# EVALUATION OF A VITIATED AIR GENERATOR FLOW CONDITIONS FOR THE 14-X HYPERSONIC VEHICLE COMBUSTOR TESTS

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***Abstract.*** *To study the supersonic combustion physical phenomena it is required ground test facilities such as shock tunnels, shock tubes and vitiated air generators. For this purpose, a direct-connected supersonic combustion research facility is now being assembled at the Institute for Advanced Studies (IEAv/DCTA). This facility was first mounted at the Combustion and Propulsion Laboratory (LCP/INPE) and last year was transferred to the IEAv, in order to help the research of the supersonic combustion inside the combustor of the 14-X hypersonic vehicle that is being developed at this Institute. The direct-connected supersonic combustion test bench consists basically of a vitiated air generator (VAG) unit and a nozzle directly coupled to the supersonic combustor to be tested. The flow at the exit of the test facility simulates the air conditions behind the oblique or conical shock waves formed ahead of vehicles flying at hypersonic speeds. These are the same conditions at a scramjet (supersonic combustion ramjet) combustor entrance and it is a high temperature supersonic flow. To simulate this flow on the test facility, oxygen enriched air is heated by combustion inside the VAG and then accelerated through the nozzle, generating the "vitiated air" containing the desired flow properties plus the heating process combustion products, while keeping the same atmospheric oxygen content. In order to control and adjust the flow test conditions at the facility exhaust, for the new values, i.e., for the conditions inside de 14-X combustor, an evaluation of the flow inside the entire facility should be done to find the new equivalence ratio of the reactants (used to heat the air), and the new shape of the nozzle to reach the desirable Mach number (the one inside the combustor) at the exit of the test bench. This work presents details of the study of the entire flow inside the facility where the combustion process in the vitiated air generator is analyzed, using the software CHEMKIN-III, and the flow inside the nozzle is evaluated, using the Jameson scheme, which is a finite volume discretization method with artificial dissipative terms, for the solution of the Euler equations, considering two gas models: a calorically perfect and a frozen one. This study allows us to adjust and control the test flow conditions, at nozzle exit, to adapt the ground test facility to the research of the supersonic combustion inside the 14-X combustor.*

***Keywords:*** *vitiated air generator, transonic nozzle, ground test facility, reactive flow*

## 1. INTRODUCTION

Aerospace vehicles must be tested in ground test facilities before the flight tests, in order to obtain all the parameters necessaries for the research and development of the flight model. For the first flight of the scramjet, the hypersonic vehicle, 14-X, which is now being developed at IEAv, one of the most important parts of the research is the study on the supersonic combustion inside its combustor. For this purpose it is used a shock tunnel, to obtain the aerodynamics conditions of the flow inside its combustor, and a supersonic combustion test bench, that simulates the same air flow condition inside the combustor, where the fuel of the supersonic combustion will be injected. This ground test facility consists basically of a vitiated air generator (VAG) unit and a nozzle directly coupled to the supersonic combustor to be tested. The flow at the exit of the test facility simulates the air conditions behind the oblique or conical shock waves formed ahead of vehicles flying at hypersonic speeds and it is a high temperature supersonic flow. To simulate this flow on this test facility, oxygen enriched air is heated by combustion inside the VAG and then accelerated through the nozzle, generating the "vitiated air" containing the desired flow properties plus the heating process combustion products, while keeping the same atmospheric oxygen content. Previous studies were done using QAV-1 (Guimarães, 1996) and JP-10 (Leite, 2006) as the fuel to heat the air inside the VAG. The purpose of this paper is to evaluate and to adapt the flow conditions inside the vitiated air generator (VAG) to simulate the test conditions, for testing the 14-X combustor, using as the fuel to heat the air GNV (Natural Gas Vehicle).

### 1.1 Scramjet engines

Scramjet engines are air-breathing propulsion systems which have no moving parts to compress the intake air, using instead the vehicles geometry to achieve the compression of the air through the oblique or conical shock waves formed in front of the noses of the vehicles flying at hypersonic speeds. The conditions of the air behind these shock waves are the ones necessaries (temperature and pressure), for the combustion inside the supersonic combustor (Leite et al, 2007; Rolim, 2009).

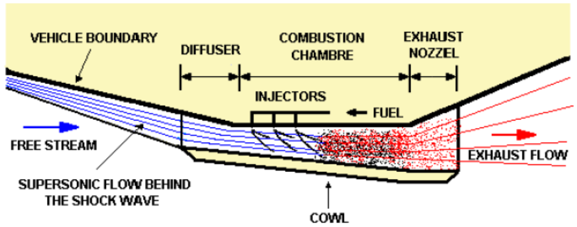


Figure 1. Schematic drawing of a scramjet engine (Curran, 1996).

Inside the combustor, fuel ($H_2$ or a hydrocarbon) is injected into the supersonic flow, where it mixes and burns in a region downstream of the fuel injector's strut, as shown in Fig. 1. The hot gases are expanded through a supersonic nozzle at the rear of the vehicle to a speed higher than that at the entrance, generating thrust.

### 1.1 Vitiated air generator operation principle

The direct-connected supersonic combustion test bench consists basically of a vitiated air generator (VAG) unit and a nozzle directly coupled to the supersonic combustor to be tested. This facility simulates the condition of the air flow inside the scramjet combustor at actual flight, which is a high temperature supersonic flow.

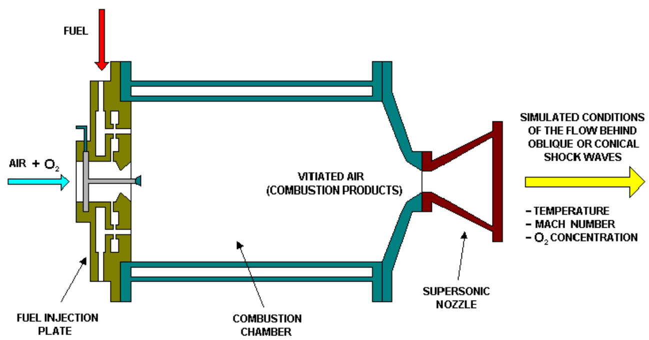


Figure 2. Schematic drawing of a vitiated air generator with supersonic nozzle (Leite et al, 2007).

According to Leite (2006), to simulate, on the facility, the high temperature and the Mach number of the flow, required for the 14-X combustor tests, oxygen enriched air is heated by combustion inside the VAG and then accelerated through the nozzle, generating the "vitiated air" containing the desired flow properties plus the heating process combustion products, while keeping the same atmospheric oxygen content. Figure 2 shows the schematic drawing of the VAG with the supersonic nozzle. The dimensions of VAG's combustion chamber combustion are: internal diameter = 310 mm and length = 1500 mm.

## 2. THE 14-X'S FLOW TEST CONDITIONS

According to Camillo and Porto's internal report, obtained by testing the 14-X's combustor model inside the IEAv's shock tunnel T3, the preliminary conditions of air flow inside the 14-X's combustion chamber, to be tested are the ones shown on Tab. 1.

Table 1. Air flow properties inside the combustion chamber.

| Property | Value |
|---|---|
| Mach number | 2.6 |
| Pressure (Pa) | 89108.0 |
| Temperature (K) | 1039.5 |
| Speed of sound (m $s^{-1}$) | 647.6 |
| Speed of the flow (m $s^{-1}$) | 1684.6 |

With these data, it is possible to calculate the flow conditions inside the vitiated air generator, i.e., these are the conditions of the flow test that should be generated at the exit of the nozzle shown in Fig. 1. In this paper, it will be developed the methodology to generate only the temperature condition of the test follow.

Before calculate the amount of fuel to heat the air inside the VAG, it's necessary to preview the temperature of the flow at the entrance of the nozzle. Although the velocity of the flow, shown in Table 1, is Mach 2.6, it will be used the old nozzle for Mach number 2.4, to simulated the temperature condition. According to the equations for the isentropic flow (Anderson, 2001), it is possible to calculate the stagnation temperature by the Eq. (1):

$$\frac{T_o}{T} = 1 + \frac{\gamma - 1}{2} M^2, \quad (1)$$

where $\gamma$ is the specific heat ratio, $M$ and $T$ are the Mach number and the temperature of the flow at the nozzle exit and $T_o$ is the stagnation temperature ate the nozzle entrance.

Considering the calorically perfect atmospheric air, inside the nozzle, with $\gamma = 1.4$, Eq. (1) provides:

$$\frac{T_o}{1039.5\,K} = 1 + \frac{1.4 - 1}{2} 2.4^2 \rightarrow T_o = 2237.0\,K \cong 2240.0\,K. \quad (2)$$

The temperature $T_o$ calculated by Eq. (2), is the one to be simulated inside the combustion chamber of the VAG.

Using again the equations for the isentropic flow (Anderson, 2001), it is possible to calculate the stagnation pressure by the Eq. (3):

$$\frac{p_o}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}, \quad (3)$$

where $p$ is the pressure of the flow at the exit of the nozzle and $p_o$ is stagnation pressure at its entrance.

As the IEAv's supersonic combustion test bench is open to the atmosphere, the value of p at the nozzle exit must be considered equal to 1 atm or 101325.0 Pa, instead of 89108.0 Pa, as shown in Table 1. Considering the calorically perfect atmospheric air, inside the nozzle, with $\gamma = 1.4$, Eq. (3) provides:

$$\frac{p_o}{1\,atm} = \left(1 + \frac{1.4 - 1}{2} 2.4^2\right)^{\gamma/\gamma-1} \rightarrow p_o = 14.62\,atm \cong 15.0\,atm. \quad (4)$$

The temperature $p_o$ calculated by Eq. (4), is the one to be simulated inside the combustion chamber of the VAG.

## 2. FLOW CONDITIONS INSIDE THE VITIATED AIR GENERATOR

In the previous work of the evaluation of the flow inside the VAG (Leite, 2006), it was used the liquid fuel, to heat the air, kerosene (QAV-1), which has the same characteristics of the jet propulsion fuel, JP-10. In the present work it will be used the gaseous fuel, GNV ("Gás Natural Veicular") because it is easier to obtain and has the required characteristics to reach the desired conditions for testing the 14-X combustor.

It is important to notice that the air must be enriched with oxygen at the entrance of the combustion chamber, in order to, after burning and passing through the nozzle, still contains 21% $O_2$ on its composition.

To study the combustion process in the vitiated air generator, it was used the software CHEMKIN-III® and the VAG's combustion chamber was split in two continuous flow reactors: a PSR (perfectly stirred reactor) and a PFR (plug flow reactor) one. This was done, because there are two different kinds of problems to be analyzed: one is the mixing of the fuel with the oxidant, the ignition and initiation of combustion, and the other one is the ending of the combustion process with the complete burning of the fuel.

### 2.1 Perfect stirred reactor

At the perfect stirred reactor it is assumed that the fuel and the oxidant are perfectly mixed, due to the high level of turbulence, as shown in Fig. 3. Thus, the conversion rate of reactants into products is controlled by the chemical reactions and not by the mixing process.

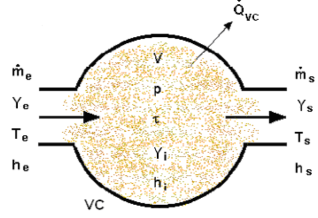


Figure 3. Perfect stirred reactor model (Leite, 2006).

 

The continuity equation that governs this phenomenon is shown in Eq. (3):

$$\dot{m}_{i(i)} - \dot{m}_{i(o)} = \dot{\omega}_i W_i V_{VC} \tag{3}$$

where $\dot{m}_{i(i)}$ here is the input mass flow of species $i$ at the volume control $\dot{m}_{i(o)}$ is the output mass flow of species $i$ at the volume control, $\dot{\omega}_i$ is the concentration change rate of species $i$, $W_i$ is the molecular weight of species $i$ and $V_{VC}$ is the reactor volume.

The species enthalpy is given by Eq. (4):

$$h_i(T) = \left[h(T) - h(T_{ref})\right]_i + \left(\Delta h_f\right)_i^{Tref} \tag{4}$$

where $h_i(T)$ is enthalpy of species $i$ at temperature $T$, and $\left(\Delta h_f\right)_i^{Tref}$ is the variation of formation enthalpy of species $i$ in the reference temperature $T_{ref}$.

The equations shown above were solved using CHEMKIN-III's AURORA-PSR package to calculate the flow inside the perfect stirred reactor.

## 2.2 Plug flow reactor

The main characteristics of this kind of reactor is that the flow inside it is steady and its properties (Mach number, temperature, chemical composition) are considered constant, and there is no mass diffusion and the gas is considered inviscid. Figure 4 shows a plug flow reactor model whose main characteristics is the fact that the flow is steady and the properties are assumed to be constant along $Y$ axis, while there is no mass diffusion along the direction of the flow ($X$ axis).

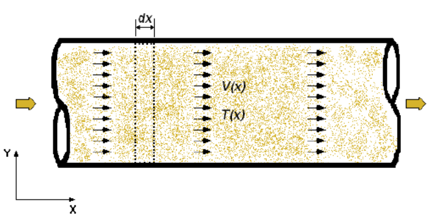


Figure 4. Plug flow reactor model (Leite, 2006).

The equations that govern the flow inside the reactor are simplified versions of the continuity, momentum and energy equations, Eqs. (6), (7) and (8), respectively:

$$\frac{d\left(\rho V_x\right)}{dx} = 0 \tag{6}$$

$$\frac{1}{\rho}\left(\frac{dp}{dx} + \rho V_x \frac{dV_x}{dx}\right) = 0 \tag{7}$$

$$\frac{1}{\rho}\left(p\frac{dV_x}{dx} + \rho V_x \frac{de}{dx}\right) = 0 \tag{8}$$

where $\rho$ is the specific mass, $V_x$ is the flow speed along the X-axis, $\frac{dp}{dx}$ is the pressure variation along the X-axis, $\frac{dV_x}{dx}$ is the flow speed variation along de X-axis and $\frac{de}{dx}$ is the energy variation along the X-axis.

The flow conditions at the exit of the plug flow reactor are ones considered as the stagnation condition at the entrance of the supersonic nozzle.

The equations shown above were solved using CHEMKIN-III's PLUG package to calculate the flow inside the plug flow reactor.

## 3. FLOW CONDITIONS THROUGH THE NOZZLE

Inside the nozzle, the vitiated air is accelerated to simulate the supersonic flow that will feed the combustor to be tested, at the nozzle exit, to the desired Mach number, pressure and temperature. The flow inside the nozzle is analyzed using the Jameson scheme, which is a finite volume discretization method, with artificial dissipative terms, for the solution of the Euler equations, considering two gas models: a calorically perfect and a frozen one. The boundary conditions at the entrance of the nozzle are the same ones at the exit of the VAG's combustion chamber.

For the calorically perfect model it was considered $\gamma = 1.4$ and for the frozen model the value of $\gamma$ was calculated the for the vitiated air (the air plus the combustion products), considering the chemical compositions, at the temperature and the pressure at VAG's exit, where $\gamma$ is the ratio between the specific heat capacity at constant pressure ($c_p$) and the specific heat at constant volume ($c_v$).

Table 2. Thermodynamic properties relation for $\gamma = 1.4$ and Mach number 2.4 and stagnation conditions used.

| $M$ | $p_o/p$ | $T_o/T$ | $p_o$ (atm) | $T_o$ (K) |
|---|---|---|---|---|
| 2.4 | 14.620 | 2.152 | 15.0 | 2240.0 |

The caloric perfect model was used to validate de code, and the data calculated for air was compared with the values of isentropic flow properties, provided by Anderson (2001), and is shown on Tab. 2 for Mach number 2.4, where $M$ is the Mach number at the nozzle's exit, $p_0/p$ is the ratio between the input pressure $p_0$ and the output pressure $p$, $T_0/T$ is the ratio between the input temperature $T_0$ and the output pressure $T$.

## 4. RESULTS

Resuming all the considerations mentioned above, it should be generated, at the exit of the VAG's the combustor chamber, the same stagnation conditions at the entrance of the nozzle ($p_o$ = 15 atm and $T_o$ = 2240 K), shown in Table 2, to have the flow test conditions of the supersonic combustion test bench at the nozzle exit ($p$ = 1 atm and $T$ = 1039 K), shown at Table 1.

To obtain that, using the software CHEMKIN-III, it was considered for the perfect stirred reactor (AURORA-PSR package): residence time = 0.3280E-02 s, volume of the reactor = 7547 cm$^3$ (diameter = 31 cm and length = 10 cm) and pressure = 15 atm, and for the plug flow reactor (AURORA-PFR package): length = 140 cm, diameter = 31 cm and mass flow rate = 0.5333E+04 g/s To achieve the desired temperature of $T_o$ = 2240 K at the exit of the plug flow reactor exit (VAG's combustor chamber exit), after several simulations, the best inlet gas phase reactants mole fractions composition considered was: $CH_4$ = 0.09365, $O_2$ = 0.400000 and $N_2$ = 0.50635.

Finally, the conditions of the vitiated air obtained at the exit of the VAG's combustion chamber were: $T_o$ = 2240 K, $p_o$ =15 atm and the gas phase mole fractions are shown in Table 3

Table 3. Vitiated air mole fraction at the nozzle entrance.

| Vitiated air mole fractions at $T_o$ = 2240 K and $p_o$ =15 atm | | |
|---|---|---|
| H = 0.9561E-04 | $H_2$ = 0.3990E-03 | O = 0.1074E-02 |
| $O_2$ = 0.2102 | OH = 0.6629E-02 | $H_2O$ = 0.1830 |
| $HO_2$ = 0.1271E-04 | $H_2O_2$ = 0.3241E-12 | NO = 0.8573E-03 |
| $NO_2$ = 0.2001E-05 | HNO = 0.4246E-07 | HONO = 0.1136E-06 |
| $N_2O$ = 0.2723E-05 | $N_2$ = 0.5044 | NH = 0.1297E-08 |
| $NH_2$ = 0.3327E-09 | $NH_3$ = 0.4454E-09 | NNH = 0.2541E-08 |
| CO = 0.1166E-02 | $CO_2$ = 0.9219E-01 | HCO = 0.2596E-07 |
| $CH_2O$ = 0.2719E-06 | $CH_3O$ = 0.8538E-07 | CH = 0.5902E-11 |
| $C_2H_2$ = 0.4934E-11 | C = 0.1866E-13 | $C_2H$ = 0.9757E-14 |
| $CH_2$ = 0.7824E-07 | $CH_3$ = 0.2021E-05 | $CH_4$ = 0.3974E-05 |

To analyze the flow inside the nozzle it was developed a code with the software MATLAB 6.1® to solve the Euler equations using the Jameson's scheme (Jameson, 1981), which is a finite volume spatial discretization method with artificial dissipative terms (Pulliam, 1986), because the Euler equations do not provide any natural dissipation mechanism, such as viscosity, in the Navier-Stokes equations, which would eliminate high frequencies caused by nonlinearities. The classical fourth order Runge-Kutta scheme was applied for the marching in time. It was considered two gas models: a calorically perfect and a frozen one.

The calorically perfect model was used to validate to validate the code. So, considering: $T_o$ = 2240 K, $p_o$ =15 atm, for $\gamma = 1.4$ and $M = 2.4$, and the relations between $p_o/p = 14.62$ $T_o/T = 2.152$, shown in Table 2, it gives $p$ = 1.023 atm and $T$ = 1040.892 K at the nozzle exit, and these are the flow conditions that should be obtained with the code. Figure 5 shows the temperature and Mach number distributions, along the nozzle, so it is possible to see that the Mach number at the nozzle exit is 2.4, as expected and the temperature values at the nozzle exit are very close to the calculated.

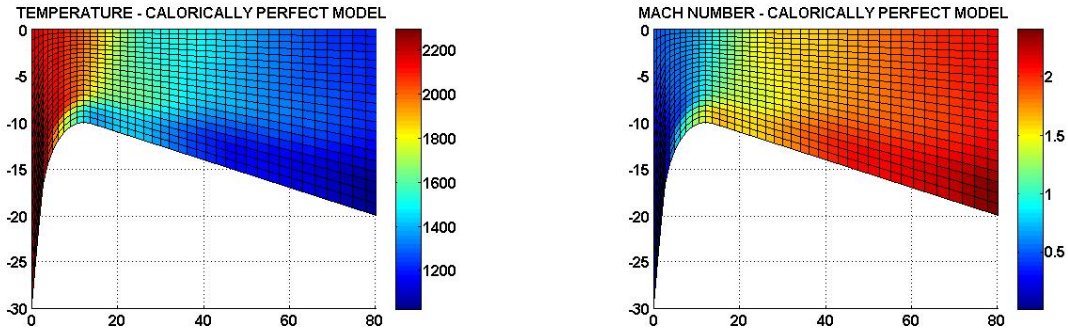


Figure 5. Temperature and pressure distributions along the nozzle for the calorically perfect model.

For the frozen model it was considered the same stagnation conditions used for the calorically perfect model: $T_o$ = 2240 K, $p_o$ =15 atm, and the mole fraction species of the vitiated air for these conditions, shown in Table 3. With these values it was calculated the new $\gamma$ = 1.1045, which was considered constant along the nozzle. The temperature and Mach number distribution along and at the exit of the nozzle for the frozen model is shown in Fig. 6.

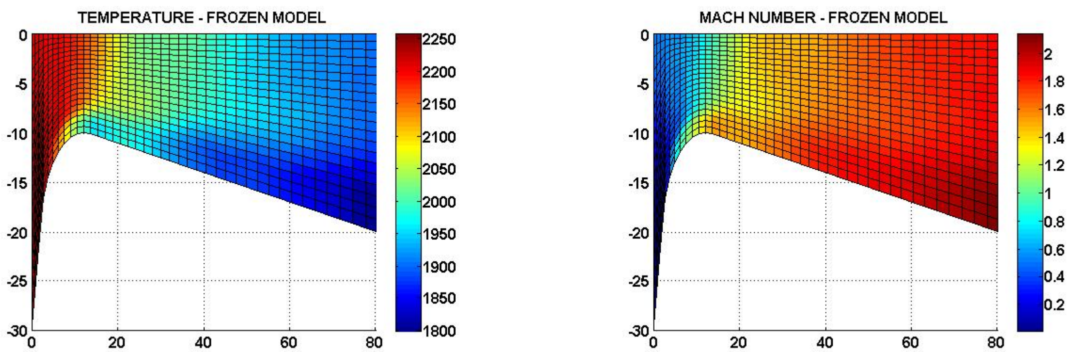


Figure 6. Temperature and Mach number distribution along the nozzle for the frozen model.

The conditions shown in Figs. 5 and 6 were calculated for the same stagnation temperature ($T_o$ = 2240 K), which was obtained considering the initial reactants mole fraction: $CH_4$ = 0.09365, $O_2$ = 0.400000 and $N_2$ = 0.50635. This was done to adapt the methodology previous developed to calculate the conditions of vitiated air flow inside the supersonic combustion test bench, using JP-10/QAV-1 as the fuel to heat the air (Leite, 2006). Now it is necessary only to adjust the fuel/oxidize ratio to obtain the desired temperature at the exit of the nozzle, considering the $CH_4$ (methane/GNV) as the fuel used to heat the air inside de vitiated air generator.

## 5. CONCLUSIONS

The study that was done, in the present work, for the entire flow inside the supersonic combustion test bench, allows us to adjust and control the test flow conditions, at nozzle exit, to adapt this ground test facility that is now being assembled at the Institute for Advanced Studies (IEAv/DCTA), to the conditions for the tests of the 14-X combustor.

The 14-X combustor was previous tested in a shock tunnel and it was obtained the flow conditions, inside the combustor, that should be simulated at the supersonic combustion test bench (with the vitiated air generator and the nozzle). To achieve these conditions, the study of the present work will help us to find the equivalence ratio between the reactants (GNV + air), to heat the air inside the VAG, and to find the new geometry of the nozzle to accelerate the vitiated air to the desired Mach number. With these results, it is possible now to begin the researches of the supersonic combustion, inside the 14-X combustor, using a vitiated air generator.

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