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Configurations of lobed nozzles for high mixing effectiveness

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ABSTRACT

The circular lobed nozzle used in the infrared suppressors of helicopters and warships has a configuration that facilitates highly effective mixing of the jet. A sword alternating-lobe nozzle and two types of spoilers (installed at the lobe peaks to improve the mixing) were introduced. In this study, numerical investigations of the jet mixings of different nozzle configurations were conducted. The nozzles considered were a baseline lobed nozzle, a baseline lobed nozzle with a central plug, a coplanar alternating-lobe nozzle, a sword alternating-lobe nozzle, and a sword alternating-lobe nozzle with lobe-peak spoilers. The dominant factors that affect the pumping performance, mixing effectiveness, and pressure loss were also analysed. It was found that, in addition to the intensity of the streamwise vortices and the distribution of the primary stream, the distribution of the streamwise vortices is also strongly related to the mixing effectiveness and determined the formation of new and plumper streamwise vortices, which improved the mixing effectiveness. The division into three segments of the side of the streamwise vortices on which the primary and secondary streams contact each other is propounded. The three segments are the windward, sideward, and leeward segments. The windward segment has the fastest mixing, followed by the sideward segment, while the leeward segment has the slowest mixing. The plumper streamwise vortices enhance mixing because their windward segment is longer.

1. Introduction

The lobed nozzle, which mixes the primary and secondary streams with high effectiveness but induces low pressure loss [1], has been widely used for heat and mass transfer in the fluid engineering field. The infrared suppressor used in the exhaust system of helicopters and warships [2–5] generally has a lobed nozzle to pump cool air from the outside and mix it with the hot exhaust gas from the engine. The primary parameters used to evaluate the performances of the lobed nozzle include pumping performance, mixing effectiveness, and pressure loss [6]. Higher pumping performance, higher mixing effectiveness, and lower pressure loss indicate that more cool air is pumped, the mixing with the hot exhaust is more effective, and there is less energy loss.

When a circular lobed nozzle is used, the secondary stream pumped by the normal lobed nozzle cannot penetrate the core of the primary stream [6,7]. This results in a large high-temperature core region. There are currently two efficient methods to fix this problem: adding a central plug at the exit of the normal lobed nozzle [3,6,7] or replacing the normal lobed nozzle with an alternating-lobe nozzle [8–11]. Investigations have revealed that the normal lobed nozzle with a central plug enhances pumping performance and mixing effectiveness, but also induces large pressure loss [6]. However, the mixing effectiveness of the existing alternating-lobe nozzle [8–11] is lower than that of a normal lobed nozzle with a central plug. In this paper, we propose a configuration to improve mixing effectiveness. This configuration is composed of a sword alternating-lobe nozzle and two types of spoilers installed at the lobe peaks. The mechanisms of the jet mixing of a lobed nozzle are analysed.

2. Geometrical configurations

Fig. 1 shows the jet mixing model, wherein the lobed nozzle is a normal lobed nozzle with a central plug (PLN). In this paper, the normal lobed nozzle without a central plug is referred to as a baseline lobed nozzle (BLN). The annular entrance of the nozzle is formed by two circles of diameters 210 and 400 mm. Through a cone of length 262.5 mm, the annular section is smoothly transformed into a circular one. The lobes are 44 mm wide, and the

Abbreviations: PLN, normal lobed nozzle with a central plug; BLN, baseline lobed nozzle; CALN, coplanar alternating-lobe nozzle; SwALN, sword alternating-lobe nozzle; LSwALN, SwALN with lobed peaks; NSwALN, SwALN with nail-like peaks; NLN, normal lobed nozzle.

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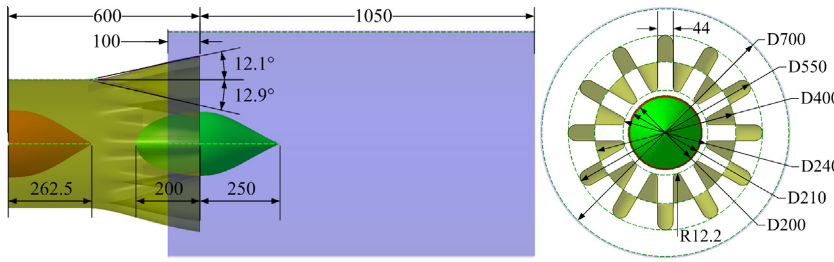

Fig. 1. Geometrical dimensions of the plugged-lobe mixer.

inward and outward lobe penetration angles are 12.9° and 12.1°, respectively. The diameters of the circles at the lobe peaks and troughs are 550 and 240 mm, respectively. The distance from the exit to the entrance is 600 mm, and the exit of BLN has an equivalent diameter d of 400 mm. The diameter of the largest section of the central plug is 200 mm, and it is located at the exit of PLN. The lengths of the central plug from the largest section forwards and backwards are 200 and 250 mm, respectively. The mixing duct is 1150 mm long, and its entrance is 100 mm ahead of the exit of the nozzle. The diameter D of the duct is 700 mm, which gives a length-to-diameter ratio (L/D) of the mixing segment of 1.5.

Fig. 2(a)–(d) shows, respectively, a coplanar alternating-lobe nozzle (CALN) [10], a sword alternating-lobe nozzle (SwALN), a SwALN with lobed peaks (LSwALN), and a SwALN with nail-like peaks (NSwALN). SwALN is produced by removing part of the lobe troughs and side walls of the normal lobed nozzle (NLN) shown in Fig. 2(e), which has a scarfing angle of 40° and a sword spoiler that smoothly extends from each new wide trough. LSwALN and NSwALN are produced, respectively, by adding lobed peaks [12] and nail-like peaks to the lobe peaks of SwALN. In CALN and SwALN, the locations of the lobe peaks and the outward lobe penetration angle are the same as those of BLN, and their equivalent exit diameters are also approximately equal to that of BLN. The diameters of the circles at the deep and shallow troughs are 150 and 293.7 mm, respectively. The detailed dimensions of the different lobed nozzles are shown in Figs. 1 and 2.

To analyse the mixing flow field of the lobed nozzles, an illustration of the tailing-edge structures of the lobed nozzles and their downstream regions is shown in Fig. 3. For a normal lobed nozzle, as shown in Fig. 3(a), **A** is a lobe peak, **B** is a lobe trough, and **C** is a side wall. In the downstream region of the normal lobed nozzle, the region in circle **I** is the core region, the area between circles **I** and **II** is the region off the side walls, and the area between circles **II** and **III** is the region off the lobe peaks. For an alternating-lobe nozzle, as shown in Fig. 3(b), **A** is a lobe peak, $\mathbf{B_1}$ is a shallow trough, $\mathbf{B_2}$ is a deep trough, $\mathbf{C_1}$ is a side wall of the shallow trough, and $\mathbf{C_2}$ is a side wall of the deep trough. In the downstream region of the alternating-lobe nozzle, the region in circle **I** is the core region, the area between circles **I** and **II** is the region between the deep and shallow troughs, the area between circles **II** and **III** is the region off the side walls, and the area between circles **III** and **IV** is the region off the lobe peaks.

3. Numerical simulation method

A numerical simulation model is shown in Fig. 4. Owing to the complex geometry, tetrahedral cells are used to discretise the simulation domain. Three-layer prism cells are used as the boundary cells, with the first layer at a height of 0.05 mm. As indicated by the arrow in Fig. 4, a refinement domain is employed where drastic changes in the velocity and temperature occur. To conduct an accurate simulation of the streamwise vortices, the maximum size of the cells in this domain is approximately 15 mm. The number of cells in the refinement domain is greater than 20 million, and the number of cells outside the domain is approximately 2 million.

The simulation was performed using the Fluent software package and the SST k–ω turbulence model. The SIMPLE algorithm was used to solve the pressure–velocity coupling. All of the convection terms were discretised by a second-order upwind scheme. The pressure inlet and pressure outlet were set far field, where the operating pressure was ** 101,325 Pa, the temperature was 300 K, and the turbulent intensity was 5%. A velocity of 125 m/s, temperature of 850 K, and turbulent intensity of 5% were assigned to the jet inlet.

Hu et al. [13–18] conducted a series of PIV experiments to investigate the jet mixing flow of a nozzle with six lobes. Fig. 5 compares the results of the simulation of the six-lobe nozzle (using the numerical simulation method of the present study) with Hu's experimental results. It can be seen that the distributions of the velocity vector and the axial velocity obtained by the numerical simulation are in good agreement with those determined by Hu's experiment. This observation validates the numerical method and the results of the simulation of the lobed nozzles in this study.

4. Results and discussion

4.1. Jet mixing performance

4.1.1. Pumping performance

The pumping ratio Φ was used to assess the pumping performance of the lobed nozzle, and is defined as

$$\Phi = m_s/m_p \tag{1}$$

where m_p is the mass flux of the primary stream, and m_s is the mass flux of the secondary stream. The pumping ratio of each lobed nozzle is listed in Table 1, where $\Delta\Phi$ is the relative difference of Φ. It can be seen that, compared with BLN, the pumping performance of CALN is slightly enhanced, and an improvement of approximately 5% is achieved in that of SwALN. For PLN, the improvement is approximately one-third. However, the two types of lobe-peak spoilers slightly weakened the benefits of SwALN.

4.1.2. Mixing effectiveness

Considering that the components of the primary and secondary streams are the same in the present study, the thermal mixing efficiency η_{tr} [19–21] can be used to evaluate the mixing effectiveness of the lobed nozzle. Its expression is as follows:

$$\eta_{tr} = 1 - \frac{\int (T_m - T_M)^2 \mathrm{d}m_m}{T_p^2 m_p + T_s^2 m_s - T_M^2 m_m} \tag{2}$$

where m_m is the mass flux of the mixing stream, T_p is the initial temperature of the primary stream, T_s is the initial temperature of the secondary stream, T_m is the temperature of the mixing stream, and T_M is the temperature after complete mixing of the primary and secondary streams.