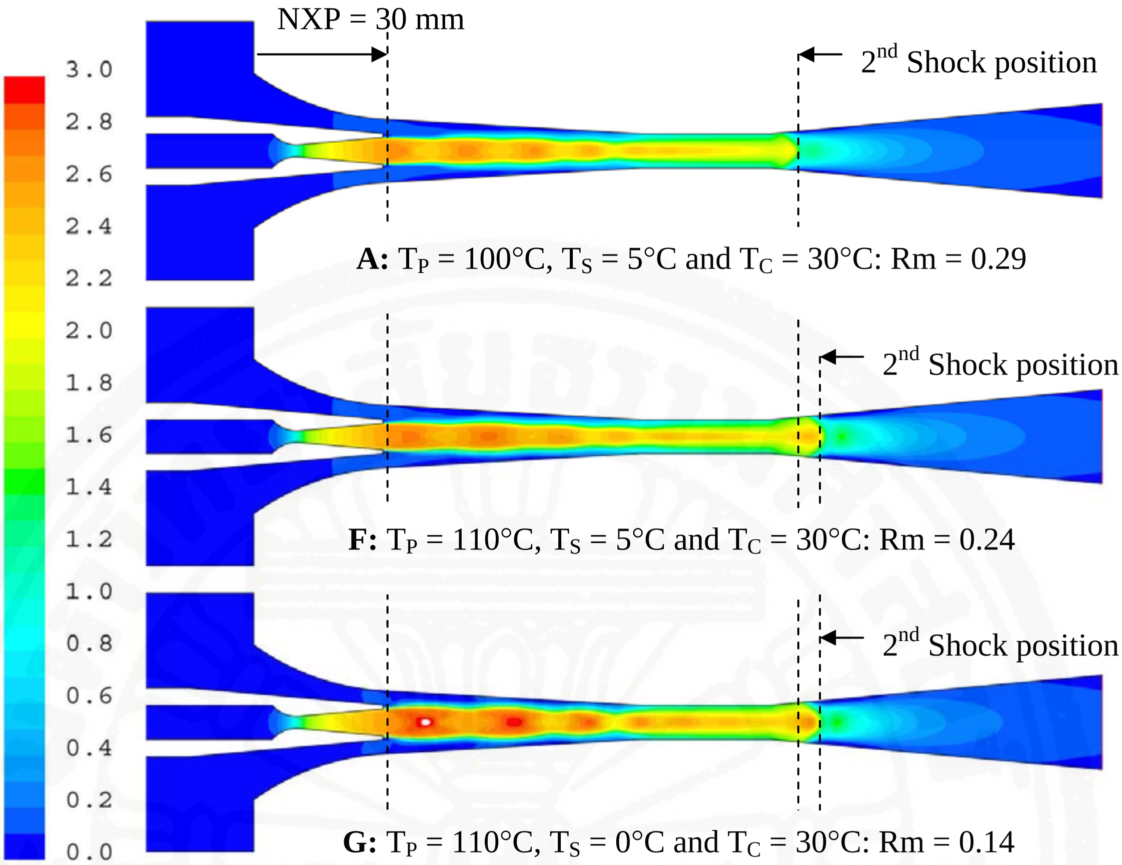
7.2 Effect of the Primary Fluid's Upstream Conditions (the vapour-generator saturation pressure)

Figure 7.4 (**A** and **F**) shows that increasing the primary fluid pressure, the Mach number of motive fluid leaving a primary nozzle remains unchanged. This obeys the principle of supersonic compressible flow; the supersonic flow leaves the different converging-diverging nozzles at the same speed when those nozzles are modeled with the identical area ratios. However, the mass flow through the primary nozzle and the momentum of the flow were increased. The increasing of momentum allowed the primary fluid to leave and further under-expand and accelerate with a larger expansion angle. This causes the diamond flow to shock at a higher Mach number at the first oblique shock. The increased expansion angle causes the enlarging of a jet core, therefore, the annulus effective area is reduced and less secondary fluid can be entrained and accelerated through the steeper converging duct. Thus the lower entrainment ratio was obtained as can be seen from the performance curves at point **A** and **F** in Figure 7.1. However, with higher momentum of the jet core, the shocking position moves downstream, and the ejector can be operated at a higher discharged pressure.

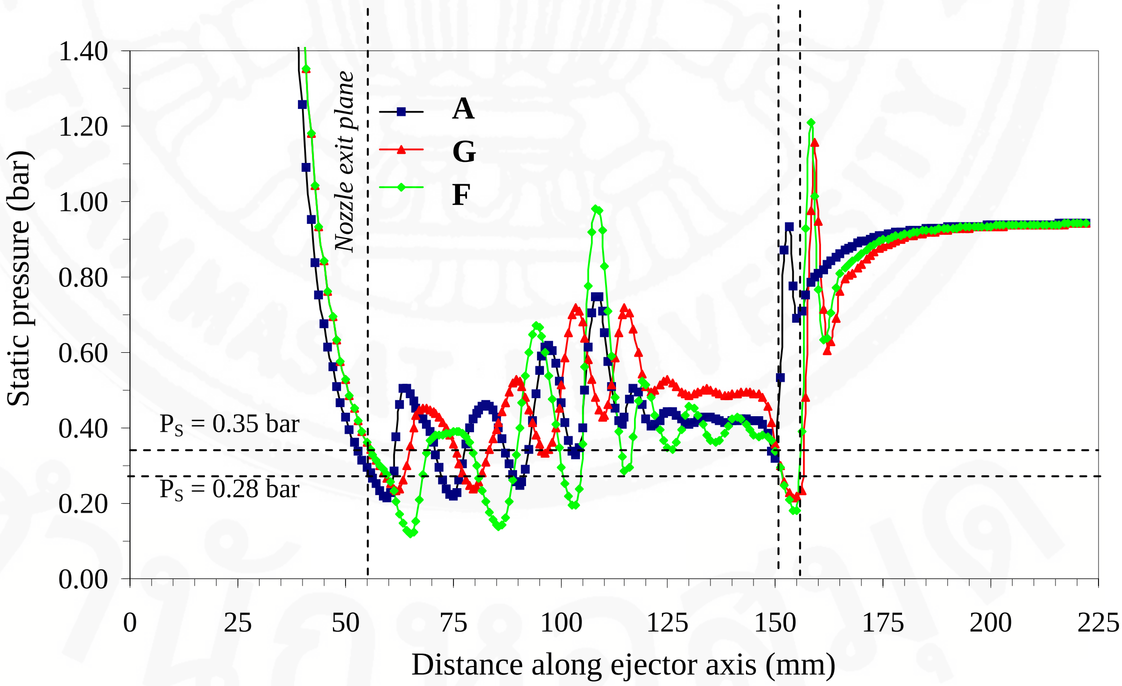
7.3 Effect of the Secondary Fluid's Upstream Conditions (the evaporator saturation pressure)

When secondary fluid pressure is increased, it can be seen from the Mach number contours, Figure 7.4 (**F** and **G**), that the expansion angle of the under-expanded wave was influenced by an increasing of the secondary fluid pressure. The pressurized condition causes the decreasing in an expansion angle, thus a smaller jet core and a larger effective area resulted. The expanded wave was further accelerated at a lower Mach number. Therefore, momentum of the jet core was reduced. However, an enlarged effective area allows a larger amount of secondary fluid to be entrained and passed through the converging duct (Figure 6.2). Total momentum of the mixed stream which was decreased by the jet core is compensated by the higher secondary fluid pressure.

So, it can be concluded that the total momentum of the mixed stream becomes higher, and the shocking position moves downstream as the secondary fluid saturated pressure rises. This enables the ejector to be operated with a higher entrainment ratio and at higher critical back pressure (Figure 7.1).



a) Filled contours of Mach number



b) Static pressure distribution along the centerline of the ejector

Figure 7.4 Effect of upstream operating conditions on the flow in the R141b ejector (All operating points, **A**, **G,** and **F**, correspond to those shown in Figure 7.1).

In addition to the cases of various operating conditions, the parameters of upstream operating conditions could be combined into a single parameter called the upstream pressure ratio (P_S/P_P) which altered the primary flow state at the primary nozzle exit's plane. At different upstream pressure ratios, it was found that the primary fluid could leave the primary nozzle's exit with different nozzle exit pressure ratios and different primary flow states, either an over-expansion state or an under-expansion state as described in the previous chapter. Hence, it could be useful to consider the effect of the primary flow states, as a result of various operating conditions, on the performance and flow characteristics of the ejector. In this investigation, the primary fluid saturation temperature was ranged from 80°C to 130°C, whilst the secondary fluid saturation temperature and the ejector's exit pressure were fixed at 5°C and 30°C, respectively. Table 7.1 and Figure 7.5 summarize the ejector's flow information when the upstream pressure ratio was varied.

It can be seen from Table 7.1 and Figure 7.5 that increasing the upstream pressure ratio to the value of 0.04644 corresponding to the primary fluid saturation temperature of 105°C and the secondary fluid saturation temperature of 5°C, there was a transition of the primary flow state from an under-expansion state to an over-expansion state.

Table 7.1 Results of CFD simulation for the R141b ejector operated with various upstream pressure ratios.

T_P (°C)	**P_S/P_P**	**$\dot{m}_P$ (kg/s)**	**$\dot{m}_S$ (kg/s)**	**Rm**	**Primary flow state**
80	0.08315	0.0103	0	0	Over-expansion
85	0.07347	0.0116	0.0030	0.256	Over-expansion
90	0.06516	0.0130	0.0048	0.365	Over-expansion
95	0.05801	0.0146	0.0053	0.370	Over-expansion
100	0.05182	0.0162	0.0049	0.303	Over-expansion
105	0.04644	0.0179	0.0045	0.251	-
110	0.04175	0.0198	0.0044	0.220	Under-expansion
120	0.03405	0.0240	0.0040	0.170	Under-expansion
130	0.02806	0.0290	0.0033	0.114	Under-expansion

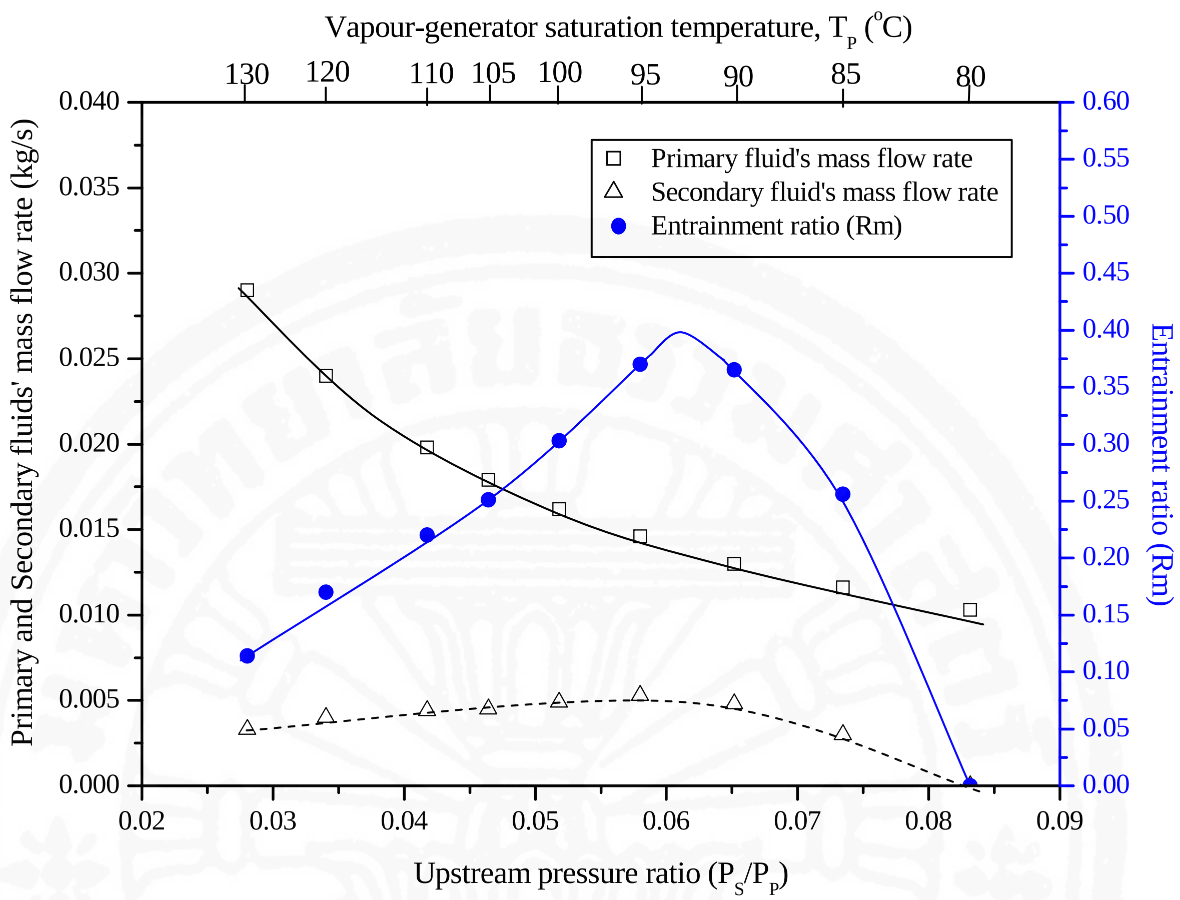


Figure 7.5 Simulated Entrainment ratio and mass flow rates of the two streams at different upstream pressure ratio.

The difference in the state of the primary flow at the primary nozzle exit causes the variation in entrainment ratio. If the primary flow state was in an under-expansion state, increasing the upstream pressure ratio caused the entrainment ratio to be increased. This is because at higher upstream pressure ratio (lower in primary fluid saturation pressure), the primary flow leaves the primary nozzle with a smaller expansion angle; therefore, a smaller jet core with larger effective area resulted. If the upstream pressure ratio was further increased, a maximum entrainment ratio existed. After the primary flow state was turned to an over-expansion state, even though the primary flow leaved the primary nozzle with a smaller expansion angle, the rate of the entrained secondary fluid dropped due to the drop in capability of the lower momentum primary fluid. In conclusion to this section, the pressure difference between the ejector primary inlet and the secondary inlet governs the amplitude of the secondary flow entrainment as reflected in the state of nozzle exit flow.

According to the investigation on the effect of the upstream pressure ratio, it was shown that the maximum secondary flow and, hence, the maximum entrainment ratio of 0.37 were produced at the primary fluid temperature at 90-95°C where the primary flow is in an over-expansion state. At the primary fluid temperature of 90°C, the upstream pressure ratio, P_S/P_P is equal to 0.065.

If we consider that in order to obtain the state of over-expanded primary flow in which the maximum entrainment ratio is achieved, the pressure ratio between the secondary fluid and the primary fluid should be at a proper value.

Let us recall the value of P_S/P_P = 0.065, and use this value for other test conditions where the primary fluid and the secondary fluid temperature were varied. The results of the investigation on effect of increasing the primary fluid temperature with a fixed P_S/P_P = 0.065 are shown in the following table.

Table 7.2 Results of CFD simulation for the R141b ejector operated with a fixed upstream pressure ratio.

T_P (°C)	T_S (°C)	$\dot{m}_P$ (kg/s)	$\dot{m}_S$ (kg/s)	Rm	Primary flow state
85	2	0.0103	0	0	Over-expansion
90	5	0.0130	0.0048	0.365	Over-expansion
100	10	0.0162	0.0062	0.383	Over-expansion
130	26	0.0290	0.0113	0.390	Over-expansion
150	36	0.0402	0.0155	0.386	Over-expansion

It can be said that, if the same P_S/P_P is applied, the following situations resulted.

- The entrainment ratio remains almost the same value when operated with the downstream pressure less than the critical back pressure.
- Properties of the flow upstream of the throat remain the same.

- The primary flow state is in an over-expansion state.
- At the primary fluid temperature of 85°C and P_S/P_P = 0.065, there is no entrained secondary flow into the ejector. This does not mean this pressure ratio is not applied to this temperature range, but, the zero-entrained fluid was influenced by the back pressure. If the back pressure is reduced, i.e. to the pressure corresponding to saturated temperature of 25°C, the entrainment ratio was found to be 0.37.

In conclusion, during operation, the proper P_S/P_P could be controlled in order to ensure the flow will leave the nozzle in an over-expanded state and to obtain maximum entrainment ratio. The disadvantage of keeping the same upstream pressure ratio is that the desired secondary fluid saturation temperature (evaporator saturation temperature) may be sacrificed.

7.4 Conclusions

This chapter proposes the theory explaining the flow characteristics reflecting the performance of the R141b ejector, when the operating conditions of the ejector were varied. With help of the CFD, the change in the flow structure, influenced by interested parameters, in the R141b ejector could be visualized. It was found that, the size of the primary jet core and the effective area (between the wall of an ejector throat and the primary fluid jet core), as can be visualized from the contours of Mach number, was directly related to the amount of the entrained secondary fluid and thus the entrainment ratio. The critical back pressure (the highest possible condenser pressure) was affected by the shocking position at some point between the constant area throat and the entrance of the diffuser. The shocking positions can be investigated from the simulated static pressure profiles along the axis of the ejector.

Table 7.3 Summarized table for the effect of operating conditions on the R141b ejector.

Effect Parameters	**action**	**Primary flow state**	**Performance Characteristic**	
			Entrainment ratio **(Rm)**	Critical back pressure **(P_C)**
Effect of Operating Conditions				
Primary fluid saturation pressure	(-)→ (+)	Over-expansion	↑	↑
		Under-expansion	↓	↑
Secondary fluid saturation pressure	(-)→ (+)	Over-expansion / Under-expansion	↑	↑
Downstream saturation pressure	(-)→ (+)	Choked flow	**Unchanged**	
		Unchoked flow	↓	

During the simulation, it was discovered that the primary flow state at the nozzle exit plane play a significant role in the performance of the ejector at various operating conditions. The influences of the studied parameters associated with the primary flow state on the performance characteristic of the R141b ejector are presented in Table 7.3.

From Table 7.3, it can be seen that the performance of the R141b ejector, both the entrainment ratio and the critical back pressure, can be improved by the following:

- Increasing of the primary fluid saturation pressure when the primary flow state was in the over-expansion state.
- Increasing of the secondary fluid saturation pressure when the primary flow state was either the over-expansion state or under-expansion state.

Changing the downstream condition or the back pressure in the choked flow region, caused the entrainment ratio to remain constant. In the unchoked flow region, if the back pressure was increased, the entrainment ratio is reduced.

The enhancement of the critical back pressure, but with the decrease in the entrainment ratio could be found, when adjusting the following:

- Increasing of the primary fluid saturation pressure when the primary flow state was at the under-expansion state.

In conclusion, this chapter shows the advantage of CFD in investigating the flow mechanisms and the performance of the R141b ejector when operating with various operating conditions. Using the information provided in this chapter leads to the development in the design and the operation of the ejector for refrigeration purposes.