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ORGINAL ARTICLE

Numerical simulation of a hydrocarbon fuelled valveless pulsejet

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Abstract Jet propulsion technology has been limited to being identified largely with turbojets and turbo-machinery driven jet engines. Of late there has been a renewed interest in pulsejet technology and it has once again caught the imagination of academia. The specific characteristics of the pulsejet, such as easy scalability, absence of moving parts, reduced combustion temperatures; lower NO_X formation and the like make it possess varied capabilities for use in the field of jet propulsion and the most viable option for small-scale jet propulsion. In the current work, a numerical analysis encompassing feasibility and validation of a valveless pulsejet engine was attempted using CD-adapco's STAR-CCM+ CFD package. Due to lack of comprehensive established mathematical laws to govern the working of a pulsejet, most experimental work being performed is done by trial and error. This necessitates in-depth computational studies in order to shed more light on the understanding of valveless pulsejets. The results have been encouraging and in agreement with observed experimental conclusions such as, i) changes in dimensions affect the working of a pulsejet, ii) presence of a flare enhances the working of a pulsejet, and the close agreement in the frequency of operation. Through continuous study, an optimum initial condition was achieved which enabled the

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pulsejet to begin operation even before 0.05 s, thereby greatly reducing computational costs if a higher time-scale were to be used.

1. Introduction

A pulsejet is one of the simplest of engines from a design and manufacturing aspect. It should be borne in mind that there is no conclusively established comprehensive mathematical law governing the working of a pulsejet, hence all new and innovative modifications to pulsejets are done on a trial and error basis [1,2]. This greatly hinders progress since the effect of any change in the design is 'unpredictable'.

But this has not deterred academicians and scientist from attempting to develop a theoretical model of the working mechanism [3,4]. A considerable number of analyses ranging from using acoustic analogy studies to numerically solving the flow-field internal to the pulsejet have been performed in the past and though each one sheds fresh insight into a specific process/processes occurring in the pulsejet, no single theoretical model has been able to sufficiently explain all the processes. The systemic nature of the processes involved in this jet engine leaves a fragmented analysis of it wanting, hence requiring further understanding of 'how it works' and 'what makes it work' [1].

1.1. *Thermodynamic cycle*

The pulsejet operation cycle, as has been observed experimentally, can be summarized as:

1. Combustion occurs in the combustion chamber and the ensuing heat release increases the pressure and drives out the hot gases through the exhaust and produces thrust. The hot gases expand down the exhaust and inlet tubes, but due to a difference in the cross-sections of the inlet and exhaust pipes, a major portion of hot gases are expelled through the exhaust pipe.
2. Once the combustion gases have expanded to atmospheric pressure, over-expansion of the gases due to inertia (Kadenacy effect) inside the combustion chamber, causes the chamber pressure to decrease to sub-atmospheric levels.
3. The sub-atmospheric pressure causes fresh reactants to enter the combustion chamber through the inlet (the inlet air column has a lower inertia) and a small fraction of the exhaust gases from the exhaust tube.
4. The residual gases and heat transfer from the walls raise the temperature of the air-fuel mixture to the auto-ignition temperature thereby initiating combustion. The entire cycle repeats itself at a regular interval.

1.2. *History and background*

Though a lot of research had been performed prior to Marconnet by researchers like Holtzwarth and Karavodine in the field of pulsed combustion, the use of pulsed combustion as a method of direct thrust generation was first carried out by Marconnet [1] in his "reacture-pulsateur". P. Schmidt [5] applied the concepts of Marconnet's 'wave engine' to the development of an intermittent pulsejet engine, called the Schmidtrohr, directed towards use for vertical take-off and landing vehicles.

The Argus MotorenGesellschaft of Berlin, under the development of Dr. Fritz Gosslau, developed the famous Argus AS 109-014 powering the Vergeltungswaffe 1 (V-1) “Buzz Bomb” of World War-II [5]. It has been erroneously reported in numerous publications that the Argus work was in conjunction with P. Schmidt [6]. Post World War-II, research in pulsejets was undertaken by the US Navy under Project Squid. French engineers at SNECMA did extensive research on pulsejets. Lockwood of Hiller Aircraft, with the support of the French engineers, investigated the working of pulsejets and this work is a landmark achievement as it is the only completely documented, systematic study in existence. He

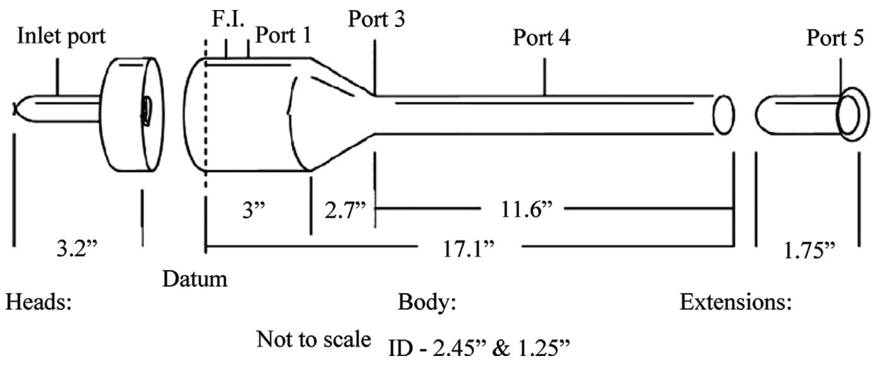

Figure 1 Experimental pulsejet model studied by Rob Ordon.

utilized analytical tools developed by J.V. Foa, which though not conclusive, were the most complete analytical approach available at that time. E. Tharratt's heuristic approach by linearization of a highly nonlinear problem was the next major development in the analytical evaluation of pulsejets. J.A.C. Kentfield and his associates from the University of Calgary pioneered work on developing computer simulations of the cyclic operations of the valveless pulsejet. Dudley Smith [1] of the University of Texas, Arlington developed a numerical model of a valveless pulsejet to include combustion, while assessing the performance of a pulsejet with a synchronous injection ignition system.

Since 2004, a fair amount of research on pulsejets, including experimental, analytical and numerical studies, has been undertaken by North Carolina State University and these studies have demonstrated the feasibility of operating pulsejets of sizes as small as 8 cm in length [7].

A few points should be mentioned to bring out the approach of the experimental work; the similarities and differences, and thereby the implications, it holds for this numerical study.

First the valveless pulsejet used for experiments was not designed theoretically and then manufactured for testing. Rather, a working commercial valved pulsejet was modified to a valveless setup.

Secondly, the immediate goals of these experiments were to determine the effects of geometric variation on the valveless pulsejet’s performance which is different from the aim of the numerical study.

Table 1 Settings used in the numerical simulation.

Settings		Value
Base cell size		5 mm
Volumetric controls cell size	Combustion chamber	1 mm
	Inlet region	2 mm
	Exhaust region	2 mm
Prism layer	Number of prism layers	10
	Thickness	0.5 mm
Initial boundary values	Pressure outlet	101325 Pa
	Mass-flow fuel Inlets	1.3×10^{-5} $kg \cdot s^{-1} \cdot rad^{-1}$
	Pulsejet inner-wall convective heat transfer coefficient	$25\ W \cdot m^{-2} \cdot K^{-1}$
Stepping interval	Time step	0.0001 s

Fuel mass flow rate obtained from the literature [6].

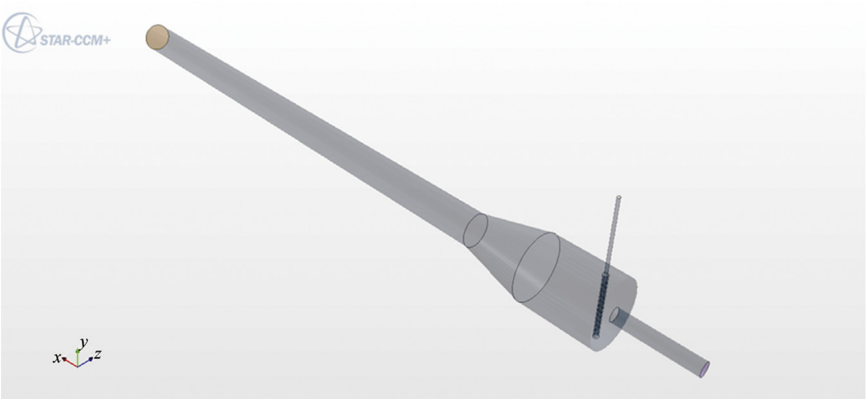

Figure 2 CAD model of the pulsejet.

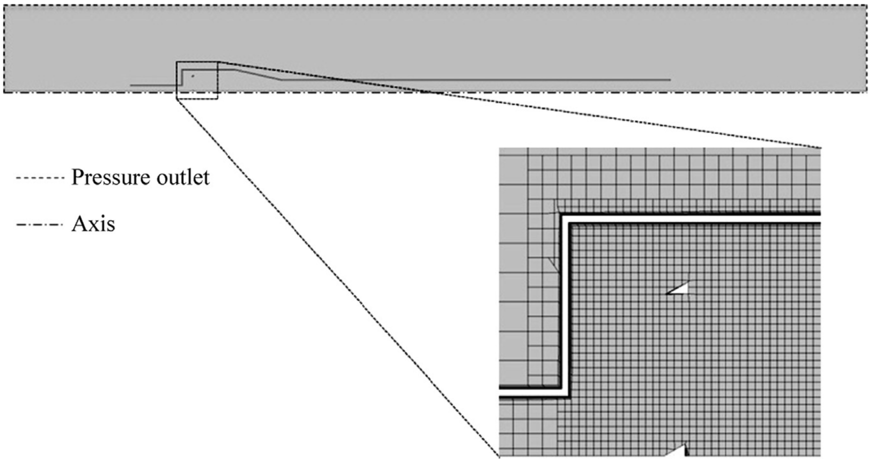

Figure 3 Flow domain of the numerical model.

The point of convergence of the experimental study and numerical simulation is in the fact that the research finally aims at developing competency to scale down existing valveless pulsejet designs for application in Micro Air Vehicles (MAVs). With this in mind, both the experimental study and the numerical analysis were carried out using propane as fuel in-order to further the understanding of the physics. Thus, the numerical study that was carried out can be considered as an extension of the experimental work [6].

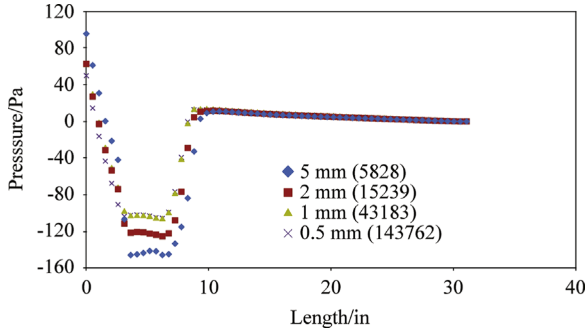

Figure 4 Pressure variations for different base sizes (mesh count).

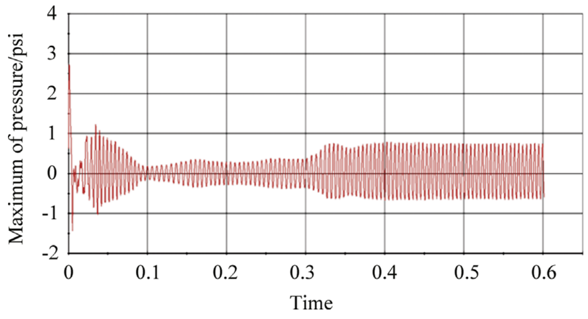

Figure 5 Observation of pressure at port 1.

2. Simulation model

The model chosen to carry out the numerical study was taken from Robert Lewis Ordon's [6] masters' thesis and is shown in Figure 1. The CAD model of the pulsejet is shown in Figure 2.

An external fluid domain was modeled around the pulsejet as shown in Figure 3. The flow field in the pulsejet can be considered as axisymmetric if the fuel injection scheme is modified [8-10]. Hence a 2-D axisymmetric setup was defined and used as it was considered to be a valid approximation of the actual pulsejet setup. Propane was used as fuel.

A Trimmer mesh setup was used with volumetric controls in the inlet, exhaust and combustion chamber. A ten-layer Prism Layer Meshing scheme was used to resolve the boundary layer.

The details of the grid size and spacing, prism layer thickness, etc. are given in Table 1. The mesh setup was chosen such that a balance was struck between accuracy of results and computational time. Since the pulsejet is a steady pulsed thrust producing engine following an unsteady process, a small time-scale was chosen to ensure that all the intermediate processes were successfully captured.

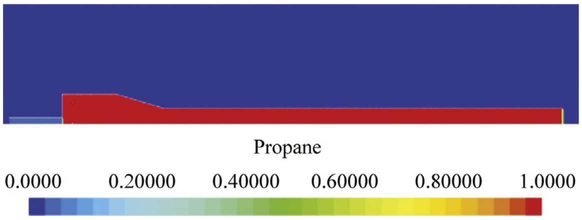

Figure 6 Initialization of propane (fuel).

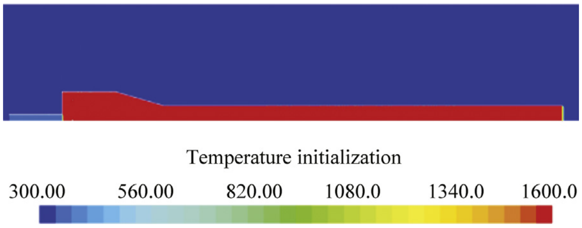

Figure 8 Temperature initialization.

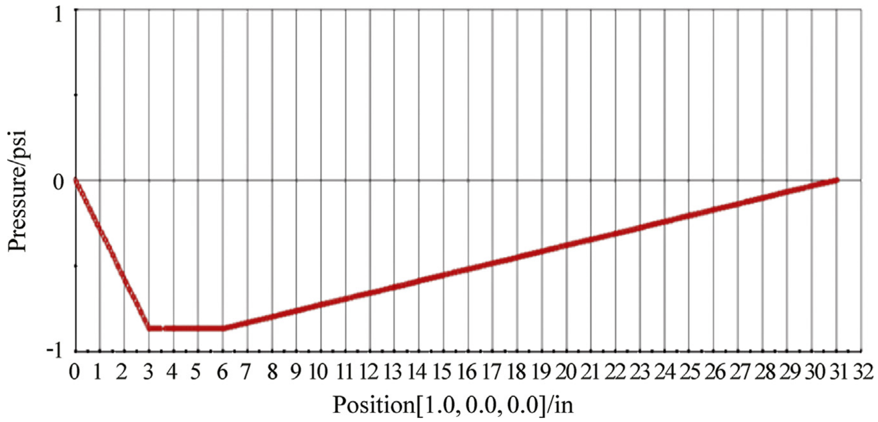

Figure 7 Initialization of pressure inside the pulsejet.

Table 2 Frequency of operation for different dimensions.

Pulsejet dimension		Frequency	
Inlet diameter	Exhaust extension length	Numerical value	Experimental value
0.0159 m	0.0762 m	209 Hz	183 Hz
	0.1524 m	220 Hz	214 Hz
0.0127 m	0.1524 m	236.2 Hz	220 Hz

Geometric parameters obtained from the literature [6].

Table 3 Comparison of pressure peak at port 1.

Pulsejet dimension		Amplitude
Exhaust extension length	End geometry	
0.0159 m	Without flare	0.90 psig
	With flare	1.07 psig

A mesh independence study was carried out before the above mesh scheme could be arrived at. The approach used for grid refinement involved one half of the pulse cycle. As the exhaust cycle post-combustion nears completion, the aspiration of fresh air through the inlet begins. The experimental data provided in the literature included the Test Fuel Flow Rate value [6]. This value provided a base point and a theoretical value of air that needed to enter through the inlet, in-order to ensure stoichiometric combustion, was calculated. Simulations were run with the theoretically arrived air mass flow-rate at the inlet specified for a 2-D axisymmetric setup and the velocity was monitored. The velocity profile obtained matched the theoretical value of velocity from mass flow-rate, which helped fix the physics of the setup. Once this was finalized, the pressure was monitored at various points along the axis of the pulsejet and the mesh scheme was varied.

The grid that sufficiently captured the pressure changes and fluctuations while possessing low values of mesh count was achieved through comparison of the results obtained for different simulations. Pressure variations for different base sizes are shown in Figure 4.

In order to capture wave motions and their interactions and to minimize numerical diffusion in the simulations, second order advection schemes were used [11]. The turbulent flow was modeled using the k-ε turbulence model. Combustion was modeled using the Standard Eddy Break Up model with a single-step propane combustion mechanism.

The boundary conditions for the model were a pressure outlet free stream, a convective inner pulsejet wall and two mass flow inlets.

3. Observations and results

Numerical simulation of the valveless pulsejet - that is a combustion driven pulsating flow, was successfully implemented using STAR-CCM+.

At this juncture, it is important to quantify the idea of 'the pulsing action of a pulsejet'. The pulsejet is said to work successfully if it is able to maintain a stable pressure oscillation, of constant frequency, with the minimum pressure of the said oscillation going below atmospheric pressure. Hence the successful working of a pulsejet is quantitatively observed by monitoring the pressure at specific points. The pressure at one such point is shown in Figure 5. This point where the pressure was measured in the simulation is at the same location as port 1 of the experimental model [6].

The simulation was started by initializing a band of stoichiometric propane-oxygen mixture inside the combustion chamber. The pulsing phenomenon was achieved when the wall of the pulsejet was modeled as a convective boundary. When modeled as an adiabatic boundary, i.e., when it was assumed that there was no heat transfer through the wall, no pulses were observed. This is in agreement with experimental observations which have shown that a higher wall temperature tends to premature ignition thereby killing the pulse cycle [12].

Optimum initial conditions were also developed to reduce the time taken for the pulsing action to initiate. These initial conditions include a low pressure in the combustion chamber, a high temperature for the fluid inside the pulsejet and completely filling the pulsejet with the fuel as shown in Figures 6, 7 and 8.

The results of the numerical simulation show a close match in the frequencies between the numerical work and the experimental data. Also certain trends, on variation of operational parameters, were observed in the numerical study and these are in agreement with experimental observations.

The trends that were observed were,

– Effect of exhaust tube length
– Effect of inlet tube diameter
– Effect of including a flare at the exhaust
– Effect of exhaust tube length
  The frequency of operation increased with decrease in the length of the exhaust tube as seen in Table 2 [6].
– Effect of inlet tube diameter
  The frequency of operation increased with increase in the diameter of the inlet tube as seen in Table 2 [13].
– Effect of including a flare at the exhaust

The presence of a flare at the exhaust greatly enhanced the operation of the pulsejet, i.e., for the same fuel flow rate a higher chamber peak pressure was observed as seen in Table 3 [8].

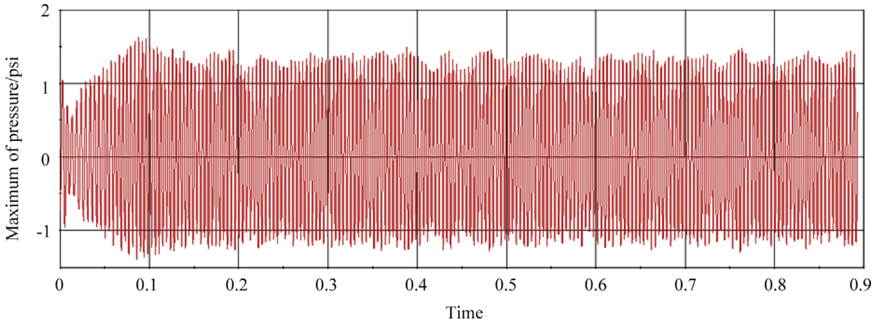

Figure 9 Pressure at port 1 for a pulsejet with a flare.

Another advantage of using a flared exhaust pipe is that it helped to start the pulsing action much quicker than when a flare was not used as seen in Figure 9 [8].

4. Conclusion

A good quantity of research work in the field of valveless pulsejets has been devoted to the resolution of the flow-field internal to the pulsejet, either analytically or numerically.

From this study, it can be seen that the observed pulse cycle and operational frequencies are in agreement with those recorded in experiments, which is a valid indication that the pulsejet combustion cycle has been captured in the simulation. Through continuous studies, encompassing numerical and experimental research, a theoretical framework of pulsejet operation and performance can be developed. From a computational aspect, more detailed turbulence and combustion modeling ought to be developed specifically for application to pulsed combustion (pulsed fluid-flow) simulations.

The results are also promising with regard to the use of hydrocarbon fuels for pulsejet operation. Further investigation into aspects such as fuel injection schemes, performance of the engine, thrust capability and the like need to be investigated before pulsejets can be considered as an alternative to gas-turbine jet propulsion technology.

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References

[1] D.E. Smith, The synchronous injection ignition valveless pulsejet, Ph.D. Dissertation, Faculty of the Graduate School, University of Texas at Arlington, TX, 1987.
[2] J.A. Olorunmaiyae, J.A.C. Kentfield, Prediction of optimum geometry, and the performance of valveless pulsed combustors in gas turbines, using a mathematical model, Journal of the Brazilian Society of Mechanical Sciences 13 (4) (1991) 281–307.
[3] J.G. Logan, Jr., Summary report on valveless pulsejet investigation, Technical Memorandum, Project SQUID Technical Memorandum No.CAL-42, Report No. DD-420-A-37, 1951.
[4] J.G. Logan, Jr., Valveless pulse jet investigations, part 1: test of small scale models, Technical Memorandum, Project SQUID Technical Memorandum No.CAL-27, Report No. DD-420-A-27, 1949.
[5] TH. Benecke, A.W. Quick (Eds.), History of german guided missile development, AGARD, First Guided Missiles Seminar, AGARDograph No 20, pp. 375–418, Munich, Germany, April, 1956.
[6] R.L. Ordon, Experimental investigations into the operational parameters of a 50 cm class pulsejet engine, M.S. Thesis, Department of Mechanical and Aerospace Engineering, NC State University, Raleigh, NC, 27695, 2006.
[7] A.P. Kiker, Experimental investigations on mini pulsejet engines, M.S. Thesis, Department of Mechanical and Aerospace Engineering., NC State University, Rayleigh, NC, 27695, 2005.
[8] T. Geng, Numerical simulations of pulsejet engines, Ph.D. Dissertation, Department of Mechanical and Aerospace Engineering, NC State University, Raleigh, NC, 27695, 2007.
[9] J.S. Sayres, Jr., Computational fluid dynamics for pulsejets and pulsejet related technologies, M.S. Thesis, Department of Mechanical and Aerospace Engineering, NC State University, Raleigh, NC, 27695, 2007.
[10] F. Zheng, Computational investigations of high speed pulsejets, Ph.D. Dissertation, Department of Mechanical and Aerospace Engineering, NC State University, Raleigh, NC, 27695, 2009.
[11] T. Geng, D.E. Paxson, F. Zheng, A.V. Kuznetsov, W.L. Roberts, Comparison between numerically simulated and experimentally measured flowfield quantities behind a pulsejet, in: Proceedings of the 44th Joint Propulsion Conference and Exhibit, AIAA/ASME/SAE/ASEE, Hartford, Conneticut, July 21-23, 2008.
[12] P.J. Litke, F.R. Schauer, D.E. Paxson, R.P. Bradley, J.L. Hoke, Assessment of the performance of a pulsejet and comparison with a pulse-detonation engine, in: Proceedings of the 43rd AIAA Aerospace Sciences Meeting and Exhibit, January 10-13, AIAA 2005-0228, pp. 2,7, 2005.
[13] M.A. Schoen, Experimental investigations in 15 cm class pulsejet engines, M.S. Thesis, Department of Mechanical and Aerospace Engineering, NC State University, Raleigh, NC, 27695, 2005.