A PULSE JET OPERATIONAL SIMULATION THROUGH COMPUTATIONAL FLUID DYNAMICS

Luiz Antonio Negro Martin Lopez
The University Center of FEI, Mechanical Engineering Department
Av. Humberto A. C. Branco, 3972 – São Bernardo do Campo – SP – Brazil – 09850-901
Tel# 55-11- 43532900 r. 2172 – luizlope@fei.edu.br

Daniel Kao Sun Ting
Instituto de Pesquisas Energéticas e Nucleares, IPEN/CNEN-SP, Nuclear Engineering Center
Av. Prof. Lineu Prestes, 2242– Cidade Universitária, São Paulo – SP – Brazil – 05508-900
Tel# 55-11-38169423 – dksting@net.ipen.br

Edvaldo Angelo
The University Center of FEI, Mechanical Engineering Department
Av. Humberto A. C. Branco, 3972 – São Bernardo do Campo – SP – Brazil – 09850-901
Tel# 55-11- 43532900 r. 2172 – eangelo@usp.br

Abstract. *The thermodynamic processes which occur in a pulse jet are complex and hard to evaluate. Analytical methods use fluid dynamics and thermodynamics relations which are most of times imprecise. To overcome this limitation, pulse jet experimentation is made but this method is expensive and time demanding. Nowadays Computational Fluid Dynamics (CFD) is being extensively used as a quick, cheap and flexible tool for thermodynamic and fluid dynamic behaviour prediction. In this work, ANSYS CFX software is used to simulate the operation of a pulse jet under several operational conditions. The software and analytical results are compared with experimental results obtained in a pulse jet laboratory stand.*

Keywords: *pulse jet, operational simulation, computational fluid dynamics*

1. INTRODUCTION

Pulse jets are extremely simple machines wherein the combustion occurs in pulses and do not use rotating components as compressor or turbine. They are easy to maintain and simple to construct. Those machines are basically cylindrical tubes which have a diffuser and a valve in the intake, a combustion chamber in the center and a nozzle in the exit. The combustion in pulse jets occurs at constant volume due to valve closing.

The first pulse jet was developed by Martin Wiberg in the end of XIX century at Sweden (Treager, 1998). The first war use of the pulse jet concept was as the Germanic V1 flying bomb, also known as "Buzz Bomb" due to its peculiar noise. During World War II pulse jets were also used as boost motors for conventional airplanes like Junkers Ju 88G-6 and for missile using.

The operational cycle of a pulse jet comprises the four phases ignition, combustion, admission and compression as schematically presented in Fig. 1.

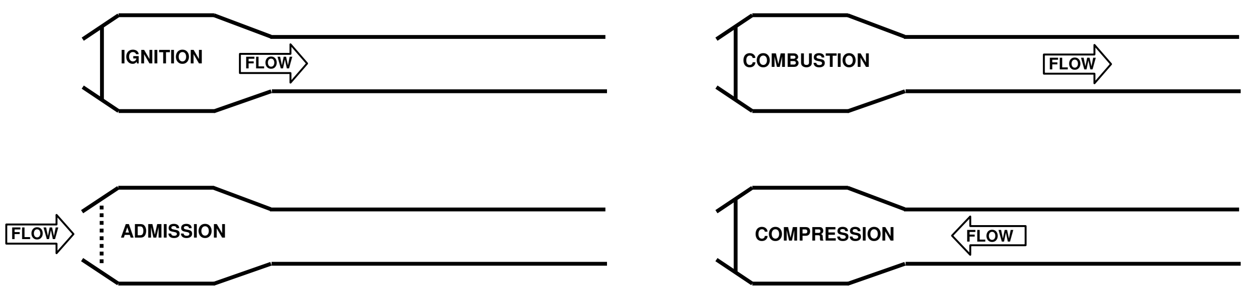

Figure 1. The four phases of pulse jet operation

Ignition is the first step for pulse jet starting but, before that, it is necessary an external source to provide air under pressure for the one-way air intake valve opening through which the incoming air passes. The air dynamic pressure provides the necessary air compression when the pulse jet is moving in the air. If the pulse jet have no relative to air velocity, the necessary air pressure is provided by an external starting compressor. The ignition of the compressed air with fuel is made through a spark plug. As a result of ignition, the combustion of the fuel/air mixture occurs and the pressure is raised to many times the initial pressure shutting the inlet one-way valve. Consequently, the pressurized combustion gases can only leave the pulse jet to the rear through the tail pipe.

Under steady state conditions, the spark plug electricity feeding can be turned off by high temperature reached in the combustion chamber as showed in Fig. 2 (Pompermayer, 2006), allowing the mixture ignition by the residual heat from the previous cycle.

Figure 2. Pulse jet steady state operation

Due to the inertia of the exhaust gases, a low pressure in the combustion chamber is reached and a new portion of air is admitted through the upstream one-way spring plate mechanical valve and a new cycle begins. The difference of flow speed between the intake and exhaust of the pulse jet causes the engine to provide a forward thrust.

Despite pulse jets are noisy and present high vibration they are appropriate for thermodynamic studies due to their simplicity. Being low cost and low weight, nowadays pulse jets are very used in jet aeromodels as propulsion reactors.

Another potential application of pulse jets is helicopter propulsion. It is well known that helicopter tail rotors are very susceptible for mechanical fail and collisions with the ground or obstacles during departure and landing operations. To overcome this problem, some initiatives were made during the years. As an example, Fig. 3 presents the experimental Hiller HOE-1 helicopter with no tail rotor and pulse-jet propulsion. The principle of this helicopter operation is the thrust force application directly in the blade tip resulting in no anti-torque tail rotor necessity.

(National Air and Space Museum, Smithsonian Institution)

Figure 3. Pulse jet steady state operation

In this work, the pulse jet presented in Fig. 2 was tested and some experimental data as frequency, pressure, temperature, fuel consumption and forward thrust force were obtained. The fuel used was automotive gasoline injected in the intake of pulse jet through a fuel pump. The analytical determination of operational parameters was made and the experimental and analytical results were compared with computational (Anderson, 1995) results obtained through CFD ANSYS CFX software using.

2. ANALYTICAL DETERMINATION OF PULSE JET OPERATIONAL PARAMETERS

Operational parameters such as frequency, pressure, temperature, heat, velocity, thrust and fuel consumption were obtained analytically through a simplified theory for pulse jet as presented in the following items. Figure 4 presents the main states in a pulse jet, where (0) refers atmospheric conditions, (1) refers stagnation conditions when the one-way air intake valve is closed, (2) refers the combustion chamber conditions when the charging process finishes and (3) refers to the end of combustion conditions.

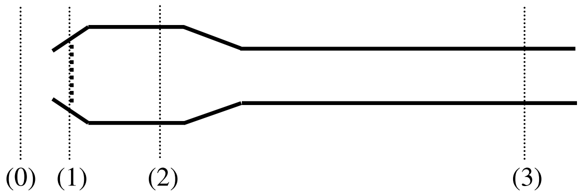

Figure 4. Pulse jet states

2.1 Pulse jet frequency

The pulse jet cycle frequency depends on the sound velocity propagation and on the length of the pipe. For a small pulse jet like that used in this work, the frequency reaches 300 Hz. As pulse jet increases, the frequency decreases. As an example, in a large device such as the V1germanic bomb, the frequency was around 45 Hz.

Recently, Zulkifli *et al.*(2004) presented the following expression for the pulse jet frequency which has been used in this work:

$$f = \frac{\overline{V}_{sound}}{4L} \tag{1}$$

where $\overline{V}_{sound}$ is the velocity of sound propagation and L is the pipe length.

2.2 Pressure and temperature rates

When the inlet valve is closed, stagnation pressure is reached (Brunetti, 2005), and can be obtained through Eq. (2):

$$\frac{P_1}{P_0} = \left(1 + \frac{k-1}{2} M_0^2 \right)^{\frac{k}{k-1}} \tag{2}$$

where P_0 is the atmospheric pressure, M_0 is the Mach number at atmospheric temperature and k is the adiabatic constant:

$$k = \frac{c_p}{c_v} \tag{3}$$

where c_p is the constant pressure specific heat and c_v is the constant volume specific heat.

In the same way, the temperature rate is:

$$\frac{T_1}{T_0} = 1 + \frac{k-1}{2} M_0^2 \tag{4}$$

where T_0 is the atmospheric pressure.

2.3 Combustion heat

The heat flux added to the mass flow of air $\dot{m}_{air}$ between states (2) and (3) (Ieno and Negro, 2004) is:

$$Q = \dot{m}_{air}\, c_v \left(T_3 - T_2 \right) \tag{5}$$

where T_2 and T_3 are, respectively the combustion chamber and exhaust temperatures.

By considering the adiabatic constant presented in Eq. (3), Eq. (5) can be written as:

$$Q = \dot{m}_{air} \frac{1}{k}\, c_p\, T_3 \left(1 - \frac{T_2}{T_3} \right) \tag{6}$$

In order to reduce the number of temperature readings, and by considering that the combustion is carried out at constant volume, the Clapeyron equation applied to the process between states (2) and (3) is simplified to:

$$\frac{T_2}{T_3} = \frac{P_2}{P_3} \tag{7}$$

Substituting Eq. (7) in Eq. (6), result:

$$Q = \dot{m}_{air} \frac{1}{k} \; c_p \; T_3 \; \left[1 - \left(P_2 / P_3 \right) \right] \tag{8}$$

2.4 Exhaust velocity

The combustion gases discharge velocity is obtained by applying the First Law of Thermodynamics (Van Wylen, 1995) to the exhaust tube:

$$\overline{V}_3 = \sqrt{\frac{2k}{k-1} \frac{P_2}{\rho_2} \left[1 - \left(P_0 / P_2 \right) \right]^{\frac{k-1}{k}}} \tag{9}$$

where P_2 is the combustion chamber pressure, ρ_2 is the gases density, k is the adiabatic constant and P_0 is the atmospheric pressure.

2.5 Thrust

The thrust of a pulse jet is due to mass flow velocity difference between the intake and the exhaust (Eidelman, 2000). The exact expression of the pulse jet thrust is:

$$F = \dot{m}_{gases} \overline{V}_3 - \dot{m}_{air} \overline{V}_0 \tag{10}$$

where $\dot{m}_{gases}$ is the exhaust mass flow, $\overline{V}_3$ is the discharge velocity, $\dot{m}_{air}$ is the admission air mass flow and $\overline{V}_0$ is the pulse jet velocity if it is moving in the air, or the admission air velocity if the pulse jet is stopped.

The exhaust mass flow is:

$$\dot{m}_{gases} = \dot{m}_{air} + \dot{m}_{fuel} \tag{11}$$

However, taking in to account that the fuel mass flow is much smaller when compared to the air mass flow, Eq. (10) can be simplified to:

$$F = \dot{m}_{air} \left(\overline{V}_3 - \overline{V}_0 \right) \tag{12}$$

2.6 Fuel consumption

To calculate the pulse jet fuel consumption it is applied the First Law of Thermodynamics under steady state conditions to the engine. As a result, the following expression is obtained:

$$\dot{m}_{fuel} = \frac{Q}{HHV \; \eta_{CC}} \tag{13}$$

where Q has been already presented in Eq. (8), HHV is the High Heat Value of gasoline and η_{CC} is the combustion chamber efficiency.

3. RESULTS

Some parameters such as pressure, temperature, fuel consumption, thrust and frequency were obtained analytically by using the previous equations and compared with experimental and/or CFD results.

Figure 5 presents CFD pressure distribution in the pulse jet after combustion when the valve was closed.

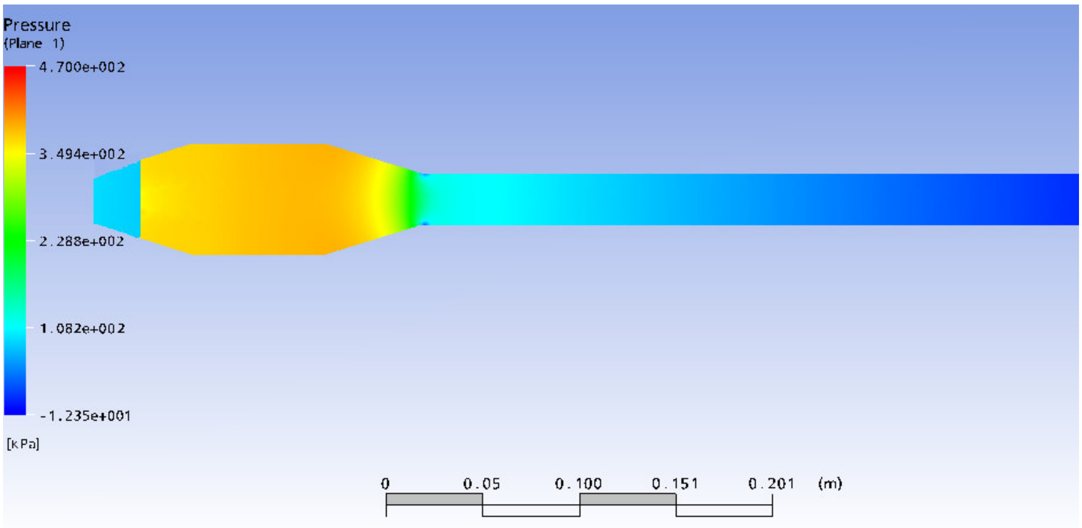

Figure 5. Pressure after combustion

The stagnation pressure before the valve, obtained through Eq. (2) was 137 kPa while the pressure obtained experimentally in five measurements presented values around 140 kPa as shown in Fig. 6.

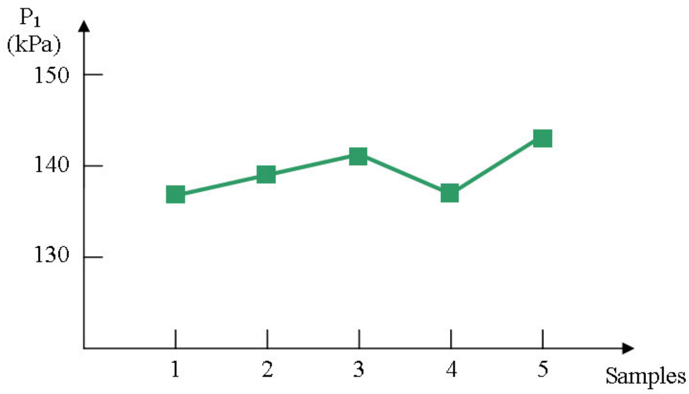

Figure 6. Pressure before valve

Figure 7 presents CFD temperature distribution in the beginning of ignition. The stagnation temperature, obtained through Eq. (4) was around 21^{o}C while the experimental results were around 22^{o}C as presented in Fig. 8.

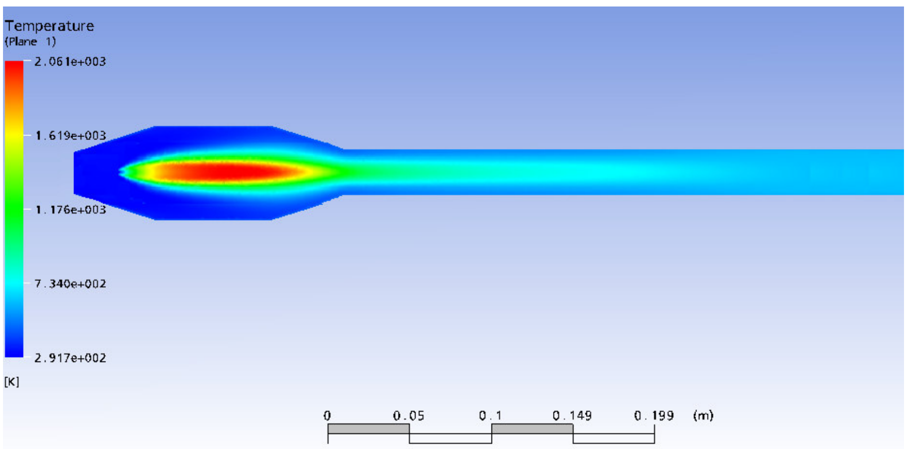

Figure 7. Temperature distribution

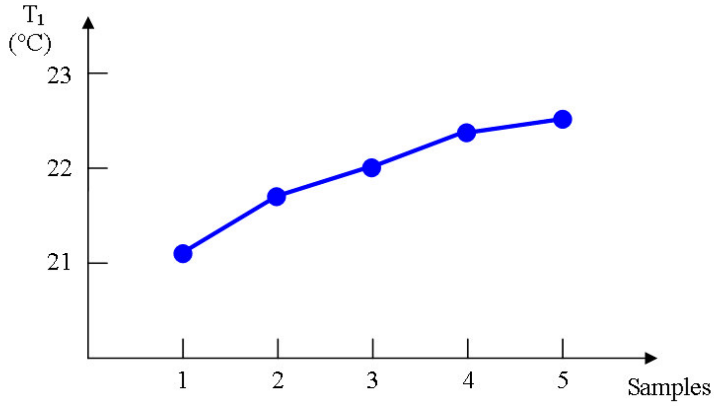

Figure 8. Temperature before valve

The thrust value obtained through Eq. (12) was 12,7 N. This value was compared with experimental results presented in Fig. 9, obtained by using a spring force measuring device.

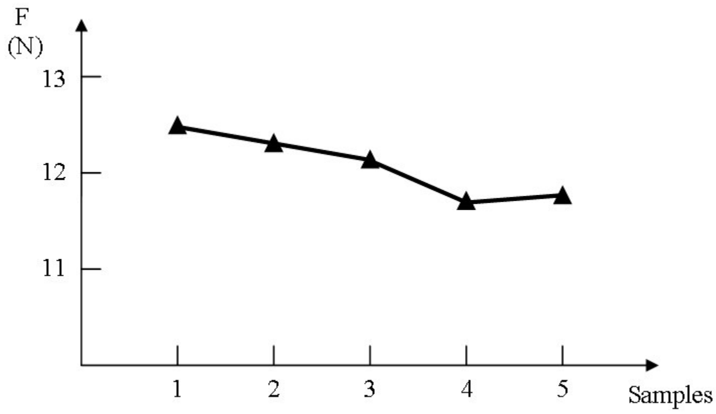

Figure 9. Pulse jet thrust

The theoretical fuel consumption, calculated through Eq. (13), was 52,8 x 10^{-3} kg/min. The values obtained experimentally by fuel tank weighting are presented in Fig. 10.

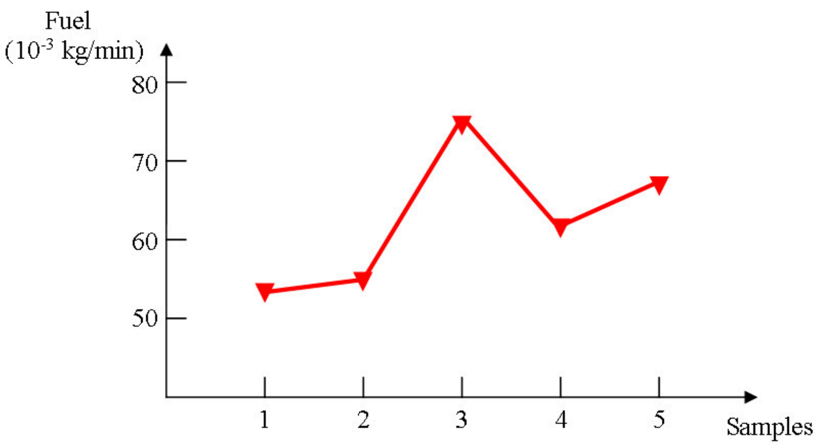

Figure 10. Fuel consumption

The frequency obtained analytically through Eq. (1) by using pulse jet dimensions and sound velocity value is 164 Hz. Experimental results are presented in Fig. 11 as a function of stagnation pressure P_1.

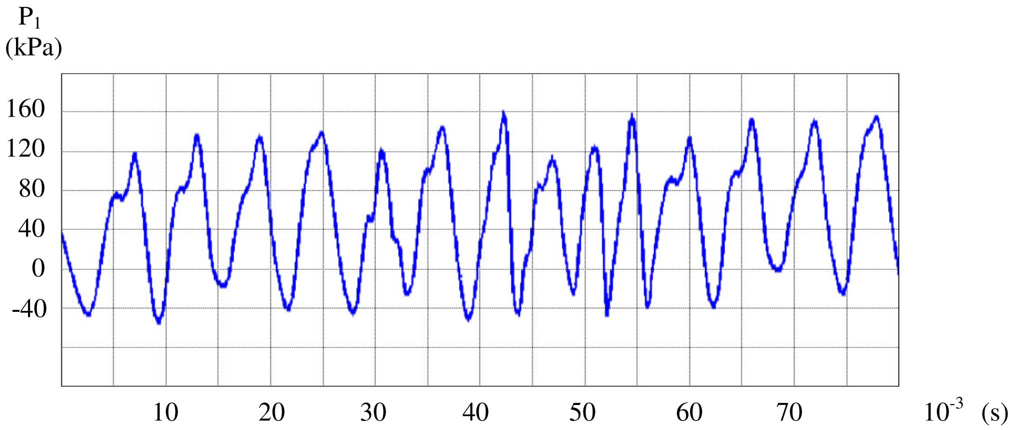

Figure 11. Pulse jet (frequency) $^{-1}$

4. CONCLUSIONS

The frequency results obtained experimentally are very closer to the analytical ones. Figure 11 presents a peach to peach time interval around 6 x 10^{-3} seconds which corresponds to the calculated theoretical frequency 164 Hz. The maximum P_1 pressure (around 140 kPa) is similar to the analytical value.

Due to pressure and temperature values acquisition difficulties in the combustion chamber and discharge tube, those experimental values were not presented in this work and this task is proposed as a future work as well as thrust values and fuel consumption determination through CFD.

Despite a simplified fuel consumption analytical calculation use, the theoretical results are very closer to the experimental ones.

5. ACKNOWLEDGEMENTS

The authors thank to Gustavo Martins Pompemayer from the University Center of FEI for assistance.

6. REFERENCES

Anderson, J.D., 1995, "*Computational Fluid Dynamics*". 1.Ed., Mac-Graw Hill.

Brunetti, F., 2005, "*Mecânica dos Fluídos*", Ed. Pearson Prentice Hall, São Paulo, Brazil, 278 p.

Eidelman, S., Sharov D., Book, D., 2000, *"Aerothermodynamics of Pulsed Detonation Engines"*, Science Applications Inc., McLean, VA, 12 p.

Hall, E.J., 1998, "*Aerodynamic modeling of multistage compressor flow fields: Part 1: Analysis of rotor-stator-rotor aerodynamic interaction"*. ProQuest Science journals pg. 77.

Ieno, G. O., Negro, L. A., 2004, "*Termodinâmica*", Ed. Pearson Prentice Hall, São Paulo, Brazil, 228 p.

Levin, V., 2005, "Ignition and Supersonic Burning of Air – Fuel Mixtures Initiated by Electrical Discharges", Moscow State University, Russia, 139 p.

Maliska, C. R., 1995, "*Transferência de calor e mecânica dos fluidos computacional"*. 1.Ed., LTC.

Pompermeyer, G. M., 2006, "*Pulse Jet Theoretical and Experimental Study"*, Final Report, The University Center of FEI, São Paulo, Brazil, pp. 24.

Treager, I. E., 1998, "*Aircraft gas turbine engine technology",* 3.Ed., Mac-Graw Hill.

Van Wilen, G. J., Sonntag, R.E., Borgnakke, C., 1995, "*Fundamentos da Termodinâmica"*. 4.Ed., Edgard Blücher.

Zulkifli, R., Benard, E., Raghunathan, S., 2004, "*Effect of Pulse Jet Frequency on Impingement Heat Transfer*", Proceedings of the 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, USA.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.