Temperature oscillations in the wall of a cooled multi pulsejet propeller for aeronautic propulsion

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Temperature Oscillations in the Wall of a Cooled Multi Pulsejet Propeller for Aeronautic Propulsion

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Abstract

Environmental and economic issues related to the aeronautic transport, with particular reference to the high-speed one are opening new perspectives to pulsejets and derived pulse detonation engines. Their importance relates to high thrust to weight ratio and low cost of manufacturing with very low energy efficiency. This papers presents a preliminary evaluation in the direction of a new family of pulsejets which can be coupled with both an air compression system which is currently in pre-patenting study and a more efficient and enduring valve systems with respect to today ones. This new pulsejet has bee specifically studied to reach three objectives: a better thermodynamic efficiency, a substantial reduction of vibrations by a multi-chamber cooled architecture, a much longer operative life by more affordable valves. Another objective of this research connects directly to the possibility of feeding the pulsejet with hydrogen. This paper after a preliminary analysis of the pulsejet takes into account two necessary stages of this activity with the initial definition of the starting point of this activity, which aim to define an initial thermodynamic balance of a Lenoir cycle and a preliminary but effective estimation of the thermal problem. It analyses the heat transfer process through the wall of the combustion chamber of a pulsejet for aeronautic propulsion. The inside wall is exposed to burning gases with an average temperature of 1500 K, which oscillates with an amplitude 500 k and a frequency of 50 Hz. It has been considered the possibility of using Hydrogen injection to reduce the environmental impacts at the price of introducing a cooling water envelope at an average temperature of 80 °c. The water mass flow to ensure this condition has been evaluated and it has been evaluated both the average temperature profile within the wall and the effects of the oscillations of gas temperature inside the combustion chamber. Obtained results have allowed starting an effective activity through a radically new pulsejet architecture, which is expected to outclass any former pulsejet in term of operative life and of compression ratio with a consequent step increase in terms of thermodynamic efficiency.

Introduction

Generalities

A pulsejet engine is a jet engine with combustion occurring in pulses. It is made with no moving parts [1] or a simple moving valve [2]. It is capable of running statically (i.e. it does not need to have air forced into its inlet typically by forward motion). Pulsejet engines are a lightweight and cheap jet propulsion, but the usually suffer of both poor compression ratio and low specific impulse. Pulsejets operate according to Lenoir cycle [3], which has not any compression process and leads to lower thermal efficiency than Otto and Diesel cycle [4].

Historic Background

Pulsejet is probably the oldest jet propulsion system. Early attempts to utilize the power from explosions for propulsive applications date back to late 17th-early 18th centuries and the contributions of Huygens and Allen are note worthy. In 1729, Allen proposed a jet-propelled ship by explosion of gunpowder in a proper engine [4]. Berthelot and Vieille, and Mallard and Le Chatelier moved their attention to gaseous explosions and combustion modes. They discovered [5] a combustion mode propagating at a velocity ranging from 1.5 to 2.5 km/s. They obtained this result by igniting gas with a high-explosive charge. Similar effects have been produced in long tubes even when gas was ignited by non-explosive means (spark or open flame). Flame acceleration along the tube, often accompanied with flame speed oscillations, was detected prior to onset of detonation. It has been also discovered that detonation velocity is independent of the ignition source and tube diameter. It is primarily a function of the composition of the explosive mixture, with severe mechanical effect implying the development of high pressure in the propagating wave, which is governed by adiabatic compression of the explosive mixture rather than by molecular diffusion of heat [6]. Initially, the interest in detonation was associated only with preventing explosions in coalmines. Mikhelson (1890), Chapman

(1899), and Jouguet (1904) estimated the detonation parameters by considering one-dimensional (1D) flow, mass, momentum and energy conservation laws according to the shock wave theory of Rankine and Hugoniot. This model describes the detonation wave as a pressure discontinuity coupled with the reaction front (instantaneous reaction) and presents a good agreement with observed detonation velocities.

During the first decades of the 20th century, a fundamental advancement has produced by experimentation and analysis of detonations, which deal with the development of reciprocating internal combustion engines [7]. Lorin (1913) designed the first subsonic pulsejet, which has never achieved high enough speed for operating. Fonó (1915) studied a ramjet propulsion unit to launch heavy projectiles with long range and low initial velocity from lightweight guns.

The historic milestone for pulsejet development has been the German Fieseler Fi 103 (V1 middle range bomb) [8, 9], which was propelled by Argus As 014 pulsejet. The research activity that produces such an engine was based on the design of a pulsejet engine by Paul Schmidt. Schmidt and Madelung (1934) proposed a "flying bomb" powered by his pulsejet. In 1938, they demonstrated that a pulse jet-powered unmanned bomber could be realized even if the prototype lacked range and accuracy and was expensive. Further developments of this project leaded to the Argus engine [10], which equipped the V1 bombs.

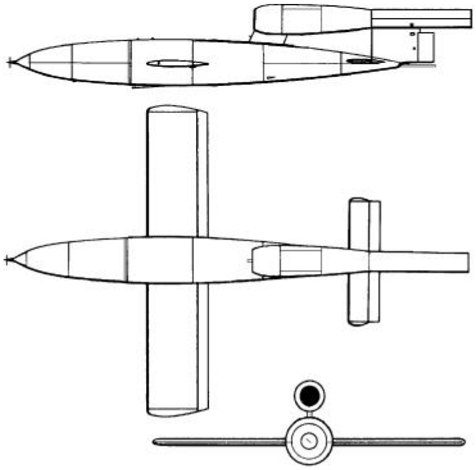


Figure 1. Fieseler Fi 103 - V1 Bomb

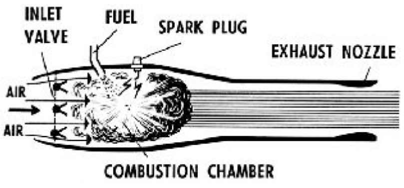


Figure 2. Schema of Argus As 014 pulsejet engine of V1 bomb.

Argus As 014 has been probably the valved pulsejet with the longer operative life (around 40 minutes).

After WW II, the pulsejet has been nearly abandoned. Other architectures had preferred because of vibration-induced problems, acoustic impacts, low operative life, low thrust and specific fuel consumption.

Derived concepts such as ramjets and scramjets achieved a higher success level because of higher performances.

Pulsejet Potential and Limits

The key advantage of pulsejets lays on its simplicity with respect to any other propulsion system. The construction of pulsejets is cheap and not sophisticated. It is a fundamental advantage in the field of miniature propulsion. Thermodynamic cycle of a pulsejet can be approximated by the Lenoir cycle, because unsteady pulsating combustion does not happen at constant pressure such as in most jet propulsion systems. Pulsejets burn fuel intermittently in a quick succession of detonating pulses. The consequent pressure shocks and formation of gaseous product of combustion produces the thrust of the system with a net pressure gain between the air intake and outlet. The absence of a compression stage reduces the thermodynamic efficiency, but also eliminates the energy consumption by the compressor. The gain by pulsating combustion is difficult to be utilized for propulsion. It can be stated that pulsation is both the central problem and the main benefit of this propulsion system. Some historic realizations demonstrate that the efficiency of a pulsejet can be increased when it is used as a combustor of a turbine engine. If the air is preliminary compressed the pressure gain is multiplied by the high-pressure environment. The architecture of British centrifugal turbojets such as Rolls Royce Derwent (Figure 3) is a demonstration of this statement.

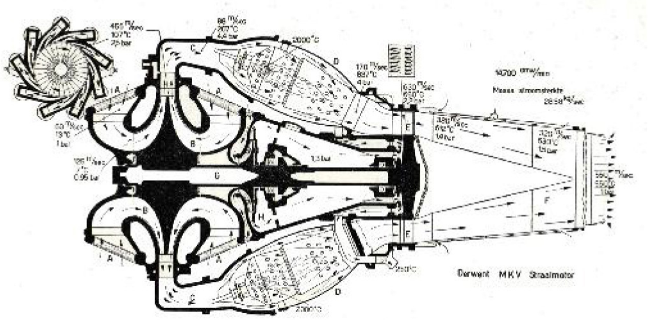


Figure 3. Rolls Royce Derwent

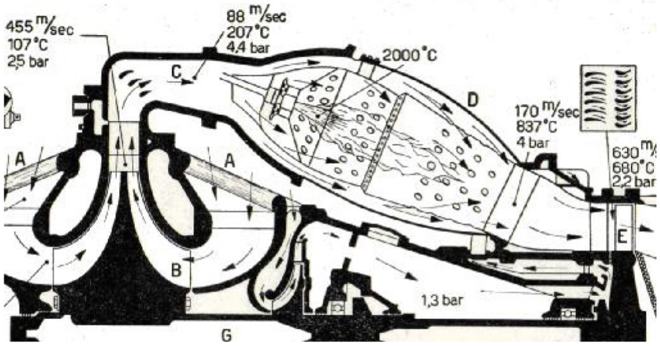


Figure 4. Detail of combustion chamber of Rolls Royce Derwent

It is evident that the combustion chamber of Derwent (Figure 4) has the same architecture of a valueless pulsejet.

If compared to traditional constant pressure combustors, pulsejets have smaller mechanical losses and lower fuel consumption or higher fuel efficiency. The system irregularity produces problems with axial turbine blades. Radial turbines are more solid on this point of view but they have lower efficiency especially with intermittent flows.

The effects of pulsation and high temperatures are also evident on the pulsejets with petal valve, which have a very low operative life. They generate evident accelerated fatigue stresses, which appears the main cause of these failures.

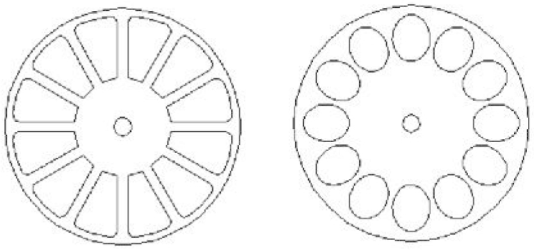
Today Valved Pulsejet Architecture

Today, pulsejets seem promising as a low cost solution for alternative propulsion purposes in the subsonic velocity range. The main problem is that valved pulsejets, which are the more viable for high thrusts, suffers of a very low operative life of the valves There are three basic types of valve systems used in the average pulsejet engine. The calculator generates the dimensions of all three types regardless of how much thrust you want from the engine.

The first type is a petal valve system, and is the most common type used in small pulsejet engines. The petal valve system has two key elements: a surface with drilled holes, a disk with valve petals that covers the holes. This system is simple, economic, easy to manufacture, but presents different problems: low affordability and large reduction of valve area. It is not used for larger engines, but it gives optimal performances in small pulsejets. If the thrust of your engine falls in the range of thrust between 1 to 5 kg. Some applications up to 50 kg of static thrust have been produced but they look inefficient and have a very low operative life. Today valved pulsejets uses petal valves, which have a very short life span. When subject to the extreme temperatures, pressures and very high frequency, tests performed at NASA Glenn [13] demonstrated that the valves last approximately fifty seconds. This is detrimental to pulsejet performance and hinders research efforts. Figure 6 presents two images depicting a failed valve (left) and the valve head (right).

High efficiency petal valve system is similar to the regular petal valve system in that it is a circular array of valve holes, but uses valve plate area by adopting optimized and shaped valve holes. The optimized shape of the inlet holes increases the efficiency of the pulsejet and requires a smaller diameter combustion chamber for the same amount of thrust. In particular, this solution has reduced drag and better airflow through the engine. On the other side, it has higher costs because each valve hole must be machined to the correct shape and size, instead of simply drilling the hole. The applications range spaces from 1 to 50 kg.

Larger pulsejet engines (Figure 7) adopt the valve grid system, which is directly derived from the original design of the Argus engine of the V1 bomb. A valve grid is a rectangular array of valved holes. Unlike the previous two types, the valved holes are not perpendicular to the axis of the combustion chamber. Valves are still reed valves, which are constituted by a set of thin plates and are placed on inclined planes. They open when the pressure in the combustion chamber decreases allowing the airflow through the holes, and closes when pressure increases.



"Wedge" Shape Holes

Circular Drill Holes

Figure 5. Small pulsejets' valve designs

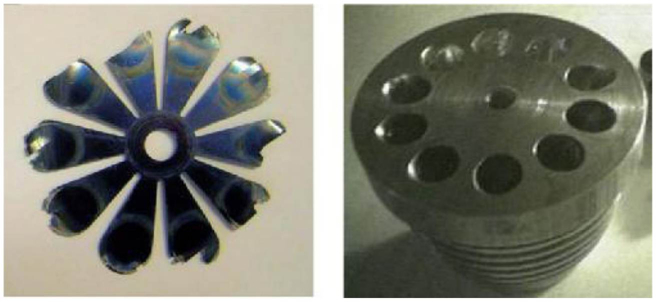


Figure 6. Image of failed valve (left) and the valve head (right) [13]

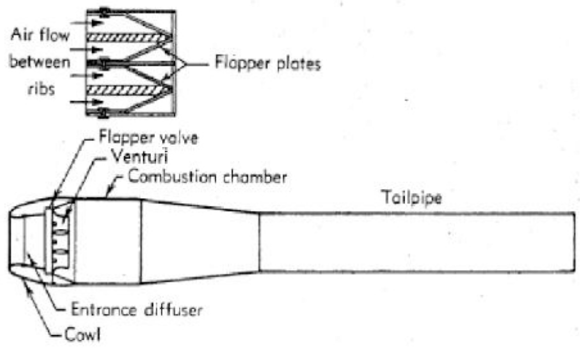


Figure 7. Architecture and valve detail of a high thrust pulsejet based on Argus 0.14 design.

Figure 8. High temperatures during a Lockwood-Hiller experiment

The must have limited dimensions in order to seal correctly the combustion chamber. This architecture allows a more optimized fluid dynamic of the inlet section and a larger area of openings. Thus, they further reduce the fluiddynamic losses and have a smaller diameter of the combustion chamber and less aerodynamic drag. Usually this architecture is used for engines with a thrust above 20 kg and increases it competitiveness with increasing thrust.

A New Pulsejet Development Hypothesis

This paper is a preliminary step of an independent research project with the aim of increasing both the performances and the robustness of pulsejet related propulsion. The first step relates to an effective preliminary analysis of the thermodynamic cycle of a pulsejet. This analysis will be the reference for the design activity of pulsejets with a preliminary air compression stage. The second stage focuses on the possibility of using more robust valve systems which use requires an effective reduction of the temperatures on the envelop of the combustion chamber and an increased thermal stability of the system. In particular, to reach this goal a cooling system has been taken into account and analysed.

Calculation Assumptions

It has been assumed that the combustion chamber is exposed to burning gases with an average temperature of *1500 K*, oscillating *500 K* at *30 Hz*. Inside the chamber it has been assumed a convective coefficient in line with values of ICE (Internal Combustion Engine): $U = 1000\ W/(m^2 \cdot K)$ including radiation transfer [11, 12].

The outside is exposed to cooling water at 353 K, with a heat transfer coefficient including convection and radiation of 5000 W/ ($m^2 \cdot K$) [12, 13]. In addition, this case is in line with the values assumed for ICE. The wall is supposed made of stainless steel 2 mm thick with the following values of conductivity:

$$k = \begin{cases} 25°C \rightarrow 16 W/(mK) \\ 125°C \rightarrow 17 W/(mK) \\ 225°C \rightarrow 19 W/(mK) \end{cases} \quad .$$

Dimension of combustion chamber have been evaluated to be a cylinder with diameter 0.25 m and length 0.8 m.

Lenoir Cycle

The thermodynamic cycle that best describes the pulsejet behaviour is the Lenoir cycle. It is composed by four main phases:

1-2. Constant volume (isochoric) heat addition;
2-3. Isentropic expansion with no heat interaction and production of work;
3-1. Constant pressure (isobaric) heat rejection with consume of some work.

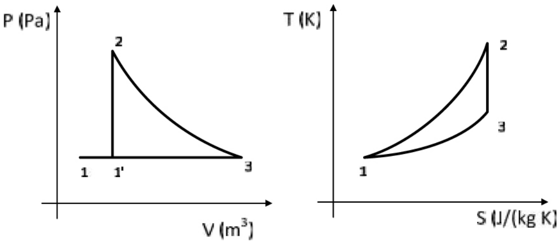


Figure 9. PV and TS Diagram of Lenoir cycle.

Constant Volume Heat Addition (1-2)

The heat addition phase (combustion) of a Lenoir cycle is an isochoric (constant volume) transformation. In the ideal gas version of the traditional Lenoir cycle, the first stage (1-2) involves the addition of heat in a constant volume manner. This results in the following for the first law of thermodynamics:

$$Q_{12} = m \cdot c_v \cdot (T_2 - T_1)$$

and from the definition of constant volume specific heats for an ideal gas:

$$c_v = \frac{R}{\gamma - 1}$$

There is no work during the process because the volume is held constant:

$$W_{12} = \int_1^2 p \cdot dV = 0$$

The pressure after the heat addition can be calculated from the ideal gas law:

$$p_2 \cdot V_2 = R \cdot T_2$$

Isentropic Expansion (2-3)

The second stage involves a reversible adiabatic expansion (in the ideal case) or an isentropic expansion of the fluid back to the original pressure. For an isentropic process, the second law of thermodynamics can be expressed by the following expression:

$$\frac{T_2}{T_3} = \left(\frac{p_2}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_3}{V_2}\right)^{\gamma-1}$$

Where $p_3 = p_1$ for this specific cycle. The first law of thermodynamics results in the following for this expansion process:

$$W_{23} = \int_2^3 p \cdot dV$$

because for an adiabatic process: $Q_{23} = 0$

Constant Pressure Heat Rejection (3-1)

The final stage (3-1) involves a constant pressure heat rejection back to the original state and according to the first law of thermodynamics it can be described by

$$Q_{31} - W_{31} = U_1 - U_3$$

From the definition of work assumes the following expression:

$$W_{31} = \int_3^1 p \cdot dv = p_1 \cdot (V_1 - V_3)$$

And the amount of heat rejected during this process is:

$$Q_{31} = (U_1 + p \cdot V_1) - (U_3 + p \cdot V_3) = H_1 - H_3 = m \cdot c_p (T_1 - T_3)$$

where

$$c_p = \frac{\gamma \cdot R}{\gamma - 1}$$

Efficiency

The overall efficiency of the cycle is determined by the total work over the heat input,

$$\eta_{tot} = \frac{W_{23}+W_{31}}{Q_{12}} = \frac{\int_2^3 p \cdot dV + p_1 \cdot (V_1 - V_3)}{m \cdot c_v \cdot (T_2 - T_1)}$$

Note that pulsejets gain work during the expansion process but lose some during the heat rejection process.

Numerical Results

The volume V of the combustion chamber is 39 dm^3, and the frequency f is 50 Hz. According to the above ideal model, a total work of 490 KJ can be evaluated with about 25 kN at the specified frequency.

Assuming that the fuel is gasoline with a LHV of 43.4 MJ/kg the fuel consumption can be evaluated according to [14] and [15]. Mass of air is about 0.04 kg and requires about 0.0032 kg of fuel/explosion. It means 0.16 kg fuel/s. It means that the energy introduced by mean of fuel is around 6.9 MJ/s with fuel efficiency around 7.1%.

Assuming that the combustible is Hydrogen it is necessary 0.00115 kg fuel/explosion with a unitary consumption of 0.046 Kg fuel/s.

Those results show clearly that a serious improvement is necessary to make the pulsejet energetically competitive against other propulsion systems. But on the other side very low cost very high simplicity and large improvement potential opens large spaces for the research on new and more efficient architectures of controlled pulsejets.

Reducing Thermal Stresses

This paper is a preliminary part through an effective definition of a new pulsejet architecture. This architecture is designed to take advantage of traditional spring actuated valves. Those valves will problems in the range of temperatures at which the combustion chamber of a pulsejet operates.

It has been then assumed the possibility of analyzing the opportunity of cooling the combustion chamber of a pulsejet by modelling the heat transfer through the walls. It can be then possible to evaluate the average state of the temperature profile within the wall and the effect of the oscillations of gas temperature.

Steady State Solution

The geometry and nomenclature are graphically presented in Fig. 10, together with the expected solution. Notice that a planar geometry is assumed because the wall thickness is assumed much smaller than the diameter of the cylinder.

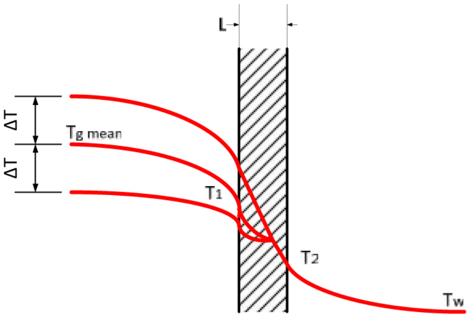


Figure 10. Temperature profile across the walls of the combustion chamber in a pulsejet.

The planar approximation allows simplifying the average temperature profile within the wall, $0<x<L$ by a linear function

$$T(x)=T_1 \cdot (T_1\text{-}T_0)\frac{x}{L}.$$

The end values, and the unitary heat flux, are:

$$\dot{q} = \frac{T_g - T_w}{\frac{1}{U_g}+\frac{L}{k}+\frac{1}{h_w}}$$

$$\dot{q} = h_w \cdot (T_2 - T_w) = \frac{k}{L} \cdot (T_1 - T_2) = U_g \cdot (T_g - T_1)$$

from which

$$\dot{q} = 918\,kW$$

$$T_1 = 582\ K,$$

and

$$T_2 = 533.5\ K.$$

Transient Analysis

Transient analysis of the specific case is a complex problem also by mean of numerical simulation by mean of CFD or other codes because of its transient periodic nature. The simplest solution seems to be the analytical one, by integrating the heat equation considering a periodic boundary condition in a semi-infinite slab.

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0$$

A solution can be reached assuming that the thickness of the pipe is adequate and that the high-frequency excitation produces only a small penetration depth of the oscillations. This paper in particular does not look at the initial transient condition when the engine starts started. It focuses on the periodic solution when the system has reached the operating regime.

The following solution gives the If we try a solution to the heat equation within the solid wall. The period is assumed τ=1/30 s, and decays exponentially with a penetration x_c. Those conditions lead to the following law of temperature:

$$T(x,t) = C\exp(-x/x_c)\cos(2\pi \cdot t/\tau - x/x_c)$$

By substituting this expression into heat equation, it results:

$$2C\frac{\alpha t - \pi x_c^2}{\alpha t x_c^2} \cdot e^{(-x/x_c)}\sin\left(\frac{2\pi t}{\tau} - \frac{x}{x_c}\right) = 0$$

and then

$$x_c = \sqrt{\frac{\alpha\tau}{\pi}}$$

and assuming $t \gg \tau$ it results

$$\frac{T(x,t) - T_{0,mean}}{T_{0,\max} - T_{0,mean}} = e^{(-x/x_c)}\cos\left(\frac{2\pi t}{\tau} - \frac{x}{x_c}\right)$$

where $T_{0,\text{mean}}$ and $T_{0,\text{max}}$ are the average and peak values of the temperature oscillation on the solid surface.

Instead of the solid-surface temperature, the far-field temperature in a fluid in contact with that surface is imposed,

$$T_{fluid}(t) = T_{1,mean} + \Delta T_1 \sin(2\pi t/\tau)$$

This equation can be solved by introducing a damping in surface-temperature amplitude and a phase-shift in the time response. They can be computed from the convective heat-transfer equation:

$$h(T_{fluid}(t) - T(0,t)) = -k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0}$$

The temperature field within the solid can be expressed as a function of Biot number in line with Dumas and Trancossi [16, 17] former solution to a crossflow heat exchanger.

$$\frac{T(x,t) - T_{0,mean}}{T_{0,\max} - T_{0,mean}} \overset{t \gg \tau}{=}$$
$$= \frac{1}{\sqrt{1 + \frac{2}{Bi} + \frac{2}{Bi^2}}} \cdot e^{(-x/x_c)} \cdot \sin\left[\frac{2\pi t}{\tau} - \frac{x}{x_c} - \arctan\left(\frac{1}{1+Bi}\right)\right]$$

$$Bi = \frac{h \cdot x_c}{k}$$

with $T_{1,\text{mean}}$=1500 K the mean temperature of the combustion gases, $T_{1,\text{max}}$=1500+500=2000 K is maximum value (i.e. the gas temperature oscillates from 1000 K to 2000 K sinusoidally at 50 Hz).

The characteristic penetration depth is 0.37 and Biot number: 0.0074.

The value for the amplitude damping at the surface-temperature is

$$1\Big/\sqrt{1 + \frac{2}{Bi} + \frac{2}{Bi^2}} = 0.052$$

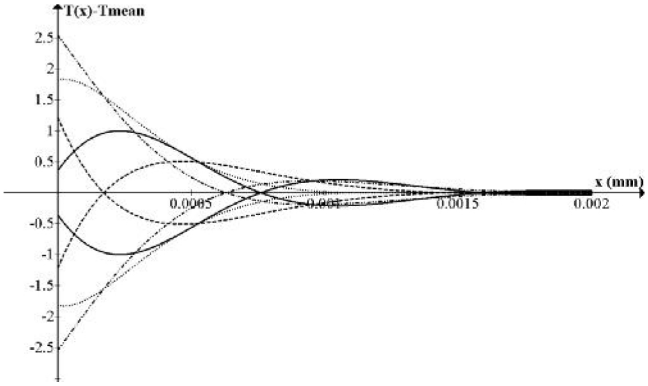


Figure 11. Temperature oscillations in the wall (they are only noticeable near the internal surface of the combustion chamber).

It means that the surface temperature oscillates only 500·0.0052=2.6 K (to be superposed to the mean temperature value of 582 K, previously found), and the phase shift relative to the imposed gas oscillations

$$\arctan\left(\frac{1}{1+Bi}\right) = 0.78\,\text{rad}$$

Some temperature profiles have been presented are in Fig. 11.

Analysis of the Results and Future Directions

The presented results are a preliminary milestone through the design of a new pulsejets' family that can overcome the well-known limitations of today ones. In particular, they can be analysed separately with specific reference to the specific aspects, which have been analysed in this paper.

The thermodynamic analysis shows clearly that an increase of the air pressure at the inlet can produce a major increase of thermodynamic and fuel efficiency. In particular, inlet pressures around 2 bars can almost double the efficiency of the system. Further increases are possible by much higher pressures. Another important aspect relates to the fact that an increase of pressure could allow a reduction of the dimensions of the combustion chamber. The known problems related to the use of axial turbines forces to take into consideration different architectures such as a centrifugal turbine similar to the one of Rolls Royce Derwent. In addition, pass-through fans will be considered together with other breakthrough configurations.

The preliminary heat exchange analysis shows that some cooling of the combustion chamber could be possible. This result is fundamental for an effective design of more efficient and enduring valve systems, which can be an effective element of the preliminary compression system. The pulsating nature of combustion authorizes to explore also the hypothesis of a pulsejet with a double chamber; a compression one and combustion one. When the valves are closed, air is compressed in one chamber and combustion is produced in the other. At the end of the combustion pressure decreases in the combustion chamber and compressed air pressure opens the valves and produces air inlet into the combustion chamber.

Conclusions

This paper has analyzed pro and contra of pulsejet propulsion focusing on valved pulsejets. In particular, after presenting the nature of the thermodynamic cycle it has focused on the definition of the guidelines for future improvements analysing also pro and contra of pulsejet propulsion. The intrinsic weakness related to valves allows taking into considerations new architectures. In particular, to verify the feasibility of a new configuration, which is currently under study it has been, analyzed the efficacy of possible cooling system considering both steady values and transient ones. This analysis has verified that water-cooling can be effective authorizing the continuation of the investigation through new pulsejet architecture with much longer life-cycle and much higher thermodynamic performances.

References

1. Geng, T., Schoen, M. A., Kuznetsov, A. V. and Roberts, W. L., “Combined Numerical and Experimental Investigation of a 15-cm Valveless Pulsejet”. Flow, Turbulence and Combustion 78(1): 17-33, 2007. doi:10.1007/s10494-006-9032-8.
2. Honecke, K., “Jet Engines: “Fundamentals of Theory, Design and Operation”. Shrewsbury : Airlife, 1997.
3. Heywood, J. B., Internal Combustion Engine Fundamentals. New York: McGraw-Hill, 1988.
4. Shavit A., and Gutfinger, C., “Thermodynamics from concepts to applications”, 2009. Second edition. New York: CRC Press, Taylor&Francis Group, ISBN 978-1-4200-7368-3.
5. EDELMAN, L., "The Pulsating Jet Engine-Its Evolution and Future Prospects," SAE Technical Paper 470212, 1947, doi:10.4271/470212.
6. Reynst F. H., “Pulsating Combustion”, Frankfurt/Main, Goethe-University, 1959.
7. O'Brien, J, G., “The Pulsejet engine a review of its development potential”, Naval Postgraduate School, Monterey, CA, USA, 1973.
8. VV.AA., Jane's Fighting Aircraft of World War II. London. Studio Editions Ltd, 1989. ISBN 0-517-67964-7
9. Gunston, Bill. World Encyclopedia of Aero Engines. Cambridge, England. Patrick Stephens Limited, 1989. ISBN 1-85260-163-9
10. Zaloga, S., V-1 Flying Bomb 1942-52, Oxford, UK: Osprey Publishing, 2005. ISBN 978-1-84176-791-8.
11. Mohammadi, A., Yaghoubi, M., Rashidi, M., Analysis of local convective heat transfer in a spark ignition engine, International Communications in Heat and Mass Transfer, 35, pp.215-224, 2008.
12. Przybyla, G., Postrzednik, S., and Zmudka, Z., " The heat transfer coefficient calculation in the ICE cylinder based on ice pressure data", Journal of KONES Powertrain and Transport, Vol. 20, No. 4, 2013.
13. Sandford, M. and Postlethwaite, I., "Engine Coolant Flow Simulation - A Correlation Study," SAE Technical Paper 930068, 1993, doi:10.4271/930068.
14. Moeckel, M., "Computational Fluid Dynamic (CFD) Analysis of a Six Cylinder Diesel Engine Cooling System with Experimental Correlations," SAE Technical Paper 941081, 1994, doi:10.4271/941081.
15. O’Brien, J. G., “The pulsejet engine a review of its development potential”, US Naval Postgraduate School, Monterey, California, USA, 1974
16. Chaurasia, S. R.. Gupta R., and Sarviya, R. M., “Performance Analysis of a Pulsejet Engine”, International Journal of Engineering Research and Applications (IJERA), Vol. 3, Issue 4, pp.605-609, 2013, ISSN: 2248-9622.
17. Winter Berger E., “Application of Steady and Unsteady Detonation Waves To Propulsion”, California Institute for Technology, 2004.
18. Torda, P., et al., “Compressible Flow Through Reed Valves for Pulse Jet engines. 1. Hinged Reed Valves, Technical Report No. 9, Project 9, 1948.
19. Gaiser, K., Paxson, D., T’ien J., “Improved Design of a Self-Actuated Valve for Pressure Gain Pulsejet Combustors”, Case Western Reserve University, 2010.
20. Dumas A., Trancossi M., “A Mathematical Based Design Methodology for Crossflow Heat Exchangers”, ASME 2009 International Mechanical Engineering Congress and Exposition (IMECE2009), November 13-19, 2009 , Lake Buena Vista, Florida, USA, Paper no. IMECE 43826;, pp. 1159-1165, Volume 9: Heat Transfer, Fluid Flows, and Thermal Systems, Parts A, B and C, 2009. doi: 10.1115/IMECE2009-43826
21. Dumas, A. and Trancossi, M., "Design of Exchangers Based on Heat Pipes for Hot Exhaust Thermal Flux, with the Capability of Thermal Shocks Absorption and Low Level Energy Recovery," SAE Technical Paper 2009-01-3074, 2009, doi:10.4271/2009-01-3074.

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Definitions/Abbreviations

α - Positive constant of heat equation

γ - heat capacity ratio

τ - Period [s]

c_p - Specific heat at constant pressure [kJ/kg K]

c_v - Specific heat at constant volume [kJ/kg K]

h - Convection coefficient [W/(m^2·K)]

k - Thermal conductivity [W/(m K)]

p - Pressure [Pa]

q - Heat for unitary surface [J/m^2]

$\dot{q}$ - Heat flux [J/(s m^2)]

t - Time [s]

x - Thickness [mm]

x_c - Penetration [m]

Q - Heat [J]

R - Universal gas constant [8.31446 JK^{-1} mol^{-1}]

T - Temperature [K]

U - Overal heat transfer coefficient (including radiation) [$W/(m^2 \cdot K)$]

V - Volume [m^3]

W - Work [J]

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