Vortex Shedding Mechanism of Post Cyclone-Bluff Body Stabilized Combustion

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Abstract. V-gutter is one of the typical bluff bodies that often used for flame stabilization in the afterburning chamber of present turbine engine. For its small range of lean/rich fuel limits, weak anti disturbance capability and low combustion efficiency which may cause the flame in combustion chamber easily to be extinguished, the V-gutter still needs to improve performance. In this paper, a new method that adding a cyclone behind the bluff body to enhance the flame stabilization by the interaction of shedding vortex of bluff body and this cyclone is proposed. Vortex shedding mechanism of the flow around V-gutter with post cyclone is studied. The numerical result shows that the post cyclone has an important impact on the vortex shedding mechanism of the flow around V-gutter. The flow resistance and fluctuation are reduced and the length of the recirculation zone is increased, which can lead to the improvement of the flame stabilization. On the contrary, the flow resistance and fluctuation increase, and the recirculation zone become shorter when the post cyclone source is outside, which is negative to the flame stabilization. The influence of the post cyclone diameter cannot be ignored either. The flow resistance is increased, the fluctuating characteristic is strengthened, the recirculation zone is shortened and the vortex shedding frequency is decreased when the cyclone diameter is increased.

1. Introduction
The bluff body is a significant and commonly used component for combustion in high speed flow. When the high-speed fluid flows around the bluff body, burning in the lower speed vortex behind the bluff body can make the flame rapidly spread to the whole downstream flow field. V-gutter is one of the typical bluff bodies that often used for flame stabilization in the afterburning chamber of present turbine engine. For its small range of lean/rich fuel limits, weak anti disturbance capability and low combustion efficiency which may cause the flame in combustion chamber easily to be extinguished, the V-gutter still needs to improve performance.

Mehta and Soteriou [1] commented on vortex shedding as it relates to bluff body flame blow-out. Ericson et al. [2] conducted another model study where the temperature rise across the flame was varied. In their study they concluded that at lower temperature ratios across the flame, the flame near blowout was dominated not by small turbulent vortices but by large Karman Street type vortices. These same
structures were also captured by Porumbel and Menon [3], and Fureby [4] in their combusting Large Eddy Simulation (LES) investigations.

Barry Kiel, Kyle Garwick, et al[5,6] studied the behavior of 3 types of bluff bodies’ wake flow using modern fluid test method and numerical simulation. In their works, high speed images of combustion and equivalence ratio taken at blow out agree with assertions made by Ozawa [7] and Zukoski [8]. Lean blow out also correlate very well when using the correlation parameter set down by Dezubay [9].

On the basis of these above research works, a new method for high-speed flame stabilization is proposed in this paper. That is, adding a cyclone behind the bluff body to enhance the flame stabilization by the interaction of shedding vortex of bluff body and this cyclone. This method is no longer focusing on the geometric structure of bluff body, as is considered make little influence on flame stabilization [5], but trying to change the vortex dynamics by an extra swirl. Vortex shedding mechanism of the flow around square cylinder and V-gutter with post cyclone are discussed based on the results of numerical simulation.

2. Nomenclature
Re  Reynolds Number
Rms  root mean square
St  Strouhal Number
U  velocity
C_D  resistance coefficient

3. Geometry model
Barry Kiel et al.’s experiment study [5, 6] on V-gutter has been proved reliable. So, we use their V-gutter model (Fig.1) and experimental data to verify the simulation results, and then also set a series of swirl inlet inside the V-gutter in order to investigate the vortex dynamics dominated by the interaction of the new-generated streamwise vortex and the existing shedding vortex. Model parameters are given in Table 1.

![Figure 1. V-gutter model](image)

| parameter       | Diameter | Uin  | Re    | Blockage ratio | Aspect ratio | Turbulence intensity |
|-----------------|----------|------|-------|-----------------|--------------|----------------------|
| V-gutter        | 0.45m    | 30m/s | 40500 | 43%             | 2.22         | 7%                   |

4. Numerical Methods

4.1. Meshing
As shown in Figure 2, The calculation domain of V-gutter is divided into structured discrete grid by using the ICEM grid generator. The grid sensitivity is verified, and the cells number is controlled at about 1.3 million for computational efficiency under the premise of ensuring numerical accuracy.
4.2. Boundary Condition

The boundary condition of simple square cylinder case is set to the same as Rodi’s experimental condition [10], i.e. Re=21400, inlet velocity Uin=0.535m/s, and atmospheric pressure outlet. The post cyclone square cylinder case has the additional boundary condition of inlet cyclone mass flow rate Qt=1.57×10^{-5}kg/s, 3.14×10^{-5}kg/s and 6.28×10^{-5}kg/s.

The boundary condition of simple V-gutter bluff case is set to the same as Barry Kiel’s experimental condition, i.e. Re=40500, inlet velocity Uin=30m/s, and atmospheric pressure outlet. The post cyclone V-gutter case has the additional boundary condition of inlet cyclone mass flow rate Qt=1.25×10^{-4}kg/m^3, 3.75×10^{-4}kg/m^3 and 6.25×10^{-4}kg/m^3.

The wall boundary of left and right sides in all cases is set to symmetric, and the up and down sides’ wall boundary condition is non-slip.

4.3. Validation of Numerical Methods

In order to ensure the numerical accuracy, several commonly used RANS turbulence models have been tested. All calculation process is completed by Couple Solver integrated in ANSYS Fluent. The high precision node-based Gauss Kleene function method is used to discrete gradient. The standard discrete method is adopted to deal with the pressure. The second order upwind is adopted to discrete the turbulent kinetic energy and dissipation rate. And time is discreted to the first order implicit.

Barry Kiel (2006)’s V-gutter experimental data is applied to verify the numerical results. In Re=40500, inlet turbulence ratio 7%, blockage ratio 0.43 condition, the central axis dimensionless velocity distribution u/U and downstream at Z/D=0.5 dimensionless velocity distribution u/U (at X-axis), v/U (at Y-axis) are given. (Fig 4). The St number validation is given in Table 2.

As shown in Figure 3 and table 2, all these RANS turbulence models can make accurate prediction of St number, and the Realizable κ-ε is better than other models in prediction of velocity shown in Figure 3. Thus, the Realizable κ-ε model is selected to simulate the flow around the V-gutter in this paper.
5. **Results and discussions**

5.1. *Simple V-gutter*

![Streamline on Central Section](image)

Figure 4. Streamline on Central Section

Fig 4 shows the distribution of instantaneous streamline in a full vortex shedding period along the central cross-section of the simple V-gutter. The vortex shedding mechanism of V-gutter is close to the square cylinder, but in detail, for the strength of shear flow around the V-gutter is not as strong as square cylinder, the shedding vortex downstream the V-gutter is always keeping structure complete. So compared with the square cylinder vortex shedding, the larger size vortex swallow smaller vortex situation during the vortex shedding process does not appear in simple V-gutter case, and the vorticity transport is more direct downstream V-gutter which can reduce the kinetic energy dissipation during transport.

5.2. *Post Cyclone V-gutter*

In Fig 5, the V-gutter diameter is D, and the dimensionless swirl outlet position Z/D is 0, 0.5, 1, 1.5, named as P1, P2, P3, P4 in simulation results. The standard case is the result of simple V-gutter.

![Position of Swirl Outlet](image)

Figure 5. Position of Swirl Outlet

| Case      | $\bar{C}_D$ | $C_{D,\text{rms}}$ | St  |
|-----------|-------------|-------------------|-----|
| Standard  | 1.272       | 6.58x10E-3        | 0.247 |
| P1        | 1.099       | 2.87x10E-4        | 0.193 |
| P2        | 1.087       | 3.42x10E-4        | 0.193 |
| P3        | 1.096       | 2.95x10E-4        | 0.193 |
| P4        | 1.237       | 7.64x10E-3        | 0.249 |

Table.3 Flow Resistance and the Vortex Shedding Period

The numerical results of resistance characteristic and shedding period are shown in Tab.3, the flow average/fluctuating resistance decrease in cases of P1, P2, P3, compared with standard case, for the similar reason of post cyclone square cylinder cases. The St number also decrease in P1, P2, P3 cases. But in case P4, all these resistance parameters jump to a much higher level, because of the destruction of V-gutter structure which could change the vortex shedding mechanism. So, for V-gutter, the swirl outlet cannot extend out of the bluff geometric range.
Fig. 6 shows the time average streamline of 4 different swirl outlet position cases. The average recirculation zone length in P1 and P3 cases is longer than P2 and P4. Fig. 9 shows the dimensionless velocity u/U distribution along flow direction, the back-flow point in P1 and P3 is obviously further than P2 and P4, and the area of velocity curve envelope in P1 and P3 is also larger than P2 and P4, indicating that the average recirculation zone of P1 and P3 is better than P2 and P4. Considering the P1 structure is simpler, in this paper, the P1 model is selected for subsequent research.

The V-gutter bluff bodies with swirl tube diameter of 10mm, 20mm and swirl mass flow rate of 1.25×10^{-4}kg/s, 5×10^{-4}kg/s respective are also compared in this paper. The data in Tab. 4 indicates that with the swirl tube diameter increase, the flow resistance increases, the fluctuation of the downstream flow is enhanced, and the St decreases. Obviously, the large diameter swirl inlet may destroy the shape of bluff body, and the stronger swirl flow in the downstream of the bluff body generates greater flow resistance which could cancel out the reduction of pressure difference, so the swirl tube diameter should not be too large.

The previous analysis has been made to join that the added center cyclone will dominate the vortex shedding mechanism of the bluff body. In Fig 7, with the swirl tube diameter increase, the cyclone diameter increase, and the recirculation zone is crowded wider and shorter, which is not conducive to the organization of combustion. Thus, the swirl tube diameter of 10mm is better.

The flow resistance coefficient, the vortex shedding period and the average recirculation zone with the swirl inlet mass flow rate of 1.25×10^{-4}kg/s, 3.75×10^{-4}kg/s and 6.25×10^{-4}kg/s are also studied.

| Swirl Tube Diameter | C_d^- | C_d^mv | St     |
|---------------------|-------|--------|--------|
| 10mm                | 1.099 | 2.87×10^{-4} | 0.193   |
| 20mm                | 1.2185 | 8.16×10^{-3}  | 0.183   |
| 0                   | 1.272 | 6.58×10^{-3}  | 0.247   |

Fig. 7. Time Average Streamline on Central Section
Table 5 Flow Resistance and the Vortex Sheding Period

| Case   | Swirl Mass Flow Rate | $C_D$  | $C_D^{rms}$ | St  |
|--------|----------------------|--------|-------------|-----|
| Standard | 0                    | 1.272  | 6.58×10^{-3} | 0.247 |
| S1     | 1.25×10^{-4}kg/s    | 1.096  | 2.95×10^{-4} | 0.193 |
| S2     | 3.75×10^{-4}kg/s    | 1.095  | 2.60×10^{-4} | 0.192 |
| S3     | 6.25×10^{-4}kg/s    | 1.091  | 1.83×10^{-4} | 0.193 |

Tab 7 shows the resistance and shedding period of the V-gutter with post cyclone under different swirl mass flow rate. The swirl mass flow 0 case is the simple V-gutter. The flow average and fluctuating resistance significantly decrease in all post cyclone V-gutter cases. The shedding frequency also decreases remarkably. These are beneficial to the combustion stability.

![Figure 8. Time Average Streamline on Central Section](image)

Fig.8 shows the average streamline on the central section of V-gutter. For the standard case, there are two small symmetrical concentrated vortex inside the V-gutter. The stagnation point of the recirculation zone is also inside the bluff body. In Fig.8 (b), the added cyclone pushes the two large vortex downstream the bluff body tend to be flat, and moves backwards, so the length of the recirculation zone increases. With the swirl mass flow rate increase, the large vortex in recirculation zone moves downstream, the recirculation zone tends to be flat and elongated, and the area is gradually reduced after reaching a maximum value. Therefore, the swirl mass flow should not be too large, otherwise the bluff body vortex will be blown off, which is obviously negative to reduce the fluid flow velocity and combustion stabilization.

It can be seen in Fig.9 that the time average velocity distribution of the 3-post cyclone V-gutter cases is close. The position of the recirculation zone moves backwards and the back-flow mass rate increases in the recirculation zone which will enhance the combustion stabilization. But the negative result is that the flow direction velocity recovery is slightly worse, which is due to the stronger central cyclone flow strengthens the flow shear dissipation, and increases the fluid kinetic energy loss.

![Figure 9. Time average flow on the central section of the V-gutter with post cyclone](image)
So, it can be considered that the added swirl flow mass rate is not the bigger the better, but also need to match the main flow velocity and the bluff body size. Meanwhile, adding too much swirl in engineering project will also have some difficulties, such as reducing the mainstream of the aircraft engine flow and resulting in the loss of thrust and so on. In this study, the $1.25 \times 10^{-4}$ kg/s case is more reasonable.

![Streamline on Central Section](image1)

**Figure 10.** Streamline on Central Section

Fig.10 shows the vortex shedding process of post cyclone V-gutter with inlet swirl mass flow rate of $1.25 \times 10^{-4}$ kg/s. Compared with the simple V-gutter in Fig.4, the downstream shedding vortex size increases. This is due to the vorticity transport from the added streamwise vortex to the spanwise shedding vortex. Meanwhile, because of the action of the added cyclone, the shedding vortex core is further from the bluff’s trailing edge and elongating the recirculation zone.

6. Conclusion

In this paper, numerical simulation method is used to study the vortex shedding mechanism of the post cyclone square cylinder and V type bluff body, the following conclusions are drawn:

1. The vortex shedding mechanism of simple V-gutter is dominated by the boundary layer instability. While for post cyclone bluff body, this mechanism is dominated by the added cyclone.

2. For post cyclone V-gutter, compared with standard V-gutter, the flow average and fluctuation resistance decreases, the vortex shedding frequency decreases, and the average recirculation zone becomes longer.

3. In the detail design of post cyclone V-gutter, multiple factors are also considered. The cyclone outlet position can't extend to the bluff body outside, otherwise it will damage the bluff body structure, increase flow resistance, and reduce the size of the recirculation zone length; The swirl tube diameter could not be too large, otherwise it will also destroy the bluff body shape and lead to the recirculation zone became thick and short; the swirl mass flow rate should not be too large, otherwise it will blow the downstream shedding vortex away.

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