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# EXPERIMENTAL RESEARCH ON THE AERODYNAMIC PERFORMANCES OF 2-D LOBED EXHAUST EJECTOR SYSTEMS

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## ABSTRACT

Experimental research for seven exhaust ejector system combinations, including four two-dimensional ( 2-D ) lobed nozzles and three 2-D mixing tubes, has been conducted to investigate the effect of the lobe structure on the aerodynamic performances of the ejector systems. Test results show that: 2-D aligned lobed nozzles have better pumping and mixing enhancement abilities than the 2-D staggered lobed nozzles, but they also cause bigger pressure losses; the 2-D lobed nozzle with equal lobe width have better aerodynamic performances than the 2-D lobed nozzle with bigger inner lobe width. 2-D aligned scalloped lobed nozzle has the best pumping and mixing enhancement performances, but it also has the biggest pressure loss coefficient. Among the tested combinations, the combination of 2-D staggered lobed nozzle with equal lobe width and 2-D mixing tube with multiple-ring cooling structure has the best combined aerodynamic performances.

## NOMENCLATURE

| | |
|---|---|
| A | Cross sectional area |
| D | Diameter of the mixing tube |
| L | The required pressure recovery length along the mixing tube. |
| M | Mass flow rate |
| T | Temperature |
| V | Velocity |
| ρ | Density |
| $\Delta P_{PT}^{*}=\dfrac{P_{PT}-P_{a}}{\frac{1}{2}\rho_{P}V_{P}^{2}}$ | Pressure loss coefficient |
| $T^{*}=\dfrac{T_{S}}{T_{P}}$ | Temperature ratio of secondary to primary flow. |
| $\Phi=\dfrac{M_{S}}{M_{P}}$ | Pumping coefficient |
| $\Psi=\dfrac{\Delta P_{PT}^{*}}{(1+\Phi T^{*})(1+\Phi)}$ | Nondimensional combined aerodynamic parameter |

## SUBSCRIPTS

| | |
|---|---|
| a | Ambient |
| P | Primary flow |
| S | Secondary flow |
| T | Total |
| 1 | Inlet of the mixing tube |
| 2 | Exit of the mixing tube |

## INTRODUCTION

An ejector is a device which converts a high velocity fluid flow of given mass flow rate into a fluid flow of lower velocity. This conversion is achieved by the transfer of energy through viscous interaction of the high velocity ( primary ) fluid flow with a lower velocity ( secondary ) fluid flow within a mixing tube (Fig.1). During the past twenty years this fluid dynamic device has been further utilized to improve aircraft performance in a variety of ways, including engine component cooling, thrust augmentation, and exhaust noise and infrared radiation reduction.

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The conventional mixing of the primary and secondary flow in a mixing tube occurs very slowly, which is performed mainly by the small scale viscous mixing in a shear layer. Thus, a conventional ejector requires long mixing tube to entrain the secondary flow, and the long mixing tube result in large wall friction loss, extra weight and higher cost. For this reason, a lobed nozzle is used as a primary nozzle for the ejector system (Fig. 2). It can cause large scale streamwise vortices to be shed at the trailing edge of lobes so that the downstream of flow field is embedded with an array of streamwise vortices of altemating sign, and a rapid exchange of energy is achieved by means of intense mixing and a nearly uniform flow results within a short downstream with very little loss (reference 1).

Due to the above advantage, The lobed primary nozzle of the ejector/mixer system has been paid great attention by many researchers in the recent years (reference 1-10) and have also been widely applied to the aeroengine area (reference 11).

The circular lobed ejector/mixer systems have been greatly studied in the past several years. However, much work still need to be done for the 2-D lobed ejector/mixer systems to understand the effect of various lobe structures, such as the lobe configuration, the lobe width and the way of lobe placement, on the performance of the systems. The object of the present paper is to present the results of the experimental comparison study for seven 2-D lobed ejector systems to investigate the effects of the lobe configuration, lobe width and way of lobe placement on the aerodynamic performances of the systems.

## EXPERIMENTAL SET-UP

The tests were conducted on the low speed exhaust ejector system test rig in the Jet Propulsion Department of Beijing University of Aeronautics and Astronautics (BUAA). The primary flow was supplied by a compressor with a combustor, and its flow rate and temperature can be adjusted. Figure 3 is the schematic of the test section. The flowrate of the primary flow was measured by a flow nozzle installed before the test section. The total temperature and total pressure of the primary flow were obtained by the thermocouple and total pressure located at the inlet of the 2-D lobed nozzle, respectively. The temperature and pressure fields at the exit of the mixing tube were measured by a 12 point temperature / pressure rake with a traverse mechanism. The flowrate of the secondary flow can be obtained by the flow nozzle installed at the top of the settling chamber ( Fig. 3 ) or/and by the above measurements of pressure and temperature fields at the exit of the mixing tube. The static pressure along the mixing tube was obtained by two rows of six static pressure tabs along the mixing tube. Dne row is at the top of mixing tube and another row is at the side of mixing tube (see Fig. 4(b)).The signals of thermocouples and pressure transducers were transferred to a IBM PC computer for data acquirement and procession. During the test, the flowrate of the primary flow is 1.0 Kg/s, and the exit velocity of the primary flow is around 70m/s. The detail information of the experimental set-up can be obtained from the reference 12.

The four tested 2-D lobed nozzles (Fig. 4(a)) were designed to have same exit area (6400mm$^2$), and also, the same cross section area for three mixing tubes (Fig. 4(b)) (19200 mm$^2$). Therefore, the area ratios between lobed nozzles and mixing tubes of the tested ejector combinations were the same (1:3). The mixing tube 1 and 2 are simple 2-D configuration, which have the same aspect ratio ( AR ) as the 2-D lobed nozzle a ( AR=1.0 ) and b ( AR=1.2), the 2-D mixing tube 3 (AR=1.2) is a multiple-ring cooling structure and has a 20 degree diffuser at the end of the tube.

## TEST RESULTS AND DISCUSSION

During the experiment, cold tests were conducted firstly to determine the aerodynamic performances of seven 2-D lobed exhaust ejector system combinations listed in the table 1, then, three representative 2-D lobed exhaust ejector systems were selected from the seven for further experiment at hot test condition. The primary flow temperature at the inlet of the lobed nozzle was 573±5K during the hot test. The studied aerodynamic performances include pumping coefficient, pressure loss coefficient, combined aerodynamic parameter, static pressure recovery characteristics along the mixing tube and the velocity and temperature distributions at the exit of the mixing tube.

### 1. Pumping coefficient $\Phi$

The pumping coefficient $\Phi$ was defined as the ratio of secondary flowrate to the primary flowrate. The pumping coefficient of the conventional circular ejector is 0.45 ( reference 13). The experimental results listed in table 1 show that: The pumping coefficients of the tested 2-D lobed ejector systems (0.84-1.34) are much higher than that of the conventional ejector, that is, the pumping abilities of the 2-D lobed ejector systems are about 1 to 2 times higher than that of the conventional ejector.

Among the tested combinations, the pumping coefficient of combination b+3 is higher than that of the combination b+1 and b+2. This can be explained by that there is a diffuser at the end of the 2-D mixing tube 3 which improves the pumping ability of the ejector and the 2-D mixing tube 3 has a multiple-ring cooling structure making the combination b+3 as a multiple stage ejector system which also cause a bigger pumping coefficient. From the comparison of combination b+3, c+3 and d+3, we can see that, the pumping abilities of the aligned lobed nozzles are bigger than that of the staggered lobed nozzles, the reason may be that the scale of the streamwise vortices induced by aligned lobed nozzle is higher than that of the staggered lobed nozzle (Fig. 5, reference 3). Scalloping the 2-D aligned lobed nozzle forms the 2-D aligned scalloped lobed nozzle d, and additional vortices can be generated at the parallel sides of lobes for the nozzle d (Fig. 6, reference 9). This results in a larger vortices roll-up and enhances the "stir up effect" (reference 3) of the large scale streamwise vortices. Thus the combination d+3 has the highest pumping coefficient among the tested combinations.

### 2. Pressure loss coefficient $\Delta P_{PT}^{*}$.

The pressure loss coefficient $\Delta P_{PT}^{*}$, which was defined as the ratio of the pressure difference between the total pressure at the inlet of the primary nozzle and ambient pressure to the dynamic pressure of primary flow, can indicate the power loss of an engine caused by the installation of an ejector system. The bigger the pressure loss coefficient is, the higher the engine power loss will be. The experimental results show that: the 2-D aligned lobed nozzles c and d have the bigger pressure loss coefficient than the 2-D staggered lobed nozzles with same mixing tube. The explanation of this is that the 2-D aligned lobed nozzles can induce larger scale streamwise vortices as mentioned above, which cause bigger mixing loss. The combination with 2-D aligned scalloped lobed nozzle d, which generates the additional vortices at the parallel sides of lobes and has the highest pumping coefficient among the tested combinations has the biggest pressure loss coefficient.

### 3. Combined aerodynamic parameter $\Psi$

An ejector system was always expected to have a higher pumping coefficient and a smaller pressure loss coefficient. However, from the above analysis we can see that a ejector with higher pumping coefficient always has a bigger pressure loss. A combined aerodynamic parameter $\Psi$ (reference 14) is introduced in the paper to evaluate the overall aerodynamic performance of an ejector system.

$$\Psi = \frac{\Delta P_{PT}^{*}}{(1+\Phi T^{*})(1+\Phi)}$$

From the definition of the parameter $\Psi$, we can see that, the smaller the parameter $\Psi$ is, the better the ejector system will be. It can be seen from the table 1 that: the combination with 2-D aligned lobed nozzle has bigger combined aerodynamic parameter $\Psi$ than the combination with 2-D staggered lobed nozzle, the combination with 2-D staggered lobed nozzle of bigger inner lobe width a has the bigger aerodynamic combination parameter $\Psi$ value than the combination with the 2-D staggered lobed nozzle of equal width b. The combined aerodynamic performance of the combinations with the same aspect ratio (AR) of 2-D nozzle and mixing tube, i. e. a+1 and b+2, are better than that of the hybrid combinations (a+2 and b+1). Among the tested combinations, the combination of the staggered lobed nozzle b with mixing tube 3 has the best combined aerodynamic performance and the 2-D aligned scalloped lobed nozzle d with mixing tube 3, which has the highest pumping coefficient and the biggest pressure loss coefficient, has the worst combined aerodynamic performance.

### 4. Characteristics of static pressure recovery

The characteristics of static pressure recovery is the static pressure distribution along the mixing tube of an ejector system. As we know, the faster the static pressure recovery is, the shorter the mixing tube can be. This will be benefit to the size and weight of ejector systems. Two typical measured static pressure recovery characteristics are shown in Fig. 7. Based on the figure, we can obtain the required pressure recovery distance (L/D) which mixing flow can reach near uniform condition for each ejector system, and the data are shown in table 1. The test results indicate that: the required pressure recovery distance L/D of the tested combinations are about 0.7-1.8, which is very shorter than that required by a conventional ejector system (which is probably greater than 10, reference 9 ).

### 5. Exit velocity and temperature distributions

The velocity and temperature distributions at the exit of a mixing tube directly indicate the mixing efficiency of the primary gas and pumped ambient air in the mixing tube. Three typical measured velocity and temperature distributions at the exit of the mixing tubes for b+3, c+3 and d+3 combinations are given in Fig. 8 and Fig. 9. It can be seen from the figure that: the region of the high speed and high temperature flow has been bifurcated and moved away from the center at the exit of mixing tube due to the "stir up effect" of the streamwise vortices induced by the lobes. Because the 2-D aligned lobed nozzles can generate bigger scale streamwise vortices and has higher pumping ability than the 2-D staggered lobed nozzles, the areas of the high speed and high temperature at the exit of the mixing tube of the combination c+3 is less than that of the combination b+3. Further more, because the 2-D aligned scalloped lobed nozzle d can cause additional vortices at the parallel sides of lobes and enhance the roll-up and "stir up effect" of the streamwise vortices, a bulk of low speed and cold flow was engulfed to the center of the mixing flow.

Comparison of the average and highest temperature values at the exit of the mixing tube for the combinations of b+3, c+3 and d+3 listed in the table 1, we can see that: the average and highest temperatures of the combinations c+3 and d+3 are less than that of the combination b+3 respectively. This indicates, once more, that the 2-D aligned lobed nozzle has higher pumping ability and better mixing enhancement ability than the 2-D staggered lobed nozzle, and the 2-D aligned scalloped lobed nozzle d can generate additional vortices and enhance the "stir up effect" of the streamwise vortices. Thus, the combination d+3 has the least average and highest temperature at the exit of the mixing tube among the tested combinations.

## CONCLUSION

From the above analysis and discussion, we can see that: compared with the conventional circular ejector, the ejectors with 2-D lobed nozzle can improve pumping ability 200%-300%, and reduce the required mixing length (L/D) to 1/4-1/8. The various lobe structures, such as the lobe configuration, lobe width and way of lobe placement, can influence the aerodynamic performances of 2-D lobed ejector systems.

Through the experimental research, the following conclusion can be obtained:

1. The comparison of the staggered lobed nozzles with aligned lobed nozzles show that, the 2-D aligned lobed nozzles have higher pumping coefficients and mixing enhancement abilities, but also cause bigger pressure losses. Thus, they are very fit for the area where the higher pumping coefficient and mixing enhancement are mainly required and the pressure loss don't need severe consideration.

2. The 2-D staggered lobed nozzle with equal lobe width has better aerodynamic performance than the 2-D staggered lobed nozzle with bigger inner lobe width.

3. The combination of the 2-D staggered lobed nozzle with equal lobe width and 2-D mixing tube with multiple-ring cooling structure has the smallest combined aerodynamic parameter $\Psi$, i. e. has the best combined aerodynamic performance among the tested combinations.

4. The combination with 2-D aligned scalloped lobed nozzle, which has the highest pumping coefficient and mixing enhancement ability, and also cause the biggest pressure loss, has the worst combined aerodynamic performance among the tested combinations.

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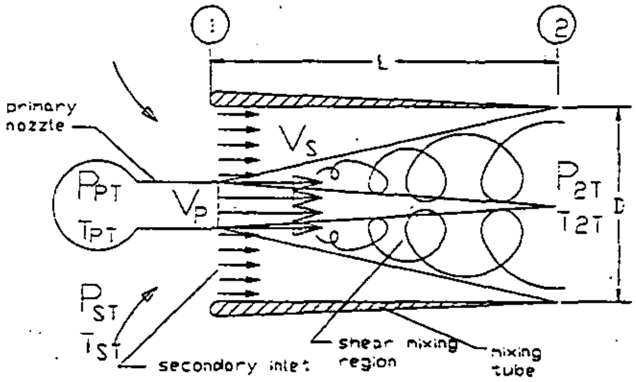


Figure 1. Schematic of a conventional ejector

Table 1. Aerodynamic performance table of seven tested 2-D lobed ejector system combinations.

| combinations | Cold Test | | | | | Hot Test ( $T_P = 573k$ ) | |
|---|---|---|---|---|---|---|---|
| | pumping coefficient $\Phi$ | pressure loss coefficient $\Delta P_{PT}$ | combined aerodynamic parameter $\psi$ | static pressure recovery distance L/D( at side) | static pressure recovery distance L/D( at top ) | average temperature at the exit of the mixing tube (k) | highest temperature at the exit of the mixing tube (k) |
| a+1 | 0.87 | 1.251 | 0.358 | 1.3 | - | - | - |
| a+2 | 0.84 | 1.231 | 0.364 | 1.8 | 0.7 | - | - |
| b+1 | 0.87 | 1.245 | 0.356 | 1.8 | 0.7 | - | - |
| b+2 | 0.87 | 1.226 | 0.351 | 1.8 | 0.7 | - | - |
| b+3 | 0.98 | 1.245 | 0.318 | 1.8 | 0.7 | 429.3 | 492.3 |
| c+3 | 1.02 | 1.342 | 0.329 | 1.8 | 1.3 | 425.2 | 488.3 |
| d+3 | 1.34 | 2.298 | 0.420 | 1.8 | 0.7 | 401.3 | 431.7 |

Note: During the test, the used thermocouples have the range of 300-1073k, accuracy for the full range is 0.1%, and the used pressure transducers have the range of 0-0.2MPa, accuracy for the full range is 0.02%

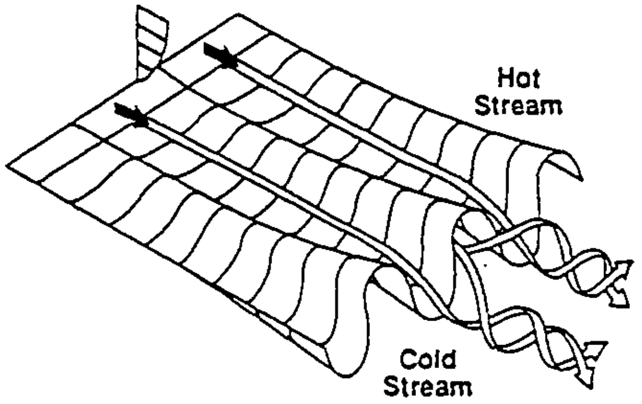


Figure 2. The concept of lobed mixing enhancement structure

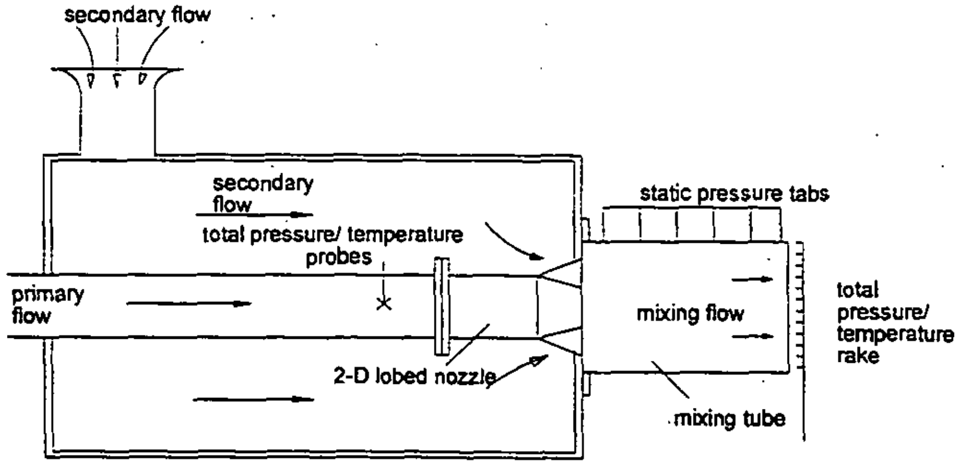
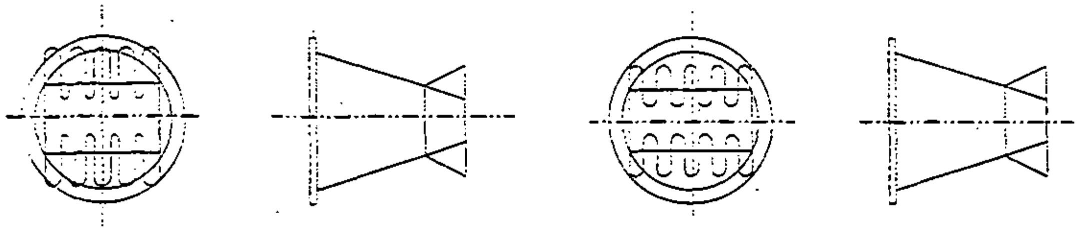
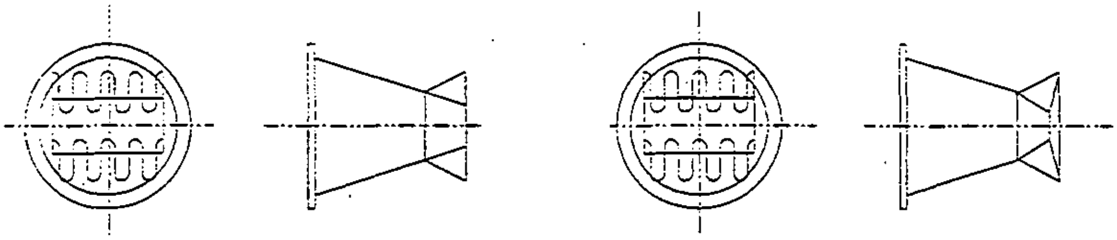


Figure 3. Schematic of the test section



a. 2-D staggered lobed nozzle with bigger inner lobe width

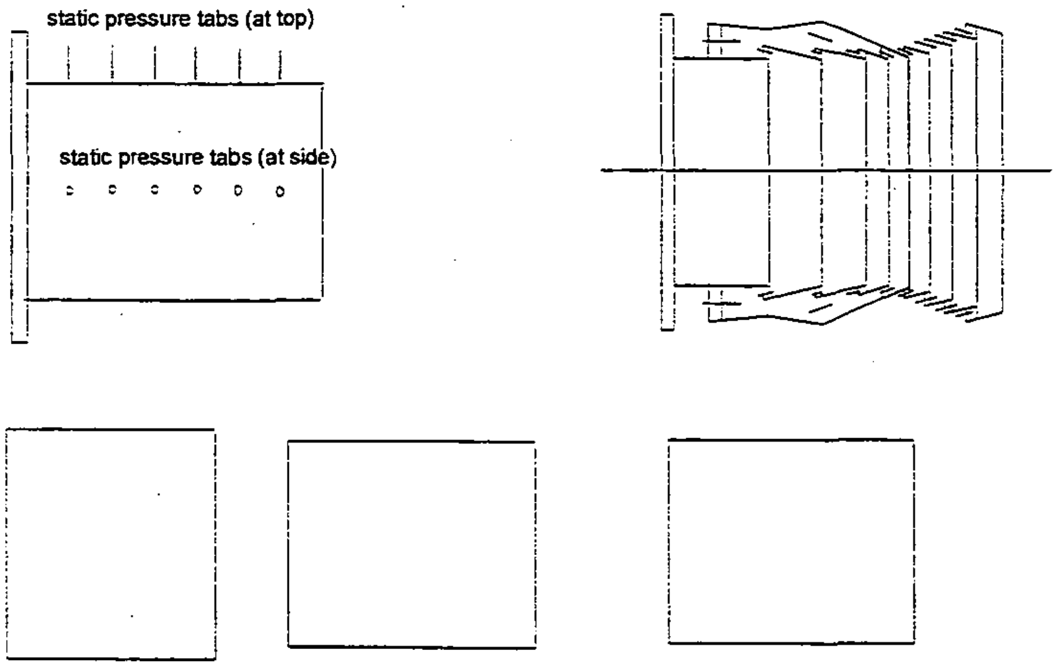
b. 2-D staggered lobed nozzle with equal lobe width



c. 2-D aligned lobed nozzle with equal lobe width

d. 2-D aligned scalloped lobed nozzle with equal lobe width

Figure 4(a). Tested 2-D lobed nozzles



2-D simple mixing tube 1 ( AR=1.0)

2-D simple mixing tube 2 (AR=1.2)

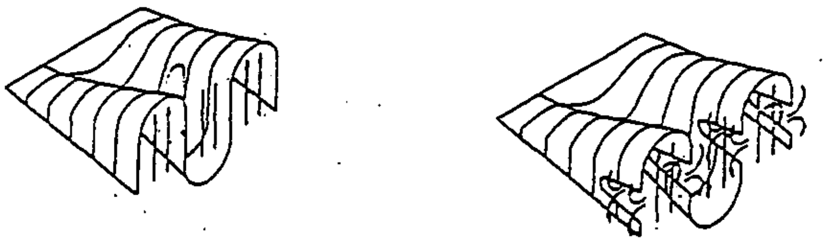
2-D mixing tube 3 with multiple-ring cooling structure (AR=1.2)

Figure 4(b). Tested 2-D mixing tubes

A. staggered lobed nozzle

B. aligned lobed nozzle

Figure 5. the schematic of the streamwise vortices induced by 2-D lobed nozzles



A. conventional lobe

B. scalloped lobe

Figure 6. Scalloping effects of lobes

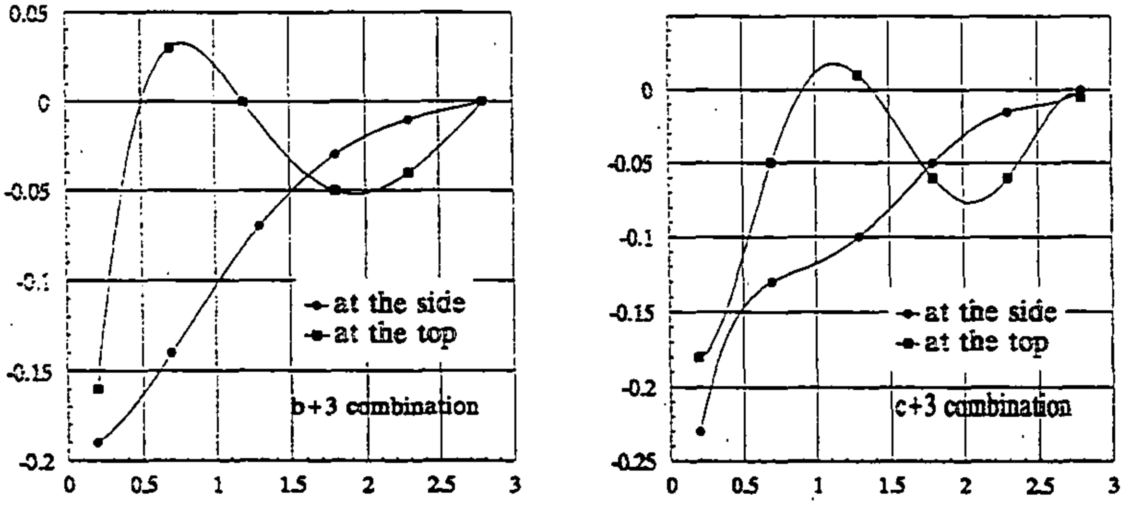
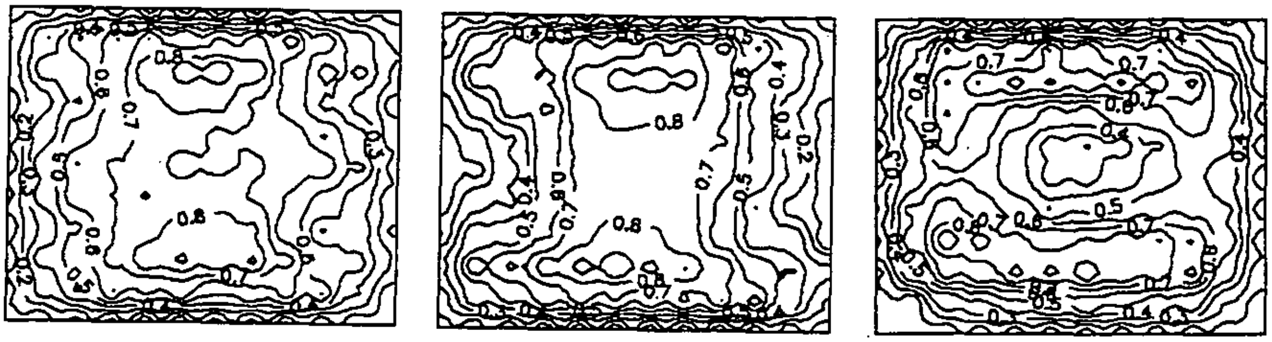
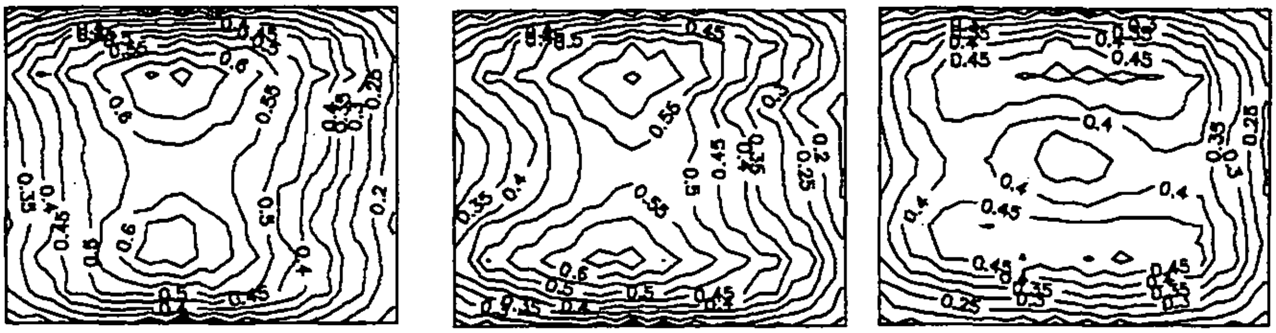


Figure 7. Static pressure recovery characteristics of tested ejector systems



b+3 combination c+3 combination d+3 combination

Figure 8. Velocity distributions ($V_z/V_p$) at the exit of mixing tubes for b+3, c+3 and d+3 combinations (cold test)



b+3 combination c+3 combination d+3 combination

Figure 9. Temperature distributions ($T_{zT}/T_{PT}$) at the exit of mixing tubes for b+3, c+3 and d+3 combinations (hot test)