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Effect of suction on a sort of supersonic inlet

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Abstract

The influence of boundary layer suction on the aerodynamic performance of a two-dimensional mixed compression variable geometry inlet was studied. The preliminary calculation results show that the main reason of the inlet's unstarting is the obstruction of throat caused by the smaller area of it. In this paper, the design of the suction scheme is carried out, and the suction is carried out in the severely separated part of the area. The ultimate goal is to design a relatively excellent suction scheme: when the inlet does not start, improving the the aerodynamic performance of the inlet to guarantee its starting. Improving the aerodynamic performance of the inlet as much as possible after its starting.And the influence of suction on the aerodynamic performance of inlet is studied.

Keywords: variable geometry inlet, boundary layer suction, porous plate.

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Nomenclature

X – X axis coordinate
Y – Y axis coordinate
Z – Z axis coordinate
Greek
σ – total pressure recovery
ε – Opening rate of plate
φ – mass flow rate
Ma – Mach number of inflow at inlet isolator
V_0 – velocity of inflow
V – velocity

1. Introduction

The supersonic and hypersonic propulsion systems will generate the boundary layer with a certain thickness when they are running. The existence of the boundary layer has a significant impact on the flow field in the internal channel of the whole propulsion system, the aerodynamic performance of the aircraft and the operating range of them. The flow field of the ramjet inlet is complex,which including viscous flow mainly and the interaction between shock waves,shock wave and boundary layer. For the ramjet inlet, the effective control of the flow separation in the inlet can obviously improve the starting performance and the aerodynamic performance of the inlet, then ensuring the normal operation of the entire aircraft at design point.

Boundary layer suction is a flow control method that can reduce the thickness of boundary layer and enlarge the velocity of airflow near the wall by removing part of fluid in the boundary layer (suction and stripping). At present, domestic experts and scholars have done a lot of research on the structure of the wave system before the throat, the shock wave and boundary layer interference before the throat, and boundary layer suction [1-2]. The relationship among pressure difference, thickness-diameter ratio and opening rate of the boundary layer suction is established by experiments on the porous plate[3-4]. The numerical simulation results are in agreement with the experimental results. The results show that the given boundary conditions of the boundary layer suction are correct and feasible. The results obtained by this method show that the suction position and flow rate have a significant effect on the performance of the two-dimensional hypersonic inlet [5], and the upper throat area suction has a better effect on the performance of the inlet. The effect of suction on starting, restarting ability and improving the maximum backpressure of hypersonic inlet is more obvious[6-7].The results of numerical simulation of a hypersonic inlet side-pressed show that the suction can significantly improve the self-starting performance of the inlet and the effect of suction on the separated zone of flow field is pretty good. Wind tunnel test verifies the effectiveness of suction on improving the self-starting performance of the inlet [8]. Numerical simulation was used to study the simultaneous suction of multiple positions in the inlet model[9]. The occurrence and development of secondary flow in the external compression section and the internal contraction section and the influence of suction on the boundary layer were analyzed. The influence of different suction positions on the total pressure recovery coefficient of inlet was studied by experiments[10].The effect of suction on the performance of different types of inlets is studied[11-13]. Foreign research results show that shock-boudary layer flow separation can be achieved by controlling shock-boudary layer interactions with boundary layer suction, blowing through microarrays and suppressing shock boundary layer flow separation through small slopes.

In this paper,a variable geometry inlet is studied and compared with single-area and multi-area suction respectively,and the effect of the suction opening rate on the performance of inlet and the comparison of the inlet performance before and after suction are studied. Finally,a better suction scheme is determined to make the inlet work properly.The boundary condition of boundary layer suction proposed in reference [3] is used to simulate the wall of inlet plate which need suction. The UDF command in Fluent software is set to simulate the wall.The method has been verified by many domestic experts and scholars, and the numerical simulation results are reasonable and feasible. Therefore, the UDF function is used to complete the numerical simulation of suction control in some areas. Five areas of A,B,C,D and E were selected from the inner contraction section between the inlet and the throat, and the suction boundary layer was set up in the above areas. The main parameter involved in the suction boundary layer is the suction opening rate, which is defined as the ratio of the total area of the suction hole to the total area of the wall of the plate which need suction.The letter of opening rate is "ε".

2. Physical models and Calculation methods

2.1. Physical models

In this paper, a two-dimensional mixed compression inlet with the adjustable throat is studied. The diagram is given in Fig. 1 and Fig. 2. The inlet external compression section are three stages and the compression angles are 7, 5 and 4 degrees. The variable geometry structure is adopted at the throat, and the lower wall of the throat is an adjustable plate. Three plate positions 1, 2 and 3 correspond to different throat contraction ratios,they were 1.10, 1.43 and 2.25 respectively. When the throat is at location 2 and 3, the inlet can not start easily. Therefore, it is preliminarily considered to install a flood relief channel at the throat. The expansion section of inlet is gradually transforming into a circular outlet with a diameter of 70 mm by a square-to-circular design.

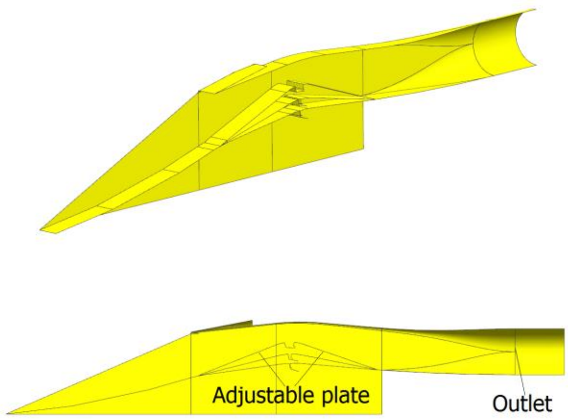


Fig 1. Model of the variable geometry inlet

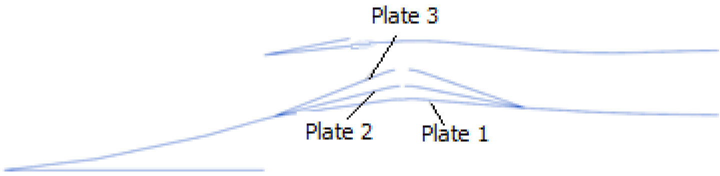


Fig 2. Two-dimensional line of the adjustable plate of inlet

2.2. Numerical calculation method and Grid

Ansys Fluent numerical simulation software is used for calculation. The finite volume method based on density is used to solve the N-S equation. The turbulence model is SA model. The flux space is discretized with second-order accuracy and the time is implicitly advanced. The convergence criterion uses the equations of continuous equation, momentum equation and energy equation. Structured grids are used to fill the computational domain, and local areas are densified to better capture shock waves. The inlet boundary condition is the far pressure field, the outlet is the pressure outlet, and the symmetrical boundary condition is used to calculate the 1/2 flow field. The non-slip adiabatic boundary is used to calculate the wall as shown in Fig. 3.

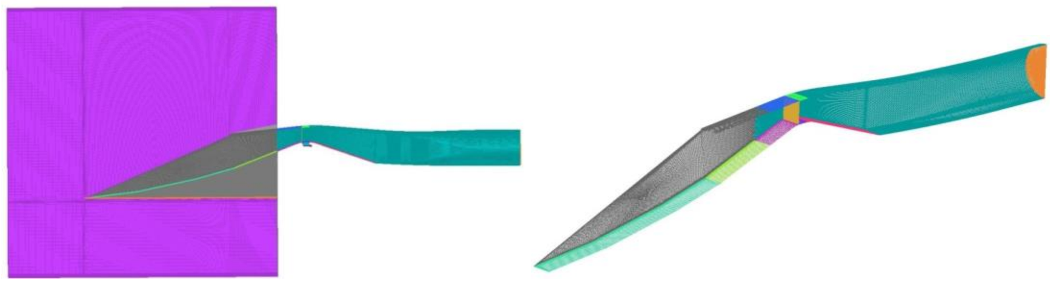


Fig 3. The flow field and grid of inlet

The designed Mach number of inlet is Ma=3.0, and Mach number of inflow is Ma=1.8, Ma=2.0, Ma=2.5 and Ma=3.5,corresponding to different flight altitudes. The angles of attack are all 0 degrees, and the side slip angles are all 0 degrees. Different inflow conditions correspond to different plate positions, as shown in Table 1.

Table 1. Different throat positions corresponding to the the plate positions

Position of plate	Mach number of inflow
position 1	Ma＝1.8 Ma＝2.0
position 2	Ma＝2.5
position 3	Ma＝3.0 Ma＝3.5

3. Analysis of calculation results without suction

Fig. 4 shows that the equivalence diagram of Mach number in the flow field on the symmetrical plane XY (Z =0m) and the selected side surface (Z =-0.025m) near the side wall of the inlet.

When the adjustable plate is at position 1 and Mach number of inflow is 2.0, the flow separation of the internal flow field is small, the shock wave is stable in the internal compression section, and the inlet can start.

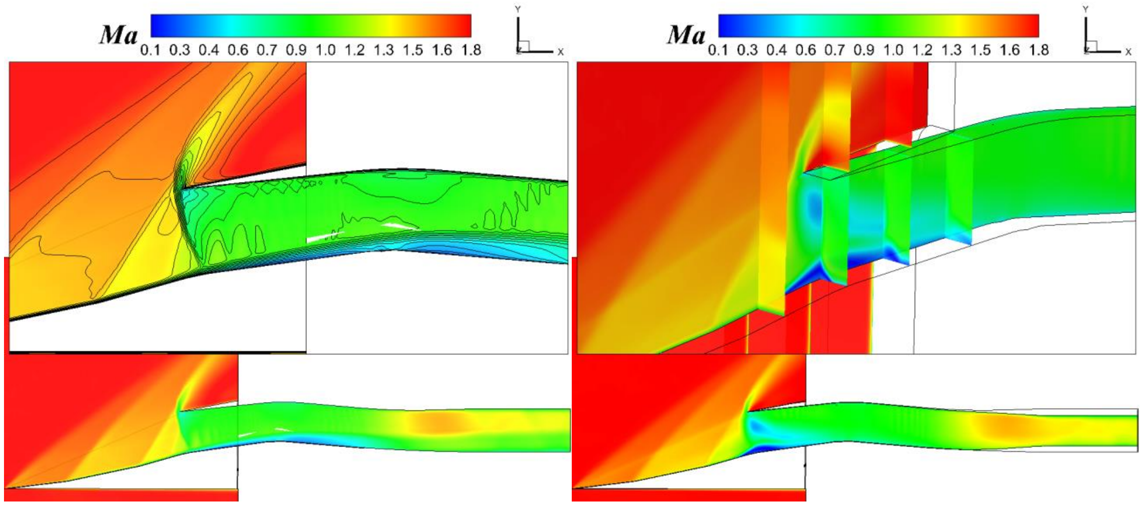
When the adjustable plate is at position 1 and Mach number of inflow is 1.8, the shock wave on the symmetric surface is stable in the internal compression section, and there is a part of low velocity area on the lower wall of the internal compression section befoe the throat, while the flow separation is small during the transition from the symmetrical surface to the selected side surface, and a small flow separation is formed near the selected side surface.

When the adjustable plate is at position 2 and Mach number of inflow is 2.5, the shock wave on the symmetrical surface of the flow field is stable in the internal compression section, and small flow separation occurs in the upper and lower wall of the throat. The flow separation occurs during the transition from the symmetrical to the side wall of inlet, and the flow separation is larger when it is closer to the side wall. When the adjustable plate of throat is adjusted at 2.0 degrees, the flow field in the inlet is better, and the flow separation in front of throat is obviously eliminated. Although there is a small flow separation near the side wall of inlet, the performance of inlet has been improved significantly.

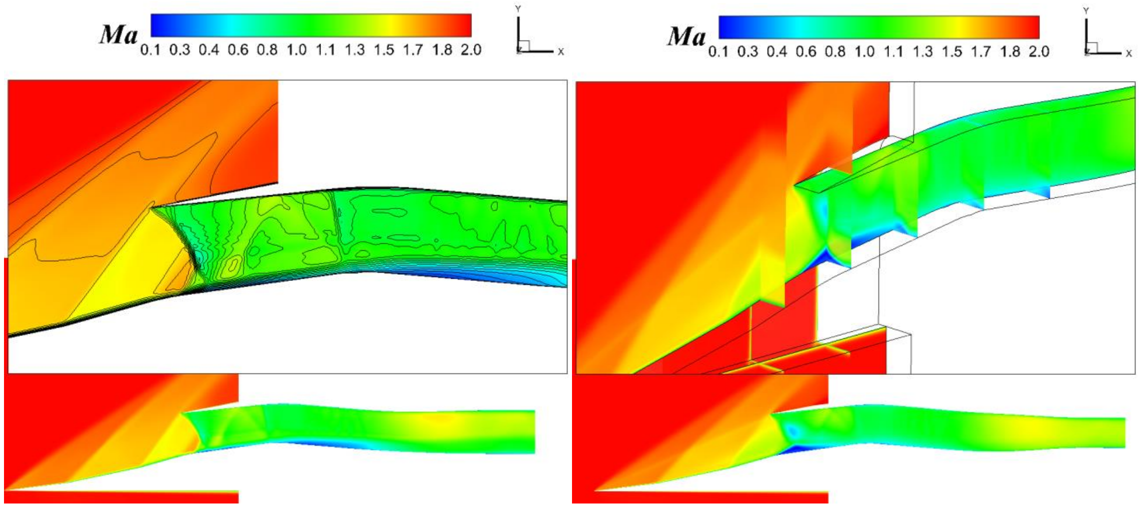
When the adjustable plate is at position 3 and Mach number of inflow is 3.0, the throat contraction ratio is 2.25. There is a narrow and thick flow separation between the second compression surface of the external compression section and the inlet throat. The flow field is bad and the inlet does not start.

The flow field of the inlet under the designed condition is analyzed, as shown in Fig. 5. When Mach number of the throat decreases to 1.3, there is no obvious flow separation near the throat. When Mach number of the throat decreases to 1.04, the boundary layer near the throat gradually develops toward the inlet direction, and finally a large flow separation is formed in the compression section of the inlet and the inlet does not start. According to the development trend of the flow field in the throat and its upstream area with different calculating steps, it is concluded that the cause of the unstart of inlet is the throat congestion.

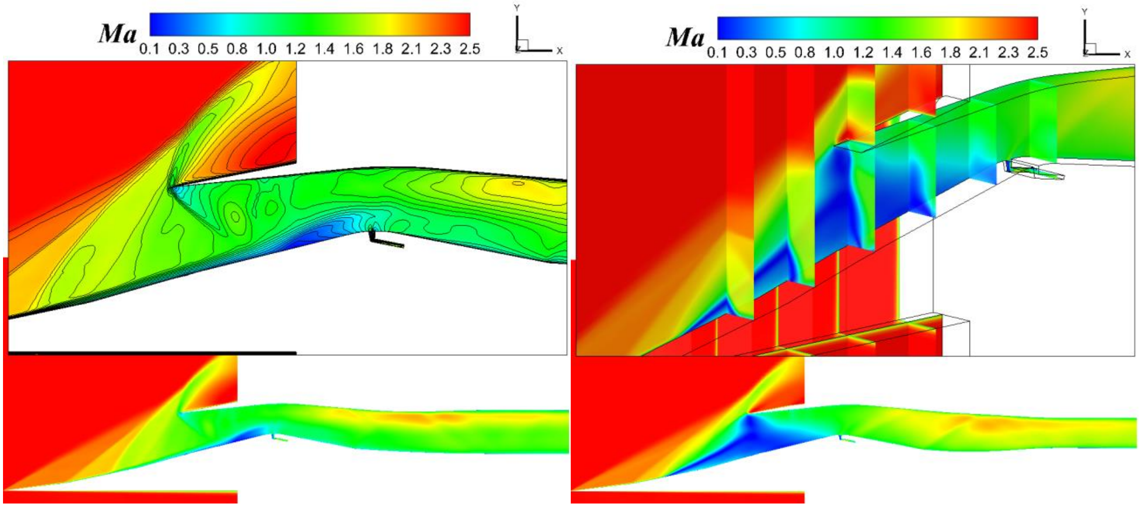
When the adjustable plate is at position 3 and Mach number of inflow is Ma=3.5, the inlet can start, and there is a small flow separation in the internal channel.



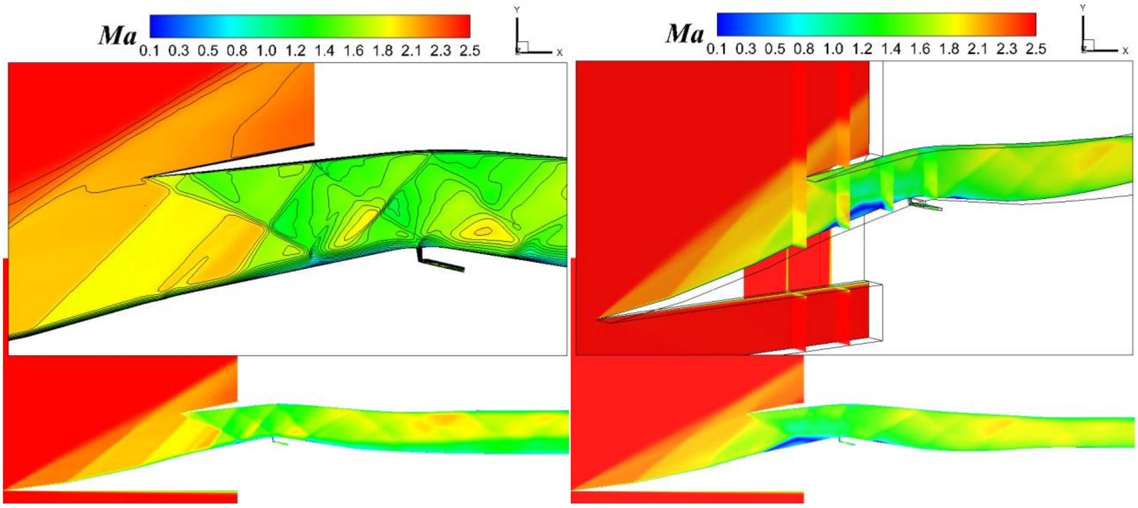
(a)Position 1,Ma=1.8



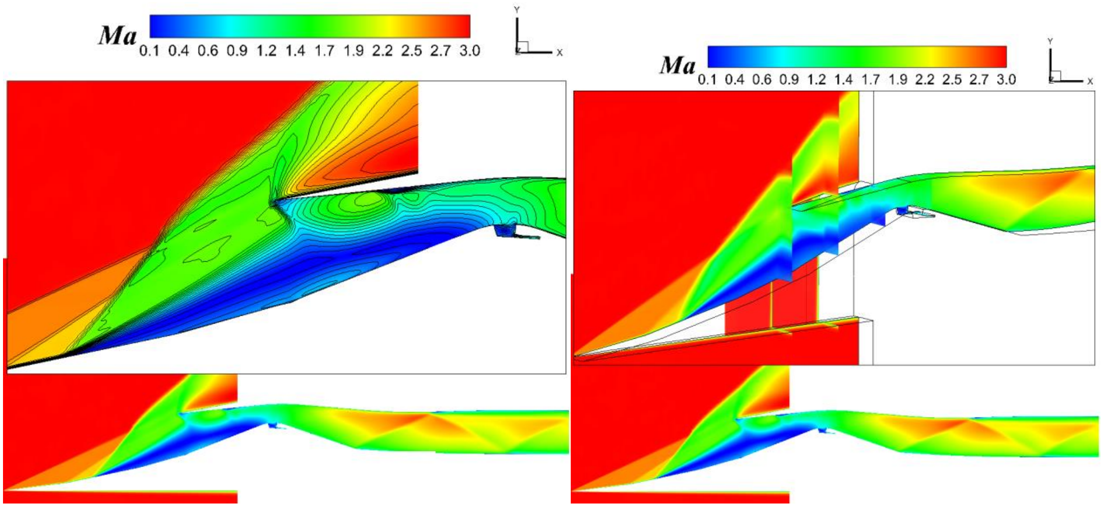
(b)position 1,Ma=2.0



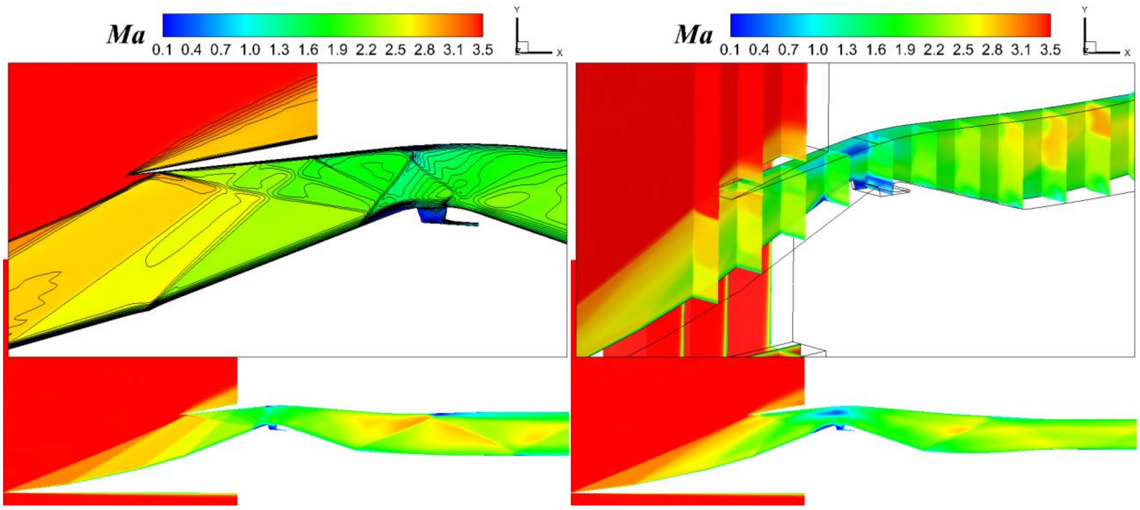
(c)position 2,Ma=2.5



(d)position 2,Ma=2.5-2°

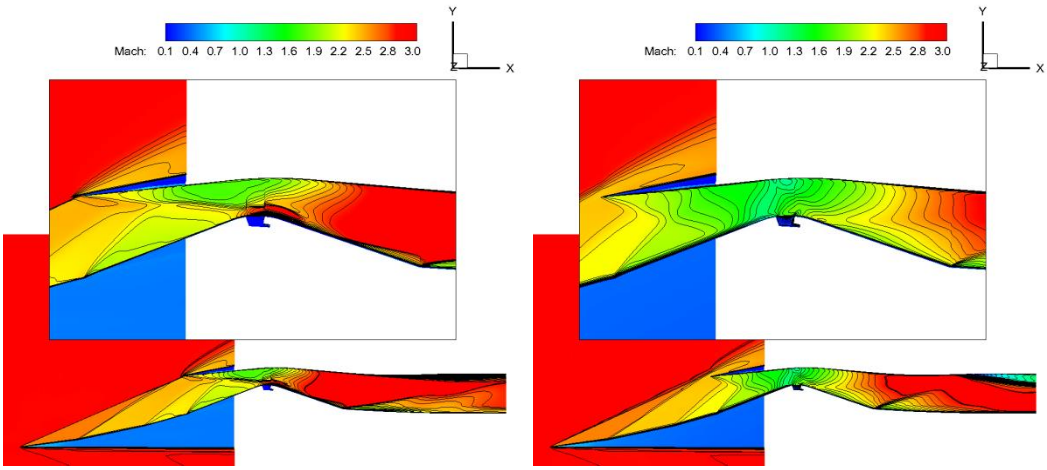


（e）position 3,Ma=3.0

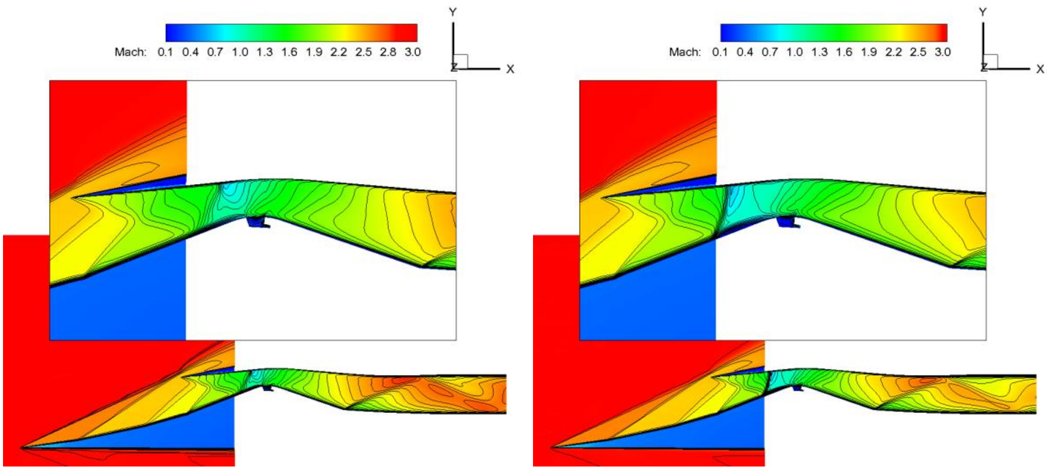


（F）position 3,Ma=3.5

Fig 4. Mach number contour map of inlet



(a) (b)



(c) (d)

Fig 5. Variation of Mach number contour map of at designed point

In order to ensure that the inlet can work normally at design point, it is necessary to take measures to remove the boundary layer to eliminate large-scale flow separation near the throat, enlarge the aerodynamic throat and eliminate the throat congestion. The following is the design of the suction scheme.

4. Analysis of calculation results with suction

According to the designed characteristics of the inlet and the data obtained from the previous calculation, the area A ,B and C is studied after analysis. The inlet condition is Ma = 3.0, the angle of attack is 0 degrees and the side slip angle is also 0 degrees.

This process is divided into the following aspects:

(1) the effects and differences of suction in different areas;

(2) when the suctioned area is the same, the influence of different opening rates of suctioned plates on aerodynamic parameters;

(3) the coupling effects of simultaneous suctioning in different areas;

(4) comparison of aerodynamic performance before and after suction.

4.1. Influence of suction position on inlet performance

4.1.1. Calculation of initial model with suction

First, suction at different areas, and the suctioned area is divided into five areas of A,B,C,D and E, as shown in Fig. 6. The research and analysis show that the area D needs to be suctioned more to start the inlet, and the area E has less effect on the starting performance of inlet. Therefore, the three areas of A,B and C are studied emphatically. Each area is suctioned respectively, and the opening rate is 20%. At the same time, the suctioned areas of suctioned plates are guaranteed to be the same.

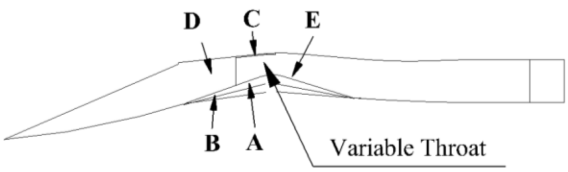


Fig 6. Sketch map of suctioned areas

As shown in Table 2, when the area of throat is increased, suctioning respectively in three areas of A ,B and C with the opening rate is 20%, the area A, B and C is not ideal and the inlet does not start. At this point, the main reason for the inlet not to start is still that the throat area is too small, resulting in a large-scale flow separation near the throat, the inlet does not start.

Considering the increasing opening rate of plate suctioned, other parameters remain constant.

Increasing the opening rate of area C by 35% will increase the overall suction area of the area, and the inlet will not start at this time.

When the opening rate of area A is increased by 35%, and the suction flow rate of area A is significantly increased, the inlet still does not start. It can be seen that it is difficult to start the inlet by suction in area A alone at this plate position.

In conclusion, when the plates are in initial position, area A ,B and C suctioned respectively is not ideal, the inlet can not start.

Table 2. Result of suction on single area

Position	A	A	B	B	C	C
ε	20%	35%	20%	35%	20%	35%
Start	×	×	×	×	×	×

4.1.2. Analysis of calculation results on area D,E

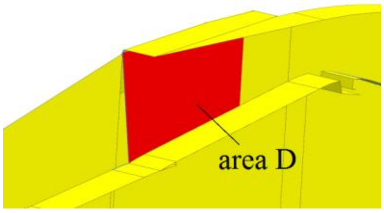


Fig 7. Sketch map of suctioned area D

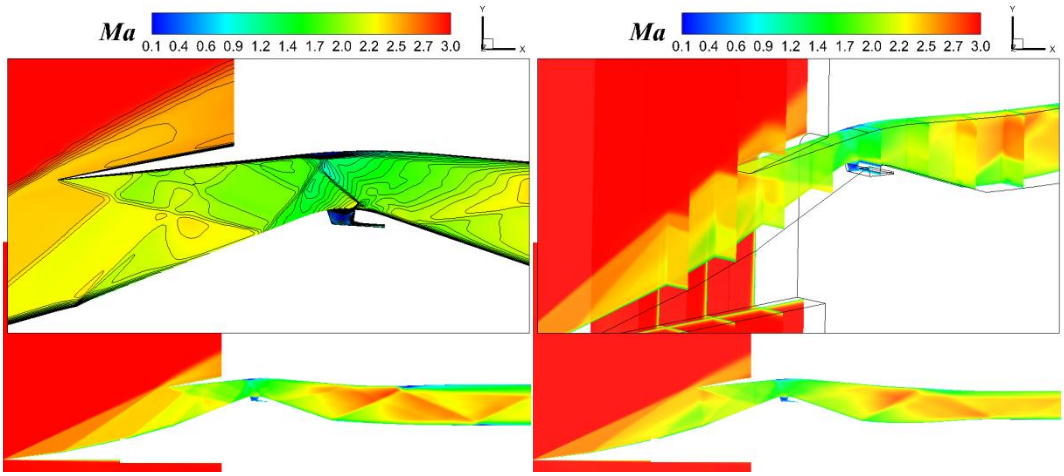


Fig 8. Mach number contour map of inlet

As shown in Fig. 7 and Fig. 8, the total area of the suction area and the suction opening rate are adjusted to ensure that the effective suction area is the same as the above, and the inlet does not start at this time. If the area A-B-D is suctioned, the suction flow coefficient is large when the inlet can start. If the area D suctioned is too large, the performance of the inlet will be not so ideal.

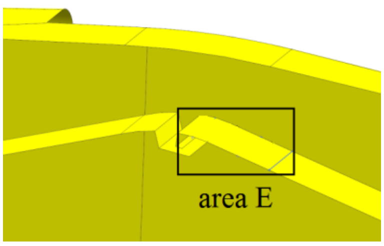


Fig 9. Sketch map of suction area E

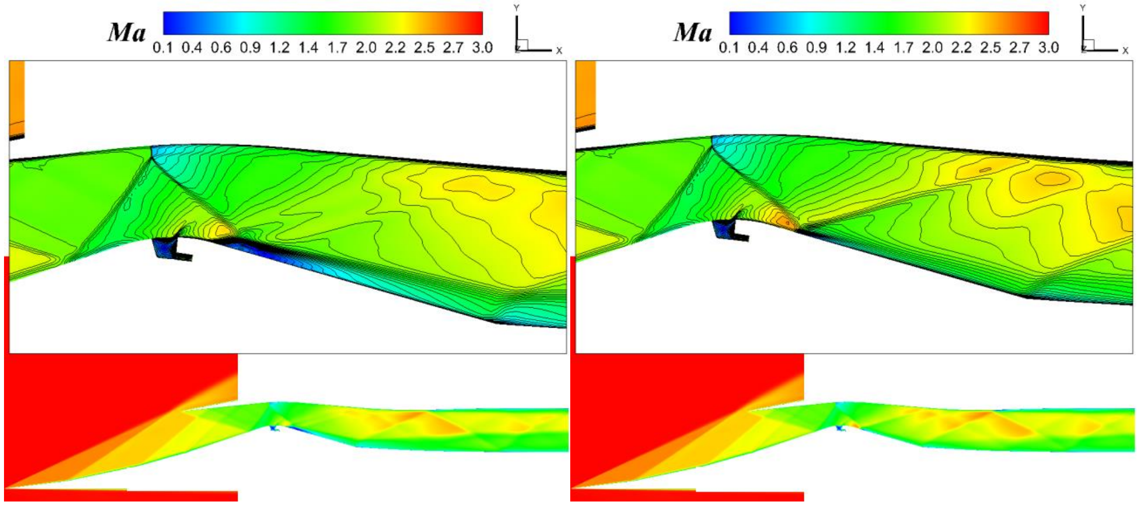


Fig 10. Mach number contour map of inlet

As shown in Fig. 9 and Fig. 10, it is difficult for inlet to start only when the area E is suctioned, but also when the other areas of the inlet are suctioned and the opening rate is larger. After suctioning in area E of inlet and inlet is starting, the flow separation phenomenon behind the throat disappears obviously.After suctioning,the pressure ratio of throat and outlet is slightly affected,but other aerodynamic parameters are not affected obviously.

4.1.3. Calculation of suction after adjusting throat

Because the initial design of inlet can not start when the suction opening rate is as high as 35% in a single area, it is impossible to compare and analyze the specific effects of suction on the inlet aerodynamic performance parameters at this time. After calculating and comparing, a group of effective results are obtained after adjusting the size of inlet throat (increasing the throat area by adjusting the angle of adjustable plate position, the specific angle is 1.9 degrees). The following is shown in Table 3.

Table 3. Result of suction on single area

Position	A	B	C	C
ε	0.20	0.20	0.20	0.21
Start	√	×	×	×

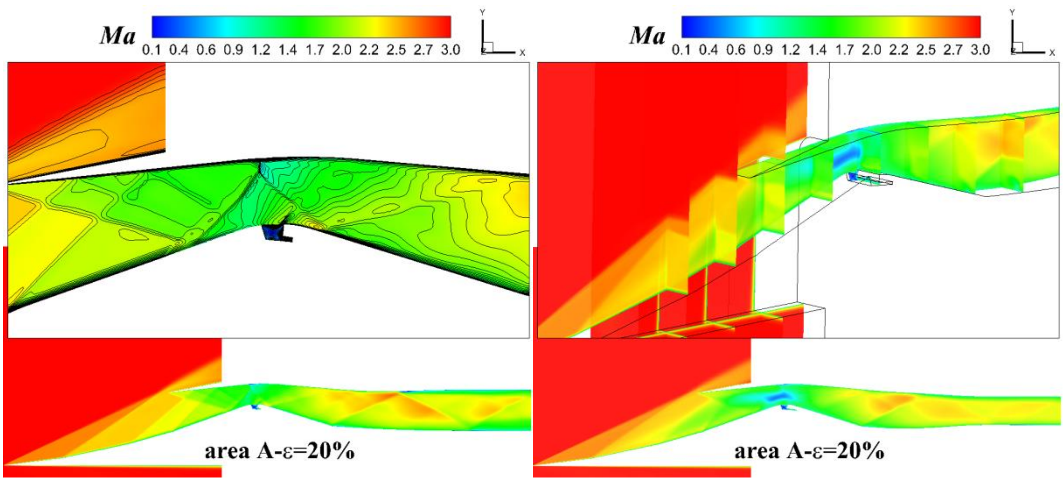


Fig 11. Mach number contour map of inlet

Fig. 11 shows the Mach number contour map of that suctioning in area A and the inlet is starting.

Combining with the results Table 3, it can be seen that when A,B and C is suctioned respectively, the effect of suction in area B and area C is not ideal, and the inlet does not start.The inlet can start when area A is suctioned. At this time, the structure of the internal shock wave in the inlet is more regular and the shock wave can keep stable, there is no large-scale flow separation in the upper wall of the throat,and there is no boundary layer low-energy flow in this area.

Increasing the opening rate of area C by 21%, the overall effective suctioned area of area C is larger than that of area A and area B, and the inlet still does not start. This indicates that the suction effect on C area is not ideal.

It is shown that the suction effect of area A is better than that of B and C under the same suctioned area.

4.2. Influence of opening rate on the performance of inlet

There are suction opening rates 5%, 8%, 10%, 12% and 15% to be used on the plates. Suction was carried out for area A, area A-B and area A-B-C. The influence of different opening rates on typical aerodynamic parameters of inlet is studied.

When area A-B is suctioned at the same time, the aerodynamic parameters change little in a short period of time, but the flow field is unstable. After a short period of near-stable state, the flow field becomes bad and the inlet does not start.

Fig. 12 shows a comparison diagram of aerodynamic parameters corresponding to different opening rates. With the increase of the opening rate, the flow coefficient of the inlet decreases and the total pressure recovery coefficient at the inlet outlet increases. This is because the boundary layer area at the wall decreases correspondingly with the increase of the suction opening rate, and a part of the low energy flow is suctioned out. At the same time, the more the area involved in the suction, the smaller the flow coefficient of the inlet, and the greater the total pressure recovery coefficient of the inlet. This is because the removal effect of the boundary layer increases with the increase of suction area.

Considering that the engineering realizability and material requirements have certain limitations on the wall opening, the opening rate should be as small as possible under the premise of the normal operation of the inlet.

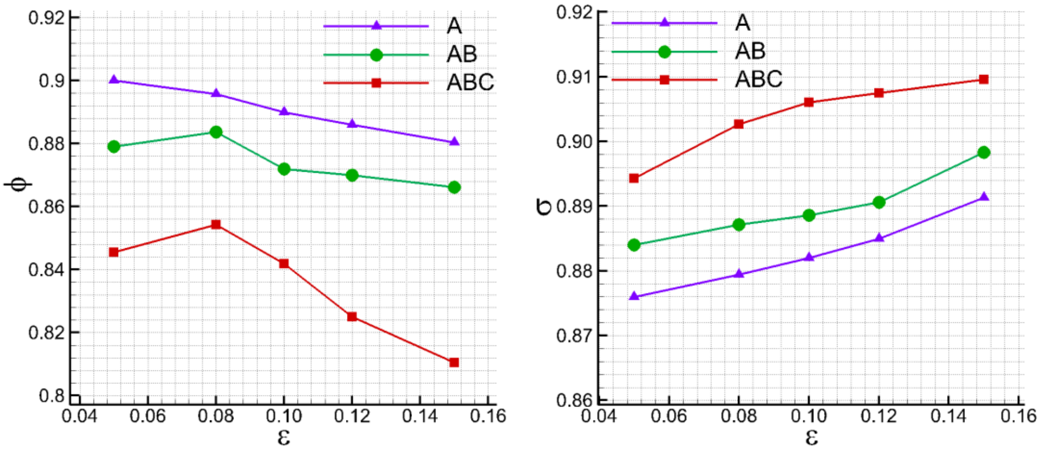


Fig 12. Comparison of aerodynamic parameters corresponding to the different opening rate

4.3. Influence of multiple suction areas on the performance of inlet

This section shows the influence of the coupling effect on the starting performance of suctioning in multiple suction areas, such as combinatorial area A-B, A-C, B-C and A-B-C. Table 4 and Table 5 show the results.

When the opening rate of area A-B is 20%, the wave system is stable, the thick flow separation in the inner flow field disappears, inlet is closed to starting state.It can not start when the opening rate is 8% and 15%.

The inlet can not start normally when the opening rate are at 8%, 15% and 20%, but it is closer to the critical starting state when the area A-C is suctioned, and the wave system can keep relatively stable before the shock wave is launched, which is better than the scheme that suctioning in the area B-C.

When area B-C or A-C is suctioned,Mach number of the throat is about 1. Although there is no obvious and large flow separation between the internal and external compression section near the throat, the shock wave has been pushed out.

The inlet does not start when the opening rate of area A-B-C is 12%, so it can be preliminarily concluded that the area A-B-C must be suctioned at the same time when inlet can start, but it is observed that the flow field of A-B-C can maintain relatively stable for a period of time, approaching the starting state, and then the shock wave is pushed out of the inlet. Therefore, the optimum opening rate of the boundary layer is 12% to 15%.

The inlet can start when the opening rate of area A-B-C is 15%, at this time the inlet internal wave system structure is more regular, there is no obvious flow separation near the upstream of throat, the total pressure recovery coefficient at the throat significantly increased,Mach number of throat is larger than that without starting, except for a small part of the downstream of throat,the thick flow separation of the internal flow passage of inlet mostly disappeared.

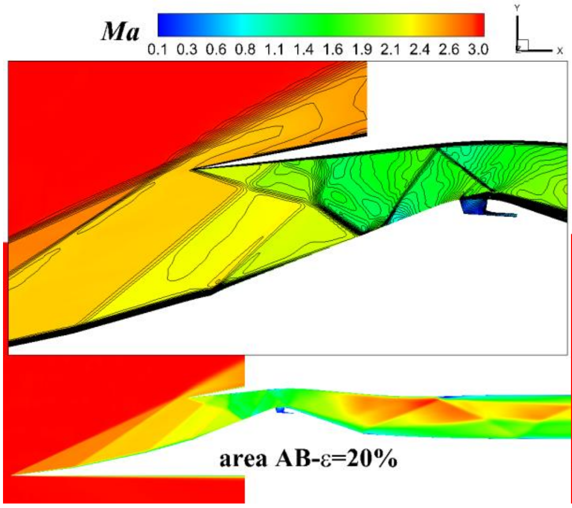
Table 4. Result of suction on multiple area

Position	**AB**			**AC**		
ε	8%	15%	20%	8%	15%	20%
Start	×	×	√	×	×	×

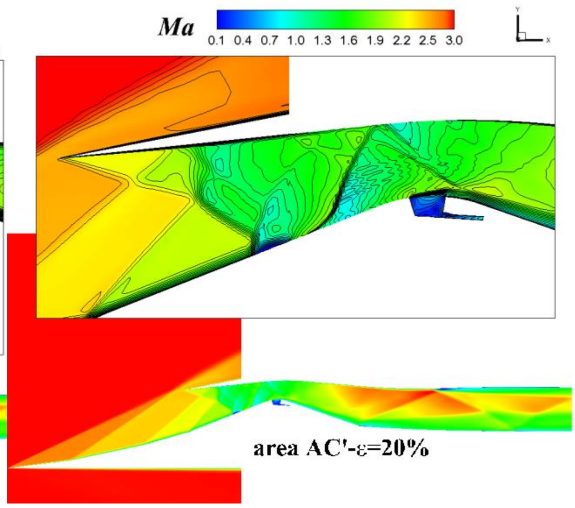
Table 5. Result of suction on multiple area

Position	**BC**			**ABC**		
ε	8%	15%	20%	8%	12%	15%
Start	×	×	×	×	×	√

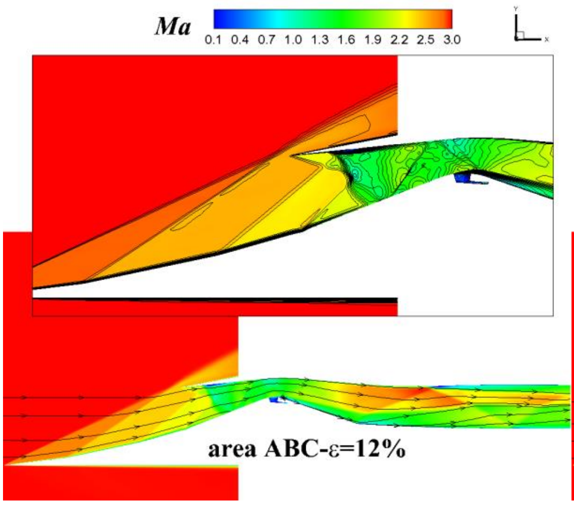
Fig. 13 shows Mach number contour map of the flow field.



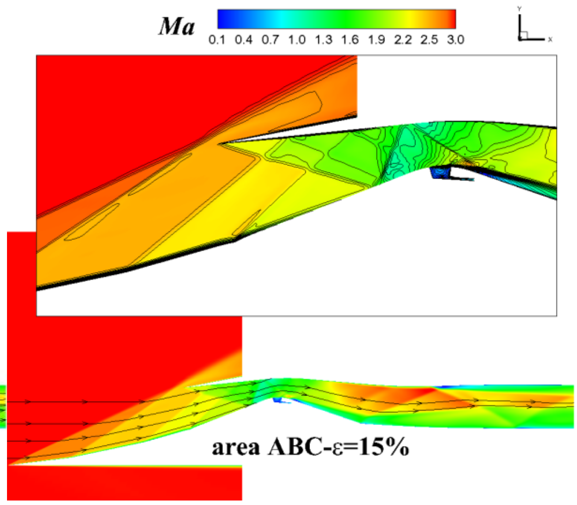
(1) arae A-B,Ɛ=20%



(2) arae A-C,Ɛ=20%



(3) arae A-B-C,Ɛ=12%



(4) arae ABC,Ɛ=15%

Fig 13. Mach number contour map of inlet

In summary, compared with area A-C and B-C,area A-B has the better effect with suction because the suctioned combined areas can effectively eliminate the flow separation caused by throat congestion, then improving the starting performance of the inlet, but at this time the minimum opening rate of the plate to guarantee the starting of inlet is larger, while the three areas of A-B-C are suctioned at the same time. It can disperse the suction flow of the single suctioned area to reduce the opening rate and ensure the effect of improving the starting performance of inlet.

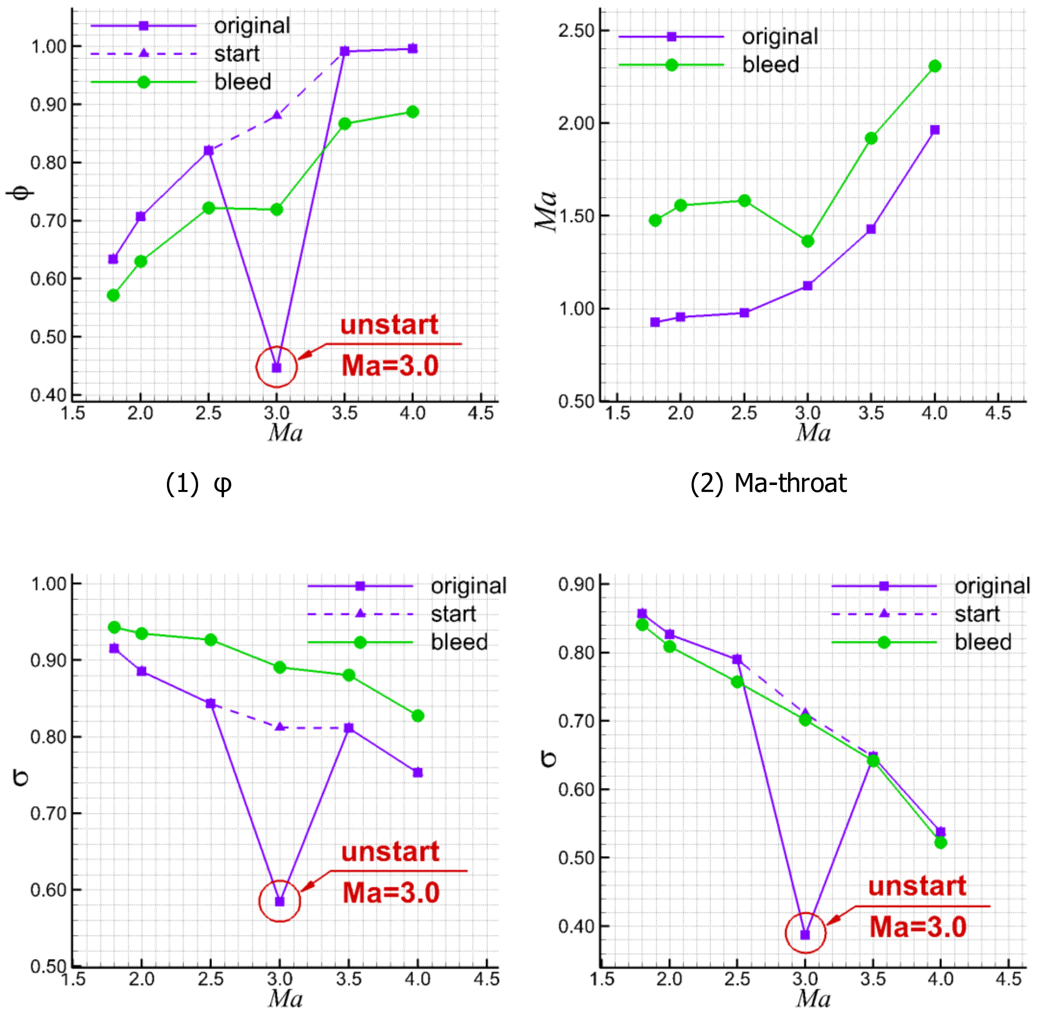
4.4. Comparison of performance before and after suction on inlet

The aerodynamic and the starting performance of inlet before and after suction were compared and analyzed.

Compared the results of A,B,C suction scheme with that of non-suction scheme, the curves of several typical aerodynamic parameters varying with Mach number are given in Fig. 14.

The diagram shows that the flow coefficient of inlet decreases,Mach number of throat increases, the total pressure recovery coefficient of throat increases, the total pressure recovery coefficient of outlet decreases, and changes regularly with Mach number of inflow.

Fig.15 shows that the velocity ratio distribution curve of the flow separation after suction (the velocity ratio distribution at the wall of the area A and area B of the upper throat is X = 0.30m, X = 0.34m, X = 0.37m, X = 0.39m, X = 0.42m), which indicates the relative thickness of the boundary layer, and the thickness of the boundary layer decreases significantly when compared with that the inlet does not start. This is due to the elimination of the main flow separation affecting the performance when suction is carried out.At design point, the inlet does not start when the it is not suctioned, and the inlet can start when the suction scheme is adopted. There is a small numerical fluctuation in the flow coefficient and the total pressure recovery coefficient curve. The reason is that the inlet can start normally when the it is suctioned at design point, but the original flow separation still exists as a small one.



(1) φ

(2) Ma-throat

(3) σ-throat

(4) σ-outlet

Fig 14. Comparison of aerodynamic parameters before and after suction

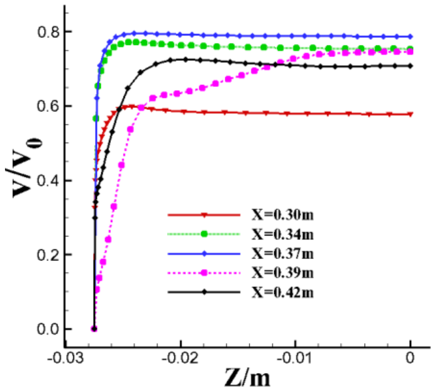


Fig 15. Distribution curve of velocity ratio after suction

5. Conclusions

(1) The influence of boundary layer can be reduced and the starting performance of inlet can be improved more effectively by suctioning in area A; the influence of boundary layer can be reduced effectively by suctioning in area B, but the overall effect of improving starting performance is weaker than that of area A; the overall effect of improving starting performance in area C is less than that of area A and B; and the effect of suction in area D of side plate wall can be improved by suction in area B. The starting performance of the inlet is improved. However, compared with other areas, under the same conditions, the flow needed to be suctioned out in this area is larger; suctioning in area E can effectively reduce the thickness of the boundary layer, but has little effect on the starting performance of the inlet, so area D and E are not so proper to be suctioned;

(2) Compared with area A-B, A-C and B-C, area A-B had the best effect and the area B-C had the worst effect on improving the performance of inlet.

(3) When the suction area is constant, the main aerodynamic parameters of the inlet vary with the opening rate of the suction. With the increase of opening rate, the total pressure recovery coefficient increases,the suction flow coefficient increases, the flow coefficient decreases,Mach number increases, and the starting performance of inlet is better.

(4) Comparison of aerodynamic performance before and after suction:Suction can reduce the flow coefficient of the inlet, increase the total pressure recovery coefficient of the suction area, increase Mach number of throat, and effectively improve the starting performance of the inlet;

(5) Considering the realizability of the engineering, the opening rate should be as small as possible, so the scheme that multi-area are suctioned is superior to the single-area suction scheme under the same suctioned flow.Therefore,suctioning in the area A-B-C can simultaneously satisfy the starting requirements and have the better realizability of the engineering.

To sum up,in order to improve the overall performance of the inlet studied in this paper,the final scheme is suctioning in the area A-B-C with the opening rate is 15%.

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References

1. Cai Qiao-yan, Tan Hui-jun. Effects of the forebody boundary layer state on flow structure and performance of hypersonic inlets [J]. Journal of Aerospace Power,2008,23(4):699-705.
2. Yan Hong-ming,Zhong Jing-jun,Han Ji-ang1,Feng Zi-ming,Yu Yang.Research on boundary-layer suction in the throat of supersonic inlet [J]. Journal Of Propulsion Technology,2009,30（2）:175-181.
3. Qian Hua-ju. Experimental investigation of aerodynamic characteristics of porous plates and numerical simulation of boundary layer suction [D].NanJing: NanjingUniversity of Aeronautics and Astronautics,2000.
4. Liang De-wang, Qian Hua-ju.Experimental investigation of aerodynamic characteristics of porous plates and numerical simulation of boundary layer suction[J]. Acta Aeronautica Et Astronautica Sinica2002,23（6）:512-516.
5. Wang Wei-xing, Yuan Hua-cheng, Huang Guo-ping, Liang De-wang. Impact of suction position on starting of hypersonic inlet [J].Journal of Aerospace Power,2009,24（4）:918-924.
6. Yuan Hua-cheng,Liang De-wang. Effect of suction on starting of hypersonic inlet [J]. Journal Of Propulsion Technology. 2006,27(6):525-528.
7. Chang Jun-tao, Bao Wen, Cui Tao, Yu Da-ren. Effect of suctions on maximum backpressure ratios of hypersonic inlets [J]. Journal of Aerospace Power ,2008,23(3): 505-509.
8. Zhao Yilong,Fan Xiaoqiang,Wang Yi,Wang Zhenguo. Effects of bleeding on self-starting characteristics of side-compression hypersonic inlet[J].Journal of Aerospace Power.20113, 28(5):1101-1106.
9. Gippet J,Rollin G,Murakami A. Design evaluation of a hypersonic inlet for a SST/HST engine by CFD and test [C]//Thirteenth International Symposium on Air Breathing Engines. Chattanooga,Tennessee,USA:ISABE,1997:193-203.
10. Utaka Y,Taneda H,Murakami A.The aerodynamicdesign and wind tunnel tests of a combined intake for a supersonic transport[C]//Thirteenth International Symposium on Air Breathing Engines.Chattanooga,Tennessee,USA:ISABE,1997:1035-1043.
11. Zhao Jian,Fan Xiao-qiang,Tao Yuan,LI Teng-ji. Study on Performance Impact of Boundary Layer Bleed on Curved Wall with Center Clapboard in Chamber [J]. Journal Of Propulsion Technology ,2017,38（5）:1009-1015.
12. Luo Guang-qi,, Zheng Jiu-zhou, Song Di-yuan. Design of a two-dimensional mixed-compression supersonic inlet with boundary layer consideration [J]. Journal of Aerospace Power,2009,24（9）:2065-2068.
13. Li Yongzhou,Zhang Kunyuan,Sun Di.effect of suction on performance of inward turning inlet with rectangular-to-circular shape transition. Journal of Aerospace Power ,2016,37（2）:3626-3633.
14. Anderson,BernhardH,TinappleJon,etal.Optimalcon-trol of shockwave turbulent boundary layer interactionsu-singmicro-array actuation[R].AIAA 2006-3197.
15. Atkinson MichaelD.Numerical investigation of super-sonic inlet using bleed and micro-ramps to control shock-wave /boundary layer interactions [R].AIAA 2007-24.
16. GefrohDerek,Loth Eric,DuttonCraig.Controlofanob-lique shock/boundary-layer interaction with aeroelasticmesoflaps[J].AIAAJournal,2002,40(12).