Comparison of two-dimensional and quasi -one-dimensional scramjet models by the example of VAG experiment

R K Seleznev [1,2,3]

[1] Dukhov Research Institute of Automatics (VNIIA), Suschevskaya Street 22, Moscow 127055, Russia
[2] Moscow Institute of Physics and Technology (State University), 9 Institutskiy per., Dolgoprudny, Moscow Region, 141701, Russia
[3] A. Ishlinsky Institute for Problems in Mechanics, RAS Vernadsky Street 101(1), Moscow, 119526, Russia

rkseleznev@gmail.com

Abstract. In the paper two-dimensional and quasi-one dimensional models for scramjet combustion chamber are described. Comparison of the results of calculations for the two-dimensional and quasi-one dimensional code by the example of VAG experiment are presented.

1. Introduction

Recently, a study of combustion processes in the ramjet and scramjet is becoming more and more important in connection with attempts to create a hypersonic aircraft. Carrying out physical experiments in this field is connected with a lot of technical difficulties and is too expensive. Special requirements have to meet the fuel and combustion chamber geometry. Therefore, computational and theoretical studies of combustion processes in scramjet begin to play an increasing role. At the first stage of designing the scramjet it is very important to make an accurate prediction of the engine efficiency. In recent years, the quasi-one-dimensional scramjet model is widespread [1–14]. In these models to calculate the chemical concentrations, temperature and pressure fields, the set of ordinary differential equations should be solved, and the area of the combustion chamber is defined as a function of a longitudinal coordinate. However, the quasi-one-dimensional model does not allow to describe a structure of flow fields. There are two-dimensional [15] and three-dimensional [16] models for describing the structure of flows in scramjet chamber.

In [17] the comparison of the results of calculations for the two-dimensional and quasi-one dimensional code has been presented for HyShot-2 experiment. The purpose of this paper is to compares the quasi-one-dimensional and two-dimensional models by the example of numerical simulation of VAG experiment [18].

2. Description of VAG experimental setup

The VAG [18] experiment is similar to T4 at the University of Queensland.[19,20]. In [19] the comparison of data between this two experiments was carried out. The experiment was conducted for a rectangular channel expanding part, as shown in figure 1. The width of the camera was constant and equaled to 94.3 mm. Fuel injection is executed from the gap strut in the center of the chamber. On the top and bottom of the strut there were located 4 holes with a diameter of 2.5 mm, through which

hydrogen is carried out perpendicular to the flow. At the end of the strut there were located 4 holes with a diameter of 2.5 mm, through of hydrogen injected the parallel to the flow. The experiment studied the effect of the strut geometry on the results obtained. The length of the wedge spacers (33.5 mm, 37.6 mm, 39.6 mm, 43.8 mm and 44.8 mm) was varied. In the experiment the pressure distribution on the chamber wall was measured. In this paper only normal hydrogen injection and equivalence ratio φ=0.61 was considered. The following incoming air flow parameters were used for verification:

Incoming flow pressure:	$P = 0.58$ atm;
Incoming flow temperature:	$T = 1258$ K;
Incoming flow Much Number:	$M = 2.44$;
Incoming flow gas mixture:	Air;
Fuel Much Number:	$M = 1$.
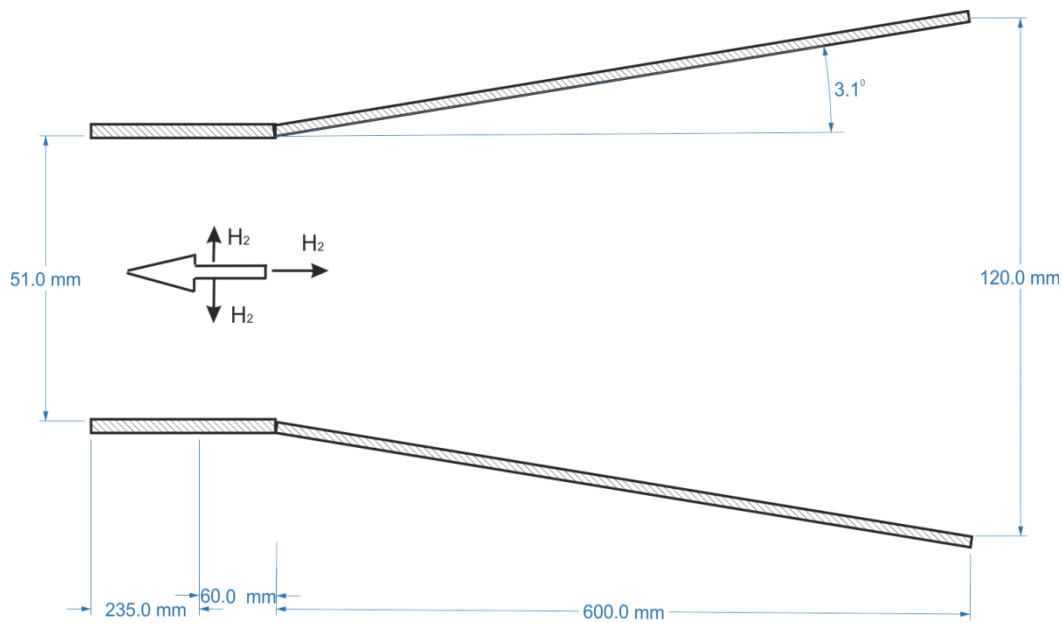
Figure 1. Scheme of the VAG[18] supersonic combustion experiment.

3. Quasi-one-dimensional computational fluid dynamic model

In [17] the quasi-one-dimensional computational fluid dynamic model described in detail. To describe the fluid flow in scramjet the conservation laws for mass, momentum and energy should be specified. The governing equations are based on the following assumptions:1) ideal gas law is fulfilled in the combustor, 2) quasi-one-dimensional flow (all flow variables are functions of the axial distance along the combustor),3) continuous flow (changes in stream properties are continuous functions), 4) steady-state flow. Quasi-one-dimensional approach requires that we state these equations into the set of ordinary differential equations (ODE). The equations solved are:

$$\frac{dU}{dx} = \frac{1}{\alpha}\left\{ -\frac{1}{A}\frac{dA}{dx} + \frac{1+\gamma M^2(1-\varepsilon)-\left(h_0/\hat{h}\right)}{\dot{m}}\frac{d\dot{m}}{dx} + \right.$$

$$\left. +\frac{1}{\hat{h}}\left[-\sum_i h_i \frac{dY_i}{dx} + \frac{1}{\dot{m}}\sum_i \left(h_i \frac{d\dot{m}_i}{dx} \right)_{added} \right] - \frac{1}{MW}\frac{dMW}{dx} + \left[\gamma M^2 - \frac{c_p(\mathrm{T}_{aw}-\mathrm{T}_w)}{\hat{h}\cdot \mathrm{Pr}^{\frac{3}{2}}A} \right]\frac{2C_f}{D} \right\}, \tag{1}$$

$$\frac{dT}{dx} = \frac{1}{\hat{c}_p}\left[-\sum_i h_i \frac{dY_i}{dx} + \frac{1}{\dot{m}}\sum_i \left(h_i \frac{d\dot{m}_i}{dx} \right)_{added} - \frac{2C_f c_p \left(T_{AW} - T_W \right)}{\mathrm{Pr}^{\frac{2}{3}} D \cdot A} - \frac{h_0}{\dot{m}}\frac{d\dot{m}}{dx} - U\frac{dU}{dx} \right],$$ (2)

$$\frac{d\rho}{dx} = \rho\left[\frac{1}{\dot{m}}\frac{d\dot{m}}{dx} - \frac{1}{U}\frac{dU}{dx} - \frac{1}{A}\frac{dA}{dx} \right],$$ (3)

$$\frac{dp}{dx} = -\gamma p M^2 \left[\frac{1}{U}\frac{dU}{dx} + \frac{1}{2}\left(\frac{4C_f}{D} \right) + \frac{1}{\dot{m}}\frac{d\dot{m}}{dx} \right],$$ (4)

$$\frac{d(Y_i)}{dx} = \frac{1}{\dot{m}}\frac{d\dot{m}_{i,added}}{dx} + \frac{\dot{\omega}_i MW_i}{\rho U} - \frac{Y_i}{\dot{m}}\frac{d\dot{m}}{dx},$$ (5)

where $\alpha = 1/U\left(1 - \gamma M^2 + U^2/\hat{h} \right)$; $\hat{h} = \hat{c}_p T$; $\hat{c}_p = \tilde{c}_p - \frac{1}{\dot{m}}\left\{ \sum_i \dot{m}_i \left(c_{pi} + \tilde{c}_{pi}T \right)_{added} \right\}$; $\tilde{c}_p = c_p + \sum_i T\tilde{c}_{p_i}Y_i$;

$T_{aw} = T\left[1 + \mathrm{Pr}^{\frac{1}{3}}\left[(\gamma-1)/2 \right]M^2 \right]$; $D = \frac{4A}{P_W}$; $MW = \frac{1}{\sum_i \frac{Y_i}{MW_i}}$; $h_0 = h + \frac{U^2}{2}$; $\varepsilon = U_f/U_\infty$ is the ratio of

injection velocity in the downstream direction to a flow (under perpendicular injection $\varepsilon = 0$); A -is the sectional area being a function of the coordinate x. The skin friction is found using the Eckert

Reference Temperature method. $C_f = \frac{0.664\sqrt{C^*}}{\sqrt{\mathrm{Re}}}$; $C^* = \left(\frac{T^*}{T} \right)^{1/2}\left(\frac{1 + R/T}{T^*/T + R/T} \right)$; $R = 111K$;

$T^* = 0.5T_W + 0.28T + 0.22T_{aw}$. The method is valid for estimating frictional drag at subsonic to hypersonic speed and is suitable for aircraft design. The method assumes that the vehicle surface is at the adiabatic wall temperature T$_{aw}$.

We use the supersonic mixing model [2]. Hydrogen was considered as a fuel. Global kinetic mechanism suggested by Westbrook [21] was used. The set of ODE was solved numerically using the Runge-Kutta method and generalized Newton method [22].

4. Two-dimensional computational fluid dynamic model

For two-dimensional calculations we used the NERAT-2D computer code [15]. NERAT-2D realizes the time-relaxation method. At each time step the following groups of governing equations were integrated successively: the Navier – Stokes and continuity equations, the equations of mass conservation of chemical species, the equation of energy conservation. These equations are formulated in the following form:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}\left(\rho \mathbf{V} \right) = 0,$$ (6)

$$\frac{\partial \rho u}{\partial t} + \mathrm{div}\left(\rho u \mathbf{V} \right) = -\frac{\partial p}{\partial x} - \frac{2}{3}\frac{\partial}{\partial x}\left(\mu\,\mathrm{div}\mathbf{V} \right) + \frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial \mathrm{v}}{\partial x} + \frac{\partial u}{\partial r} \right) \right] + 2\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x} \right),$$ (7)

$$\frac{\partial \rho \mathrm{v}}{\partial t} + \mathrm{div}\left(\rho \mathrm{v} \mathbf{V} \right) = -\frac{\partial p}{\partial r} - \frac{2}{3}\frac{\partial}{\partial r}\left(\mu\,\mathrm{div}\mathbf{V} \right) + \frac{\partial}{\partial x}\left[\mu\left(\frac{\partial \mathrm{v}}{\partial x} + \frac{\partial u}{\partial r} \right) \right] +$$
$$+ 2\frac{\partial}{\partial r}\left(\mu\frac{\partial \mathrm{v}}{\partial r} \right) + 2\mu\frac{\partial}{\partial r}\left(\frac{\mathrm{v}}{r} \right)$$ (8)

$$\frac{\partial \rho_i}{\partial t} + \mathrm{div}\,\rho_i \mathbf{V} = -\mathrm{div}\,\mathbf{J}_i + \dot{w}_i, \quad i = 1, 2, \dots, N_s,$$ (9)

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$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{V} \operatorname{grad} T = \operatorname{div}\left(\lambda \operatorname{grad} T\right) + \frac{\partial p}{\partial t} + \mathbf{V} \operatorname{grad} p +$$

$$+ \Phi_\mu - \sum_{i=1}^{N_s} h_i \dot{w}_i + \sum_{i=1}^{N_s} \rho c_{p,i} D_i \left(\operatorname{grad} Y_i \cdot \operatorname{grad} T\right),$$

(10)

where $\quad \Phi_\mu = \mu \left[2\left(\frac{v}{r}\right)^2 + 2\left(\frac{\partial v}{\partial r}\right)^2 + 2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial r}\right)^2 - \frac{2}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial r} + \frac{v}{r}\right)^2 \right]$ is the dissipative

function; ; μ, λ are the viscosity and heat conductivity coefficients, c_p is the specific heat capacity of gas mixture; $c_p = \sum_i^{N_s} Y_i c_{p,i}$; Y_i is the mass fraction of species i; $c_{p,i}, h_i$ are the specific heat capacity at constant pressure and specific enthalpy of species i; $\dot{w}_i$ is the reaction rate for species i; D_i is the effective diffusion coefficient of species i; $\rho_i, \mathbf{J}_i$ are the density and mass diffusion flux for species i; $\mathbf{J}_i = -\rho D_i \operatorname{grad} Y_i$; N_s is the number of species. We used the kinetic mechanism proposed by Evans and Schexnayder [23].

5. Results

Comparison of the pressure distribution calculated by two-dimensional model (blue line) and quasi-one-dimensional model (red line) with experimental data (green triangles) are shown in figure 2. It should be noted that the pressure increase appears to be a more significant under two-dimensional modeling. This can be explained by the fact that the flow in the channel is actually three-dimensional, and therefore it is necessary and very important to consider the fuel injection features for a correct description of the flow and combustion in the channel. One can also see a good agreement between the quasi one-dimensional simulation results and experimental data.
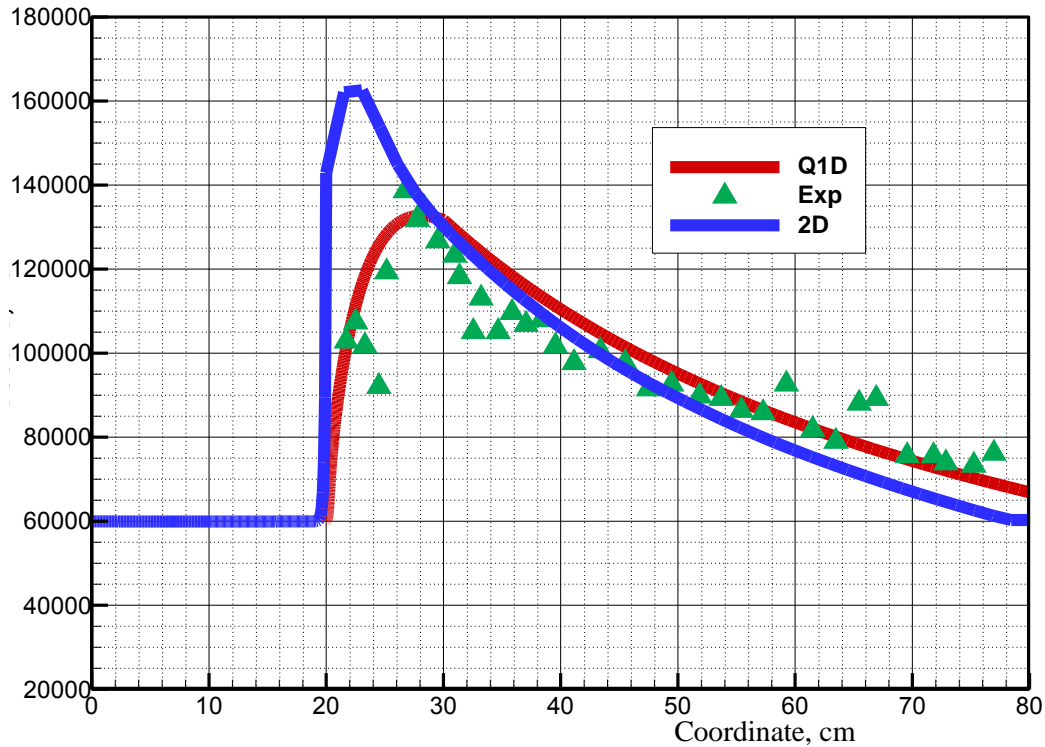
Figure 2. Comparison the pressure distribution calculated by two-dimensional model (blue line) and quasi-one-dimensional model (red line) with experimental data (green triangles).

6. Conclusion

Comparison of the pressure distribution calculated by two-dimensional model and quasi-one-dimensional model with experimental data for VAG experimental setup is presented. This work presents a continuation of our efforts on the verification and validation of numerical methods and computational codes for calculation of various hypersonic vehicles and energetic devices [22-31].

Acknowledgments

References

[1]   Brien T F, Starkey R P and Lewis M J 2001 Quasi-One-Dimensional High-Speed Engine Model with Finite-Rate Chemistry *J. Propuls. Power* **17** pp 1366–1375
[2]   Birzer C, Doolan C 2009 Quasi-one-dimensional model of hydrogen-fueled scramjet combustors *J. Propuls. power* **25** pp 1220–5
[3]   Tourani C 2011 Computational simulation of scramjet combustors – a comparison between quasi-one dimensional and 2-D numerical simulations *17th AIAA international space planes and hypersonic systems and technologies conference*
[4]   Doolan C, Boyce R 2008 A Quasi-One-Dimensional Mixing and Combustion Code for Trajectory Optimisation and Design Studies *AIAA Paper-2008-2603*
[5]   Zabaikin VA 2003 Quality of a high-enthalpy flow upon electric-arc heating of air in a facility for investigating supersonic combustion *Combust. Explos. Shock Waves* **39** pp 23–30
[6]   Zhang D, Feng Y, Zhang S, Qin J, Cheng K, Bao W and Yu D 2016 Quasi-One-Dimensional Model of Scramjet Combustor Coupled with Regenerative Cooling *J. Propuls. Power* pp 1–11
[7]   Sforza P M 2012 Quasi-One-Dimensional Flow Equations *Theory Aerosp. Propuls. pp* 35–53
[8]   Zhao Y, Shen Q and Guan F 2016 Quasi-One-Dimensional Analysis of Supersonic Combustor Performance *52nd AIAA/SAE/ASEE Jt. Propuls. Conf.* pp 1–8
[9]   Koo H, Donde P and Raman V 2011 A quadrature-based LES/transported probability density function approach for modeling supersonic combustion *Proc. Combust. Inst.* **33** pp 2203–10
[10] Seleznev R K, Surzhikov S T 2015 Quasi-One-Dimensional and Two-Dimensional Numerical Simulation of Scramjet Combustors *51th AIAA/ASME/SAE/ASEE Joint Propulsion Conference,. AIAA Paper-2015-4166* pp 1-28
[11] Birzer C and Doolan C J 2007 Quasi-One-Dimensional Modeling of Hydrogen Fuelled Scramjet Combustors *AIAA Paper-2007-4314* pp 1-13
[12] Frezzotti M L and Nasuti F 2015 Response Function Modeling in the Study of Longitudinal Combustion Instability by a Quasi-1D Eulerian Solver pp 1–13
[13] Vanyai T, Bricalli M, Brieschenk S and Boyce R R 2014 A Quasi-One-Dimensional Investigation Into the Effect of Combustion Processes on Scramjet Performance *19th AIAA International Space Planes and Hypersonic Systems and Technologies Conference* pp 1–13
[14] Tian L, Chen L, Chen Q, Li F and Chang X 2014 Quasi-One-Dimensional Multimodes Analysis for Dual-Mode Scramjet *J. Propuls. Power* **30** pp 1559–67
[15] Surzhikov S T, Seleznev R K, Tretjakov P K, Zabaykin V A 2014 Unsteady Thermo-Gasdynamic Processes in Scramjet Combustion Chamber with Periodical Input of Cold Air, *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA Paper-2014-3917* pp 1-25
[16] Englbom W, Frate F and Nelson C C 2005 Progress in Validation of Wind-US for Ramjet/Scramjet Combustion *AIAA Paper-2005-1000* pp 1-18
[17] Seleznev R K, Surzhikov S T, Shang J A 2016 Quasi-One-Dimensional Analysis of Hydrogen-Fueled Scramjet Combustors AIAA 2016-4569, *52nd AIAA/ASME/SAE/ASEE Joint*

Propulsion Conference, *AIAA Paper-2016-4569* pp 1–27

[18] Masuya G, Komuro T, Murakamit A, Murayama M and Katsura O 1995 Ignition and Combustion Performance of Scramjet Combustors with Fuel Injection Struts *J. Propuls. Power* **11** pp 301–307

[19] Boyce R R, Paull A, Stalker R J, Wendt M, Chinzei N and Miyajima H 2000 Comparison of Supersonic Combustion Between Impulse and Vitiation-Heated Facilities *J. Propuls. Power* **16** pp 709–717

[20] Stalker R J Shock Tunnels for Real Gas Hypersonics

[21] Ó Conaire M, Curran H J, Simmie J M, Pitz W J and Westbrook C K 2004 A comprehensive modeling study of hydrogen oxidation *Int. J. Chem. Kinet.* **36** pp 603–22

[22] Seleznev R K, Surzhikov S T 2013 A Generalized Newton Method for Differential Equation of Chemical Kinetics *44th AIAA Thermophysics Conference*. *AIAA Paper-2013-3009* pp 1–17

[23] Evans J and Schexnayder C 1980 Influence of Chemical Kinetics and Unmixedness on Burning in Supersonic Hydrogen Flames *AIAA J.* **18** pp 188–193

[24] Surzhikov S T, Zheleznyakova A L, Shang J S, Rivir R B 2013 Simulating gasdynamic interaction and radiative heating within scramjets with hydrocarbon fuels *44th AIAA Thermophysics Conference*

[25] Surzhikov S T 2011 Radiative-Convective Heat Transfer of a Spherically Shaped Space Vehicle in Carbon Dioxide *High Temperature* **49**(1) pp 92–107

[26] Surzhikov S T 2012 Coupled radiative gasdynamic interaction and non-equilibrium dissociation for large-scale returned space vehicles Chemical Physics **398** pp 56–63

[27] Shang J S, Surzhikov S T 2012 Nonequilibrium radiative hypersonic flow simulation *Progress in Aerospace Sciences* **53** pp 46–65

[28] Surzhikov S T. 2012 Radiative-Collisional Models in Non-Equilibrium Aerothemodynamics of Entry Probes *Journal of Heat* Transfer **134** pp 031002-1 – 031002-12

[29] Shang J S, Surzhikov S T 2010 Simulating Nonequilibrium Flow for Ablative Earth Entry *Journal of Spacecraft and Rockets* **47**(5) pp 806-815

[30] Shang J S, Surzhikov S T 2011 Simulating Stardust Earth Reentry with Radiation Heat Transfer *Journal of Spacecraft and Rockets* **48**(3) pp 385-396

[31] Surzhikov S T, Shang J S 2012 Coupled Radiation-Gasdynamic Model for Stardust Earth Entry Simulation *Journal of Spacecraft and Rockets* **49**(5) pp 875-888