Research on the Rectangular Lobed Exhaust Ejector/Mixer Systems*1 

By Hui Hu,*2 Toshio Kobayashi,*2 Tetsuo Saga,*2 Nobuyuki Taniguchi,*2 Huoxing Liu*3 and Shousheng Wu*3

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Abstract

Experimental research of seven rectangular exhaust ejector/mixer systems, which were the combinations of four rectangular lobed nozzles with three rectangular mixing tubes, has been conducted to investigate the effect of the geometry of rectangular lobed nozzles on the aerodynamic performances of exhaust ejector/mixer systems. The experimental results showed that: rectangular aligned lobed nozzles have better pumping and mixing enhancement abilities than rectangular staggered lobed nozzles, while they also cause bigger pressure losses. Scallop treatment on the lobe structure can improve the pumping ability and mixing enhancement performance of a lobed nozzle, but it will also cause a big extra pressure loss. Among the seven tested exhaust ejector/mixer systems, the exhaust ejector/mixer system which is a combination of the staggered lobed nozzle B and the rectangular mixing tube III has the best aerodynamic performances.

Nomenclature

\[ A \text{ cross sectional area} \]
\[ D \text{ diameter of the mixing tube} \]
\[ L \text{ the required pressure recovery length along the mixing tube} \]
\[ M \text{ mass flow rate} \]
\[ P \text{ pressure} \]
\[ T \text{ temperature} \]
\[ \rho \text{ density} \]
\[ \Delta P_{PT}^* \text{ pressure loss coefficient} \]
\[ T^* \text{ temperature ratio of secondary flow to primary flow} \]
\[ \Phi \text{ pumping coefficient} \]
\[ \Psi \text{ nondimensional combined aerodynamic parameter} \]

Subscripts

a: ambient
P: primary flow
S: secondary flow
T: total

Introduction

An exhaust 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 momentum and 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 decades, 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.

The conventional mixing of the primary and secondary flow in a mixing tube occurs very slowly, which is performed mainly by a small scale viscous mixing in a shear layer. Thus, a conventional ejector requires a long mixing tube to entrain the secondary flow, and a long mixing tube results in large wall friction loss, extra weight and higher cost. For this reason, a lobed exhaust ejector/mixer system (Fig. 2), in which a lobed nozzle was used as a primary nozzle, was proposed in the past several years. It was found that a lobed nozzle can cause large scale streamwise vortices to be shed at the trailing edge of lobe structures, so the downstream of the flow field is embedded with arrays of large scale streamwise vortices, and a rapid exchange of momentum and energy.

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*1 Received May 12th, 1998.
*2 Institute of Industrial Science, The University of Tokyo, Tokyo, Japan.
*3 Jet Propulsion Laboratory, Department of Jet Propulsion, Beijing University of Aeronautics and Astronautics, Beijing, 100083, P. R. China
research, seven rectangular lobed ejector/mixer systems, which were the combinations of four rectangular lobed nozzles with three rectangular mixing tubes, were studied experimentally to investigate the effect of the geometry of rectangular lobed nozzles on the aerodynamic performances of rectangular lobed exhaust ejector/mixer systems.

2. Experimental Set-Up

An experimental research was conducted on the low speed exhaust ejector system test rig (corresponding to the case of helicopter used aero-engine) in the Jet Propulsion Laboratory of Beijing University of Aeronautics and Astronautics (BUAA). The primary flow is supplied by a compressor with a combustor, and its flow rate and temperature can be adjusted. Figure 3 is a schematic of the test section. The flowrate of the primary flow is measured before the test section. The total temperature and total pressure of the primary flow are obtained by the thermocouples and total pressure sensor located at the inlet of the tested exhaust ejector/mixer system. The temperature and pressure fields at the exit of the mixing tube are 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 measured pressure and temperature fields at the exit of the mixing tube. The static pressure distributions along the mixing tube are obtained by two rows of six static pressure tabs along the mixing tube. One row is at the top of mixing tube and the other row is at the side of mixing tube (see Fig. 5). The signals of thermocouples and pressure sensors are transferred to an IBM PC computer for data acquirement and procession. During the test, the flowrate of the primary flow is about 1.0kg/s, and the exit velocity of the primary flow is around 70 m/s. The detail information of the experimental set-up can be obtained from the Ref. 13.

It had been found that the geometrical parameters of the lobed structures, such as the lobe height, the lobe penetration angle, the form of the lobed structure, the area ratio of the primary nozzle, mixing tube etc, can affect the aerodynamic performance of a lobed ejector/mixer system very much. The detail information can be found in the papers of Skebe et al.,1) Presz et al.,3) Eckerle et al.,5) and Wu.11) Based on these previous researches, all the rectangular lobed nozzles used in present study are designed to have the same lobe penetrate angle, lobe height and lobe form. Only the effects of the lobed width, the way of lobe structure arrangement and the scalloping treatment of the lobed structures on the aerodynamic performance of a lobed ejector/mixer system are discussed in the current paper.

The four rectangular lobed nozzles used in the pres-
ent research are shown in Fig. 4. Nozzle A and nozzle B are the rectangular lobed nozzles with a staggered arrangement of the two rows of the lobe structure. The difference between the nozzle A and the nozzle B is that, for the lobed nozzle A, the inner lobe width is two times the outer lobe width, while the lobed nozzle B has the equal value of inner lobe width and outer lobe width. Nozzle C and nozzle D are rectangular lobed nozzles with an aligned arrangement of the two rows of the lobe structure. The rectangular lobed nozzle D is designed the same as the rectangular lobed nozzle C but with a scalloping treatment (Yu et al.14) of the lobe structure. All these four rectangular lobed nozzles have the same exit area (6400 mm², equivalent diameter is about 90 mm). Rectangular lobed nozzle A has an aspect ratio ($AR$) of 1.0, while the aspect ratios ($AR$) of lobed nozzle B, lobed C and lobed D are same, which is 1.2.

The three mixing tubes used in the present study are shown in Fig. 5. The mixing tube I and mixing tube II are simple rectangular tubes which have the same aspect ratio ($AR$) as the rectangular lobed nozzle A ($AR = 1.0$) and nozzle B ($AR = 1.2$). The rectangular mixing tube III ($AR = 1.2$) is designed to have a multiple-stage cooling structure and a 20 degree diffuser at the end of the tube. The length of these three mixing tubes is the same, which is 450 mm. All the mixing tubes have the same cross section area (19,200 mm²), therefore, the area ratios between the rectangular lobed nozzles and mixing tubes of the seven tested ejector/mixer systems are the same, which is 1:3.

### 3. Experimental Results and Discussions

During the experiment, cold tests (the temperature of the primary flow is the same as the secondary flow, which was 295 K) were conducted firstly to determine the aerodynamic performances of seven rectangular lobed exhaust ejector/mixer systems listed in Table 1.
three representative rectangular 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 ± 5 K, while the temperature of the secondary flow was 295 K). The studied aerodynamic performances of the exhaust ejector/mixer systems 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.

3.1. Pumping coefficient $\Phi$ The pumping coefficient $\Phi$ was defined as the ratio of secondary flow rate to the primary flow rate. The pumping coefficient of a conventional circular ejector with the same area ratio (1:3) of the primary nozzle and mixing tube is about 0.45 (Hu et al.13). The pumping coefficient of a circular lobed ejector/mixer system with the same area ratio (1:3) and the same lobe configuration as used in current study is about 0.81 (Hu et al.14). However, from the experimental results listed in Table 1, it can be seen that the pumping coefficients of the seven tested rectangular lobed ejector/mixer systems (0.84–1.34) are much higher than that of a conventional circular ejector. That is, the pumping abilities of the rectangular lobed ejector systems are about 1 to 2 times that of the conventional ejector. It can also be seen that a rectangular lobed ejector/mixer system will have a much bigger pumping ability than a circular lobed ejector/mixer system does for the same lobe configuration. This may come from the difference between the rectangular geometry and the circular geometry of the primary nozzle.

Among the tested exhaust ejector/mixer systems, it can also be seen, there is no apparent difference be-
between the ejector/mixer systems using nozzle A and nozzle B as primary nozzles (system 1, system 2, system 3 and system 4) in terms of pumping coefficient. However, considering along with the pressure loss coefficient and combined aerodynamic parameter (to be discussed later), the ejector/mixer systems using nozzle B as primary nozzle seems to be a bit better than the one using nozzle A. Among the exhaust ejector/mixer systems with nozzle B as primary nozzle (system 3, system 4 and system 5), the pumping coefficient of the exhaust ejector/mixer system 5 (combination B+III) is the best. This can be explained by presence of a diffuser at the end of the rectangular mixing tube III, which can improve the pumping ability of the ejector system (Skebe et al.)

Meanwhile, the mixing tube III also has a multiple-stage cooling structure (Fig. 5), which makes the exhaust ejector/mixer system 5 a multiple stage ejector system, this also resulting in a bigger pumping coefficient.

From the comparison of the exhaust ejector/mixer systems 5, 6, and 7 (combinations B+III, C+III and D+III), it can be said that, the pumping abilities of the aligned lobed nozzles (nozzle C and nozzle D) are higher than that of the staggered lobed nozzle (lobed nozzle B). The reason may be that the scale of the streamwise vortices induced by aligned lobed nozzles will be bigger than that of the staggered lobed nozzle B (Fig. 6) and larger streamwise vortices will give a higher pumping ability (Presz et al.). From the comparison of the exhaust ejector/mixer systems 6 and 7 (combinations of C+III and D+III), it can be suggested that scalloping treatment of the lobe structure can improve the pumping ability of the lobed nozzle greatly. The reason may be that additional vortices can be generated at the parallel sides of lobes by the scalloping treatment of the lobe structure (Fig. 7 and Fig. 6 of the Ref. 15, Yu et al.). This will result in a larger vortices roll-up and enhances the “stir up effect” (Presz et al.) of the large-scale streamwise vortices, hence the lobed nozzle D has the highest pumping ability.

3.2. Pressure loss coefficient $\Delta P_{pr}$

The pressure loss coefficient $\Delta P_{pr}$, which is defined as the ratio of the pressure difference between the total pressure at the inlet of the primary nozzle and the ambient pressure to the dynamic pressure of primary flow, can indicate the power loss of an aero-engine caused by the installation of an ejector system. The bigger the pressure loss coefficient is, the higher the engine power loss will be. From the experimental results listed in Table 1, it can be seen that: the exhaust ejector/mixer systems with rectangular aligned lobed nozzles as primary nozzles (exhaust ejector/mixer system 6 and 7) have the bigger pressure loss coefficients than those with rectangular staggering lobed nozzles as primary nozzles (exhaust ejector/mixer system 1 to 5). The explanation of this is that the rectangular aligned lobed nozzles can induce larger scale streamwise vortices as mentioned above (Fig. 6), which will also cause bigger mixing loss. The exhaust ejector/mixer system 7, which uses rectangular aligned scalloped lobed nozzle D as primary nozzle and can generate additional vortices at the parallel sides of lobe structure and has the highest pumping coefficient among the tested exhaust ejector/mixer systems, also has the biggest pressure loss coefficient.

3.3. Combined aerodynamic parameter $\Psi$

An exhaust
ejector was always expected to have higher pumping coefficient and smaller pressure loss coefficient. However, from the above experimental results, it can be said that, the exhaust ejector/mixer system with higher pumping coefficient always has bigger pressure loss. So, a combined aerodynamic parameter \( \Psi \) (Hu et al.\(^{16}\)), which indicates the ratio of the momentum of exhausted flow from an exhaust system with and without an exhaust ejector/mixer system installation, is introduced to evaluate the overall aerodynamic performance of an exhaust ejector system.

From the definition of the parameter \( \Psi \), it can be seen that, a bigger pumping coefficient and a less pressure loss coefficient will cause a smaller combined aerodynamic parameter \( \Psi \). So, the smaller the parameter \( \Psi \) is, the better aerodynamic performance will be given by the ejector system. From the combined aerodynamic parameter \( \Psi \) values listed in Table 1, It can be seen that, the exhaust ejector/mixer systems 6 and 7, which uses rectangular aligned lobed nozzles (nozzle C and nozzle D) as primary nozzles, have bigger combined aerodynamic parameter values than the one with rectangular staggered lobed nozzles as primary nozzles (the exhaust ejector/mixer systems 1 to 5).

Among the exhaust ejector/mixer systems with rectangular staggered lobed nozzles as primary nozzles (the exhaust ejector/mixer systems 1 to 5), the one with nozzle A (which has bigger inner lobe width) as primary nozzle has a bigger combined aerodynamic parameter \( \Psi \) than the one with the rectangular lobed nozzle B as primary nozzle. Meanwhile, the exhaust ejector systems with the same aspect ratio (AR) of rectangular lobed nozzle and mixing tube, i.e. system 1 (combination A+I) and system 3 (combination B+II), are better than the hybrid systems (system 2 (combination A+II) and system 4 (combination B+I)). Among the seven tested exhaust ejector/mixer systems, the system 5 (combination B+III), has the smallest combined aerodynamic parameter value, so it has the best combined aerodynamic performance, while, the system 7 (combination D+III), which has the highest pumping coefficient and the biggest pressure loss coefficient, has the worst combined aerodynamic performance.

### 3.4. Characteristics of static pressure recovery performance

The static pressure recovery performance is characterized by the static pressure distribution along the mixing tube of an ejector system. It is well known that, the faster the static pressure recovery is, the shorter the mixing tube can be. This will be beneficial to the size and weight of ejector systems. Two typical measured static pressure recovery characteristics are shown in Fig. 7. Based on the figures, the required pressure recovery distance \((L/D)\) at which mixing flow reaches near uniform condition for each ejector/mixer system can be obtained, and the results are listed in Table 1. From the data listed in Table 1, it can be seen that: the required pressure recovery distance \(L/D\) of the tested combinations is about 0.7–1.8, which is much shorter than that required by a conventional ejector (which is about 4–6 (Presz et al.\(^{9}\)). This means that, unlike the conventional ejector, the required mixing tube length can be reduced to 1/2 or 1/3 with a lobed nozzle as the primary nozzle of the exhaust ejector/mixer system. Waitz et al.\(^{17}\) also got a similar result.

### 3.5. Exit velocity and temperature distributions

The velocity and temperature distributions at the exit of a mixing tube can 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 the exhaust ejector systems 5, 6 and 7 (combinations B+III, C+III and D+III) are given in Figs. 9 and 10. From the figures, it can be seen that the region of the high speed and high temperature flow is bifurcated and deviates from the center at the exit of mixing tube due
to the “stir up effect” of the streamwise vortices induced by the lobed nozzles. Since the rectangular aligned lobed nozzles (lobed nozzle C and lobed nozzle D) can generate bigger scale streamwise vortices and has higher pumping ability than the rectangular staggered lobed nozzles (lobed nozzle A and lobed nozzle B), the size of the high speed and high temperature at the exit of the mixing tube of the exhaust ejector/mixer system 6 (combination C + III, Fig. 9(b) and Fig. 10(b)) is less than that of the exhaust ejector/mixer system 5 (combination B + III, Fig. 9(a) and Fig. 10(a)). Furthermore, since the rectangular aligned scalloped lobed nozzle D can generate additional vortices at the parallel sides of lobe structure and enhance the roll-up and “stir up effect” of the streamwise vortices, the bulk of low speed and cold flow is engulfed into the center of the mixing flow (Fig. 9(c) and Fig. 10(c)).

From the comparison of the average and highest temperature values at the exit of the mixing tube for the exhaust ejector/mixer systems 5, 6 and 7 (combinations B + III, C + III and D + III) listed in Table 1, it also can be seen that: the average and highest temperature values of the systems with aligned lobed nozzles (combinations C + III and D + III) as primary nozzle are smaller than that of the combination B + III. This indicates that the rectangular aligned lobed nozzle has one step higher pumping ability and better mixing enhancement ability than the rectangular staggered lobed nozzle. The rectangular aligned scalloped lobed nozzle D can generate additional vortices and enhance the “stir up effect” of the streamwise vortices. Thus, the exhaust ejector/mixer system (combination D + III) has the smallest average and highest temperatures at the exit of the mixing tube.

4. Conclusion

From the above analysis and discussions, it can be said that: compared with a conventional circular ejector, the exhaust ejector/mixer systems with rectangular lobed nozzle as primary nozzle can improve pumping ability 200%-300%, and reduce the required mixing tube length \((L/D)\) to 1/2-1/3. The geometry of the lobed nozzles, such as the lobe configuration and the way of lobe arrangement can influence the aerodynamic performances of rectangular lobed exhaust ejector/mixer systems.

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

(1) The way of the arrangement of the lobe structures can affect the pumping ability and mixing enhancement performance of the rectangular lobed nozzles very much. Compared with the rectangular staggered lobed nozzles, rectangular aligned lobed nozzles have higher pumping coefficients and mixing enhancement abilities, but they have 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 does not call for severe consideration.

(2) The scalloping treatment of the lobe structures can improve the pumping ability greatly and mixing enhancement of the lobed nozzle, but it will suffer a big
extra pressure loss.

(3) Among the seven tested systems, the exhaust ejector/mixer system 5 (combination B+III) has the smallest combined aerodynamic parameter value, i.e. has the best combined aerodynamic performance of the tested combinations. The exhaust ejector/mixer system 7 (combination D+III), which has the highest pumping coefficient and mixing enhancement ability, but suffers the biggest pressure loss, has the worst combined aerodynamic performance of the tested combinations.

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References