CODEN STJSAO ISSN 0562-1887
ZX470/1522 UDK 532.517.2:623.463:519.62/.63

Investigation of the Pressure Distribution in a 2D Rocket Nozzle with a Mechanical System for Thrust Vector Control (TVC)

***Zoran STEFANOVIĆ*[1], *Marko MILOŠ*[1] *Ivana TODIĆ*[1] and *Milan PAVLOVIĆ*[2]**

1) Mašinski fakultet, Univerzitet u Beogradu, (Faculty of Mechanical Engineering, University of Belgrade), Kraljice Marije 16, 11120 Beograd, **Republic of Serbia**

2) Univerzitet u Novom Sadu, Tehnički fakultet u Zrenjanin "Mihajlo Pupin" (University of Novi Sad, Technical Faculty Zrenjanin "Mihajlo Pupin"), Đure Đakovica bb, 23000 Zrenjanin, **Republic of Serbia**

mmilos@mas.bg.ac.rs

Keywords

Upravljanje vektorom potiska
Mehanička prepreka
Potisak
Raspodjela tlaka
Strujanje
Šliren fotografija
2D mlaznik

Ključne riječi

Gas flow
Mechanical obstacle
Pressure distribution
Schlieren photo
Thrust
Thrust vector control
2D nozzle

Received (primljeno): 2010-06-25
Accepted (prihvaćeno): 2011-05-30

Original scientific paper

This paper introduces a new physical model of the gas flow through the 2D nozzle with the tilted obstacle in exit section. Experimental research on the 2D full span model in the supersonic indraft tunnel, which includes over three hundred tunnel runs, are presented. Variable geometric parameters were: nozzle shadow area, obstacle-nozzle wall angle, obstacle-nozzle gap and nozzle area ratio. In its conclusion, the paper discusses results and presents some suggestions for the future research.

Istraživanje raspodjele tlaka u 2D raketnom mlaznjaku s mehaničkim sustavom za upravljanje vektorom potiska (TVC)

Izvornoznanstveni rad

Rad predstavlja novi fizički model strujanja u 2D mlažnjaku sa preprekom u izlaznom presjeku. Predstvljeno je eksperimentalno istraživanje koje uključuje preko 300 testova realiziranih s 2D mlažnjakom realnih dimenzija u supersonicnom tunelu. Promjenjivi geometrijski parametri tijekom eksperimenata: zasjenčena površina mlažnjaka, kut između prepreke i zida mlažnjaka, razmak između prepreke i izlaznog presjeka mlažnjaka, geometrijski stupanj širenja mlažnjaka. U zaključku su komentirani rezultati i date preporuke za dalji rad.

1. Introduction

Gas dynamic systems are a special group within the rocket TVC systems. They operate on the basic (principles) of direction and intensity change in the rocket motor thrust. This paper deals with the performance analysis of the thrust vector control (TVC) system by means of stream deflection, i.e. - the supersonic stream is deflecting by using a mechanical obstacle at the nozzle exit section. As a result of introduced obstacle, the gas flow in the nozzle is separated, and the pressure along the nozzle wall and obstacle is redistributed, thus changing the direction and intensity of the thrust. The common name of this system is the mechanical system for TVC with unmovable nozzle. Determination of the system performances is related with the thorough knowledge of the disturbed zone parameters in the nozzle. This paper deals with the above mentioned matters from the standpoint of the research work carried out by our group, on problems of pressure distribution along the nozzle walls.

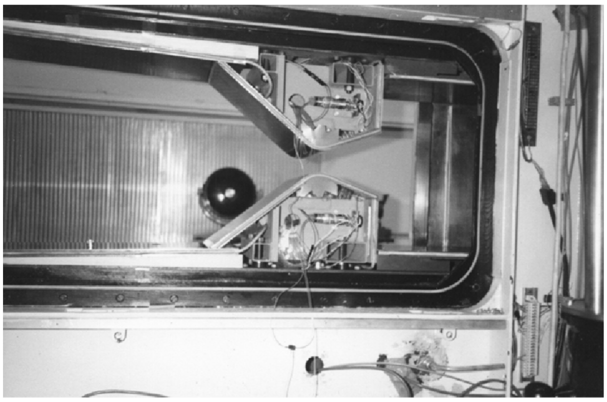
2. Experiment Setup

Generally speaking, experiments with 2D model were performed to discover the real physical model and to measure all the necessary parameters in the nozzle disturbance zone (separation point, pressure distribution on the wall, and pressure distribution along the front and back side of the obstacle).

Experiments took place in a supersonic indraft type wind tunnel, where the working section of a full span 2D model was set up (shown on the Figure 1). The so-called cold investigations were conducted on this installation (e.g. stagnation conditions were p = 1 bar T = 288°K).

Symbols/Oznake

A_z	- nozzle shadow area, m^2 - zasjenčena površina mlažnjaka	δ	- obstacle-nozzle gap, mm - razmak između prepreke i izlanog presjeka mlažnjaka
p_p	- plateau pressure, Pa - plato tlak	ε	- nozzle area ratio - geometrijski stupanj širenja mlažnjaka
β	- obstacle-nozzle wall angle, rad - kut između prepreke i zida mlažnjaka		



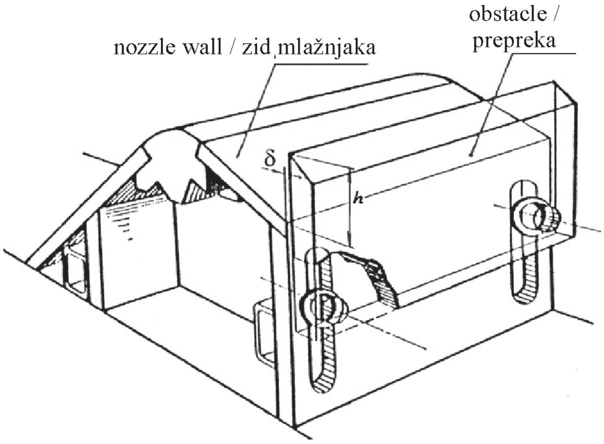


Figure 1. Nozzle in the test section of supersonic wind tunnel
Slika 1. Mlažnjak u test sekciji supersoničnog aerotunela

During the test, pressure distribution was measured through the characteristic zones of the nozzle, and a research of the flow field was done by visualization with the Schlieren photographs.

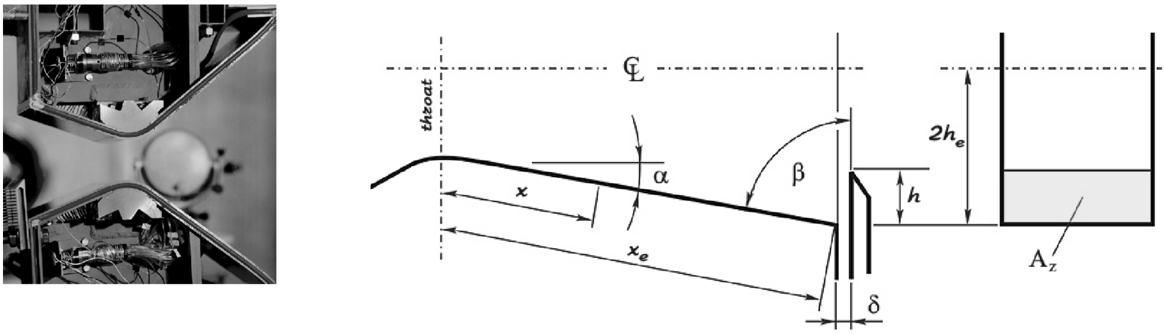


Figure 2. Closer look to the model and nozzle geometry
Slika 2. Detalj modela i geometrija mlažnjaka

Over three hundred tunnel runs were conducted with this experimental set, on which the following geometric parameters varied (according to the Figure 2): nozzle shadow area A_z (height of the obstacle), obstacle-nozzle wall angle β, obstacle-nozzle gap δ, nozzle area ratio ε.

3. Results of Measurements and Discussion

Experimental research examinations had shown that, due to the obstacle in the exit section of the nozzle, *gas wedge* is placed inside the nozzle (recurrent flow district), consequently causing the nozzle *wall separation of the flow* to occur, thus changing the pressure distribution and the entire flow picture.

Experimental results were normalized and shown in two ways: correlated through the geometric parameters of nozzle-obstacle, and correlated trough the nozzle fluid flow parameters.

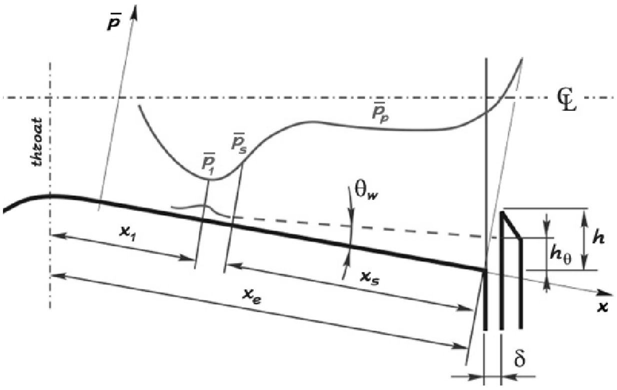


Figure 3. Main parameters and wall pressure distribution in the zone where separation of the flow is settled

Slika 3. Glavni parametri i raspodjela tlaka u zoni iskljulčnja struje

In Figure 4 typical pressure distributions on the nozzle wall in the zone of separation were presented as a function of geometric parameters (according to Figure 3). These results show that the same overall effects of the phenomena (wall pressure rise, width of the separation zone, etc.), can be achieved by different combinations of the geometric parameters of nozzle and obstacle. Conclusions which can be made from these results may be summarized as follows:

- The increase of the disturbance zone is proportional to the nozzle shadow area (or the height of the obstacle);
- The influence of the gap and nozzle-obstacle angle is similar, i.e. their increasing is connected with the nozzle disturbance zone width decreasing;nozzle disturbance zone width decreasing;

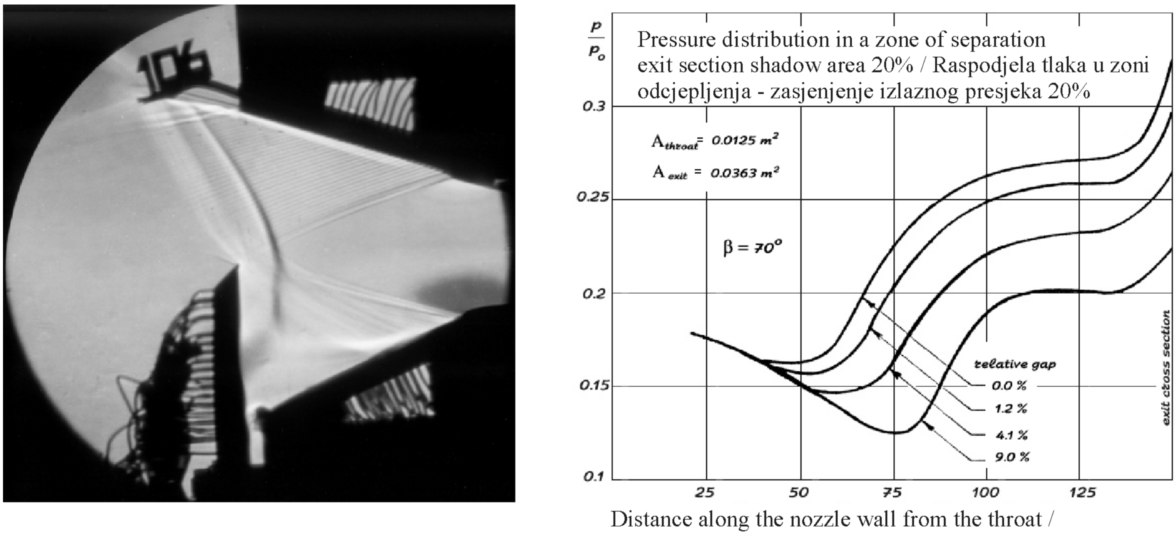


Figure 4. Data from measurements: Schlieren photo and wall pressure distribution

Slika 4. Podaci mjerenja: Šliren fotofrafija i raspodjela tlaka

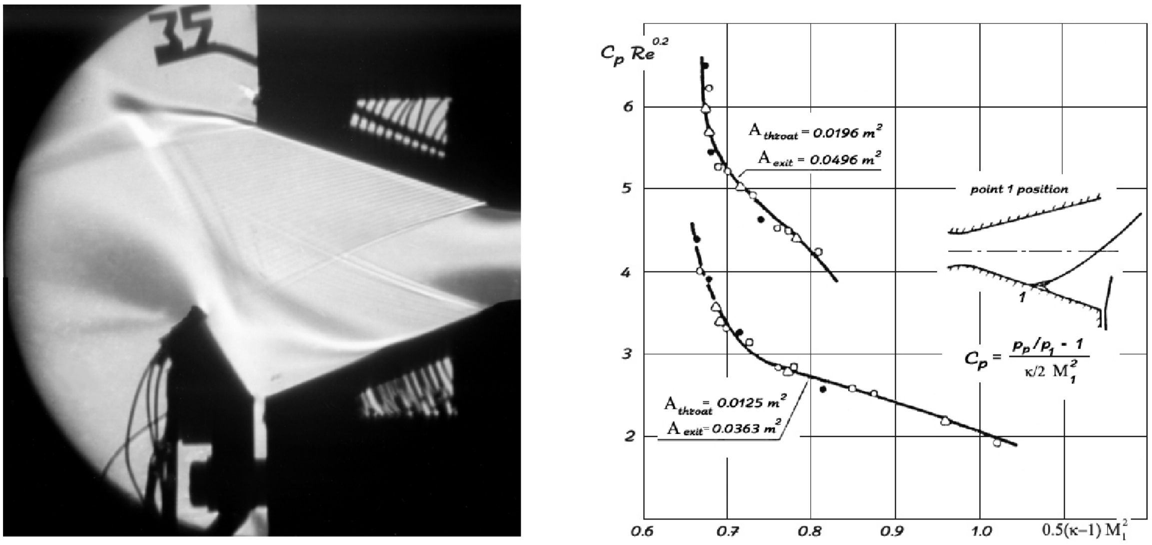


Figure 5. Data from measurements: Schlieren photo and initial separation point characteristics

Slika 5. Podaci mjerenja: Šliren fotofrafija i podaci u točki odvajanja

- Main feature of the disturbance zone is the mean pressure value, so called plateau pressure, defined by the equation

$$P_p = \frac{1}{x_e - x_1} \int_{x_1}^{x_e} p \mathrm{d}x. \quad (1)$$

- *The position of the separation point* can be expressed as a function of disturbance (function of nozzle shadow area, nozzle-obstacle gap and nozzle-obstacle angle).
- *The plateau pressure* in a separated zone is not a disturbance function but a flow parameters function

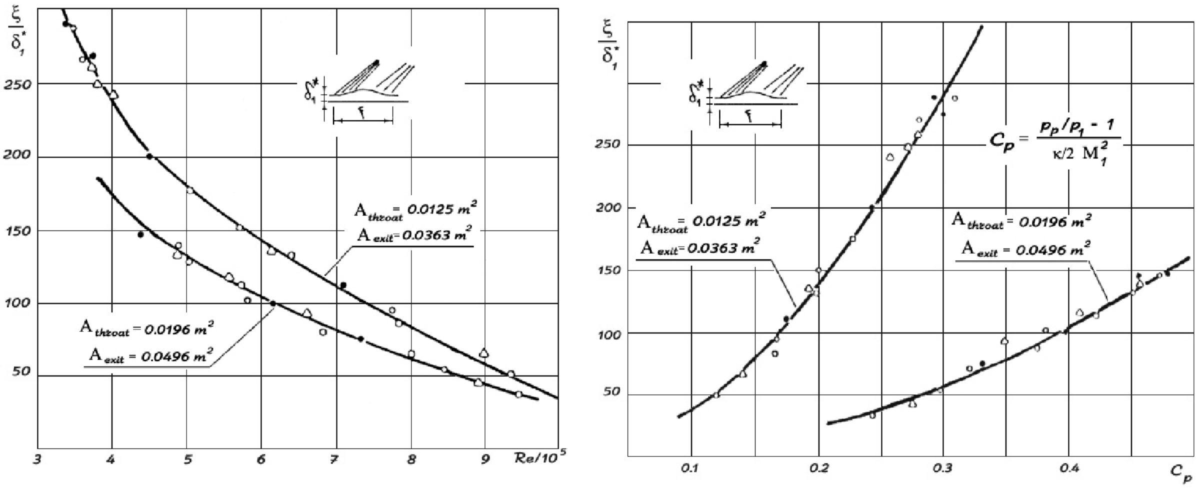


Figure 6. Characteristics in the zone of gas flow separation
Slika 6. Podaci mjerenja: podaci u zoni odcjepljenja struje

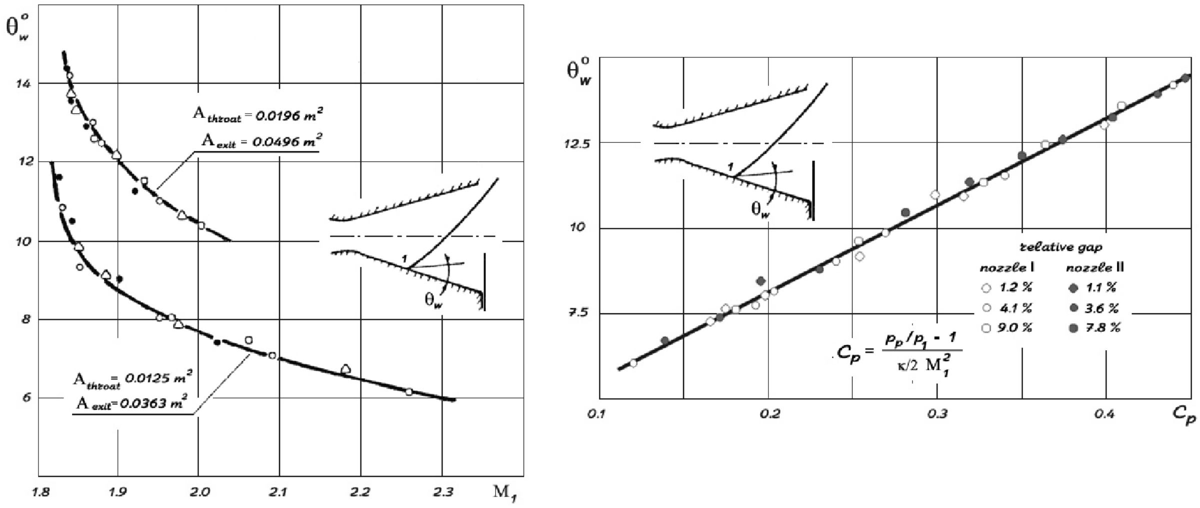


Figure 7. Angle of the gas wedge in zone of gas flow separation
Slika 7. Kut isključenja struje

In Figure 5 Figure 7 results were shown as a function of nozzle geometry and gas flow parameters. These results are very interesting because they show that the parameters of the separation zone are in function of the nozzle features in which they are achieved (e.g. nozzle area ratio, local Reynolds and Mach number, thickness of the boundary layer, etc).

From the diagrams presented, the following important conclusions can be reached:

in the point at the nozzle wall just in front of the starting separation (point 1).

- *The angle of gas wedge* is found to be a universal function of pressure coefficient C_p (defined and showed in Figure 7).

Based on our experimental work (measured pressure distribution and Schlieren photographs) we introduce a new physical model of the studied phenomena (shown on Figure 8). The main characteristics of this model are:

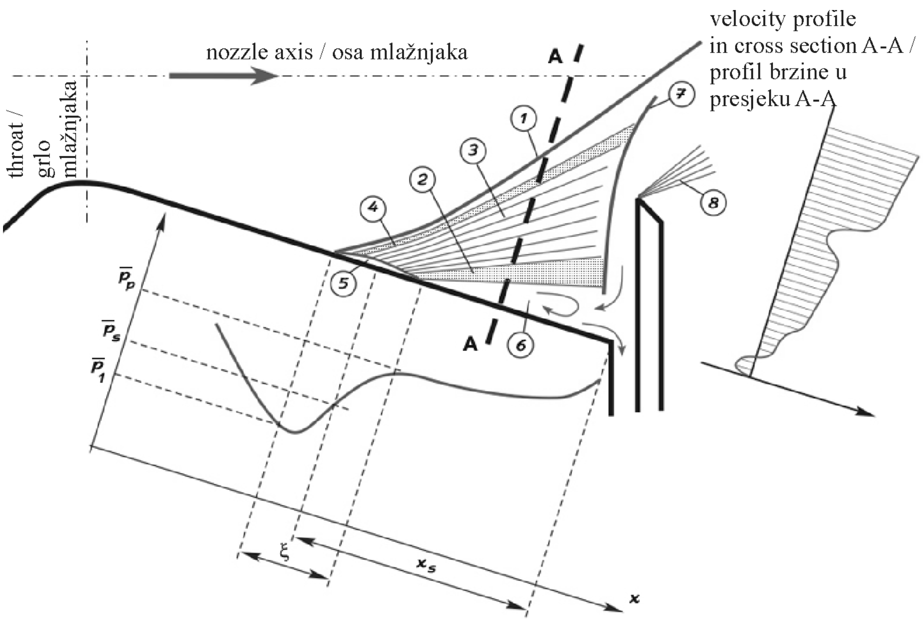


Figure 8. Physical model, pressure distribution and velocity profile in region of forced separation of flow

Slika 8. Fizički model, raspodjela tlaka i profil brzine u zoni isključenja struje

1. In disturbance zone where *the gas wedge* (6) and separation region are established, the magnitude of the gas wedge is not attached to the top of the obstacle (like in the case of 1D models of forward facing steps studied by some authors). The mean value of pressure in this zone is approximately equal to *plateau value*.
2. *The lambda bubble* (5) around the separation point is the source of *compressible* (4,2) and *expansion shock waves* (3, 8). The main *oblique shock wave* (1) has been caused by gas wedge. Very strong *shock wave* (7) has been established in front of the tilted obstacle (this is partly normal shock wave, and partly the so called 'strong solution' for oblique shock wave).
3. Mass transport phenomena in disturbance zone was demonstrated through the *mixture layers* between the gas wedge, main stream and mass loses through the nozzle-obstacle gap.
4. Pressure distribution along the obstacle is not a simple one. At this moment it can be said that pressure distribution on the front side of the obstacle is found to have two extremes, i.e. one maximum near the obstacle hub (approx. 0.8 h), and one minimum near the obstacle root (approx. 0.2 h).
5. The physical model and experimental work leads to mathematical expressions in the form:

- separation point:

$$\overline{x}_s = 1.43\left[1-0.47(\beta-1.22)^{1.774}\left(1+\overline{\delta}\right)^{9.85}\right]\cdot \cdot\overline{A}_z\left(1+\overline{\delta}^2\right)^{-2.2}. \quad (2)$$

This equation is valid in the range: $0.1<\overline{A}_z<0.3$, $0.0<\overline{\delta}<0.09$ and $1.22<\beta<2.44$

- plateau pressure:

$$\frac{p_p}{p_1} = 1 + \frac{a}{\left(M_1 - M_{cr}\right)^n}, \quad (3)$$

with: $M_{cr} = 1.73$, $a = 0.378$ and $n = 0.25$

- mean pressure along the front side of tilted obstacle:

$$\frac{p_f}{p_1} = 1.8 \text{ to } 2.2. \quad (4)$$

4. Conclusion

Presented research show the complexity of flows through the 2D nozzles with mechanical system for TVC. Experimentally obtained equations were applied to the numerical modelling and to a computer program of pressure integration and calculation global effects of TVC system (side force and thrust losses). Numerical testing of wide range 2D configurations (nozzle-obstacle) showed satisfactory results (within the reasonable engineering limits).

Our future work on 2D nozzles with mechanical system for TVC will include studying and testing the system in real gas flow conditions, which means that main concern will be placed on the problems: of so called "hot conditions", i.e. gas flows with high stagnation values of pressure and temperature, experiments with the flow of chemically reacting gas mixtures and gas-particle mixture and experiments in the case of nonisotermic nozzle walls.

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