NUMERICAL INVESTIGATION OF FLOW STRUCTURE OF DIFFERENTIAL EJECTOR

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Abstract

The differential ejector is a new conception of ejector technology, which can shorten the length of mixing chamber efficiently and show promising direction with much higher compression ratio, higher ejection coefficient and more compact size. In the contrast with the traditional ejector, the differential ejector has much more complicated configuration with a large number of asymmetric supersonic nozzles. Hence, the inner flow field of the differential ejector is much more complicated so that it is difficult to evaluate its performance accurately by engineering calculation on quasi one dimensional method or numerical simulation on two dimensional method. For the purpose of evaluating its performance accurately, we adopt both three-dimensional (3D) numerical simulation and experiments to investigate its performance and inner flow field. The investigation demonstrate that the 3D simulation results are in good agreement with the experiment results on both compression ratio and ejection coefficient, which are 0.008217 and 78.3 in contrast with 0.0082 and 78. It means that the 3D simulation method in this paper can evaluate the performance of differential ejector accurately and reliably, which could reveal the distribution of inner flow field visually and give the advising direction on the optimization design for the differential ejector.

NOMENCLATURE

Symbols:

P	Static pressure
q	Dynamic pressure
ρ	Mass density
T	Static temperature
P_0	Pressure at stagnation
ρ_0	Mass density at stagnation
T_0	Temperature at stagnation
G	Mass flow rate
k	ejection coefficient
ε	Compression ratio

Superscript:

'	Parameters of the driving gas

Subscripts:

1	Parameters of the driven gas
3	Parameters of the mix gas

1 General Introduction

Ejector is a kind of fluid transportation device which is widely used in refrigeration, aviation, spaceflight, and chemical engineering. Compression ratio and ejection coefficient are the two most important performance indexes of an ejector. But under some circumstances, compact structure of ejector plays the same important role as the above two indexes.

By connecting the ejectors in multi-stage series, higher compression ratio and ejection coefficient can be achieved at the cost of longer device and parameter matching difficulty.

In this background, a new conception of differential ejector shows an outstanding development direction. It is based on infinite multi-stage ejector, but with much more compact length size. For example, it can achieve equivalent compression ratio of a four stages constant section mixing ejector with one differential ejector, which only approximates one-fourth of the length of the former ejector. However, the configuration of differential ejector is more complicated, with a large number of asymmetric supersonic nozzles. The complicated inner flow field makes engineering calculation and quasi one dimension numerical simulation difficult, even inaccurate.

2 Differential Ejector

Generally, a single stage ejector of traditional conception contains center ejector, annular ejector and multi-nozzle supersonic ejector, as sketched in figure 1. Such single stage ejector only has a maximum compression ratio of about ten. In case of much larger compression ratio demanded in present industry field, for instance some ejector system need compression ratio of about 60-80 so that adoption of multi-stage ejector of traditional conception becomes inevitable choice, which will lead to larger size certainly.

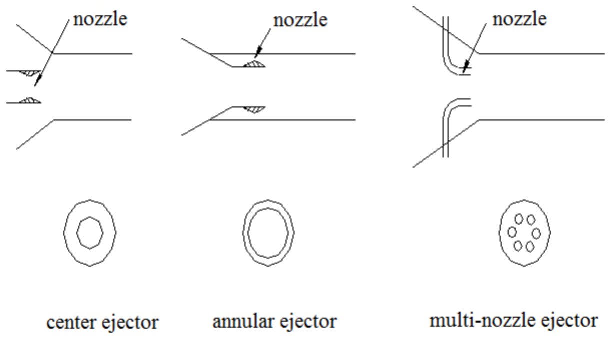


Fig.1 Conventional Ejector

To overcome this insufficiency of multi-stage ejector of traditional conception, in Russia, some researchers propose a new conception of differential ejector, which is based on infinite multi-stage ejector, as sketched in figure 2. Theoretically, it can achieve equivalent compression ratio of the four stages constant section mixing ejector with only one-third length of former ejector.

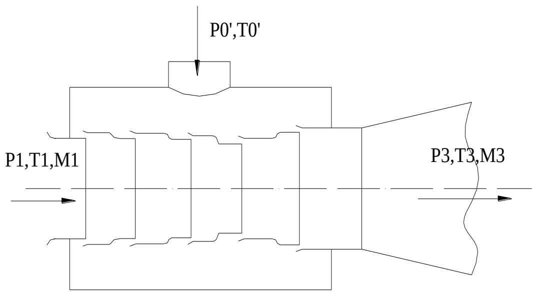


Fig.2 The Conception of Differential Ejector

However, in reality, it is hard to realize the infinite stage structure of the differential ejector with real mechanical system. Hence, some researchers make an approximate simplification with supersonic nozzles arranging in the shape of spirals, as sketched in figure 3. The driving gas is injected into the cone mixing chamber in sequence by the supersonic nozzles spirally distributed. In this case, the preliminary compression ratio and ejection coefficient is defined as 75 and 0.007, respectively.

As illustrated in figure 3, this ejector mainly includes a cone mixing chamber, a high pressure chamber, supersonic nozzles, a low pressure entrance, a diffuser, and a constant section. Because the performance of this ejector is very close to the differential ejector, we also named this ejector as differential ejector, which is investigated in this paper with supersonic nozzles spirally distributed.

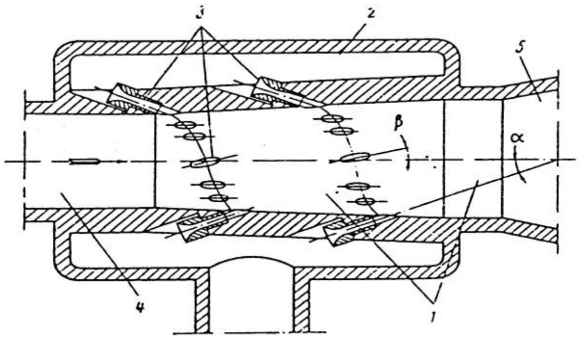


Fig.3 The Spiral Ejector

There is an angle α between the axis of the supersonic nozzle and the axis of cone mixing chamber on the differential ejector. According to some experimental data, the better range of angle α is from 5°to 10°. Nevertheless, in order to install and exchange the nozzles conveniently during experiment, we set the angle α as 15°.

Furthermore, there is an angle β between the axis of the supersonic nozzle and the axis of cone mixing chamber, which means the axis of the supersonic nozzle does not pass through the axis of cone mixing chamber. For the purpose of better mixing, the installing of supersonic nozzles should make the supersonic airflow pass between the axis of nozzle and axis of mixing chamber. Thereafter, the angle β is used to avoid the supersonic airflow gathering around the axis of cone mixing chamber so that there is no supersonic airflow around the wall of cone mixing chamber, which make the mixing worse. According to the experimental data, setting the angle β as 5° could make this situation better, the real nozzles are sketched in figure 4.

The angle β may cause the change of the direction of the airflow between the mixing chamber and diffuser. However, because this angle is little, the direction of flow will not change intensely, which will not influence the performance of differential ejector too much.

Fig.4 Nozzles of Differential Ejector

According to previous engineering test data, arranging 45 supersonic nozzles in the shape of spirals could get the better performance, which is adopted in this paper investigation. The side of cone mixing chamber is illustrated in figure 5.

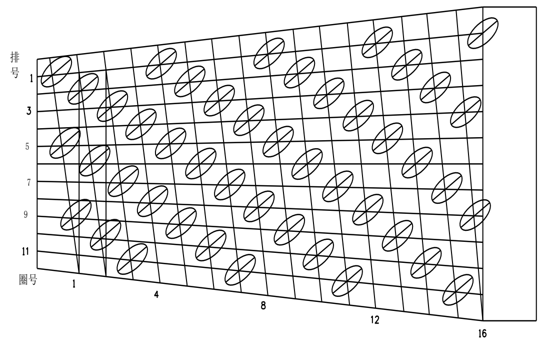


Fig.5 Differential Ejector Mixing Chamber's Side Elevation

3 Numerical Simulation

The mixing flow in the ejector is consisted of supersonic airflow and subsonic airflow which is driven by supersonic airflow. On the contrast with the traditional multi-stage ejector, the configuration of differential ejector is much more complicated with 45 supersonic nozzles so that the velocity gradient of the inner flow is extremely strong accompanying with extremely complicated distribution of shear layers and shock waves. Hence, using 3D numerical simulation method to simulate the inner mixing flow of differential ejector and analyzing accurately the performance of differential ejector are extremely difficult.

3.1 Turbulence Model

Firstly, we make a simplification to assume that the inner flow is steady flow. Secondly, what left is to choose an appropriate turbulence model to simulate the inner complicated flow much more accurately.

In the field of CFD, the k–ω turbulence model considering the influence of low Reynolds number, the influence of compressibility and the diffusion of shear flow, which means that it is good at simulating wake flow, mixing layer, jet flow, flow limited by wall and free shear flow. Besides on, the comparing of experimental data and numerical results in some papers also validate that the k–ω turbulence model can distinctly and correctly catch the whole inner flow field on the design and optimization of ejector. Even the calculation accuracy of k–ω turbulence model is comparable to the advanced Reynolds Stress model. By comprehensive consideration, we adopt k–ω Shear Stress Transport turbulence model to solve the inner complicated mixing flow of differential ejector.

3.2 Geometric Simplification

The configuration and the nozzle arrangement of traditional ejector are usually symmetric, thus the symmetric numerical model can be chosen to make the meshing and computing convenient. However, the 45 nozzles of differential ejector distribute asymmetrically along the spiral line, a universe model is needed for simulation. Furthermore, the outlet flow of nozzles are the mixing shear layer between the supersonic and subsonic flow, which means that simulating the shear layer accurately is the key point for differential ejector, so that it need fine mesh structures, lager mesh number and more computation resource.

For the purpose of convenient numerical simulation, the complicated configuration is simplified appropriately by ignoring the thickness of the wall. Furthermore, we cancel the high pressure chamber and the entity of nozzles with keeping their interface as the inlet boundary of supersonic airflow. Structural grid is generated by ANSYS ICEM software, which is transited and refined appropriately around the wall, outlet of nozzles and the axis of mixing chamber by generating O grid. After preliminary computing, the adaptive grid is generated on the pressure gradient by ANSYS FLUENT software. The grid amount is more than ten millions, the aerodynamic sketch and simplified model of differential ejector are sketched in figure 6 and 7.

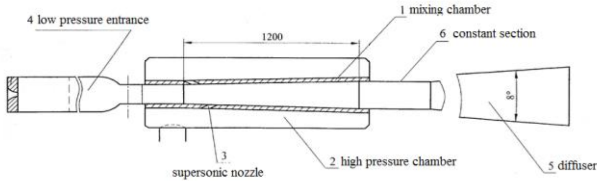


Fig.6 Aerodynamic sketch of differential ejector

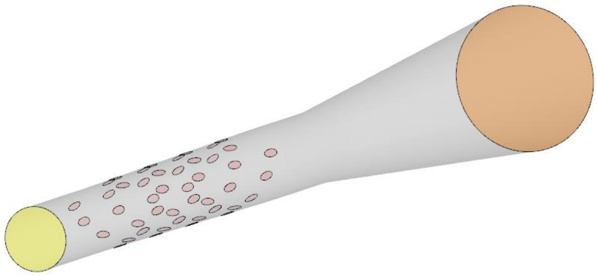


Fig.7 Model of differential ejector

3.2 Boundary Conditions

We set the boundary conditions of differential ejector by reference to the experiment for the purpose of simulating the compression ratio accurately.

Experiment conditions:

1) The total pressure of driven gas is no more than 1333Pa.

2) The flow rate of driven gas is 0.07kg/s.

3) The total pressure of driven gas is between 7.7×10^5pa and 8.5×10^5pa.

4) The diameter of supersonic nozzles is illustrated in figure 8.

5) The Mach numbers of supersonic nozzle is illustrated in figure 9.

6) The temperature of both driving and driven gas is environment temperature.

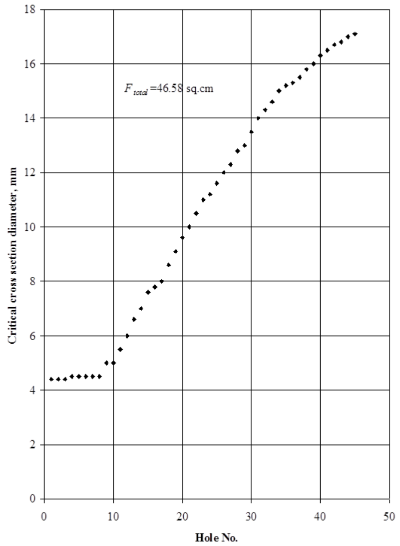


Fig.8 Diameter of throat in the nozzles

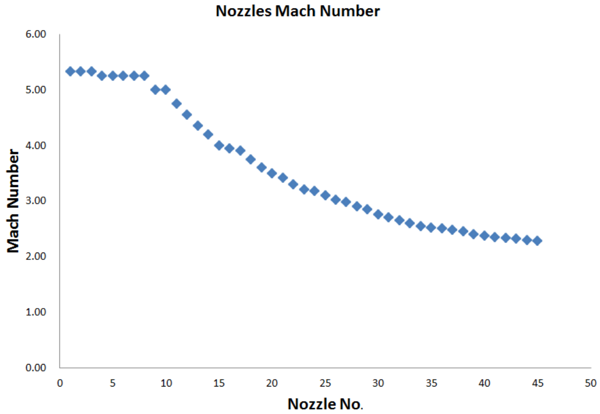


Fig.9 Mach number of nozzles exit

Boundary conditions:

1) The static pressure of driven gas is set as 1000pa.

2) The flow rate of driven gas is set as 0.07kg/s.

3) The total pressure of driving gas is set as 8.5×10^5pa.

4) The Mach numbers of supersonic nozzles are the same as experiment.

5) The total temperature of both driven and driving gas is set as 300k.

6) The pressure of outlet is set as atmosphere.

4 Results and Analysis

For an ejector, the Ejection coefficient and Compression ratio are the two most important performance indexes, as defined in equation (1) and (2).

$$k = G_1/G' \qquad (1)$$

$$\varepsilon = P_{03}/P_{01} \qquad (2)$$

Where G_1 is the flow rate of driven gas, the term G' is the flow rate of driving gas, the term P_{03} is the total pressure of mix gas on outlet and the term P_{01} is the total pressure of driven gas.

4.1 Numerical and Experimental Results

We can get the average flow rate of the supersonic nozzles and the average total pressure of driven and mix gas by integrating the numerical simulation results, as illustrated in table 1 and 2. From the tables, we can see that not only the ejection coefficient but also the compression ratio of the numerical simulation results is in good agreement with the experimental results, which is 0.008217 and 78.3 in contrast with 0.0082 and 78. The relative error of Ejection Coefficient is about 0.2% and the relative error of Compression Ratio is about 0.4%, which demonstrates the probability and reliability of this 3D numerical simulation method on extremely complicated shear flow of differential ejector.

Table.1 Flow rate of nozzles exit

Nozzle	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
Simulate	**Mass Flow Rate（g/s）**					
1	29.9	29.9	24.6	29.9	31.6	31.5
2	31.5	31.6	38.5	38.4	47.3	55.9
3	66.2	75. 3	90.3	94.1	77.7	112.6
4	125.5	134.7	154.8	165.1	178.7	181.2
5	216.9	212.2	241.8	260.2	272.7	298.9
6	312.8	324.1	291.0	357.8	326.2	362.7
7	276.1	298.8	327.4	341.7	327.4	348.6
8	379.7	413.5	451.7			
Sum	**8518.9**					
Experiment	**8600**					

Table.2 The average total and static pressure of low pressure entrance and mix exit

Simulation	P	q	P_0	ε
Driven gas	1015.44	276.41	1319.13	78.5081
Outlet	101325	2212.1	103562.5	

In fact, the values of simulation results are a little higher, for the simulation is based on very ideal condition, for instance the total pressure of the driven gas is on the maximum 8.5×10^5Pa and will not change with the passage of time. on the contrary, the experiment is based on the only one shared high pressure chamber, which means the total pressure of driven gas along the nozzle on the mixing chamber is decrease gradually. From another perspective, we think it can improve the performance of differential ejector with the multi-stage high pressure chamber so as to supply different total pressure of driven gas.

4.2 Inner Flow Structure

The inner flow of differential ejector is very different from traditional ejectors'. The driving gas and driven gas are not injected into the mixing chamber on the same section, but by different supersonic nozzle arranging on spirals. The angle β between the axis of nozzle and axis of mixing chamber, as sketched in figure 4, is the reason why there is a large inner spiral flow in the mixing chamber, as sketched in figure 10 and 11, which is an unique flow structure. We think this unique inner flow structure of differential ejector could be advantageous to the mixing of shear layer, which may decrease the size of mixing chamber.

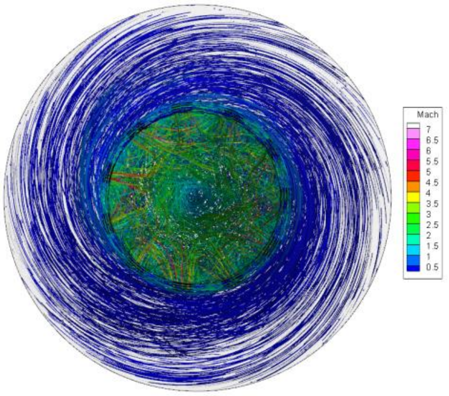


Fig.10 The angle β of velocity on nozzles exit

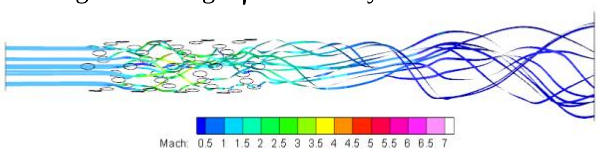


Fig.11 The swirl in mixing chamber

But, In fact, there is no spiral flow between the inlet and first quarter of mixing chamber, where the driving and driven gas are not mixed very well. The figures 12 and 13 show Mach number distributions on different section of Z and Y axis. At the beginning, the driving gas of the first few supersonic nozzles only makes a little shear action on driven gas. With the numbers of supersonic nozzles increasing along the flow direction, more and more shear action on the driven gas make the inner flow become spiral flow gradually.

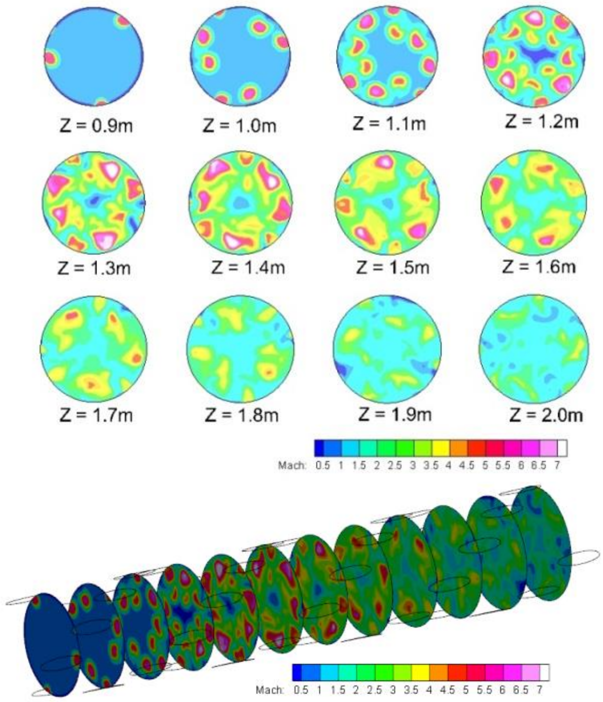


Fig.12 Mach number distribution of Z axis section in mixing chamber

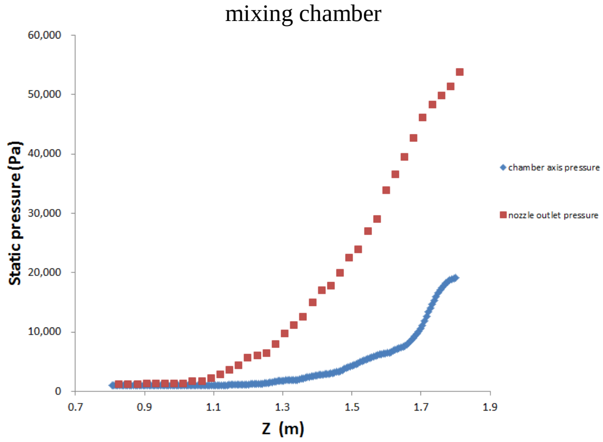


Fig.13 Static pressure distribution of nozzle outlet and mixing chamber axis

As figure 12 sketched，the Mach number of the driving gas is increasing along the flow direction, which even reaches the max more than 7 in the middle of the mixing chamber. But，this tendency is obviously contrary with the Mach number distribution of nozzles exit as figure 9 sketched. We make a preliminary analysis and think the expansion wave should be the reason why the Mach number is increasing. Hence，we make a comparation on the Static pressure of both nozzle outlet and axis of mixing chamber, as figure 13 sketched. At the first quarter of mixing chamber, the Static pressure of nozzles exit is very close to the Static pressure of the driven gas on Z axis, which is about 1000Pa. Then the Static pressure of nozzles exit becomes much larger than the Static pressure of mixing chamber axis along the flow direction, which is just the reason why the Mach number of driving gas is increasing by expansion wave.

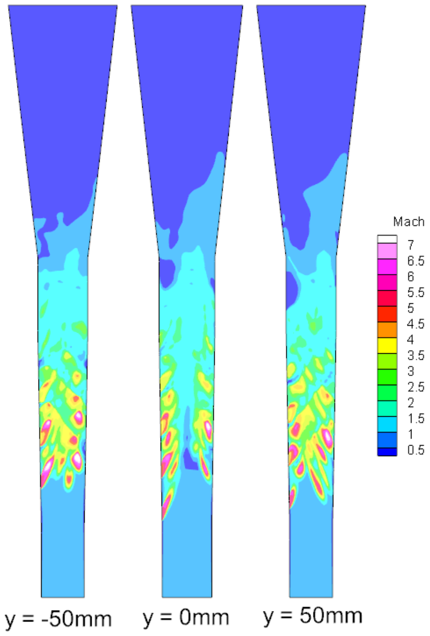
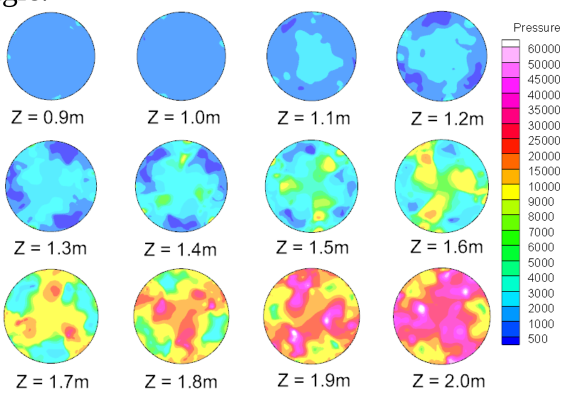


Fig.14 Mach number distribution of Y axis section in mixing chamber

From the above mentioned, the inner complicated shear flow of mixing chamber mainly gathers in the middle with taking the shape of spiral flow. And after the spiral flow appeared, we think the downstream mixing becomes much more intensive and better. Interestingly, a special phenomenon is found that the driven gas is mainly ejected along the center of spiral flow， as sketch in figure 10 and 14. We think enlarging the central region of spiral flow for driven gas could enhance the performance of differential ejector， which could be mainly relative with both the α and β angle.



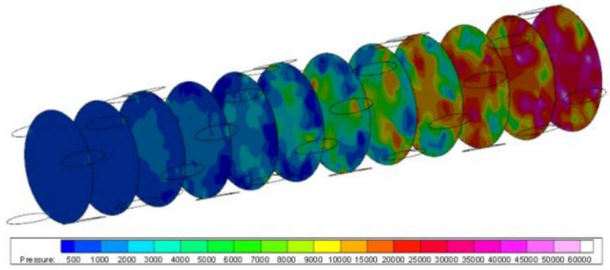


Fig.15 Static Pressure distribution of Z axis section in mixing chamber

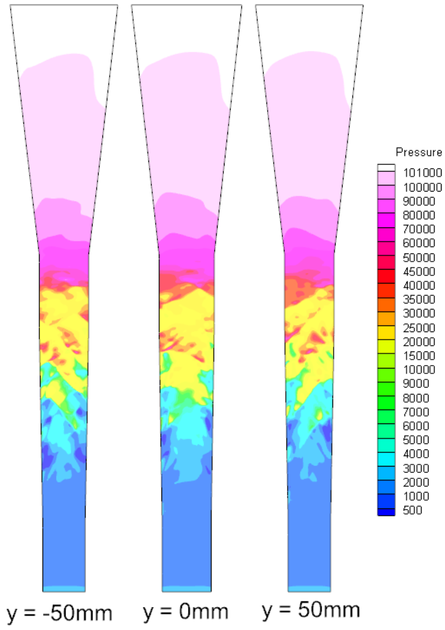


Fig.16 Static Pressure distribution of Y axis section in mixing chamber

The figures 15 and 16 show Static pressure distributions on different section of Z and Y axis. We find there is an obvious high Static Pressure gradient in the inner flow of mixing chamber. And the Static Pressure only increase suddenly nearby the nozzles，which is directly relative with the distribution of the Mach number of driving gas. It also means that the distribution of the Mach number of driving gas could influence the mixing effect of inner flow directly, which is very important for the performance of differential ejector.

In the end, we build a numerical simulation method by preliminary investigation, which demonstrates its accuracy and reliability by comparing with both numerical and experimental result. This method can supply the visual inner flow distribution, which is very helpful for the design and optimizing of differential ejector. Nevertheless, the inner shear flow is too complicated to find more obvious rules for differential ejector by common analysis. Hence, the intense research is our next step work with hoping to find more rules.

5 Conclusions and Discussion

In the present work， a 3D numerical simulation method based on k–ω Shear Stress Transport turbulence model is used to investigate the complicated inner flow structure of the differential ejector. The main conclusions are drawn as follows.

1) The accuracy and reliability of the 3D numerical simulation method are demonstrated in this paper on differential ejector by comparing with both numerical and experimental results.

2) The 3D numerical simulation method in this paper can supply visual inner complicated flow of differential ejector accurately, which is very helpful for design and optimizing of differential ejector by numerical simulation data.

For next investigation, it is suggested that：

1) It may improve the performance of differential ejector with the multi-stage high pressure chamber.

2) Adjusting the angle α and β with appropriate range may improve the performance of differential ejector， especially on ejection coefficient.

3) The distribution of the Mach number of driving gas is very important for the performance of differential ejector，which may be a good optimization direction for the next intense investigation.

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