

Experiment of drag characteristics of a novel variable geometry flame-holder

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Abstract: A novel variable geometry flame-holder (VGF) based on V-gutter was presented. The structural characteristics of the flame holder were introduced. Experimental study on drag characteristics of the VGF on un-burning and burning states was conducted in a rectangular combustion test rig. The influence of the change of gutter trailing edge width w on pressure recovery in different operating conditions was analyzed emphatically. Furthermore, drag characteristics in different trailing edge width variation modes were discussed. Results show that: (1) Narrowing w can observably raise the total pressure recovery σ but the highest σ is not obtained at minimum w . (2) The relationship of drag coefficient ϕ and w in the un-burning conditions can be well expressed in a form of exponential equation ($w/d > 0.4$). (3) Drag characteristics are not sensitive to the variation modes and speeds of w . (4) In the burning condition, σ decreases with the increasing of w basically and the course can be divided into three stages. The results and experimental data presented in this paper would enhance the phenomenological understanding of this type of VGF, and would contribute to the next experimental study and numerical calculus of this novel VGF.

Key words: flame-holder; variable geometry; afterburner; augmentor; drag characteristics

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Nomenclature

d	distance	p^*	total pressure
D	distance	T_0	inlet temperature
f	fuel-air ratio	Ma	inlet Mach number
κ	specific heat ratio	σ	total pressure recovery coefficient
l	length	ϕ	drag coefficient
O	center of rotation		

The afterburner component, which simply acts to consume the remaining oxygen in the turbine exhaust and generate usable thrust by increasing the exhaust temperature and velocity, is widely used by gas turbine engines installed on tactical aircraft. When maximum thrust is a goal, the thrust augmentation offered by the afterburner becomes critical to meeting the overall system goals for takeoff, maneuverability and acceleration. Meanwhile, with the non-stop improvement of core engine performance and the

wider and wider flight envelope pursued by human being, the afterburner combustion system will operate over a substantial range of operating conditions.

For a typical afterburner configuration in modern in-service aircraft engines, the flame is typically stabilized using an array of bluff body flame holders which are made of V-shaped gutters providing robust fluid recirculation zones in the flow to anchor the flame in space within the augmentor cavity. The array of flame holders is

arranged to provide combustion uniformity while minimizing the effects of flow blockage and pressure drop so as to introduce a minimum pressure loss in “dry” or afterburning mode^[1-2].

In the afterburning mode, pressure loss seems to be the necessary cost for the flame stabilization and combustion. Better combustion performance, in most cases, goes with bigger pressure loss^[3]. However, people never give up seeking a flame-holder with high combustion performance at a low pressure loss level, and finding the best combination point of them. A considerable amount of research has been conducted on this topic^[4-9]. Today, afterburners are facing a large range of operating conditions. It is a big challenge for the afterburner combustion system to operate at a uniform high performance. It is even more difficult for the flame-holder to keep the best combination point of flame stabilization and pressure loss in such significant condition changes.

In the “dry” mode, on the other hand, the afterburner combustion system is not be used. Afterburner component is just working as a connecting duct between the outlet of low pressure turbine and nozzle. The permanently installed flame-holder devices are of no assistance and even create pressure loss because of their geometry and the position in the afterburner chamber. This is important since flow pressure loss from the afterburner system directly decreases the thrust output in non-afterburning mode where cruise operation and fuel consumption is most important. An ideal flame-holder system, technique intuitively, should reduce the pressure loss to a minimum level when it was at the non-working state.

The concept of VGF (variable geometry flame-holder), which is based on the bluff-body flame stabilization mechanism and can adjust its feature geometry to different conditions when needed, is a direct and simple method to solve the problems mentioned above. Following scenes will be realized by VGF: providing maximal fluid recirculation zones by increasing the feature

size in the course of afterburner ignition especially high-altitude relight, increasing or decreasing the size of recirculation zones according to the operation conditions for the best combination of flame stabilization and pressure loss, minimizing the size of fluid recirculation zones for the lowest pressure loss when the engine is in the “dry” mode. Similarly, VGF can also be used for the ramjet combustor.

However, especially in the past, it was a much challenging work to design a high reliability motion mechanism of VGF which can work in high temperature and aerodynamic force environment without overabundant extra weight increase. There is little study focus on VGF except some patents^[10-13]. Actually, aspirated EB-MC (edge blowing mixture curtain) flame-holder investigated in Ref. [7] and Ref. [9] can be considered as a form of VGF. It has a streamline form head, small base width, with air and fuel mixture flowing from the slots at it's edges into the main flow. Authors believe that it has small cold pressure loss without reheat and variable blowing on reheat so as to enlarge recirculation zone and improve combustion performance. Nevertheless, with the rising of engineering design level and the application of new high-temperature material, the realizability of VGF will be increased greatly. The study on VGF, especially about flow resistance characteristics, combustion properties and control law, will become more meaningful.

On the other hand, people never stop the fundamental study on the mechanisms for bluff-body in the flow. In recent years, with the use of LDA (laser doppler anemometry), PDPA (phase doppler particle analyzer), LDV (laser doppler velocimetry) and high speed imaging, research has investigated the flowfield around a bluff-body in both the non-reacting and reacting environments. Bluff body with different geometry shapes were employed in some of these works to get a better understanding of the relevance of bluff body geometry on flow and combustion. Rizk N K and Lefebvre A H^[3] have in-

investigated the pressure loss and blow off velocity at different open-angles of V-gutter flame holders to make sure the relationship between flame stability and drag of bluff-body flame-holders. Barry K, Kyle G, et al^[14-15]. have used open and closed V-gutter, circular and square cylinder bluff body flame holder geometry to study the behavior of bluff body stabilized flames. After detail analyses of a large amount of data including non-reacting data from CFD (computational fluid dynamics) and LDV, lean blowout and high speed images, they concluded that the vortex dynamics and not geometry is the dominant mechanism for bluff body flame extinction^[14-15]. However, the data from these works relative to bluff-body geometry was discontinuous on geometry because it was unpractical to have such a large number of experiments on vast bluff-body with different geometry.

In this paper, a novel VGF based on V-gutter was proposed as the research object which can vary it's geometry continuously by a control system. Experimental study on flow resistance characteristics of the flame-holder on non-reacting and combusting states was conducted on the Afterburner/Ramjet Combustion Test Rig in Beijing University of Aeronautics and Astronautics. The influence of the change of flame-holder trailing edge width on pressure losses in different operating conditions were analyzed emphatically. Furthermore, resistance characteristics in different variation modes and speeds were discussed. The objective of this research effort is two fold. First the objective is to provide detailed experimental data on VGF for numerical calculus model validation. Second the objective is to enhance the phenomenological understanding of this type of VGF which would contribute to the next study.

1 Experiment system

1.1 Description of VGF test piece design

Fig. 1 shows the VGF test piece design in 3-D (three-dimensional) view. The design consists of power & transmitting unit (not visible in

Fig. 1), installing seat, fuel injector bar, fixed flame-holder head unit, and movable trailing plates. A V-gutter bluff body is shaped by the combination of fixed flame-holder head unit and movable trailing plates. Fig. 2 describe the geometry changes of the VGF. The distance between the trailing edges of two plates w will be changed correspondingly when the plates revolve around axis O_1 and O_2 symmetrically. By the control of software, w will be changed from 4 mm to 48 mm. In Fig. 2 we can also get the structure size that: the distance between O_1 and O_2 $d=24$ mm, the length of plates $l=30$ mm, the length of fixed head $h=20$ mm.

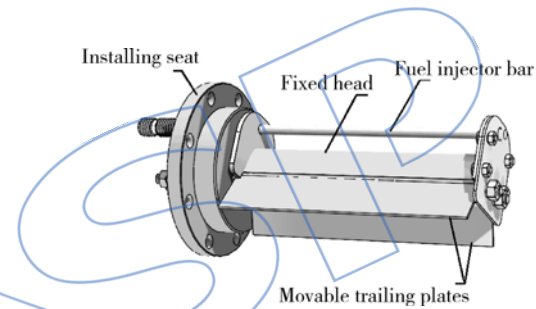


Fig. 1 Design structure diagram of variable geometry flame-holder (VGF) test piece

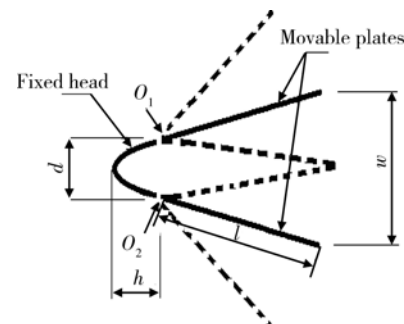


Fig. 2 Geometry changes of the VGF

VGF control software, which is generated by C++ builder programming environment, see Fig. 3, can provide multiple controls of the VGF test piece with the functions as follows:

- 1) Single step control of w by click the related button manually.
- 2) 100 levels can be chose for the rate of w change.
- 3) Displaying and saving the data of w , rate of w change, opening angle of plates in real time.

- 4) Graphical displaying the state of VGF in real time.
- 5) Multistep control of ω by programming.
- 6) Communication with the software of measurement system.



Fig. 3 Interface of VGF control software

1.2 Test facility and measurement system

Experimental investigations of the VGF were performed in the Afterburner/ramjet Combustion Test Rig at Beijing University of Aeronautics and Astronautics. A schematic of the test facility are shown in Fig. 4. The facility simulates operating conditions in a modern gas turbine engine thrust augmentor by two-stage pre-burning to produce a vitiated (low oxygen content) air stream to be supplied to the augmentor diluting air. The exhaust air is then passed

through a flow-conditioning screen before being transitioned from a circular cross-section to the 170 mm by 150 mm rectangular test-section. A thermocouple, pitot tube, and pressure sensor measure the incoming air temperature and pressure before the vitiated air stream enters the test section. Inlet air conditions range from a velocity of up to $Ma=0.4$, temperature from 500 K to 1200 K. All tests are performed at atmospheric pressure in the test section. The test section has a circular quartz window for optical access to the combustion region downstream of the flame-holder. Multiple pressure transducers and thermocouples located after the test section measure steady pressure and temperature, respectively. In this research, aviation kerosene RP-3 (similar to JP-8) was used as fuel material.

Fig. 5 is an installation diagram of the flame-holder and total pressure rakes. The VGF test piece is installed horizontally on the side wall of test section by its installing seat, as shown in Fig. 5(a). Total pressure rake, with 5 equidistant measurement points located, is used to measure flow total pressure in front and behind flame-holder. As shown in Fig. 5(b), the rakes are installed vertically on the top wall of measurement section. Fig. 6 indicates the positions of flame-holder and total pressure rakes, $D_1=760$ mm and $D_2=920$ mm. In the experiment,

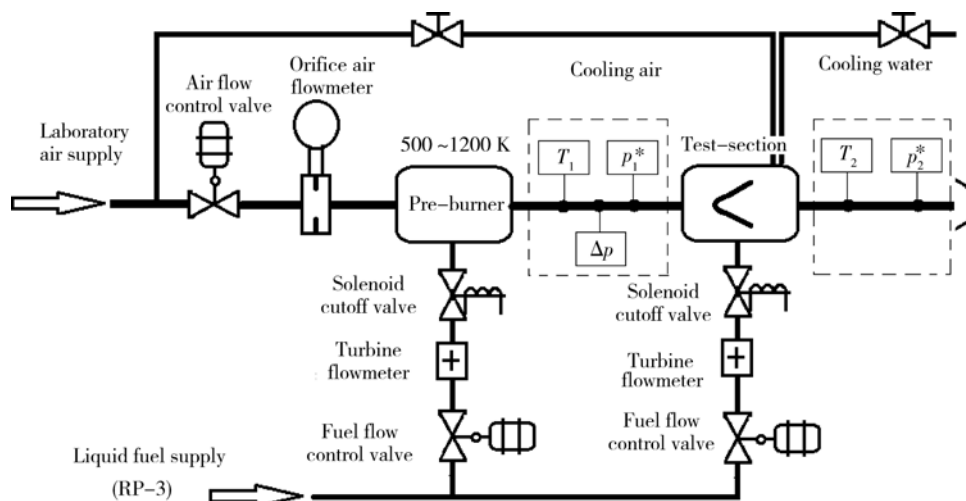


Fig. 4 Schematic of afterburner/ramjet combustion test rig

pressure data are collected automatically at 10 times per second by PCI-1710 data acquisition card.

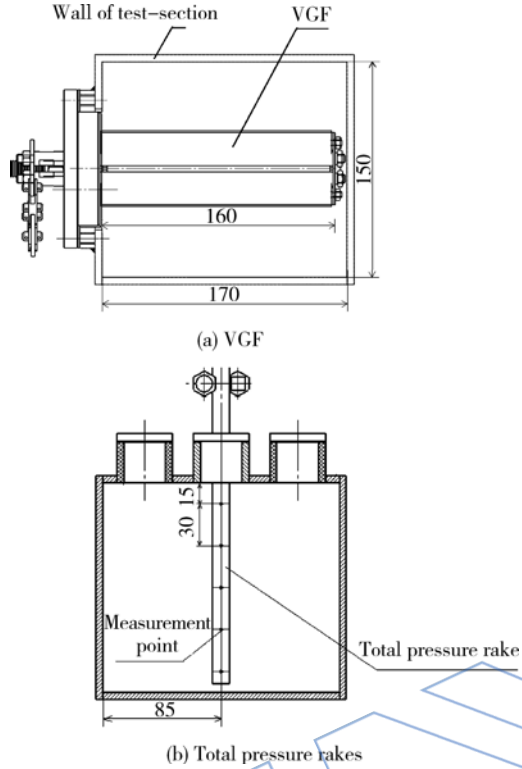


Fig. 5 Installation diagram of VGF and total pressure rakes (unit: mm)

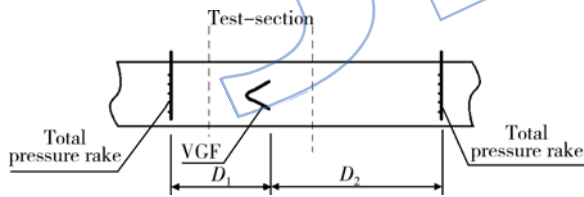


Fig. 6 Positions of VGF and total pressure rakes

1.3 Test conditions

In this paper, investigations were conducted at both contain non-reacting and combusting states. Test conditions were displayed in Table 1, in which Ma and T_0 were the Mach number and temperature of test section inlet air flow respectively. Circular symbols were taken to represent non-reacting conditions while triangles for combusting conditions. In the combusting states, the fuel-air ratio f was maintained at 0.006. The operating pressure of the test facility is near atmospheric condition.

Table 1 Test conditions

Ma	T_0/K	
	300	530
0.10	●	
0.15		▲
0.19	●	▲
0.28	●	

2 Results and discussion

The total drag produced by a gutter immersed in a ducted airstream is made up of several components. One of these is the additional skin friction drag created at the duct walls due to the increase in flow velocity past the trailing edge of the gutter. Another is the skin friction drag of the gutter itself. This can also influence the base drag since the higher the friction drag, the thicker the boundary layer over the trailing edge^[2]. The measurements of drag in this study include both these friction losses. However, for the geometries selected, they are small in comparison with the gutter base drag.

In this paper, pressure recovery coefficient σ and drag coefficient ψ are employed to describe the drag characteristics of flame-holder. The two coefficients are defined by

$$\sigma = \frac{p_2^*}{p_1^*} \quad (1)$$

$$\psi = \frac{1 - \sigma}{\frac{\kappa}{2} Ma_m^2} \quad (2)$$

where p_1^* and p_2^* are the flow total pressure at the specific main air flow cross-sections in front and behind flame-holder respectively, Ma_m is Mach number at reference section. In this investigation, as shown in Fig. 4, p_1^* and p_2^* were represented approximately by arithmetic mean values of 5 points test data captured by the front and rear total pressure rakes respectively, and Ma_m was identified by the Mach number Ma of test section inlet air flow.

2.1 Drag characteristics with continuous variation of w in un-burning state

In this case, at a specific Ma of cold inlet air

flow, the width of gutter trailing edge w was increased continuously from 4 mm (totally closed) to 48 mm within a change rate 2.42 mm/s. Data acquisition was real-time taken at 10 times per second in the whole process.

Fig. 7 depicts the relationship of pressure recovery σ and w/d at three different Ma . Dimensionless parameter w/d is used in this paper to describe the geometry of the VGF test piece. Obviously, for the specific conditions, σ decreases with the increasing w/d basically, and compared with different Ma , higher σ are captured at a lower Ma from the whole aspect. Relatively, in the condition $Ma=0.1$, σ presents a near linear variation within a small range. As Ma increasing, nonlinearity is observed, and σ has a bigger range, which can indicate that the influence of w/d to σ becomes more and more obvious with the approaching flow velocity rising. As discussed above, due to the increase of w/d , the effective flow area at trailing edge becomes smaller and the airstream past the trailing edge of the gutter will be sped up, thereby, friction losses will be enhanced. More importantly, big trailing edge width can produce large base drag caused by pressure difference between the front and back of the gutter. Furthermore, the increase of upstream velocity can enlarge these influences on drag. However the question we most care about is how much the benefit we get on total pressure recovery by making variation of flame-holder geometry. Table 2 summarizes the maximum increasing rate of σ at different Ma .

Table 2 Maximum increasing rate of σ at different Ma

Ma	$((\sigma_{\max} - \sigma_{\min}) / \sigma_{\min}) / \%$
0.10	0.3
0.19	1.3
0.28	2.9

We can also get an information from Fig. 7 that, along with the increase of upstream velocity, a peak grow up around $w/d=0.4$. It means, at high upstream velocity, the biggest total pressure recovery is not obtained when we minimize

w . Maximum σ appears at $w/d=0.32$ if $Ma=0.20$ and at $w/d=0.41$ when $Ma=0.28$. This can be most attributed to the geometric shape of the flame-holder, as described in Fig. 2, the gutter is consist of fixed head and movable trailing plates. It will be a quasi streamline shape when trailing plates are totally closed ($w/d=0.17$). In low speed flow field, there is no flow separation along the gutter surface, and the drag caused by gutter will be smallest. With the rising of speed, the flow will separate from the surface before it arrive the trailing edge of the gutter. Flow separation will generate fluid recirculation zones which can produce pressure drag. At this time, a little increase of w will make the separation points moving backward or even disappeared. Consequently, for this VGF test piece, there is an optimum value of w/d at which lowest drag can be get.

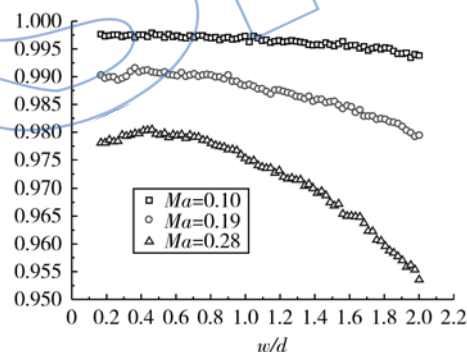


Fig. 7 σ changes with w/d at different Ma (un-burning, continuous)

To facilitate the isolation of the width change factors on the influence of drag characteristics, drag coefficient ϕ are employed to describe the characteristics in Fig. 8. It can be seen, in different Ma , the experimental data points are essentially coincident. It indicates that, in the test conditions, the flow turns into self-stimulated state and drag coefficient is independent of the flow speed, only geometry-related. As the w/d increases, the drag coefficient reaches a minimum at about $w=0.4$ before the monotonous increase.

After an average processing for the experimental data ($w/d > 0.4$) in Fig. 8, nonlinear fit-

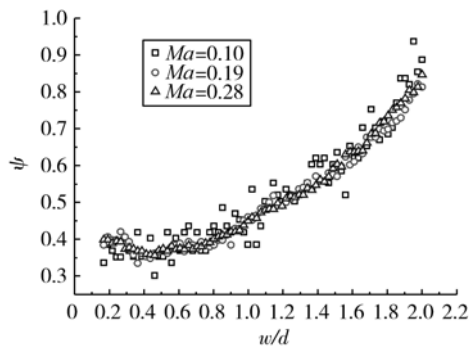


Fig. 8 ψ changes with w/d at different Ma
(un-burning, continuous)

ting is taken to describe the relation between drag coefficient and the trailing edge width. Curve fitting expression is

$$\psi = 0.0715 \times e^{\frac{w}{22.536}} + 0.2412 \quad (3)$$

Goodness of Fit $R^2 \approx 0.99$.

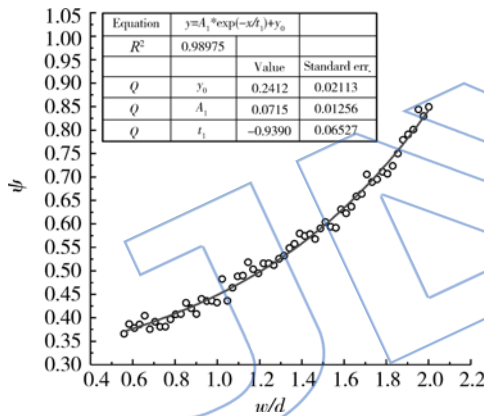


Fig. 9 Nonlinear fitting of test data in Fig. 6

2.2 Drag characteristics in different variation modes of w in un-burning state

To comprehensively understand the drag characteristics of this VGF test piece, two more experiments were taken to study the influence of different w variation modes on drag characteristics in un-burning state.

2.2.1 Drag characteristics with discrete variation of w in un-burning state

In different with the experiment of w continuous variation, the discrete variation of w means that the whole variation process will be divided into many steps, each step has a specific distance, and a pause is set after each step. In the last second of the pause time, data acquisi-

tion is taken. The pause after each step will provide sufficient time for the disturbed flow field to be steady. Then compared with the data of w continuously changing, we can determine the fluid response speed of the flame-holder geometric change in the test conditions, which is of great significance for the control related research. In this experiment, w is increase from 4 mm to 48 mm by steps. The step length is 4 mm and pause time is 2 seconds.

Fig. 10 indicates the relationship of pressure recovery σ and w/d at two different Ma .

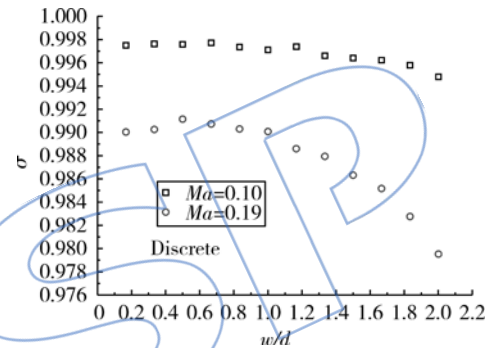


Fig. 10 σ changes with w/d at different Ma
(un-burning, discrete)

For comparative analysis, Fig. 11 plots the experiment data of both discrete variation and continuous variation (w change rate is 2.42 mm/s) at $Ma=0.10$ and 0.19. As shown in the figure, the two experiment data have basic coincidence. It means that, in the experiment conditions, flow field changes caused by geometry change of VGF test piece have a good following performance.

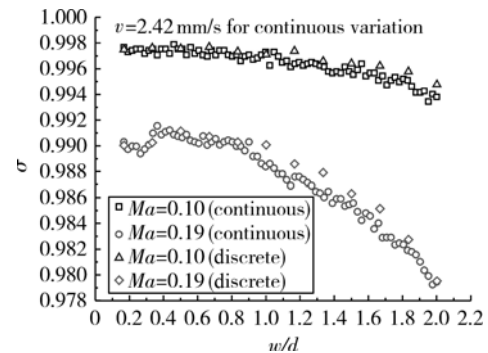


Fig. 11 Comparison of continuous and discrete data (un-burning)

2.2.2 Drag characteristics with different change rate of w in un-burning state

In this experiment, three different change rates of w are employed to discuss the influence of w change rate to the drag characteristics. As shown in Fig. 12, the flow Mach number is maintained at 0.19, three sets of test data points are basically in coincidence. Thereby, it seems that the changes of flow field are not sensitive to w change rate in the experimental conditions. This result is consistent with the analysis above that changes of flow field have a good following performance.

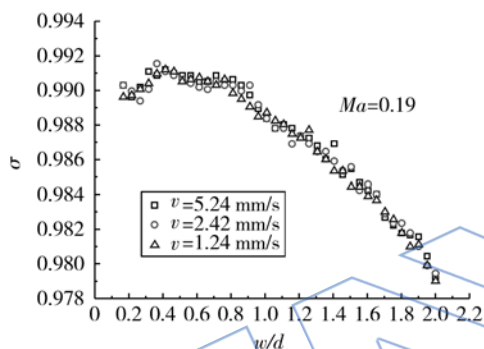


Fig. 12 σ changes with w/d at different v (un-burning)

2.3 Drag characteristics in burning state

For the afterburner in burning state, better flame stabilization performance with lower flow drag is the goal for flame-holder design. This section will study the drag characteristics of the VGF test piece in burning state. Test selected two typical combustion conditions, total pressure recovery coefficient and corresponding stabilizer width were obtained, and a group of un-burning and burning test data was compared.

Test process

1) Adjust the operating conditions to the ignition state ($Ma=0.1$, $T_0=500$ K, $f=0.006$, $w=41$ mm).

2) Ignite the flame-holder.

3) Adjust the operating conditions to the test conditions ($Ma=0.1$ or 0.2 , $T_0=530$ K, $f=0.006$, $w=48$ mm).

4) Decrease w from 48 mm to 4 mm at 1mm

step length.

The change of w/d in burning state will influence both the flow field and combustion which have a relationship with total pressure recovery. As shown in Fig. 13, for the two conditions, σ decreases with the increasing of w/d basically. Furthermore, the curve can be divided into three stages along the horizontal axis negative direction, $Ma=0.19$ as an example, the first stage is from 2.0 to 1.4, curve in this period has a quasi linear shape; the second stage is from 1.4 to 1.1, this stage is characterized by a sudden rapid increase of σ after a downturn of several points, the graph shows a large slope; third period is the section from 1.1 to 0.17, changes of σ is more gentle. With further analysis in the combustion experiments later, that, the first stage is a stable burning state, combustion state (temperature rise) has no significant change for the variation of w/d , σ is mainly related to changes in flow field. The second stage is combustion instability and extinction period, the total pressure recovery coefficient drop is due to unstable combustion, and in the post-extinction gas temperature decreases rapidly so that the total pressure recovery coefficient increase with a large slope. When the flow becomes cold, it goes into the third state which is just similar to the experimental data in cold flow.

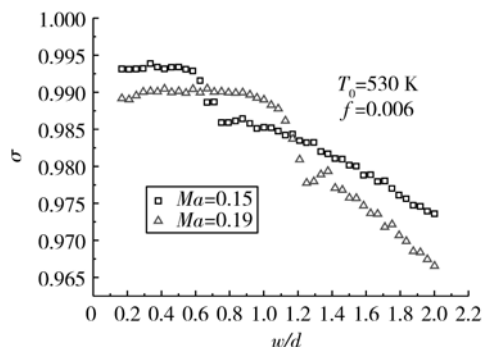


Fig. 13 σ changes with w/d at different Ma (burning)

Fig. 14 is a comparison for the un-burning and burning experimental data at $Ma=0.19$. Obviously, after extinction (from 0.17 to 1.1), the two curves well coincide. When $w/d > 1.1$

the σ at burning state has a suddenly drop because of the combustion behind flame-holder. The quickly gas expansion caused by heat release of chemical reaction will bring a large drag to the main flow. In the stable combustion period (from 1.4 to 2.0), the curve of burning data has a bigger slope than the curve un-burning. So it can be concluded that, in the combustion process, the influence of w to σ is greater than that in the un-reacting situation.

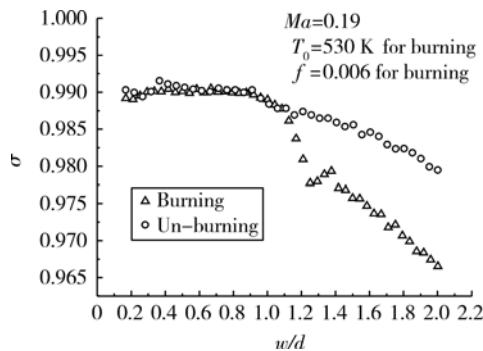


Fig. 14 Comparison of test data in un-burning and burning states

3 Conclusions

This paper presents a novel variable geometry flame-holder, through the experimental method, abundant data is obtained to describe the drag characteristics of the flame-holder in un-burning and combustion conditions. Summarily, we can also get the following conclusions:

1) Narrowing w can observably raise the total pressure recovery σ but the highest σ is not obtained at minimum w . There is a optimum value of w for achieving maximum σ .

2) The relationship of drag coefficient ϕ and w in the test conditions can be well expressed in a form of exponential equation.

3) In the experiment conditions, flow field changes caused by geometry change of VGF test piece have a good following performance and are not sensitive to w change mode and rate.

4) In the burning condition, σ decreases with the increasing of w basically and the course can be divided into three stages.

5) In the burning condition, the influence of

stabilizer trailing edge width w to the total pressure recovery coefficient σ is greater than that in the cold situation.

4 Recommendations

Continued research is required to support the conclusions. CFD method using dynamic mesh model is going to be employed for the detail description of the flow field in unsteady mode. Also planned are experiments in the non-reacting flow using PIV (particle image velocimetry). These will further quantify the flow field of the flame holders over the range of test conditions.

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