Comparative Study on the Aerodynamic Characteristics of Flame Stabilizer Employing Supersonic Jet and Subsonic Jet Based on Numerical Method

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Abstract. To compare the aerodynamic characteristics of flame stabilizer by supersonic jet and flame stabilizer by subsonic jet, this article studies the size and length/width ratio of recirculation zone, size of jet trajectory at both supersonic and subsonic jet under the same geometry and boundary conditions in the ANSYS Fluent software program. The result shows that under supersonic jet the size, length/width ratio of recirculation zone and size of jet trajectory are bigger than under subsonic jet. Due to the size of recirculation zone is related to the burning range, that means using supersonic jet as a flame stabilizer can enlarge the stable burning range of a combustion chamber. It would make a big difference when the jet flame stabilizer apply to the gas turbine aircraft engine.

Keywords: Gas turbine engine; Combustion chamber; Flame stabilizer by jet; Supersonic; Subsonic.

1. Introduction
Jet flames in crossflow have been studied by investigators for several decades due to their wide applications in gas turbine combustion chamber, stack flares, industrial burners, etc. [1]. For gas turbine combustion chamber applications, the gas-dynamic flame stabilizer by jet is commonly found. It needs to extract high pressure air from compressor and spray them from an opening on a wall or a tube into the crossflow to generates a fan-shaped aerodynamic barrier and form a recirculation zone downstream the aerodynamic barrier to achieve flame stabilization, as shown in Figure.1 [2]. The flame behaviors, stability, thermal structure, and combustion characteristics, etc. have described by many researches [2-8]. However, the existed studies of gas-dynamic flame stabilizer are all conducted under the subsonic velocity of jet, study of gas-dynamic flame stabilizer by a supersonic jet is very limited.
To research the characteristics of gas-dynamic flame stabilizer by a supersonic jet, and to find the difference between supersonic jet and subsonic jet using as the flame stabilizer, this paper conducts comparison study by numerical simulation with same geometrical and boundary conditions.

2. Physical Models and Computational Method

2.1. Physical Models and Grid Division

The paper studies the gas-dynamic flame stabilizer in a tubular combustion chamber. The tubular combustion chamber is simplified to a cylindrical tube, as shown in Fig2. Tube length L is 500mm, inner diameter is 200mm. From the left side of the tube flows mainstream to the right side with a certain flow rate. In the center of the tubular combustion chamber locates a small nozzle-pipe. At the top of nozzle-pipe has a small annular gap, through which air or air-fuel mixture is injected into the cross mainstream. The width of the gap is 0.25mm. The schematic of the whole model is shown in Fig. 2.

Two calculation models for supersonic jet and subsonic are the same, except for the shape of the gaps: one is a convergent annular gap through which it creates subsonic jets. The other one is a convergent-divergent annular gap (Laval nozzle) through which it creates supersonic jets, shown as in Fig 3.
When constructing computational grids, it is necessary to take into account the influence of the near-wall boundary layer, which in some turbulence models requires the separation of the grids and use of near-wall function. However, for some other turbulence models like SST $k – \omega$ turbulence model, the introduction of the near-wall function is not necessary. In the calculations, the thickness of the first layer of the grids was 0.04 mm. In order to reduce the computer time, calculations were performed on uneven grids with a decrease in cell size in areas of elevated parameter gradients. To eliminate the influence of grids quality on the calculating results, calculations were carried out on grids with the number of cells 50,500, 98,600 and 152,000, respectively. When grids volume exceeding 99,200 cells, the results of calculations almost coincided.

2.2. Boundary Conditions for Calculation and Turbulence Model

The comparison of subsonic and supersonic jets was carried out under the same operating conditions and boundary conditions:

- Flow rate of mainstream $m_0=2.8$ kg/s;
- Flow rate and temperature of jet $m_j=0.012$ kg/s, $T_j^*=488$ K;
- Temperatures of mainstream at which the calculations were performed, $T_0^*=488$ K;
- The composition of mainstream and jet - air;
- Turbulent intensity of mainstream - 5%, hydraulic diameter - 0.2 m;
- Turbulent intensity of jet - 3%, hydraulic diameter - 0.02 m.

When carrying out computational simulation, the SST $k – \omega$ model was chosen as the turbulence model, which best fits the experimental results on the trajectories of jets and the size of recirculation zone [9]. The transport equation of turbulence model SST $k – \omega$ as follows:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x} (\rho ku_x) = \frac{\partial}{\partial y} \left[ \Gamma_1 \frac{\partial k}{\partial y} \right] + G_k - Y_k + S_k$$

$$(1)$$

$$\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x} (\rho \omega u_x) = \frac{\partial}{\partial y} \left[ \Gamma_1 \frac{\partial \omega}{\partial y} \right] + G_\omega - Y_\omega + D_\omega + S_\omega$$

$$(2)$$

3. Numerical Simulation Results

Figure 4 shows the velocity field in the region around the gap. It can be seen that with the same boundary condition, in the case with a convergent annular gap, the jet velocity at the exit of the gap is less than the speed of sound, and in the case with the convergent-divergent annular gap, the jet velocity at the exit of the gap is greater than the speed of sound and several shock waves are obtained. Measuring the
maximal Mach number on the exit section of the gap: with a convergent gap $Ma=0.989$, with a convergent-divergent gap $Ma=1.96$.

Figure 4. Speed contours in the region of the gap (a- nozzle with a convergent annular gap, b- nozzle with a convergent-divergent annular gap)

3.1. Boundary of Recirculation Zone
In Fig. 5 shows the boundary of recirculation zone on which the axial velocity is equal to zero. And in figure 5 we know that the boundary zone of recirculation zone with a supersonic jet is greater than with a subsonic speed.

Figure 5. Boundary of recirculation zone (a- nozzle with a convergent annular gap, b- nozzle with a convergent-divergent annular gap)
Measuring the size of the boundary of recirculation zone in two models, as shown in table 1.

**Table 1.** Length and width of recirculation zone with subsonic jet and supersonic jet

| Air flow rate in jet, kg/s | Subsonic jet | Supersonic jet |
|---------------------------|--------------|---------------|
|                           |   |               |
| Length                    | 0.078m       | 0.0845m       |
| Width                     | 0.0396m      | 0.0439m       |

It can be calculated from table 1 that the length of the recirculation zone in the case of supersonic jet is 8% longer than in the subsonic case, the width of the recirculation zone in the case of supersonic jet is 10% larger than in the subsonic case.

Several cases were calculated at different momentum ratios $\frac{\rho A v^2}{\rho_0 v_0^2}$, which is considered to be the similarity parameter of jet flow [10]. By regulating the flow rates, the sizes of the recirculation zone were obtained, and presented in table 2 (with subsonic jets) and table 3 (with supersonic jets).

**Table 2.** Size of the recirculation zone with subsonic jets

| Air flow rate in jet, kg/s | 0.012 | 0.014 | 0.016 | 0.018 | 0.02 |
|---------------------------|-------|-------|-------|-------|------|
| Length L, m               | 0.078 | 0.086 | 0.095 | 0.0985| 0.103|
| Width W, m                | 0.0396| 0.0436| 0.0476| 0.050 | 0.053|
| L/W                       | 1.97  | 1.97  | 1.99  | 1.97  | 1.94 |

**Table 3.** Size of the recirculation zone with supersonic jets

| Air flow rate in jet, kg/s | 0.012 | 0.014 | 0.016 | 0.018 | 0.02 |
|---------------------------|-------|-------|-------|-------|------|
| Length L, m               | 0.0845| 0.0917| 0.096 | 0.1021| 0.1069|
| Width W, m                | 0.0439| 0.0483| 0.051 | 0.0537| 0.0562|
| L/W                       | 1.92  | 1.90  | 1.88  | 1.90  | 1.90 |

From the above tables, it is found that under the same boundary condition, the length and width of recirculation zone in the supersonic cases are greater than in the subsonic cases. The length to width ratio $L/W$ is basically constant, independent of the momentum ratios $\frac{\rho A v^2}{\rho_0 v_0^2}$, and in the subsonic cases $L/W$ is approximately 1.968, in the supersonic cases it is approximately 1.90.

### 3.2. Jet Trajectory

In Fig. 6 shows speed contours in two cases in table 1. It can be seen that in the subsonic case the recirculation zone is slightly smaller than in the supersonic case.

**Figure 6.** Speed contours (a- nozzle with a convergent annular gap, b- nozzle with a convergent-divergent annular gap)
Selecting several sections in the recirculation zone behind the nozzle, collecting the maximum speed points, can obtain the jet trajectories in two cases, shown in Fig. 7.

![Figure 7. Trajectories of jet in the cross mainstream (a- nozzle with a convergent annular gap, b- nozzle with a convergent-divergent annular gap)](image)

It can be seen that in the supersonic case, the jet penetrate deeper than in the subsonic case by 10.7%. And in the subsonic case, the jet is sucked to the axis earlier than in the supersonic case.

4. Summary
Analyzing the above calculations, the following conclusions can be obtained:

1. In the model with a convergent-divergent annular gap, the jet penetrates into the main stream at a supersonic velocity and the size of the recirculation zone and the trajectory of jet in the cross mainstream is greater than in the subsonic case.

2. At different momentum ratios \( \frac{\rho_j v_j^2}{\rho_0 v_0^2} \), the length to width ratio of the recirculation zone L/W in the supersonic case is greater than in the subsonic case.

3. Due to the size of recirculation zone is related to the burning range, using supersonic jet as a flame stabilizer can enlarge the burning range of a combustion chamber. It means the supersonic jet is more suitable than subsonic jet when the jet flame stabilizer apply to the gas turbine aircraft engine.

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