충격파가 초음속 수소-공기 화염의 안정한계에 미치는 영향

허환일

Measured Effect of Shock Wave on the Stability Limits of Supersonic Hydrogen-Air Flames

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ABSTRACT

Measured shock wave effects were investigated by changing shock strength and position with particular emphasis on the stability limits of hydrogen-air jet flames. For this purpose, a supersonic nonpremixed, jet-like flame was stabilized along the axis of a Mach 2.5 wind tunnel, and wedges were mounted on the sidewall in order to interact oblique shock waves with the flame. This experiment was the first reacting flow experiment interacting with shock waves. Schilieren visualization pictures, wall static pressures, and flame stability limits were measured and compared to corresponding flames without shock-flame interaction. Substantial improvements in the flame stability limits were achieved by properly interacting the shock waves with the flameholding recirculation zone. The reason for the significant improvement in flame stability limits is believed to be the adverse pressure gradient caused by the shock, which can elongate the recirculation zone.

초록

충격파가 초음속 수소-공기 제트화염의 화염 안정한계에 미치는 영향을 충격파의 강도와 위치를 변화시키면서 연구하였다. 이러한 목적으로 마하수 2.5의 초음속 연소기 벽면에 쐐기를 부착시켜 경사 충격파를 발생시켰다. 본 실험은 충격파가 초음속 화염에 미치는 영향을 연구한 최초의 실험연구이다. 쉬릴렌 가시화 사진과 벽면 정압, 화염 안정 한계를 측정하였으며 충격파가 없는 경우와 비교하였다. 보염 재순환 영역에 충격파를 적절히 간섭시킴으로써 화염 안정 한계가 대폭 개선되었다. 화염 안정한계가 대폭 향상된 이유는 충격파에 의해 발생한 역압력구배로 화염안정화에 중요한 아음속 재순환 영역의 크기가 증대된 때문으로 여겨진다.

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Nomenclature

H = thickness of fuel tube (=0.92cm)
L = length of recirculation zone
p = static pressure
P_0 = static pressure
ρ = density
ϕ = equivalence ratio
$\tilde{u}$ = mass weighted velocity

subscript
A = air
F = fuel
ref = reference
w = wall
1 = upstream of shock wave
2 = downstream of shock wave

1. Introduction

The technological problems associated with the SCRamjet (Supersonic Combustion Ramjet) engine encompass four important aspects: flame holding, necessity of rapid mixing, effects of shock waves on flame stability and mixing, and environmental effects such as NOx. Flame holding was the subject of a previous research by yoon et al(1). The problems of rapid mixing and effects of shock waves were studied by Huh and Driscoll(2,3). In addition, some measurements of NOx have been achieved by Yoon(4). Measured effects of shock waves on flame stability is the focus of this research.

A very efficient tool for supersonic flame stabilization is to generate subsonic recirculation zone. Flame-stabilizing-recirculation zone can be generated in various ways in supersonic flows, for example, by bluff-body-type flame holder, by contoured fuel injectors or can be observed in conjunction with fuel jets injected from the side walls without recirculation zone. The presence of the recirculation significantly slows down the flow velocity and thereby promotes ignition. Once ignited, combustion followed and the resulting flame will move into the flow field with characteristic flame propagation velocity. In order for the flame to be stabilized, the local flame speed balances the oppositely-directed local flow speed in the region of the leading segment of the flame. Considering that the laminar flame speed of hydrogen-air flame is 200-250 cm/s, fine-scale diffusive mixing and consequently reaction and flame holding are most likely to occur in local region of subsonic recirculating flows.

The present supersonic flame was stabilized along the axis of a Mach 2.5 wind tunnel using a thick-lipped fuel tube that acts as a bluff-body. Two identical small wedges on the tunnel sidewalls create oblique planar shock waves and the effects of position and strength of shock waves on flame stability limits were investigated. Previously, Winterfeld(5,6) studied flame stabilization of hydrogen-air mixtures in supersonic flow by means of recirculation zones. Winterfeld(5) interacted an oblique shock wave with a supersonic jet flame for a limited set of conditions and reported some preliminary results showing that the shock improved the flame blowout limits. Little else appears in the archival literature concerning a shock wave interacting with a turbulent jet flame; none of works quantified the shock effect on stabilization of supersonic hydrogen-air jet-like flames, which must be understood if scramjet engines are to become feasible. Motivated by this fact, the fundamental work in understanding and enhancing supersonic flame stabilization is investigated and presented.

2. Experimental Methods

Fig. 1 shows a schematic of the supersonic combustor and a coordinate system. The combustor is 55 cm long and to cross section in 5.7 cm by 4.1 cm at the fuel injection location. Two of the combustor sidewalls are parallel while the other two diverge at 4 from the axis in order to prevent thermal choking. Each of the four stainless steel sidewalls has a quartz window for optical access. The outside diameter of the fuel tube gradually changes from 2.54 cm at the end of the tube to 1.27 cm at the slightly upstream of the air nozzle throat, which is 24cm upstream. The inside diameter (d_F) is 0.70cm. A jet-like flame is stabilized on the axis of a Mach 2.5 wind tunnel using a thick-lipped fuel tube which acts as a bluff body. Hydrogen is injected at sonic speed and the fuel jet Reynolds number is typically 76,000. While the facility has an electrical air heater capable of heating the air to 1100 K, the stagnation temperature for all of the present flames is 285 K.

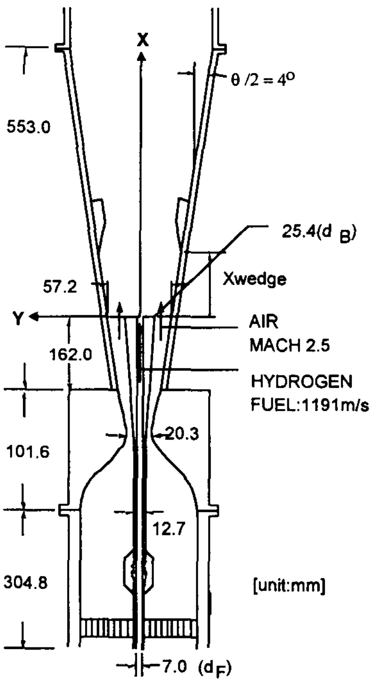
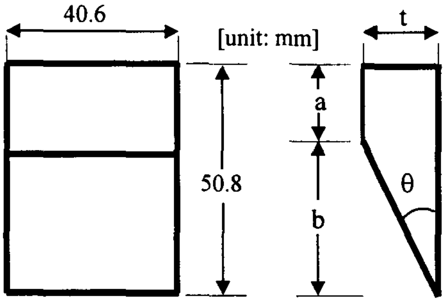


Fig. 1. Schematic diagram of the supersonic combustor.

Two identical wedges are mounted on the diverging sidewalls. The wedges span the entire 4.1cm width of the combustor and are flushed with the sidewalls, producing a 2-D planar oblique shock wave free from any observable edge effects. Fig. 2 illustrates a schematic of the shock-generating wedges. Each wedge is 5.08 cm long and has a same thickness of 0.56 cm; otherwise, flow blockage ratio will be different. Wedge angle (thus shock wave strength) was varied: 10°, 15°, 20°. Table 1 represents employed



Wedge	θ (degree)	a (mm)	b (mm)	t (mm)
1	10	18.8	32.0	5.6
2	15	29.8	21.0	5.6
3	20	35.3	15.5	5.6

Fig. 2. Schematic of shock-generating wedges.

Table 1. Shock wave generating wedges

Wedge	Wedge angle, degree	Deflection angle, degree	p_2/p_1	T_2/T_1
1	10	31.85	1.87	1.20
2	15	36.97	2.46	1.32
3	20	42.89	3.21	1.46

Table 2. Locations of wedge

Location	Up-stream	mid-upstream	mid-down-stream	Down-stream
X_{wedge}/d_F	1.0	4.0	8.5	11.5

shock-generating wedges. The pressure and temperature ratios shown in the table were calculated with the shock wave relation. Wedge location (thus shock wave position) was varied also. The locations of wedge are shown in Table 2. The locations of wedge were termed the upstream position, the mid-upstream position, the mid-downstream position, and the downstream position as shown in the table.

(a) Wedge 1 (10° wedge)

(b) Wedge 2 (15° wedge)

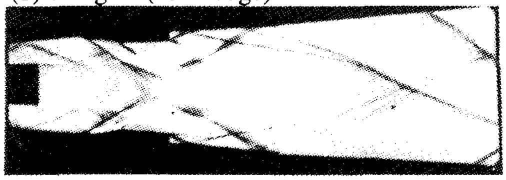
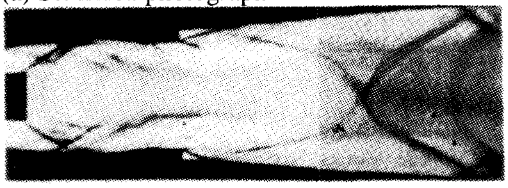


Fig. 3. Schlieren photographs of supersonic flows for two different wedge angles, with no combustion, wedges at mid-upstream location. ϕ= 0.035.

(a) Schlieren photograph



(c) Illustrative sketch

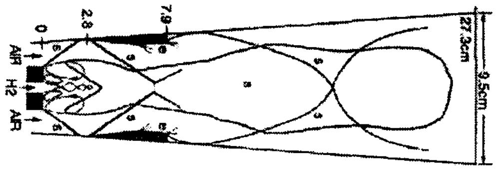


Fig. 4. Supersonic flame with shock wave interaction, wedge 1 at mid-upstream location. ϕ= 0.035.

3. Experimental Results and Discussion

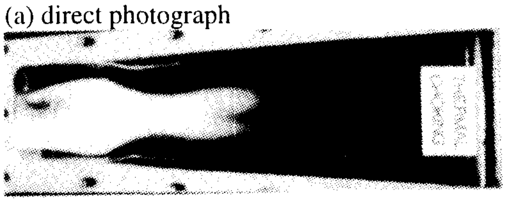
3.1 Observation of Flowfield

Fig. 3 shows Schlieren photographs of the nonreacting flow for two different wedge angles: 10° and 15°. Each Schlieren photograph shows two planar oblique shock waves which are generated by the two wedges that are described in Fig. 2. The location of the shock is 4.0 d_F, the mid-upstream location. The shocks appear more distinctly with no flame because the turbulent density gradients in the flame obscure the shocks within the flame. With wedge 2, Fig. 2(b) clearly shows the lengthening and thickening of wake. As Winterfeld$^{(5)}$ discussed, this appears to cause the elongated recirculation zone and it may affect the flame stabilization mechanism and enhance minimum blowout flame stability limits as will be discussed later.

The Schlieren photograph and illustrative sketch of a supersonic flame with shock wave interaction is in Fig. 4. The bluff-body stabilized flame has two recirculation zones; the inner recirculation zone shown is driven by the fuel jet while the other zone has recirculation in the opposite direction and is driven by the air flow. As seen in the schematic, the wedge produces a primary shock which crosses at the centerline and interacts with the upstream portion of the flame, near the liftoff location. The primary shock waves extend to the centerline within the flame shown in Fig. 4a, indicating that with combustion most of the flow downstream of the recirculation zone is supersonic. The wedge downstream corner forms expansion waves which direct the air toward the tunnel sidewalls and the highly curved recompression shocks realign the flow in the axial direction. Instead of expansion fan in a nonreacting flow, a strong oblique shock extends from the fuel tube outer lip to the outer tunnel wall. This is caused by the volumetric expansion of the highly-mixed flow behind the tube face into the path of the supersonic air stream and is a result of the overall increase in the combustor pressure level due to heat release(7).

Winterfeld(5) explained the mechanism of lengthening of recirculation zone due to shock wave interaction. In the recirculation zone, the local Mach number is well below 1. Thus, the pressure rise caused by the nozzle edge shock can propagate upstream in the wake. Due to recirculated combustion products, temperature is increased significantly within the recirculation zone. As a consequence, the density and the kinetic energy of the mass flow in the wake are small. If the kinetic energy is not sufficient to overcome the pressure rise in the wake, the flow is retarded until it comes to rest. The surrounding flow has to give way and thus the back-flow is set up and finally elongated the recirculation zone.

(a) direct photograph



(b) Schlieren photograph

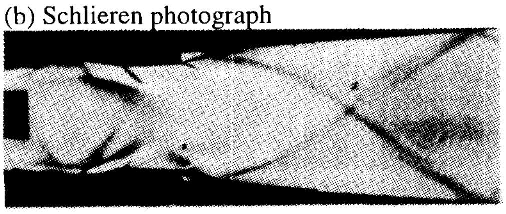


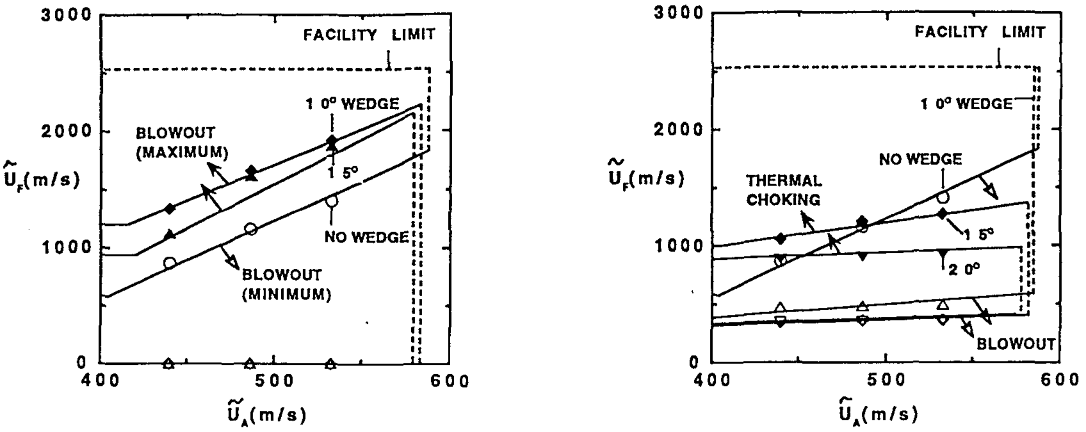
Fig. 5. Onset of thermal choking, with wedge 2 at mid-upstream location. Φ= 0.035.

3.2 Observation of thermal choking

A special case is shown in Fig. 5 for which the wedge angle is increased to 15° (wedge 2), resulting in thermal choking of the combustor. Fig. 5 illustrates the flame observed at the onset of thermal choking when two relatively strong shocks were used. Two 15° wedges (wedge 2) were located at the mid-upstream position as shown; the flame base is observed to move upstream and it surrounds the fuel tube, leading to dangerously high heat transfer rates. The schlieren image in Fig. 5 indicates that the flow is still supersonic, as evidenced by the shock waves. Further increase in the fuel flowrate will cause a strong normal shock wave to move upstream into the wind tunnel nozzle, and unstart the combustor.

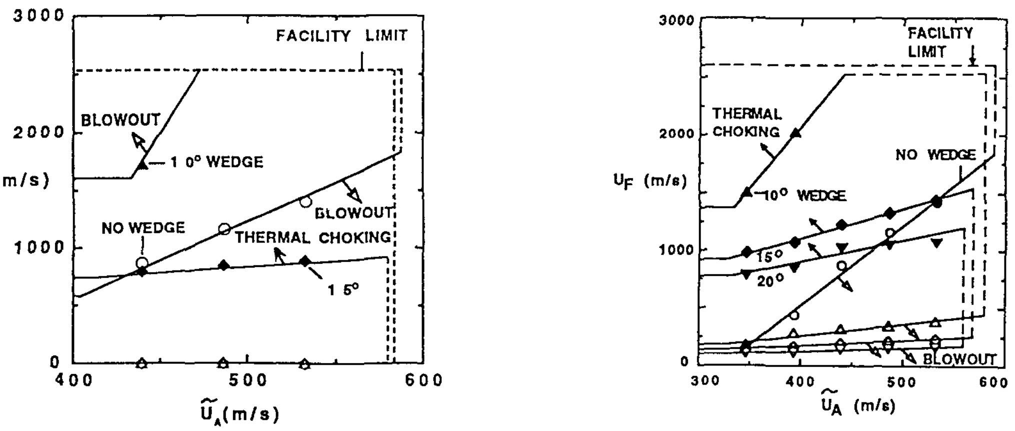
3.3 Flame Stability Limits

Shock waves have a pronounced effect on the flame stability limits that are plotted in Fig. 6. The hydrogen mass weighted velocity



(a) Upstream location

(c) mid-downstream location



(b) mid-upstream location

(d) downstream location

Fig. 6. Stability limits of supersonic flames for different values of wedge angle and wedge position.

is defined as the hydrogen mass flowrate divided by $\rho_{F,ref}$ $(\pi/4)$ d_F^2, where $\rho_{F,ref}$ is the density of fuel at the sonic fuel injector exit for the reference condition for which the fuel stagnation pressure and temperature are 3.7 atm and 285 K. In this study, $\rho_{F,ref}$ equals 0.026 kg/m^3. The mass weighted velocities are used because blowout limits are found to depend on both the velocities and densities of the fuel and air, and because mass flowrates are accurately measured while velocities must be inferred. The actual fuel exit velocity U_F equals the mass weighted value at the reference condition, but the two differ at other conditions. The air mass weighted velocity is the mass flow of air divided by $\rho_{A,ref}$ A_A where A_A is the area of combustor cross section (18.9 cm^2) at the fuel injector and $\rho_{A,ref}$ is 1.08 kg/m^3.

In Fig. 6, the location of wedge was varied to investigate the effect of wedge location on the flame stability limits. Previous work(1) has shown that with no shock waves, stability limits of supersonic flames are similar in shape to those of subsonic bluff-body flames and swirl-stabilized flames(8~10) which also contain recirculation zones. Fig. 6 shows four enclosed regions within which stable flames occur. For conditions above the enclosed regions, either blowout or thermal choking occurs. For conditions below the enclosed regions, blowout occurs. Three blowout limits usually exist, corresponding to a maximum fuel flowrate, a minimum fuel flowrate, and a maximum air flowrate. Fig. 6 quantifies the minimum fuel blowout limit for the no wedge case. It was not possible to achieve a maximum fuel flowrate or a maximum air flowrate for the no wedge case due to limited gas supplies, so the dashed lines indicate the maximum fuel and air mass weighted velocities at which stable flames were achieved. Increasing the shock strength (wedge angle) decreases the thermal choking limit and the minimum fuel blowout limit. The shock waves (and wedges) also reduce the maximum fuel flowrate, which is the upper boundary of the stable regions in Fig. 6. However, this thermal choking limit is a facility-dependent limit rather than a general limit. It is concluded that shock waves significantly stabilize the flame by reducing the minimum fuel blowout limit in Fig. 6. Since the present flames cannot be stabilized unless there is a sufficiently large bluff-body recirculation zone, it follows that the improved stability, caused by the shock waves, results from some type of interaction between the recirculation zone and the shock waves. Vorticity created by the shock wave(8) also may aid in enhancing mixing and flame stabilization.

The distributions of the wall static pressure

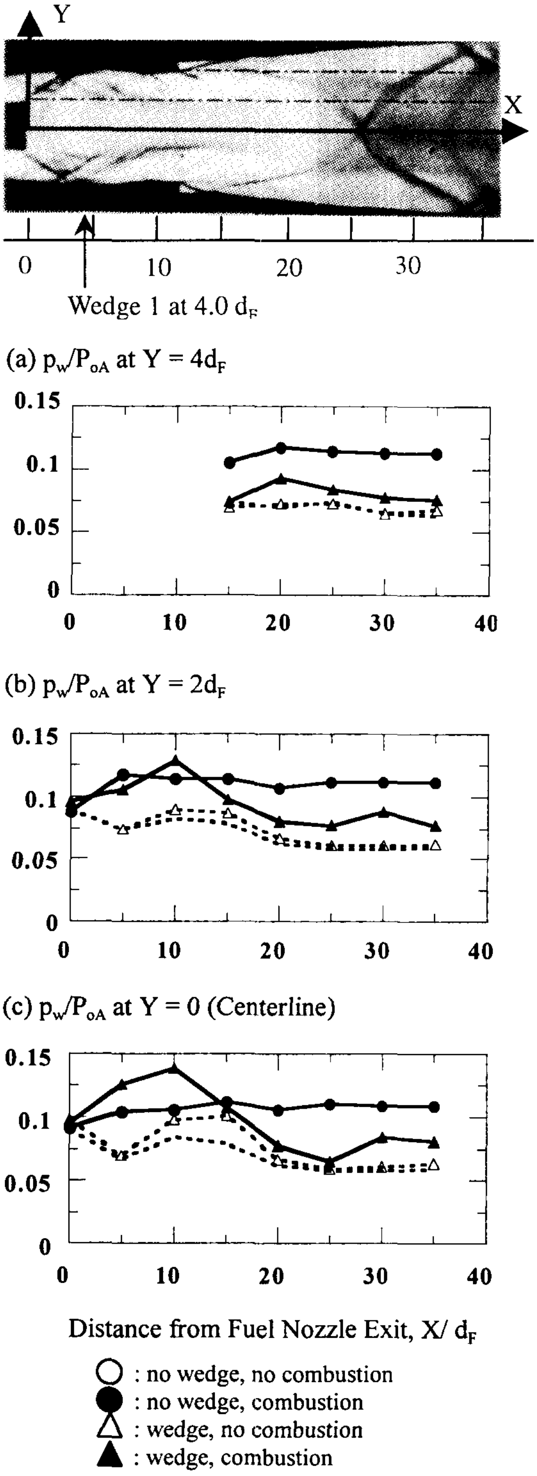


Fig. 7. Normalized Wall static pressure distribution, with and without combustion, with and without wedge. ϕ= 0.035.

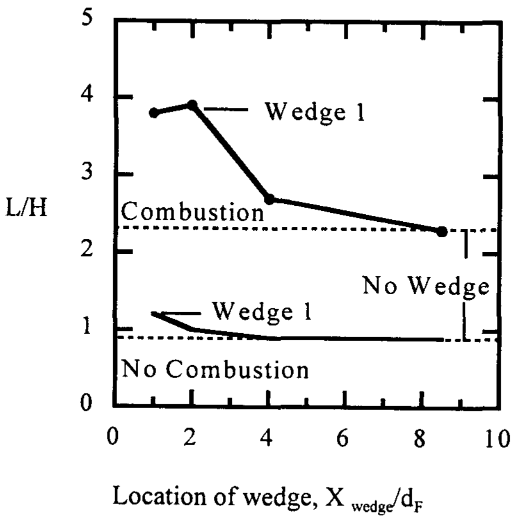


Fig. 8. Effect of shock waves on the size of recirculation zone (taken from Kim, et al.(11)). H = thickness of nozzle lip.

normalized by upstream total pressure are shown in Fig. 7. With volumetric expansion due to heat release, wall static pressures of combustion case are always greater than those of no combustion case. Fig. 7 clearly shows strong adverse pressure gradient in the upstream region ($X/d_F < 10$), with wedge and combustion. The strong adverse pressure gradient caused by primary shock waves and wedges can increase the size of an existing recirculation zone(5,11).

Recently, Kim et al.(11) reported elongated recirculation zone due to combustion and shock waves. Fig. 8 shows their numerical result. As is known from the results on subsonic combustion, the recirculation zone is lengthened when a flame is buring at the flame holder. Fig. 8 indicates that with combustion, the size of recirculation zone is elongated by a factor of 2.5 compared to corresponding nonreacting case. Shock waves further elongated the recirculation zone. Especially when a wedge was located in upstream region, the recirculation zone was elongated dramatically. Winterfeld(5) reported the measured increase L/d_F amounts to a factor of about 1.6 to 1.7.

4. Conclusions

Measured shock effects were investigated by changing shock strength and position with particular emphasis on the stability limits of supersonic hydrogen-air jet flames. Flame stability limits (flame blowout limits and thermal choking limits), wall static pressures, and Schlieren visualization pictures were measured and compared to corresponding flames without shock-flame interaction.

The major conclusions of the present study are as follows:

(1) Shock waves greatly enhance one of the flame stability limits, namely the blowout limit that is associated with a minimum fuel velocity. One explanation is that the adverse pressure gradient caused by the shock wave can enlarge the flame-stabilizing subsonic recirculation zone behind the flameholder. Measured wall static pressures indicate the strong pressure gradient caused by the shock waves and combustion.

(2) Shock waves (and/or the wedges used to create shocks) have an adverse effect on another flame stability limit, namely the maximum fuel velocity limit prior to thermal choking. Photographs show that thermal choking, which is purposely used in "dual mode" scramjet operations, causes the present flames to move upstream and surround the flameholder, leading to dangerous heat transfer rates. However, this thermal choking limit appears to be a

facility-dependant limit rather than a general limit.

(3) Effect of shock location draws no general conclusion. However, since minimum blowout limit is lowered significantly, wedge locations at either upstream or mid-upstream appear to show better results.

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