Study on modified Crocco's model for thermodynamic calculation for Dual Mode Ramjet Engine

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A pseudo-shock model is proposed, the model makes possible to estimate the distribution of parameters during the transition from a supersonic flow to a subsonic one in the structure of a mathematical model of a supersonic direct-flow propulsion system with deceleration region. A numerical simulation of the gas-dynamic parameters in the channel of the pre-chamber diffuser (isolator) of a given geometry was performed. The numerical solution is obtained using the principle of minimum entropy production. Verification of the proposed model on the data obtained in the course of experimental tests of the combustor of a dual-mode ramjet engine (DMR) has been performed. The model is intended for parametric studies as part of mathematical models of DMR.

I. Introduction

One of the most important operating conditions for a supersonic ramjet engine in the range of flight Mach numbers above 3 is the stability of its operation. This is due to the existence of stalling characteristics limiting the operation of a ramjet, such gas-dynamically connected elements as the air intake and the combustor. The use of an isolator in an engine structural design allows forming of stagnation and equalization zones of a supersonic flow, providing the following in a ramjet engine:

1. Exclusion of the influence of the combustor operation mode on the stability of the air intake;
2. Effective gas-dynamic compression of a supersonic flow in front of the combustor, achieved by the formation, according to the terminology [1], of a developed stagnation zone in the pre-chamber diffuser;
3. The coordinated functioning of the supersonic air intake and subsonic combustor as part of a ramjet engine of various schemes;

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4. Conditions for effective workflow in a supersonic combustor of a dual-mode ramjet.

According to studies [1-5], in a limited gas-dynamic channel (the so-called isolator) under the conditions of viscous interaction, a transition region, called a pseudo-shock, is formed which converts a supersonic flow into a subsonic one with increasing of static pressure.

The maximum pressure level in a pseudo-shock characterizes the compression efficiency in a channel with a supersonic inlet and is directly related to the thermodynamic cycle of the propulsion system, depending on the operating modes of the combustor and the air intake on the flight path of the vehicle. The maximum possible compression ratio should be carried out at a certain optimal length of the channel, the flow regime in which is characterized by the transition process feature of the supersonic flow to the subsonic flow and, accordingly, by the level of kinetic energy loss [1].

The increase in pressure in a pseudo-shock depends on the following main factors:

1. Mach numbers at the isolator entrance;
2. Boundary layer behavior in the isolator and changes of the isolator channel shape, usually determined by the opening angle for compensation of the boundary layer influence on the Mach number;
3. Level of flow irregularity at the isolator inlet;
4. Reynolds number and hydraulic resistance change (taking into account the characteristics of turbulence in the flow and friction on the channel walls);
5. Method of supplying fuel to the flow part;
6. Thermal and geometric engine throttling mode.

There are a number of papers [4–8] (for a detailed review, see [3]), in which models based on a limited set of experimental data are considered. The desire of many authors to summarize the findings and a more accurate quantitative description of the compression process in pseudo-shock led to the development of models using a semi-empirical theory of turbulence, various empirical dependencies that take into account the change in the channel geometry, the intensity of the throttling process from the side of the combustor and the nozzle throat.

In [9, 10], approximate modeling of the flow structure in a pseudo-shock were developed, the use of which allows calculating the distribution of the static channel along the compression zone. In the analysis of the characteristics of ramjet propulsion, pseudo-shock should not be considered as an independent gas-dynamic structure, the pressure distribution of which is not consistent with the mode of operation of the ramjet.

The determination of the length and distribution of parameters in the pseudo-shock is based on the conservation laws [11]. In that paper, an impulse balance for the gas-dynamic structure of a pseudo-shock on the assumption of zero friction on the wall for the structure itself and empirical relationships for friction before and after the pseudo-shock were used. The pressure distribution along the wall was calculated by linear interpolation, and the general result of that paper was that an accurate estimate of the length and pressure distribution of a pseudo-shock is possible with detailed modeling of the pseudo-shock structure.

In [8, 12–14] the integral methods for modeling of the compression zone are presented. In these works, the pseudo-shock models were developed taking into account the development of the dissipation zone, which in the impulse equation that simulates the pseudo-shock development zone was taken into account by introducing such factors as the hydrodynamic loss coefficient [15, 16], which were not completely defined for the deceleration zone, and the velocity profile was taken into account by the coefficient of the dissipative zone growth [12], which is usually considered for jet flows.

According to [2] and [3], for flow regimes with a Mach number of more than 1.6 before the head wave of pseudo-shock, the development of such flows is determined by the mechanism of turbulent exchange between the pseudo-shock region and the dissipation region, as well as the pattern of development of turbulence in the dissipation region itself, which provides the main contribution to entropy production. Therefore, the approaches to constructing a pseudo-shock model using approximations based on the jet analogy [12], or, for equilibrium turbulent boundary layers, on the Clauser's approximation [17] underlying the quasi-one-dimensional separated pseudo-shock model [14] in terms of the balance of forces and stresses on the dividing line, seem to be not fully adequate and somewhat overloaded for use in estimating calculations of the characteristics of a ramjet. The proposed approaches, as follows from the above works, lead to the introduction of not fully justified matching terms into pseudo-shock model.

As one of the main requirements for mathematical models, their ability to carry out a large number of parametric calculations is considered [18]; the results of parametric calculations form the preliminary design image of the ramjet and estimation its effectiveness. This requirement leads to the need to provide a quantitative result for various ramjet schemes and forces many researchers to develop a pseudo-shock model without detailing the internal structure of the compression zone [19, 20]. In [21], a "reasonable idealization" was proposed for calculating pseudo-shock parameters, which is inconsistent with the experimental data [1], which directly indicate that "pressure recovery in a pseudo-shock is 10% -15% lower than in the pseudo-shock". Therefore, an error is deliberately introduced into the scheme for calculating the of a ramjet performances with the use of normal shock ratios a due to an increase in friction losses caused by the length of the deceleration zone. This experimental fact is important to take into account for an adequate assessment of changes in parameters along the pseudo-shock development zone and, accordingly, for calculating the integral performances and evaluating the efficiency of engines in general. With this approach, the use of experimental data [1, 3, 22] integrated into the structure of the model and, as shown in this article, the application of the principle of minimum entropy production, which determines the nature of the distribution of parameters along the pseudo-shock zone and improves the adequacy of the calculation of the ramjet performances. The mechanism of entropy increase during the development of a pseudo-shock was described in [22], but the determination of the pseudo-shock length and pressure distribution is reduced to a jet analogy. Thus, the development of a new or modifying of existing pseudo-shock models allowing for fairly fast optimization calculations and determining the performances of a supersonic ramjet engine without introducing additional matching coefficients depending on the flow regime, remains an urgent task.

II. Formulation of the problem

One of the most important operating conditions for a supersonic ramjet engine in the range of flight Mach numbers above 3 is the stability of its operation. This is due to the existence of stalling characteristics limiting the operation of a ramjet, such gas-dynamically connected elements as the air intake and the combustor. The use of an isolator in an engine structural design allows forming of stagnation and equalization zones of a supersonic flow, providing the following in a ramjet engine:

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Therefore, an error is deliberately introduced into the scheme for calculating the of a ramjet performances with the use of normal shock ratios a due to an increase in friction losses caused by the length of the deceleration zone. This experimental fact is important to take into account for an adequate assessment of changes in parameters along the pseudo-shock development zone and, accordingly, for calculating the integral performances and evaluating the efficiency of engines in general. With this approach, the use of experimental data [1, 3, 22] integrated into the structure of the model and, as shown in this article, the application of the principle of minimum entropy production, which determines the nature of the distribution of parameters along the pseudo-shock zone and improves the adequacy of the calculation of the ramjet performances. The mechanism of entropy increase during the development of a pseudo-shock was described in [22], but the determination of the pseudo-shock length and pressure distribution is reduced to a jet analogy. Thus, the development of a new or modifying of existing pseudo-shock models allowing for fairly fast optimization calculations and determining the performances of a supersonic ramjet engine without introducing additional matching coefficients depending on the flow regime, remains an urgent task.

III.Crocco's pseudo-shock model

Many papers [8, 11–13, 19, 20] refer to the Crocco's model as the first model developed, but none of them show the results of its application. This is due to the Crocco's model does not take into account the friction on the wall and admits the condition of the constancy of the total pressure, which gives an inadequate result. This is indicated by the author himself [2]. However, the Crocco's non-shocked model, in which there is no detailed account of the constants of the semi-empirical theory of turbulence, no introduction of matching coefficients and no need to model the pseudo-shock detailed structure, is a convenient approach for solving problems of preliminary gas-dynamic design of the ramjet flow part and evaluating its performances. The original Crocco's model, valid for any arbitrary cross-section along the pseudo-shock zone development, is based on the redistribution of the total flow rate and momentum flux between the dissipation and compression zones:

Continuity equation

$$(1-\mu)\cdot\frac{1-w'^2}{w'}+\mu\cdot\frac{1-w''^2}{w''}=\frac{p_{x_i}}{p_1}\cdot\frac{1-w_1^2}{w_1}\,,$$

Momentum equation

$$\frac{(1-\mu)}{w'}\left(\frac{k+1}{k-1}w'^2+1\right)+\frac{\mu}{w''}\left(\frac{k+1}{k-1}w'^2+1\right)=\frac{1}{w_1}\left(\frac{k+1}{k-1}w_1^2+1\right),$$ for which the conditions $\dot{m}=\dot{m}_1$, $p=p_1$

before the pseudo-shock and the condition $p=p_2$ after the pseudo-shock must be satisfied.

The following designations are used for the Crocco's model:

$$w^2 = \frac{u_1^2}{2c_p^* T^*}; \qquad \mu = \frac{\dot{m}''}{\dot{m}_1}; \qquad 1 - \mu = \frac{\dot{m}'}{\dot{m}_1}; \; M^2 = \frac{2}{k-1} \cdot \frac{w^2}{1-w^2} \quad ,$$

where $w', \dot{m}'$ are velocity and flow rate for the compression zone,

$\boldsymbol{w'}, \boldsymbol{\dot{m}'}$ are velocity and flow rate for the dissipation zone,

$w_1, \dot{m}_1$ are velocity and flow rate for the section before the appearance of the pseudo-shock,

p_1, p_2 are pressures of the flow in the section before the pseudo-shock and in the section of the dissipation regions closure,

k is an adiabatic index,

M is Mach number

IV.Modified Crocco's pseudo-shock model

In MAI, CIAM, TsAGI, ITAM SB RAS, and others, extensive studies have been conducted for the properties of the pseudo-shock flow. The papers [1, 3, 19, 20, 22, 24, 25] present the extensive experimental data for the gas-dynamic compression zone in an isolator, these experimental data can be used to modify the Crocco's model. The development of dissipation and compression zones, the position of the pseudo--shock and its length are formed by aт overall physical process, which for this problem can be characterized by such thermodynamic functions as entropy and enthalpy. Using the differential form of the second law of thermodynamics and the formal substitution $dt = \frac{\rho}{m} dx$ obtained from the expression for the mass velocity through a unit area, the entropy change for integral flow parameters along the pseudo-shock zone development can be represented by the expression

$$\frac{ds}{dx} = \frac{1}{T}\left(\frac{di}{dx} - \frac{1}{\rho}\frac{dp}{dx}\right),$$

determining the minimum entropy production as the principle of functioning of any thermodynamic system [23]. This expression using the experimental data for the flow momentum loss [1, 3] allows numerically determine its nonequilibrium stationary state [23], which is characterized by pressure and velocity distributions along a developed pseudo-shock. This approach leads to an adequate result obtained by modifying the Crocco's dissipative model [2] for such a classic case of the entropy production process as the pseudo-shock development. The modified Crocco's model using the principle of minimum entropy production allows us to estimate the length and distribution of flow parameters along the pseudo-shock. For this, it is necessary to have the performance of the momentum impulse loss along the pseudo-shock and to ensure the implementation of the conservation equations at the beginning and at the end of the pseudo-shock development zone according to the results of the thermo-gas-dynamic calculation of the engine, the flow path of which is shown in Fig.1.

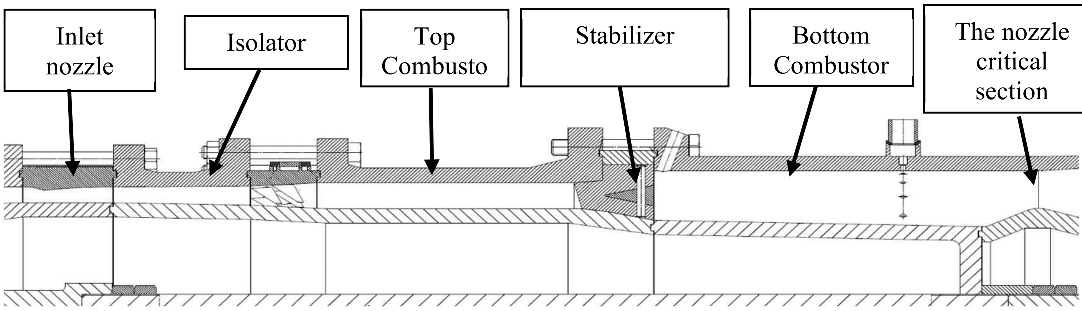


Fig. 1 Scheme of the flow part, specific cross-sections and structural elements of the direct flow channel

The modified Crocco's model is based on the same assumptions as the original version of the model [2].

To take into account the experimental characteristics in the structure of the Crocco's model, the equations written for the current section are modified and supplemented by:

1. the equation for changing the area of the isolator channel when changing its opening angle for compensation of the boundary layer influence in front of the pseudo-shock (see the flow part scheme in Fig. 1): $A_{x_i} = \pi(R_0^2 - (r_0 - x_i \cdot tg\beta\ )^2)$,

   where $R_0 = const$ is the outer radius of the isolator;

   r_0 is inner radius of the isolator in the cross section of the junction of the input nozzle and the isolator.

2. the stagnation performance in pseudo-shock expressed for an arbitrary section x_i in terms of the flow impulse loss coefficient ξ_{x_i} taking into account the wall reaction in the equation of impulses:

$$J_{x_i} = J_1 - \xi_{x_i} J_1 + \int_{x_1}^{x_i} pdA = (1 - \xi_{x_i}) J_1 + \int_{x_1}^{x_i} pdA \quad ,$$

$$J_{x_i} = (\dot{m} \cdot u + p \cdot A)_{x_i} \ .$$

3. the stagnation zone energy equation:

$$c_p T = (1 - w'^2) c_p^* T^* \quad ,$$

4. the thermodynamic dependence of air parameters as a function of pressure and temperature, varying along the pseudo-shock zone development:

$$k = f(p, T)$$

$$c_p = f(p, T)\ .$$

For convenience of comparison with the original version, the modified dissipative pseudo-shock model is written with preservation of the notation for Crocco's variables for an arbitrary section x_i:

Continuity equation

$$\frac{A_{x_i} p_{x_i}}{\dot{m}_1 \sqrt{RT^*} \sqrt{\frac{k-1}{2k}}} = (1-\mu) \cdot \frac{1 - w'^2}{w'} + \mu \cdot \frac{1 - \boldsymbol{w'}^{\,2}}{\boldsymbol{w'}}$$

Momentum equation

$$\frac{J_{x_i}}{\dot{m}_1 \sqrt{RT^*} \sqrt{\frac{k-1}{2k}}} = (1-\mu)\left(\frac{1 - w'^2}{w'} + \frac{2k}{k-1} w'\right) + \mu \cdot \left(\frac{1 - \boldsymbol{w'}^{\,2}}{\boldsymbol{w'}} + \frac{2k}{k-1} \boldsymbol{w'}\right)$$

To solve the system of equations, it is necessary to specify the pressure distribution along the pseudo-shock development zone.

For the newly designed channel, the pressure distribution can be approximated by the orthogonal Laguerre decomposition $p(x) = \sum_{j=0}^{k} b_j \cdot l_j(x)\,,\ x = [0, \infty]$,, where the coefficients b_j are determined by the numerical solution of the variational problem of entropy production minimization.

x_1 is a cross section for the pseudo-shock occurrence;

x_2 is a cross section for the pseudo-shock maximum pressure.

J_1 is a flow impulse in cross section x_1.

J_{x_i} is a flow impulse in arbitrary cross section x_i

V.Experimental characteristics used in the modified Crocco's model.

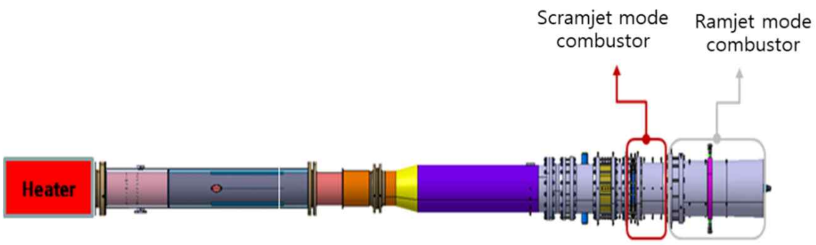


Fig. 2 Scheme of Test Facility with model combustor

Figure 2 shows the configuration of the direct-conneted type test stand. For the high Mach No. test by cooling the heater, high temperature air induction tube and diffuser, etc. to ensure the thermal stability of the facility at total temperature 1,700K. Air pressure and fuel supply conditions for the flight Mach No. are shown in Table 1. Hot firing tests were carried out from 1.0 to 3.0 range of air excess rate (α) of the fuel for each Mach No. condition according to the altitude

Table 1. Hot Firing Test condition

Flight Mach No.	Air condition		Air excess ratio (alpha)	Mass flow rate	
	Temperature [K]	Pressure [bar]		Air [kg/s]	Fuel [kg/s]
3.5	800	10.5	1.15	20.5	1.25
			1.58		0.91
			1.97		0.73
4	950	9	1.26	14	0.78
			1.37		0.72
			1.55		0.64
			1.8		0.55
5	1250	15.5	1.32	12.6	0.67
			1.43		0.62
			2.08		0.43
			2.55		0.35
6	1700	14	1.0	5~5.15	0.37

			1.7		0.21
			2.5		0.14
			3.0		0.12

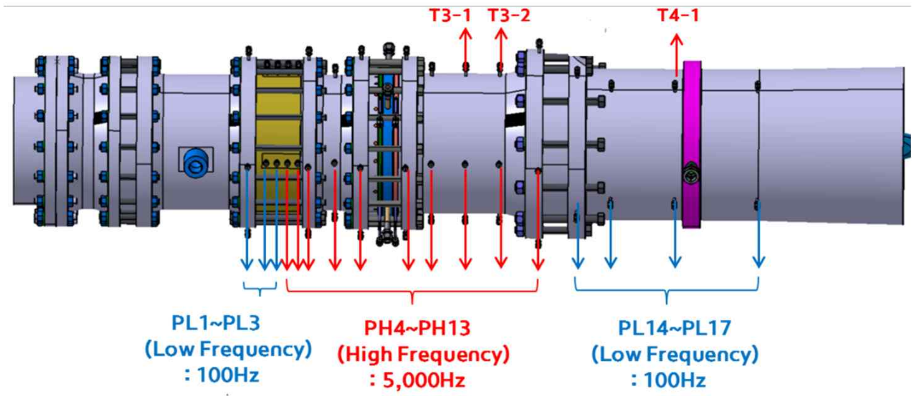


Fig. 3 Measuring Points for Pressure and Temperature Sensors

In order to measure combustion chamber pressure as shown in Figure 3, a total of 18 sensors were used, including a pressure sensor mounted on the heater outlet with 5,000Hz high frequency and 100Hz low frequency type. In order to determine scramjet combustion phenomenon in the high combustion chamber (supersonic combustion chamber), the additional temperature sensors of T3-1, T3-2 was equipped and these measured data was analyzed by averaging the pressure data for 3-5 seconds during combustion.

In the structure of the model (impulse equation), following the conclusions of [3], “it is advisable to take into account the friction force on the development of dissipative processes in the development zone of the pseudo-shock, using the input impulse loss factor $\xi_{x_i} = f\left(M_1, \left({x_i}/{D_{hyd}}\right)\right)$” in the form of a deceleration performances along the pseudo-shock development zone (Fig. 2).

D_{hyd} - is a hydraulic diameter of channel.

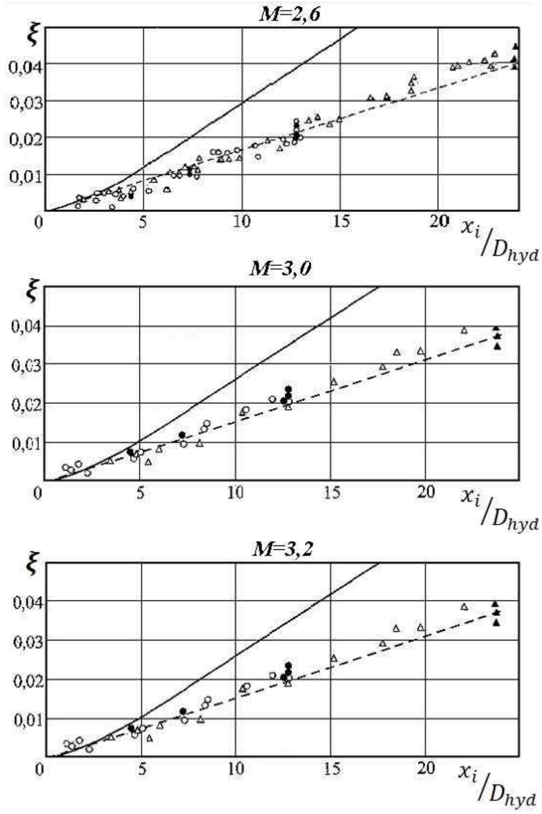


Fig. 4 Characteristics of pseudo-shock losses for various Mach numbers in front of the pseudo-shock zone

***ξ*-** is a coefficient of an input pulse loss

To verify the model, the generalized characteristics of the pseudo-shock length (Fig. 5) and the pressure distribution in the pseudo-shock (Fig. 6) were used.

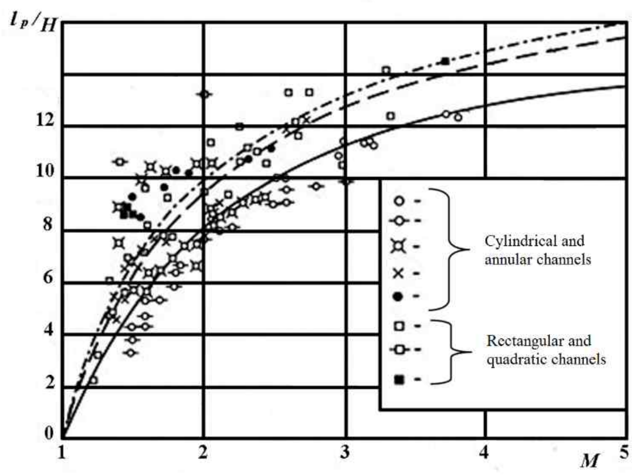


Fig. 5 Generalized pseudo-shock length performance

$$\bar{l}_p = {}^{l_p}/_{H} = \frac{4k}{k-1}\frac{M^2-1}{M^2}\left(\frac{\delta}{0.5(D-d)}\right)^{0.125}.$$

where δ is a thickness of the boundary layer before the pseudo-shock,

D is an outer channel diameter;

d is an internal diameter of the channel;

l_p is a pseudo-shock length;

$H = (D - d)$ is a channel height.

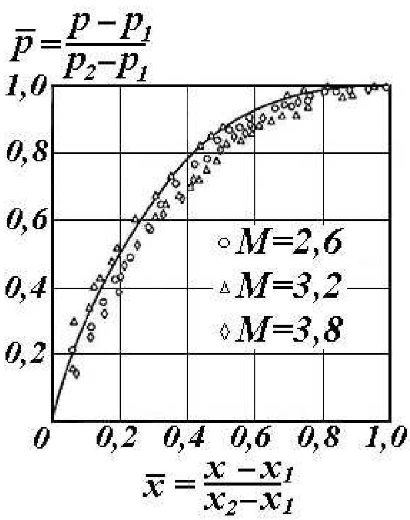


Fig.6 Generalized performance of pressure distribution in pseudo-shock.

$$\overline{p^*} = 3\bar{x} - 3\bar{x}^2 + \bar{x}^3$$

Experimental model of direct flow channel.

To test the adequacy of the modified Crocco's pseudo-shock model, experimental data were obtained from experimental testing a combustor model of a dual-mode ramjet engine with a pre-chamber diffuser (Fig. 1), at the entrance of which the air heated by methane combustion was supplied according to the attached inlet scheme. The mass content of oxygen at the inlet of the pre-chamber diffuser corresponded to its content in the atmosphere. Mach numbers, flow rates, and inlet pressures to the pre-chamber diffuser were calculated taking into account the characteristics of the air intake (Fig. 7).

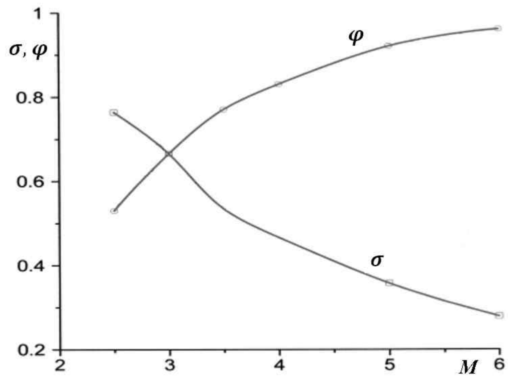


Fig.7 Characteristics of air intake.

***σ* – is** a total pressure recovery coefficient, ***φ* –** is a flow rate coefficient

The choice of flow path scheme and its design parameters are based on the following provisions:

- pseudo-shock is considered as a gas-dynamic structure, the position and parameters of which are associated with the working process of the engine;

- the design flow regime in the isolator is the mode of a fully developed pseudo-shock, corresponding to the most stable mode of operation of the propulsion system with the maximum degree of increase in static pressure;

- the conditions for the occurrence and stability of the pseudo-shock structure are guaranteed for well-defined types of channels and the flow regimes implemented in them according to the experimental data presented in [1] and shown in Fig.7. Figure 8 presents statistical data that determines the occurrence of a head wave of a pseudo-shock as a function of the relative channel width $\overline{b} = \frac{F}{P^2}$, at a certain value of which a boundary layer is formed along the channel with minimal irregularity of flow. F is a cross-sectional area, P is a channel perimeter.

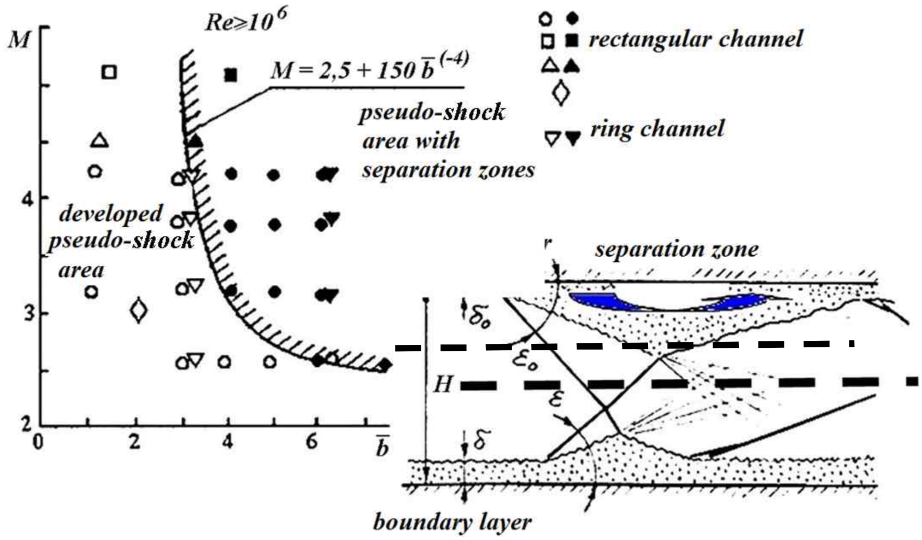


Fig. 8 the boundary separating a fully developed pseudo-shock

In addition, in Fig. 8, the dashed line schematically shows the boundary separating a fully developed pseudo-shock (dissipation region near the lower wall) from a pseudo-shock with a wide separation zone (dissipation region near the upper wall).

Changes in the pseudo-shock structure are caused by the back pressure from the combustor, by the Mach number at the entrance to the isolator, and by the flow regime determined by the Reynolds number. Therefore, in the design process of a multi-mode propulsion system, the computed mode of the propulsion system operation should be selected from the condition of not passing the regime parameters in the pseudo-shock zone beyond the limits outside of which the stall of the air intake and the combustor occurs.According to [1], the geometric characteristics and the isolator operation mode for the experimental model of a dual-mode combustor considered in this article corresponded to the parameters given below in front of the isolator in the developed pseudo-shock zone (Fig. 8).

$3 < \bar{b} < 50$; $Re \approx (6 \div 8) \cdot 10^6$; $D_{hyd} \approx 40$; range of Mach numbers = (1.6 ÷ 3.0) at the entrance to the channel. Thus, the statistical data allow us to reasonably choose the preliminary geometry of the isolator from the condition of guaranteed occurrence of a developed pseudo-shock. The location of the pseudo-shock and the distribution of pressure in it should be optimized on the basis of a mathematical model. The pre-chamber diffuser had a lower wall opening angle within 2 degrees to compensate for the effect of the boundary layer on reducing the Mach number (ensuring that the Mach number is constant before the head compression wave of the pseudo-shock). In [1, 3], it was shown that the subsonic flow formed after a pseudo-shock is similar in its properties to a one-dimensional stream, which is provided by a stagnation mechanism in a pseudo-shock. In this regard, it should be noted the paper [26], where partial mixing of the fuel supplied to the flow part is performed in pseudo-shock structures, allowing an almost homogeneous mixture to be achieved at the entrance to the combustor, which, as is well known, contributes to the greatest combustion completeness. Taking into account that the pseudo-shock structure contributes to an intensive reduction of the unevenness of the supersonic flow in the process of transferring it to the subsonic flow mode, it is advisable to supply fuel to the air flow at the final stage of pseudo-shock formation, thereby ensuring a high uniformity of the air-fuel mixture before the combustor. Therefore, in the considered scheme, fuel pylons are located in the final pseudo-shock formation zone, which provides not only high mixing quality, but also additional stabilization of the pseudo-shock position in the isolator.

The results of calculations and their comparison with experimental data

The modeling approach is to use the modified Crocco's model and the flow deceleration characteristics along the pseudo-shock development zone, in which the pressure distribution is determined from the minimum entropy production condition, to find the distribution of velocity, pressure and temperature for finding a consistent solution between the right and left pseudo-shock boundaries, the parameters in which, respectively, are determined by the operation mode of the combustor and the air intake.

For the considered flight modes according to the Mach number and the optimization methods used, one should choose the initial approximation of the pseudo-shock length (Fig. 2). The data necessary for this can be obtained using the methods of modeling the development of the boundary layer, considered in [8, 17, 19, 20].

To obtain a solution, the system of equations of the modified Crocco's model must satisfy the following condition: the Mach number of the subsonic flow at confluence of the dissipation layers must be equal to 1.0. Therefore, the following conditions must be satisfied at the pseudo-shock boundaries:

Before pseudo-shock in cross section x_1: $w' = w_{M_1>0}$; $p_{x_i=x_1} = p_1$; $\mu = 0$,

After pseudo-shock in cross sectionx_2: $w' = w_{M=1}$; $p_{x_i=x_2} = p_2$; $\mu = 1$.

The position of the pseudo-shock and the coordinates x_1 and x_2 corresponding to this position are determined from the impulse balance, which, together with the mass balance equation, allows one to find the pressure values p_1 and p_2 that are consistent with the gas-dynamic calculation of the flow path of the propulsion system:

$$p(x_1) = p_1,$$

$$p(x_2) = p_2.$$

The pressure distribution in the development zone of a pseudo-shock, represented by the orthogonal Laguerre decomposition, makes it quite easy to estimate the change in the derivative of pressure used in the expression of entropy production. In order to ensure better convergence of the numerical solution of the variational problem, additional conditions adequate to the real process were used:

$$\frac{dp(x_2)}{dx} = 0 \, ,$$

$$\frac{d^2p(x_2)}{dx^2} = 0 \, .$$

In order to obtain a more accurate estimate of the pressure distribution along the pseudo-shock development zone in the energy equation, it is possible to take into account the heat flux into the wall with a temperature factor using the asymptotic theory of the turbulent boundary layer [27].

The verification of the calculated pressure distribution along the pseudo-shock development zone using the principle of minimum entropy production was carried out by comparing with the generalizing experimental dependence $\overline{p^*} = 3\bar{x} - 3\bar{x}^2 + \bar{x}^3$. The results of numerical solutions were presented by the form $\bar{p} = f(\bar{x})$; $\bar{p} = \frac{p-p_1}{p_2-p_1}$; $\bar{x} = \frac{x-x_1}{x_2-x_1}$ for Mach numbers M = 3.0; 4.0; 5.0. Figure 9 shows the entropy production values obtained in the process of solving the variational problem as a function $\emptyset$ of the standard deviation of the pressure distributions along the pseudo-shock development zone $\bar{p}(\bar{x}_i)$ from the generalizing statistical dependence $\overline{p^*}(\bar{x}_i)$:

$$\emptyset = \sum_{i=1}^{N} (\overline{p^*}(\bar{x}_i) - \bar{p}(\bar{x}_i))^2$$

N is the number of points in the pressure distribution along the pseudo-shock development zone.

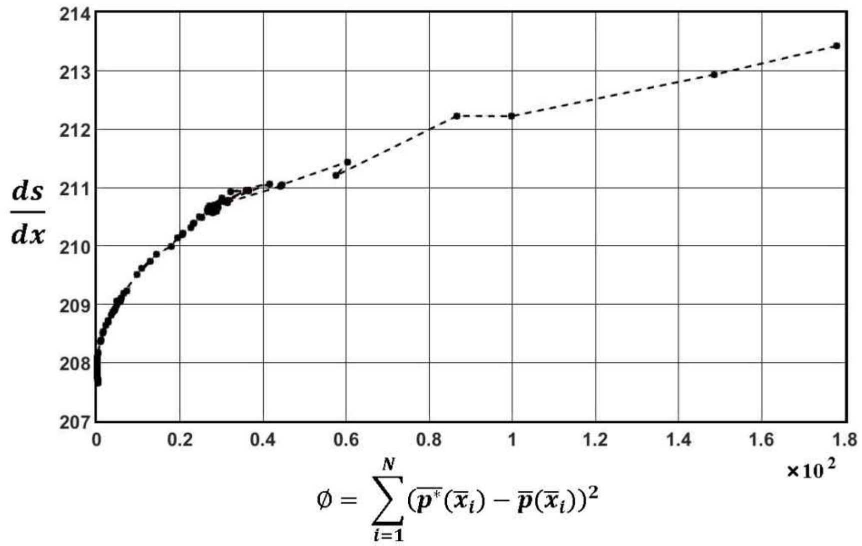
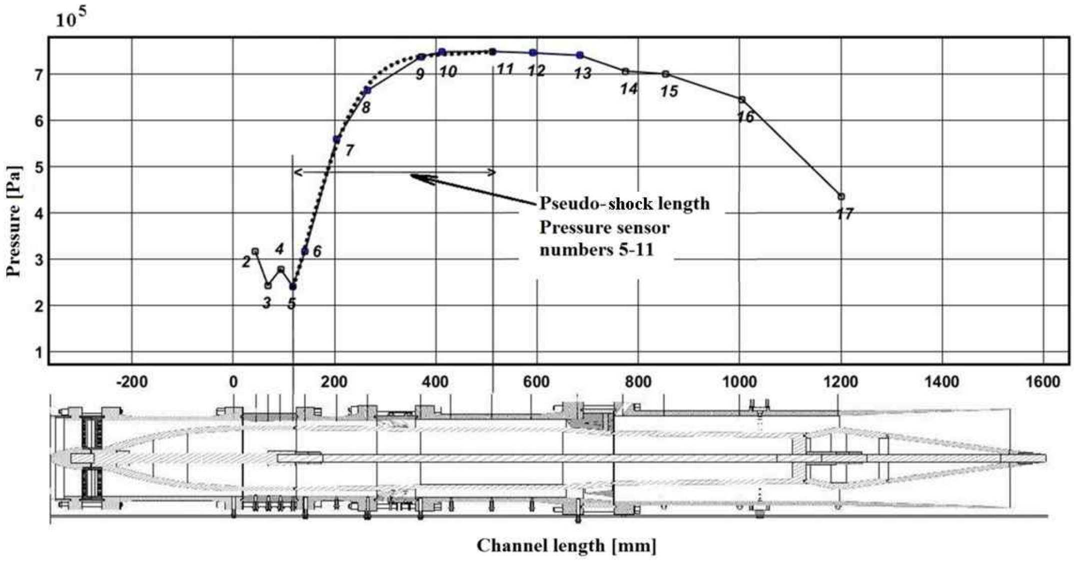
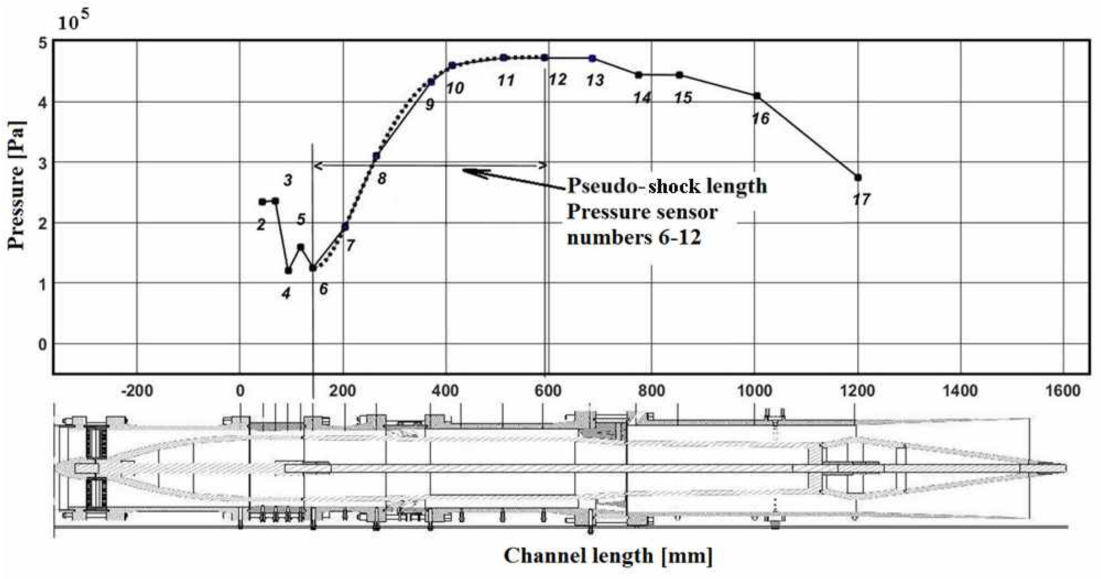


Fig. 9 Entropy production values

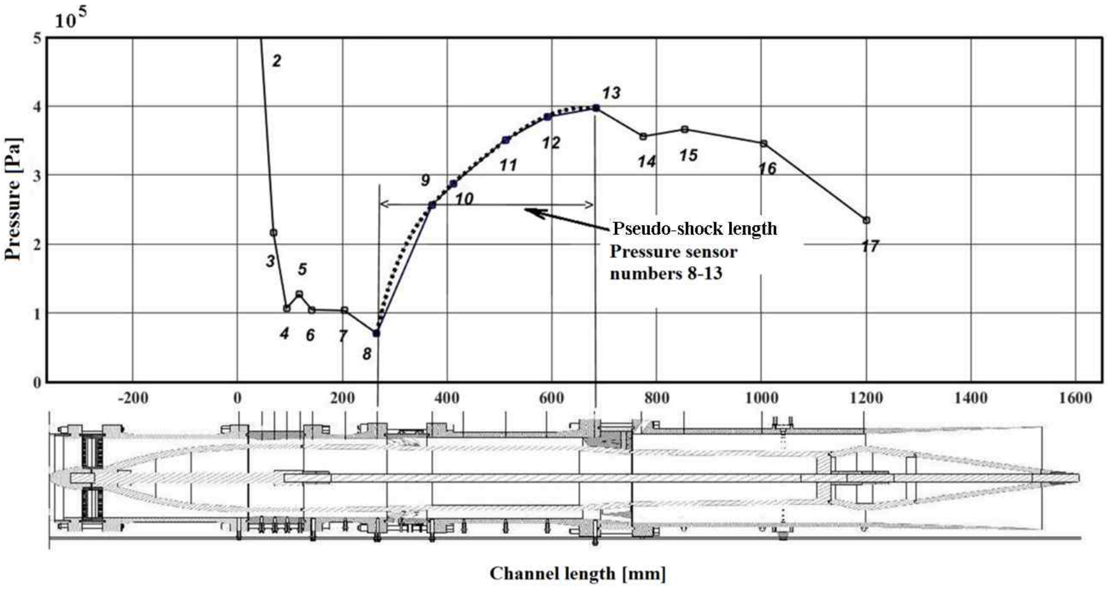
Figures 10 a, b, c for flight modes corresponding to Mach 3.0, 4.0, 5.0 shows a comparison of numerical calculation and experiment in absolute values of pressure along the flow part of the experimental model.



a



b



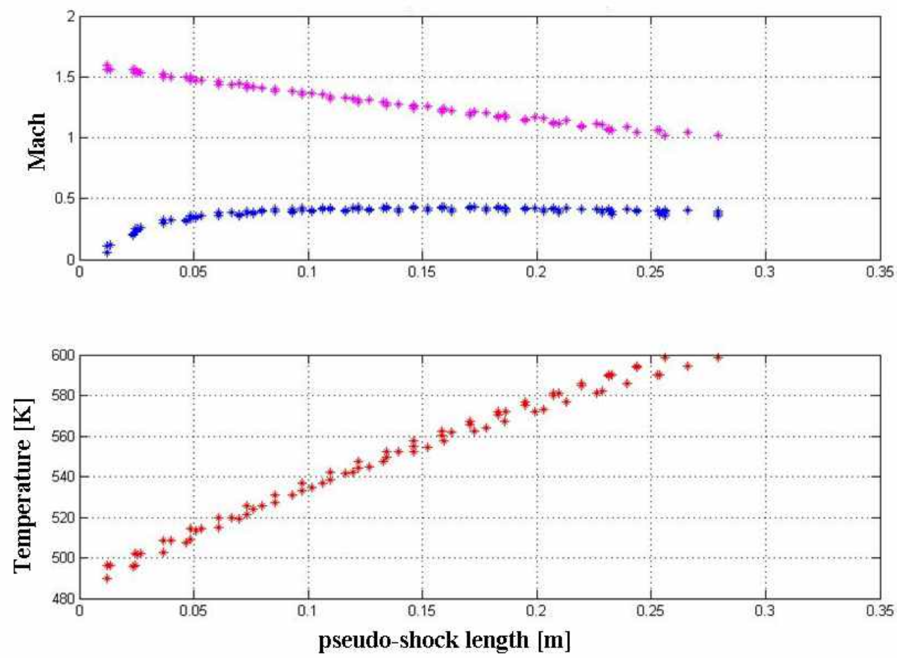
c

Fig. 10 Comparison with calculation and experimental data

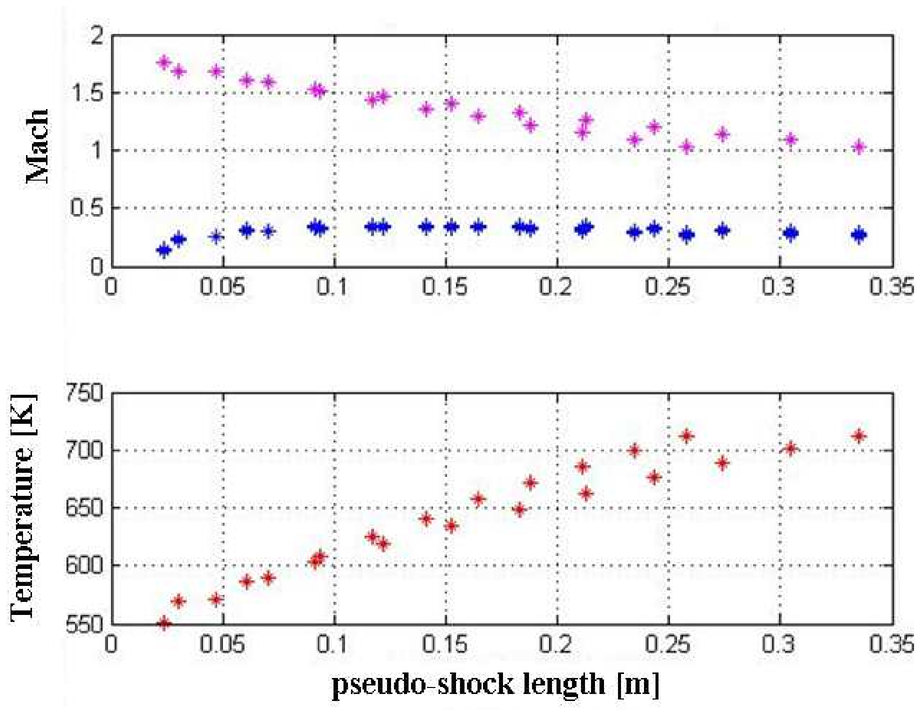
The calculation of the pseudo-shock development zone is shown by a dotted line. The solid line shows the calculation of the static pressure along the flow part of the experimental model of a dual-mode combustor. Dots indicate experimental data. There is some difference between the experimental data and the modified Crocco's model with a sufficient quantitative match for the calculations. The discrepancy between the results can be explained by the absence in the model of calculation of the entropy production in the pseudo-shock structure and by the influence of heat-mass transfer processes along the dissipation zone. In this context, the simulation results confirm the conclusion of [9] and [11] that it is necessary to take into account the detailing of the pseudo-shock structure in order to more accurately estimate the pressure distribution along the pseudo-shock development zone. The adequacy of the technique was also tested in the process of preliminary testing of a dual-mode ramjet [28].

For all flight modes M = 3.5; 4.0; 5.0 (Fig.11 a, b, c) the modified Crocco's model shows a decrease in Mach numbers to 1.0 in the pseudo-shock development zone, consistent with the experimental data [3] of the change in velocity in the dissipative zone (Fig. 12),

M=3.5



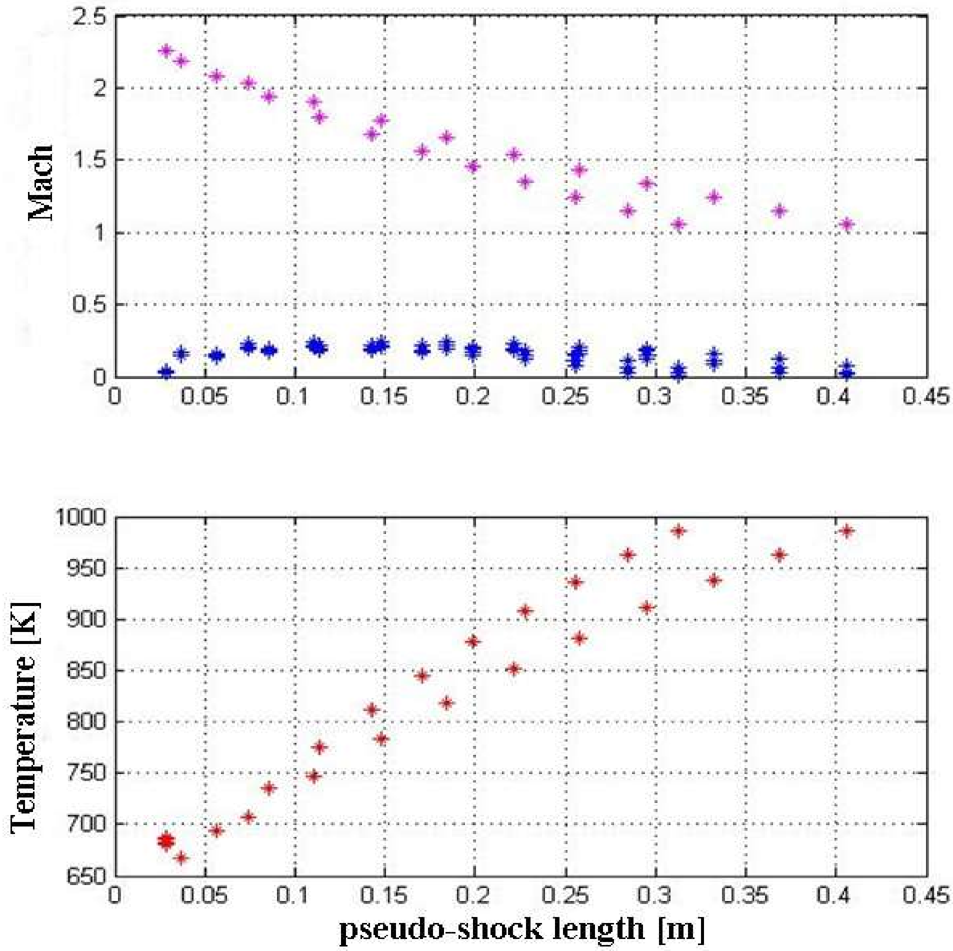
M=4.0



Mach
2
1.5
1
0.5
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Temperature [K]
750
700
650
600
550
pseudo-shock length [m]

B

M=5.0



c

Fig. 11 Mach No. and Temperature according to pseudo-shock length in modified Crocco's model

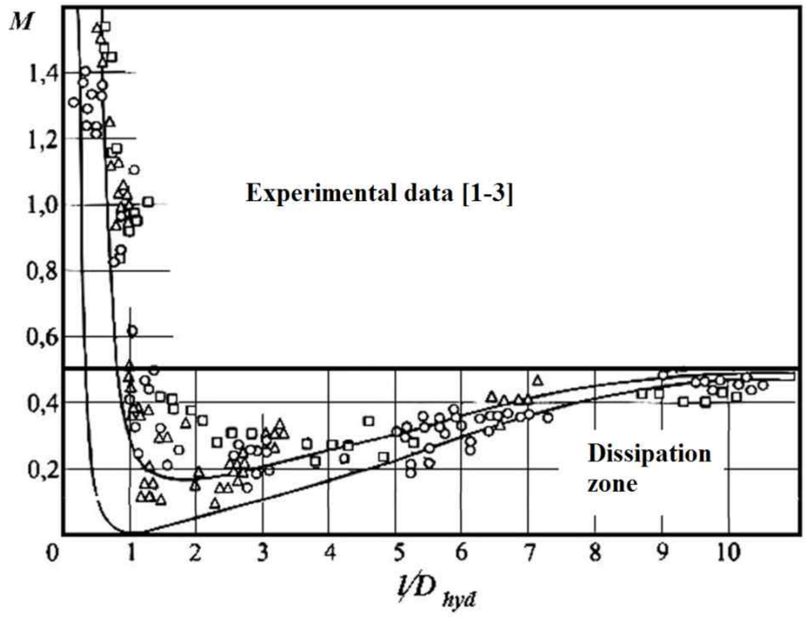


Fig. 12 Mach No according to hydraulic length (Experimental and Calculation)

Comparison of the original and modified Crocco's pseudo-shock models.

The original Crocco's model uses the condition of constancy of the total pressure $p^* = const$, which means $\frac{p_{x_i}}{p_1} = \left(\frac{1-w'^2}{1-w_1^2}\right)^{\frac{k}{k-1}}$. This assumption does not give an adequate result. Therefore, the solution of the original Crocco model [2] for the compression zone leads to the values $M > 2.0 \div 2.5$ in the cross section of the confluence of the dissipation layers. From physical estimation, the Mach number should approach 1.0 in the confluence zone of the dissipation layers, which can be achieved by modifying the Crocco's pseudo-shock dissipative model.

In fig. 13, as an example, the comparison of the distributions obtained on the basis of the original and modified Crocco's models for the flight Mach number = 5.0 at the entrance to the isolator is shown. It is seen that the modified Crocco's pseudo-shock model allows to achieve adequate results when calculating the compression zone in the isolator using additional ratios and experimental characteristics. The original Crocco's model gives an inexplicable result for a change of the average velocity in the compression zone.

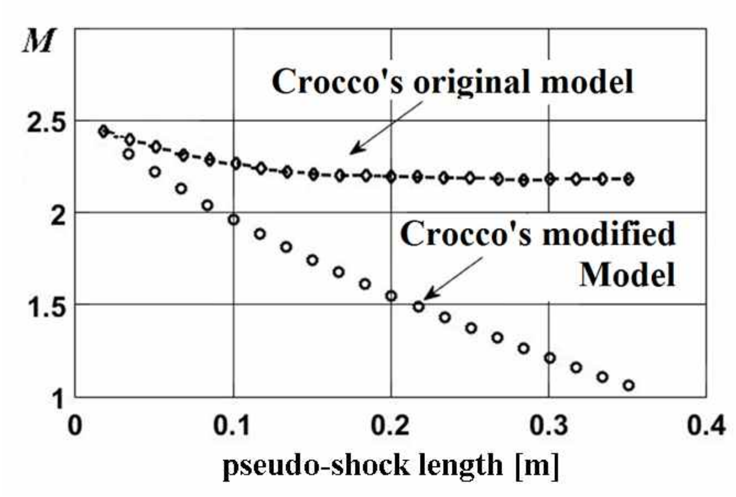


Fig. 13 Comparison of the distributions obtained on the basis of the original and modified Crocco's models

VI.Conclusion

1. The calculation results for the modified Crocco's model are consistent with the generalized experimental data.
2. It is shown that the approximation of the computed pressure distribution along the pseudo-shock to a generalizing experimental dependence is characterized by the minimum value of entropy production.
3. The modified Crocco's model is applicable for thermodynamic computed of a ramjet cycle and evaluating its effectiveness based on the principle of minimum entropy production.
4. The discrepancy between experimental and computed data can be explained by the lack of accounting for the processes of entropy production and by the influence of heat and mass transfer processes on the change of parameters in the pseudo-shock structure.
5. The obtained level of discrepancy between the computation results and experimental data testifies the significant increase in entropy associated with the dissipation region.

References

[1] Penzin V.I. Experimental study of separated flows in the channels. - M .: Izd. TsAGI, 2009. - 280s.

[2] Crocco L. One-dimensional consideration of the gas dynamics of steady-state flows. Basics of gas dynamics. Ed. G. Emmons. M .: Foreign Literature, 1963. - 702 p.

[3]Guskov OV, Kopchenov VI, Lipatov I.I. and others. The processes of inhibition of supersonic flows in channels. - M .: FIZMATLIT, 2008.- 168s.

[4] Waltrup P.J. and Billig F.S., Structure of Shock Waves in Cylindrical Ducts. AIAA Journal, Vol. 11 N. 10, 1973, pp. 1404-1408.

[5] Waltrup P.J. and Billig F.S., Prediction of Precombustion Wall Pressure Distributions in Scramjet Engines. Joutnal of Spacecraft, V.10, N9, 1973, pp. 620-622.

[6] Gimranov E.G. Ratio of parameters on pseudo-shock / Interuniversity scientific collection "Testing vehicle engines." - Ufa: 1975, №3.

[7] Gurylev V.G., Eliseev S.N. About theory of “pseudo-reversing” at entrance of channel // Uchenye zapiski TsAGI, 1972, V.3, №3.

[8] Gogish L.V., Stepanov G.Yu. Quasi-one-dimensional theory of interaction of turbulent wake with supersonic flow at channel and jet. // Proceedings of the Institute of Mechanics of Moscow State University. 1971. №11.

[9] Azevedo D. J., Liu C. S. Engineering Approach to the Prediction of Shock Patterns in Bounded High-Speed Flows // AIAA J. 1993. V. 31, N 1. P. 83–90.

[10] Medvedev A.E. Approximate modeling of the flow structure in λ-shaped pseudo-shock // Applied Mechanics and Technical Physics. - 2014. V. 55, № 6. - P. 43–59.

[11] Takeshi K. Prediction of Pseudo-shock Position in a Long Duct Using the Momentum Balance Model / Trans. Japan Soc. Aero. Space Sci. 2012Vol. 55, No. 3, pp. 199–201.

[12] Simont V.L. Levin V.M., Meshcheryakov E.A. Combustion of hydrogen in a supersonic flow in a channel in the presence of a pseudo-shock // FGW. - 1978. V. 14, №4.

[13] Gimranov E.G. Braking of a viscous supersonic flow (“pseudo-shock”) in the channels of vehicle engines. // Collection of works AIM. - Ufa: 1992. Part I. - P. 121-132.

[14] Meshcheryakov E.A., Yashina V.V. Quasi-one-dimensional tear-off model of pseudo-shock in the channel. // TsAGI's scientific notes. - T. XLIV, -2013, No. 5, - P.46-63.

[15] Gimranov E.G., Mikhailov V.G. Generalized quasi-one-dimensional equations of gas motion in DLA channels and their integrals // Vestnik UGATU. -2006. –T.7, №1 (14) –s.153-160.

[16] Gimranov EG The development of the Crocco method for solving generalized equations of gas motion in DLA and EH channels // Vestnik UGATU. - 2007. V. 9, № 1 (19). - C.3-7.

[17] Lapin Yu.V. Turbulent boundary layer in supersonic gas flows. -2 ed., Pererab. - M: Science. The main editors of physical and mathematical literature, 1982.-312c.

[18] Aleksandrov V.N., Bytskevich V.M., Verkholomov V.K. and others. Integral ramjet engines on solid fuels. Fundamentals of the theory and calculation / ed. L.S. Yanovsky. - M .: Academicbook, - 2006. - 343 p.

[19] Tamaki T. Tomita Y. Yamane R. Study of Pseudo-Shock (1st. Report, λ-Type Pseudo- Shock) // Bull. Of the JSME. 1970. V.13, N55.

[20] Tamaki T. Tomita Y. Yamane R. Study of Pseudo- Shock (2. Report, X-Type Pseudo- Shock) // Bull. Of the JSME. 1971.V.14, N74.

[21] Gunko Yu.P., Shumsky V.V. Characteristics of ramjet engines with dual-mode combustor // Thermal Physics and Aeromechanics. 2014, t. 21, No. 4. P. 521−530.

[22] Simont V.L. Ostras V.N. Calculation of a pseudo-shock in a cylindrical channel // Scientific Journal of TsAGI. - 1974. V.V., №3.

[23] Prigogine I. Modern thermodynamics. From heat engines to dissipative structures. - M .: Mir, 2008. - 464 p.

[24] Levin V.M. Problems of working process organization in ramjet // Physics of combustion and explosion. - 2010. - V. 46, № 4. - P. 45–55.

[25] Levin V.M., Karasev V.N., Kartovitskiy LL, et al. Nonstationarity of process in ramjet model // Physics of Combustion and Explosion. - 2013. - V. 49, № 6. - P. 68–75.

[26] Levin V.M., Karasev V.N., Kartovitskiy L.L. Questions of working process organization in ramjet combustor // Bulletin of the Moscow Aviation Institute. - 2009. - T.16, No. 5, P.78-87.

[27] Kutateladze S.S., Leontyev A.I. Heat and mass transfer and friction in turbulent boundary layer. M .: Energy, 1972. - 342s.

[28] Levin V.M., Karasev V.N., Kartovitskiy L.L. et al. Results of preliminary tests of dual-mode ramjet engine // Proceedings of TsAGI, 2015, No. 2736, pp. 28-34.