CHAPTER VI

FLOW CHARACTERISTICS AND MIXING PROCESS

The successful validation as was done in the previous chapter and in the past studies [26, 39, and 40] have brought to the conclusion that the CFD model can efficiently predict the performance of ejectors and provide valuable information that can represent the flow inside the ejectors. In this chapter, a basic knowledge of the flow and the mixing process of an ejector used in a jet refrigerator is provided. The details concentrate on the use of CFD in visualizing the flow phenomena inside the R141b ejector. The differences in the flow structure of the R141b ejector and the steam ejector based on the data obtained from Sriveerakul et al. [39 and 40] are discussed.

As described in the previous chapters, the study of the R141b ejector was conducted by two parallel methods which were 1) the experimental investigation and 2) the simulation of the flow within the ejector using a CFD software package. Regarding the experimental measurement, the wall static pressure curves obtained form the experiment were used to validate the results obtained from the simulation. It was fascinated that both results were agree well. However, the nature of the flow and the mixing process in an ejector are complicated, using the information of the wall pressure distribution only can not explain them clearly. Therefore, other information obtained from the simulation; for example, the Mach contour plot and the static pressure distribution along the axis of the ejector, which is a better representative of the flow, could be fairly used to explain the flow and the mixing process in the ejector. Please note that the knowledge provided in this chapter will later be applied and compared to the changes in the flow structure and the mixing process inside the R141b ejector (Chapter VII) as affected to the ejector's performance when its operating conditions and its geometry were varied.

6.1 Flow and Mixing Process of the R141b Ejector under its Choked Flow Condition

Figure 6.1 illustrates the contour lines of Mach number and static pressure distribution of the R141b ejector when it operates in the choked flow mode (the primary fluid saturated temperature (T_P) of 100°C, the secondary fluid saturated temperature (T_S) of 5°C and the back pressure (P_C) of 0.94 bar). Detailed explanation of the simulated flow structure is provided as follows.

As the high-temperature and high-pressure primary fluid exiting from the vapour-generator enters the convergent section of the primary nozzle, the subsonic motive flow accelerates to sonic value and chokes at the nozzle throat (1). In the divergent portion of the nozzle, the primary fluid accelerates and expands further to achieve a supersonic speed. At the nozzle exit plane (2), it is found that the supersonic stream could leave the nozzle with its static pressure lower or higher than the surrounding pressure in the mixing chamber (P_S = 0.35 bar). To preserve the static pressure across the free boundary between the primary jet core (3) and the surrounded fluid, the first series of oblique shock and expansion waves, called the *"diamond wave"* pattern (4), is induced. This phenomenon can be investigated from the fluctuation of static pressure at the center line of the ejector while the flow passes through a mixing chamber (Figure 6.1). In the theory of supersonic flow through a convergent-divergent nozzle as was used as the primary nozzle of the ejector, the change in the flow state at the nozzle's exit is subjected to change with the change of the exit pressure ratio [52]. This exit pressure ratio is the ratio between the pressure which exists immediately upstream of the shock wave standing at the exit of the nozzle and the pressure downstream of the shock.

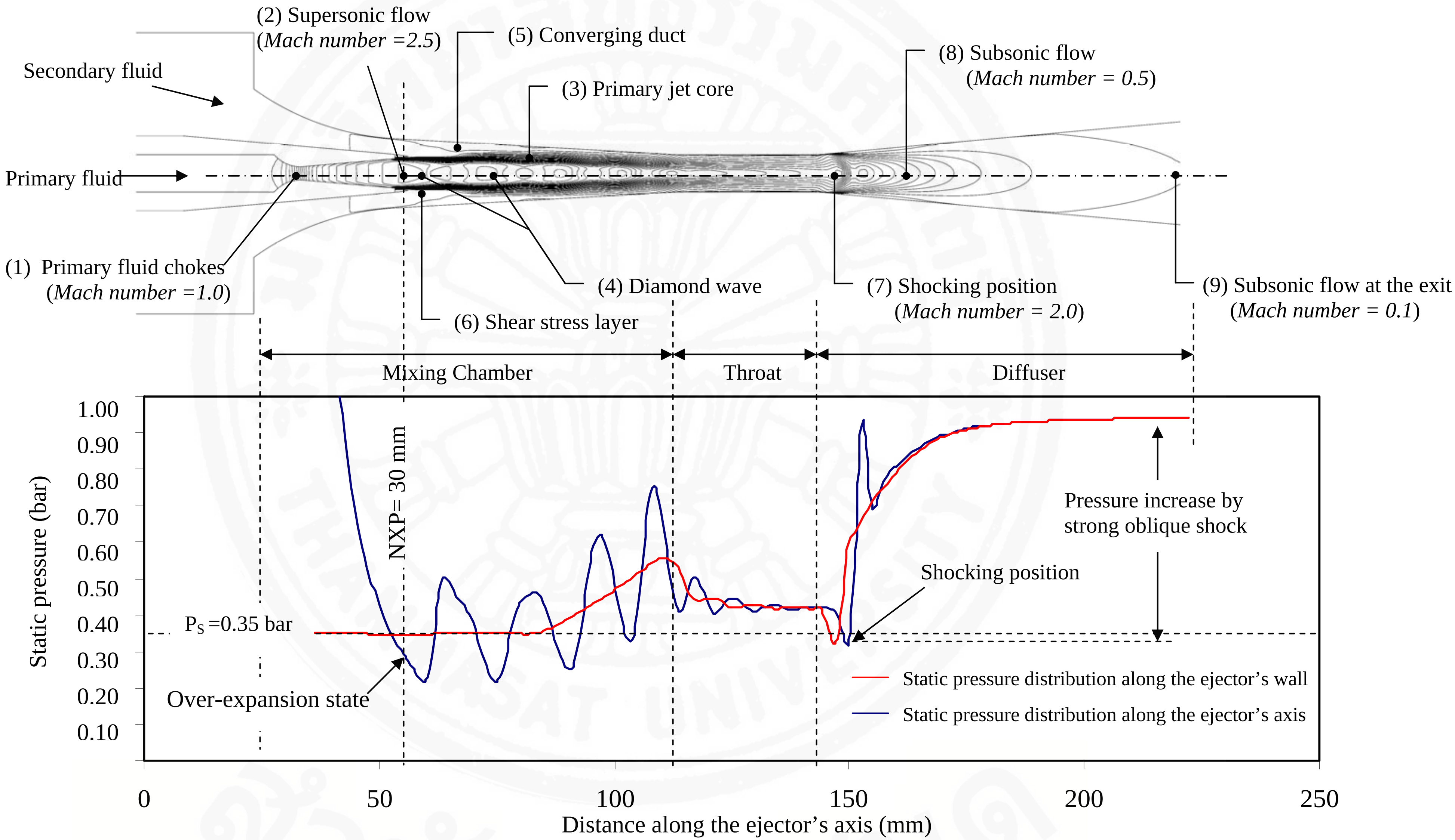


Figure 6.1 Filled contours of Mach number and static pressure distribution of the R141b ejector.

For the flow in an ejector, the pressure downstream of the shock is referred as the surrounding pressure (this pressure is assumed to be equal to the secondary fluid saturated pressure). The state of the flow immediately after leaving the primary nozzle can be called the "*primary flow state*".

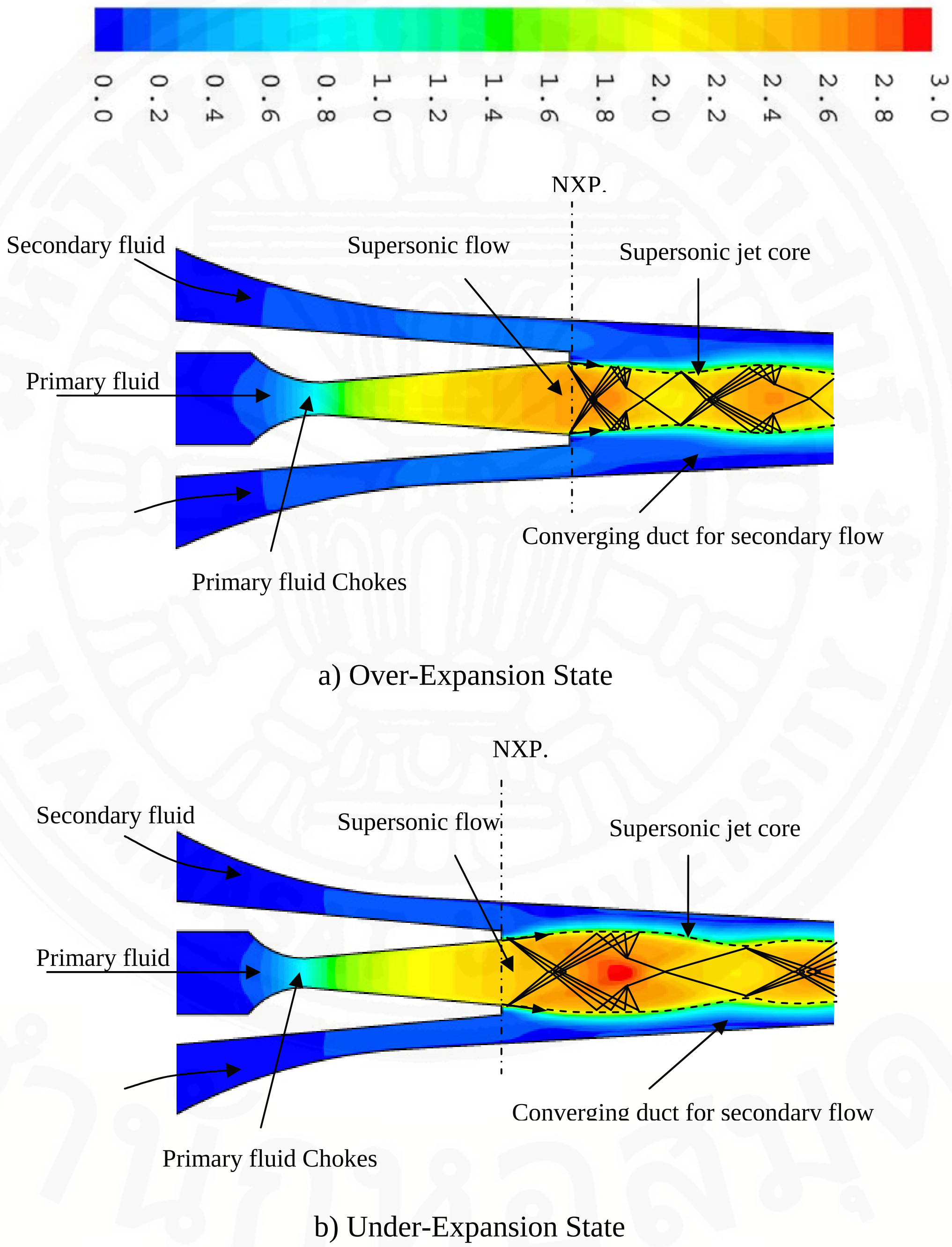


Figure 6.2 Primary flow states of the flow in the ejector colored by contours of Mach number.

The primary flow state can be classified into two states which are the "*Over-expansion state*" and the "*Under-expansion state*". In the case of the supersonic stream leaving the nozzle with its static pressure already expanded below the surrounding pressure, the primary fluid immediately leaves the primary nozzle as an "over-expansion state" with the expansion wave angle converged into the axis line of the ejector and accelerates as an over-expanded wave as shown in Figure 6.2a. If the primary fluid stream leaves the nozzle with its static pressure greater than the surrounding pressure, the flow is said to be in an "under-expansion state". In this case, the flow is capable of additional expansion after leaving the nozzle. The diamond wave pattern at the nozzle exit is at a diverged angle to the centerline of the ejector as shown in Figure 6.2b. The difference in the states of the primary flow could affect the flow field of the ejector and, hence, alter the ejector's performance which will be discussed in the next chapter.

The occurrence of a diamond wave jet core in the mixing chamber indicates the semi-separation between the high speed primary flow and the surrounded secondary fluid. Thus, the converging duct (5) for entraining a secondary fluid into the mixing chamber, similar to that proposed by Munday and Bagster [30], is formed. Moreover, according to the large velocity difference between these two streams, the shear stress layer (6) interfacing between them is presented. The shear mixing of two streams begins as the secondary fluid from the evaporator is entrained and interfaces with the expanded wave. Flowing through the converging duct, the shear mixing process causes the secondary fluid to accelerate, conversely, the shear mixing and the viscosity of the fluid cause the diamond wave to decay. As investigated in Figure 6.1, the static pressure of the flow steadily decreases at the beginning of the flow process and the violence of the diamond wave reduces, respectively.

At the throat of the mixing chamber, most of the entrained secondary fluid accelerates and reaches the sonic velocity. Very small amounts move slightly faster than the sonic value when it flows close to the shear stress layer attached to the primary jet core, but slower when it flows close to the wall boundary layer (mixing chamber's wall). Moreover, it is seen that the violence of the diamond wave reduces as the primary jet core travels with lower supersonic speed, consequently, a relatively smooth jet core results. Therefore, the secondary flow can be considered as choked. The choke area or "*effective area*" [42] of the secondary fluid can be estimated from the annulus area between the wall of an ejector throat and the primary fluid jet core. Despite using the CFD visualization, it is difficult to locate the exact position of the effective area within the ejector. During the choke flow mode, the entrainment ratios remained constant, the effective area, hence, can be estimated at anywhere within the constant area ejector's throat.

At a certain distance into the ejector throat or in the beginning of the diffuser section, called the "*shocking position*" (7), a non-uniform mixed stream produces the second series of oblique shock waves (8). Therefore, when the flow is dominated by a series of oblique shocks, the static pressure gradually recovers to discharge value and the flow speed gradually decreases to subsonic level, while it passes through the diffuser. In addition, across this process, the mixed stream loses most of its total pressure. However, in concept, a series of oblique shock should provide smaller pressure loss in total pressure than a single normal shock.

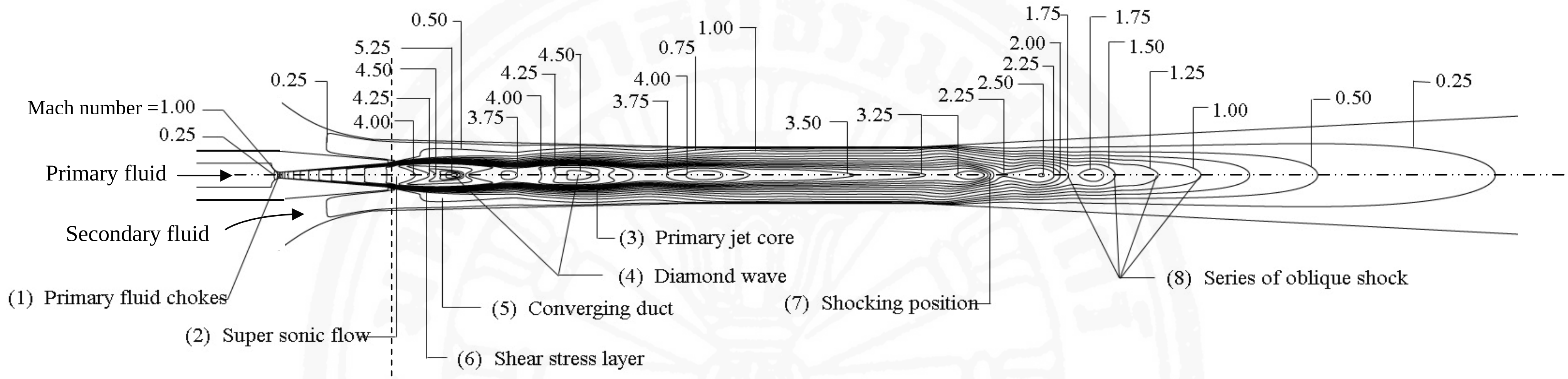
6.2 Comparison of the Flow Structures: the R141b Ejector and a Steam Ejector

This section provides an explanation of significant differences between the flow structures of the current R141b ejector and the steam ejector based on the work done by Sriveerakul et al. [39 and 40]. Figure 6.3 illustrates the flow structure of a steam ejector that was evaluated at vapour-generator temperature of 120^oC, evaporator temperature of 10^oC and condenser pressure of 30 mBar.

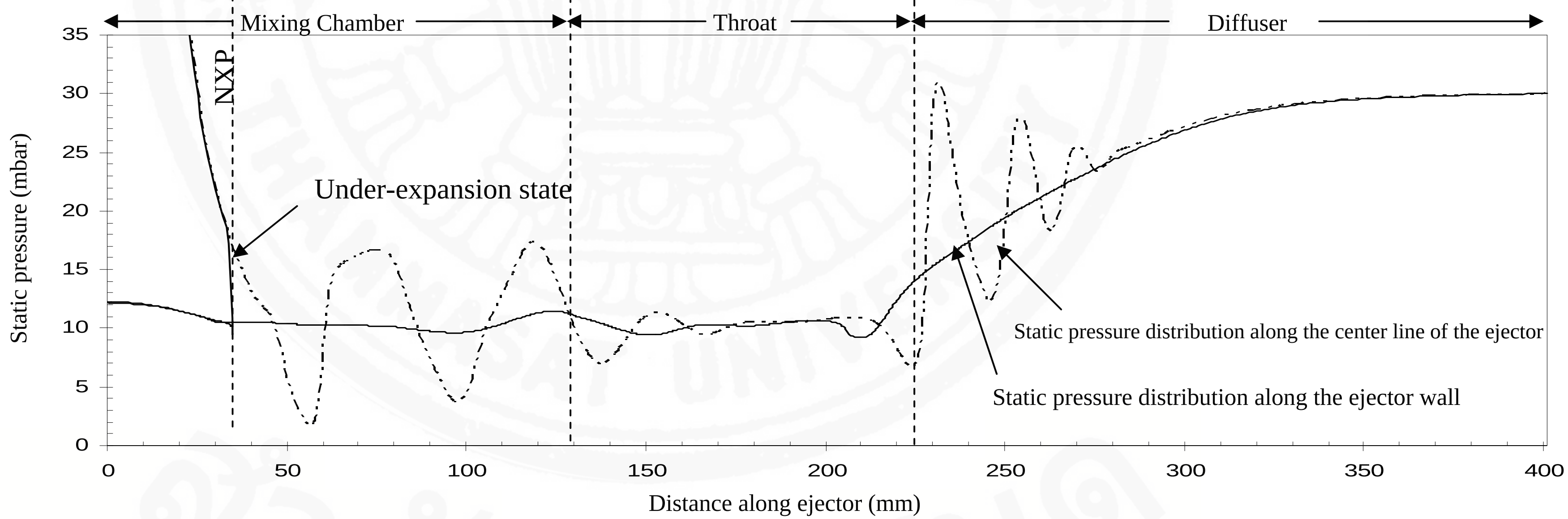
At some conditions, the flows at the exit plane of the primary nozzle of both the ejectors were found to be distinct. For the steam ejector, it normally experienced the state of under-expansion flow, since there were large pressure differences between the primary fluid and secondary fluid inlets. Consequently, the nozzle exit pressure (the pressure upstream of the shock) is usually higher than the back pressure. The flow is also capable of additional expansion after leaving the nozzle. Whereas the R141b ejector usually experienced less difference between the primary fluid and secondary fluid inlets pressures compared to the steam ejector. The state of the flow at the exit of the nozzle, hence, can be found both over-expanded and under-expanded.

Due to the high molecular weight of the HCFC refrigerants, where their momentums are large compared to that of steam, the second series of oblique shock in the recovery process is strong and likely to be a normal shock (Figure 6.1). Whereas in the steam ejector (Figure 6.3), the weak shock called oblique shock is presented. The pressure recovery zones of both ejectors were different. The shock that occurred in the R141b ejector is a combination of a bifurcated shock and a series of shocks downstream of the bifurcated shock. As indicated in Figure 6.1, there was only a small number of the repeated strong shock downstream of the bifurcated shock before all the shock disappeared. Unlike the R141b ejector, the shock found in the steam ejector was usually an oblique shock that formed a bifurcated shock with significant amount of repeated shock.

This implies that for the R141b ejector, the diffuser plays a less important role in recovering the ejector's total pressure than that in the steam ejector. The diffuser of the R141b ejector can then be designed into a short length diffuser necessary to cover the pressure recovery zone.



a) Contours lines of Mach number in the steam ejector



b) Static pressure distribution of the steam ejector

Figure 6.3 Mach number and static pressure distribution in the steam ejector based on the work of Sriveerakul et al. [39 and 40].

This implies that for the R141b ejector, the diffuser plays a less important role in recovering the ejector's total pressure than that in the steam ejector. The diffuser of the R141b ejector can then be designed into a short length diffuser necessary to cover the pressure recovery zone.

The series of oblique shocks, verified in the models, is definitely in contrast to the single normal shock which was proposed by Keenan's theory [24 and 27]. Actually, the effect of oblique shocks in an ejector has been investigated experimentally by few researchers [31, 42, 44 and 47]. Unfortunately, without the flow visualization, the collected data was discussed as a normal shock. Moreover, its pressure sudden rising behavior of a normal shock was thought to weaken by the viscous flow or it was even thought to be swallowed by the oversized diffuser of an ejector.

6.3 Conclusions

In this chapter, the theory describing the flow and mixing process in the R141b ejector using the CFD's visualization was proposed. It is summarized that the nature of flow structure of the R141b ejector used in refrigeration purposes is complicated. The primary nozzle was found to be always operated with chokes. At the nozzle exit, the primary fluid leaves the nozzle as the supersonic *"diamond wave"* jet core, with different flow states either the over-expansion or under-expansion states. The difference in the flow states is caused by the nozzle's exit pressure ratio which is mainly dependent on the upstream conditions of the ejector. According to the large velocity difference, the secondary fluid is entrained, accelerated and mixed with the primary jet core by the shear stress layer interfaces between two streams. Therefore, it is thought that the shear mixing of two streams starts as the secondary fluid is entrained into the mixing chamber.

With help of the CFD, the flow phenomena in the R141b ejector are summarized as follows.

- The CFD visualization shows that the effective area as proposed by Huang [42] does exist; however, it is difficult to locate the exact position of the effective area within the ejector. In the choke flow mode, the entrainment ratios remained constant, the effective area, hence, can be estimated at anywhere within the constant area ejector's throat.
- Two series of oblique shocks were found in the simulation. The first series was found immediately after the primary fluid stream leaves the primary nozzle and begins to mix with the secondary fluid stream. The second series of oblique shock was found at the beginning of the diffuser section as a result of a non-uniform mixed stream. A major compression effect is caused by this second series of oblique shock. This latter shock is definitely contrary to a single normal shock which was proposed by Keenan's theory [24 and 27]. This is probably because this study utilized relatively lower pressure of the primary fluid (vapour-generator saturated temperature of 120-140^{o}C), while others used larger industrial vapour-generator to produce the higher pressure primary fluid (vapour-generator saturated temperature of 160-220^{o}C).

The differences in the flow structures between the R141b ejector and the steam ejector were investigated and reported according to the differences found in:

- the flow states after the primary fluid leaves the primary nozzle
- the shock phenomena occurs before the pressure recovery region
- the pressure recovery process

In the next chapter, there will be the study of the interested parameters, which are thought to affect the performance of the ejector. The performance characteristics and the contours of Mach number of the experiment ejectors will be evaluated. The proposed flow and mixing theory in this chapter will be applied to explain the flow structures of the ejector which cause the changes of its performance characteristic.