ISSN 1068-7998, Russian Aeronautics, 2007, Vol. 50, No. 1, pp. 60–64. © Allerton Press, Inc., 2007.
Original Russian Text © V.N. Pobezhimov, 2007, published in Izvestiya VUZ. Aviatsionnaya Tekhnika, 2007, No. 1, pp. 46–48.

Simulation of a Working Process in the Pulsejet Engine with an Aerodynamic Valve on the Basis of the Thermodynamic Cycle Analysis

V. N. Pobezhimov

ZAO ENIKS, Kazan, Russia

Received December 20, 2006

Abstract—A physical and a mathematical model of a working process in the pulsejet engine based on the analysis of the thermodynamic cycle are proposed. The process of self-sustained periodic combustion is connected with special features of elementary processes comprising the cycle, influencing the engine operation and depending on its design parameters. The calculation method is based on the use of fundamental laws of conservation and basic equations of gas dynamics.

DOI: 10.3103/S1068799807010102

The construction of a closed mathematical model of a working process in the pulsejet engine is connected with establishing the physical nature of periodic combustion occurrence in such engines. It is necessary to determine a mechanism that provides a basis of the self-sustained process initiating pulsating combustion in the pulsejet engine, the nature of which has not received a single interpretation at present. In their papers different authors associate the pulsating combustion occurrence with a wavy, acoustic or vortex nature of the phenomenon [1–8].

Each of these approaches makes it possible to describe certain features of the pulsating combustion process that cannot be determined by other methods, but at the same time it possesses a number of drawbacks inherent in the physical model accepted.

The wavy theory supposes that in the pulsejet engine cycle there occurs the pressure amplitude drop with time that is proportional to a decrease of the working medium mass. The differential equations that allow the pressure drop level to be determined and the equations for calculating a wave shape were obtained in [1]. In this case, a compression wave generated by the fuel combustion process is simulated by the modified Bailey–Wilson relation establishing the law of temperature variation with time. The theoretical value of pressure attained in the combustion phase when the process of heat supply is isochoric and there is no heat removal from the combustion zone is determined as a function of geometrical dimensions of the combustion chamber. In this case, we fail to establish a dependence of thrust and specific fuel flowrate on the geometry of the engine flow passage.

The acoustic approach to the description of the working process in the pulsejet is based on the resonance character of the vibration combustion connected with the fact that acoustic vibration frequencies coincide with pressure variation frequencies in the combustion chamber [2]. The approach makes it possible to determine regions of occurrence and existence of vibration combustion regimes but is more suitable to the combustion processes in the direct-flow combustion chambers with heat supply at p = const.

The hypothesis on the vortex nature of the pulsating combustion in the pulsejet engine combustion chambers is based on the assumption that annular vortices are generated by the nonstationary pressure waves not only at the engine nozzle and valve exit but also inside the combustion chamber. In this model the character of vortex structure interaction depending on the design features of the engine flow passage exerts a governing influence on the combustion processes in the chamber. In spite of the fact that existence of vortex structures at the engine nozzle and valve exit is quite apparent, the assumption that there are annular vortices inside the combustion chamber is not confirmed experimentally.

In this paper, we present a model of the working process in the pulsejet engine with an aerodynamic valve (Fig. 1) based on the immediate application of the fundamental laws of conservation and basic equations of gas dynamics; the model is not connected with reducing initial equations in partial derivatives to the finite-difference equations.

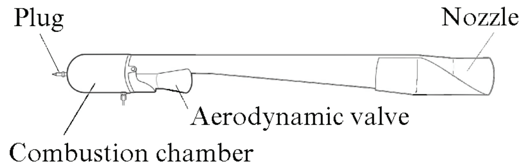

Fig. 1. Pulsejet engine with an aerodynamic valve.

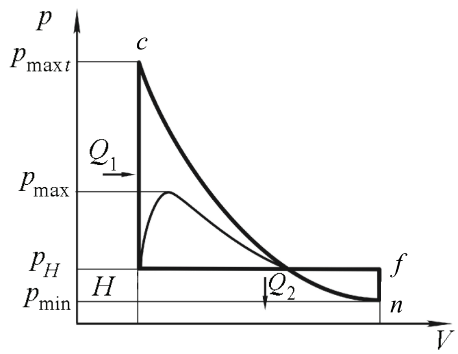

Fig. 2. Pulsejet engine cycle.

The physical model of the process is based on the modified Lenoir cycle (Fig. 2) consisting of the processes of heat supply (in the ideal cycle it is isochoric process), gas expansion and a filling process represented by the line *n f H* by convention.

In the isochoric heat supply the pressure in the chamber increases in proportion to the temperature growth. Such an ideal process is possible only when the combustion chamber is completely filled with a fresh mixture and the combustion process is instantaneous. With the finite time of combustion and incomplete filling of the chamber with the fresh mixture the pressure at the end of the heat supply process depends both on the fuel-air mixture composition and on the relative volume of the fresh mixture entering through the inlet valve. In this case, the heat supply process is not isochoric. The real value of the maximum pressure in the chamber will be determined by the expression:

$$p_{\max} = p_{bot}\xi_{fr}\xi_{exp}\left[\frac{\overline{V}_{FAM}\left(\pi^{1/k}-1\right)+1+\overline{V}_{disp}}{1+\overline{V}_{disp}}\right]^k,$$

where $\overline{V}_{FAM}$ is the relative volume of the fresh fuel-air mixture: $\overline{V}_{FAM} = V_{FAM}/V_\Sigma$, V_Σ is the total volume of the combustion chamber; $\overline{V}_{disp}$ is the relative volume of the gas displaced from the combustion chamber during the fuel-air mixture combustion: $\overline{V}_{disp} = V_{disp}/V_\Sigma$; π is the degree of pressure increase in combustion with V = const; ξ_{fr} are the losses to overcome forces of friction on the valve walls; ξ_{exp} are the sudden expansion losses; p_{bot} is the bottom pressure determined by the relation [3]:

$$p_{bot} = p_H\left(1-0.125k\mathrm{M}_{fl}^2\right).$$

The value of this pressure will determine the magnitude of the cycle-averaged pressure in the combustion chamber and the mean-integral thrust developed by the engine in the stationary conditions and in flight. Therefore, the increase in the relative volume of the fuel-air mixture entering the combustion chamber is a necessary condition for the engine thrust growth.

The relative volume of the fuel-air mixture entering the combustion chamber during filling can be determined by the expression:

$$\overline{V}_{FAM} = \frac{1 + \dfrac{1}{\alpha_{c.z} L_0}}{V_\Sigma} \left(\frac{\zeta_{in} \dfrac{\pi d_n^2}{4} + n_{val} \varepsilon_{val} \zeta_{in_{val}} \dfrac{\pi d_{val}^2}{4}}{1 + \dfrac{C_0 n^{-1} - \tau_{in}}{C_0 n^{-1} - \tau_{in_{val}}}} - C_1 V_{val} \right),$$

where ζ_{in} is the gas boundary displacement during inertial efflux from the nozzle; $\zeta_{in_{val}}$ is the gas boundary displacement during inertial efflux from the valve; n_{val} is the number of aerodynamic valves; ε_{val} is the coefficient of the relative contraction of the jet section when flowing into the valve; n is the pulsation frequency determined by the acoustic length of the flow passage L:

$$n = \frac{\sqrt{kR_c \left[T_{\max} \left(\dfrac{p_{\min}}{p_{\max}} \right)^{\frac{k-1}{k}} \right]}}{4L};$$

C_0 is the coefficient characterizing the time of engine filling determined by the oscillogram of pressure variation in the chamber; C_1 is the coefficient characterizing the quantity of the fuel-air mixture volume ejected from the valves during efflux that is determined by calculations.

The value of the maximum pressure in the combustion chamber also depends on the relative gas volume displaced from the combustion chamber during fuel burning and is determined by the geometry of the engine flow passage. The relation $p_{\max} = f\left(\overline{V}_{FAM}\right)$ at different values of $\overline{V}_{disp}$ is given in Fig. 3.

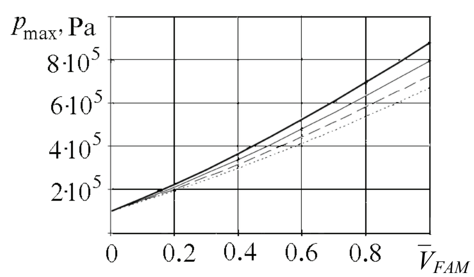

Fig. 3. Maximum pressure in the combustion chamber as a function of filling at $M_{fl} = 0$; $H = 0$: —— $-\overline{V}_{disp} = 0$; —— $-\overline{V}_{disp} = 0.1$; – – – $-\overline{V}_{disp} = 0.2$; - - - $-\overline{V}_{disp} = 0.3$.

The real filling of the combustion chamber with the fresh fuel-air mixture depends on the value of rarefaction in the combustion chamber and relative sizes of the inlet valve. The values of $\overline{V}_{FAM}$ in real designs, as a rule, do not exceed 0.15–0.2; therefore, the actual maximum pressure in the chamber may amount only to a quarter of the theoretically possible pressure.

The average pressure in the combustion chamber is also determined by a pressure decrease during inertial efflux that depends on the initial efflux velocity and the flow passage geometry. The problem on the influence of the flow passage shape on the process of inertial efflux and the pulsejet engine parameter is considered in detail in [4].

The process of filling engines, the inlet values of which are located in the bottom area of a flight vehicle in the flight direction, is significantly influenced by losses of energy for suction; the value of these losses considerably grows as the flight speed increases. A marked reduction of the engine thrust with the increase of the flight speed is connected with the deterioration of combustion chamber filling and enrichment of the fuel-air mixture composition.

The energy spent for deceleration of the flow around the engine during filling, the proportional kinetic energy of the moving gas were taken into account when calculating engine filling.

The maximum gas temperature after fuel combustion was determined by the composition of the fuel-air mixture in the combustion zone and the thermo-physical properties of fuel on the basis of the equations of the thermodynamic equilibrium state.

The simultaneous solution of the equations describing the processes of heat supply, expansion and filling that were obtained on the basis of considering the thermodynamic cycle with the use of the fundamental laws of conservation and basic equations of gas dynamics makes it possible to determine the engine parameters depending on the flow passage geometry and flight conditions.

The throttling characteristic of the pulsejet engine calculated by the model proposed is presented in Fig. 4. The dependence of the relative engine thrust on the relative fuel flowrate referred to the maximum values is shown. The calculated curve is of a less slope; therefore, the thrust dependence on the fuel flowrate is somewhat different from the experimental one in the region of average fuel flowrates. In this case, the calculation error is no more than 8.5 %. A similar correlation of the calculation results with the experiment is provided for all engines produced according to the similar scheme.

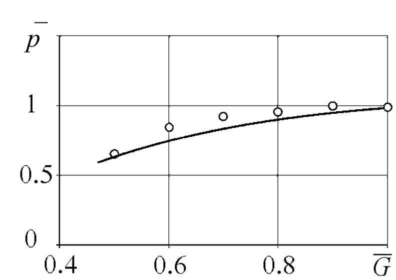

Fig. 4. Throttling characteristic of the pulsejet engine at $H = 0$, $M_{fl} = 0$: ○ – experiment; —— – calculation.

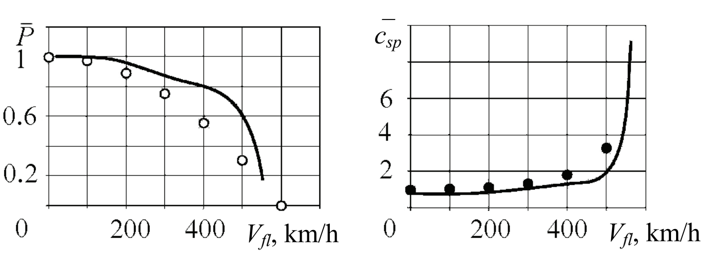

Fig. 5. Velocity characteristic of the pulsejet engine at $H = 0.5$ km: ○, ● – experiment; —— – calculation.

The calculated velocity characteristic of the pulsejet engine obtained on the mathematical model proposed is shown in Fig. 5. The generalized values of the experimental values of the engine thrust fraction and the relative specific fuel consumption obtained during flight tests by the readings of the check-recording equipment are plotted on it. The calculated model represents rather strictly the qualitative nature of the engine thrust variation in flight; the agreement between the calculated and experimental data with respect to the specific fuel flowrate is also sufficiently good.

REFERENCES

1. Tharratt, C.E., The Propulsive Duct, *Aircraft Engineering*, 1965, vol. 37, no. 12, pp. 359–371.
2. Larionov, V.M. and Zaripov, R.G., *Avtokolebaniya gaza v ustanovkakh s goreniem* (Self-Sustained Gas Oscillations in Plants with Combustion), Kazan: Kazan.Gos. Tekh. Univ., 2003.
3. *Teoriya i raschet VRD* (Theory and Calculation of Airbreathing Engines), Shlyakhtenko, S.M., Ed., Moscow: Mashinostroenie, 1987.
4. Pobezhimov, V.N., Influence of the Flow Passage Shape on the Process of Inertial Efflux and Pulsejet Engine Parameters, *Vestnik KGTU im. A.N. Tupoleva*, 2004, no. 2, pp. 22–25.
5. Winarski, L.D., A Logically Simple Method for Solving the Gas Dynamics of a Pulsating Combustor, *Proc. 1st International Symposium on Pulsating Combustion*, Univ. of Sheffield, 1971, p. 24.
6. Richardson, J.S., Artt, D.W., and Blair, G.P., A Computer Model of a Pulsejet Engine, SAE.Techn.Pap., 1982.
7. Putnam, A.A., General Survey of Pulse Combustion, *Proc. 1st International Symposium on Pulsating Combustion*, Univ. of Sheffield, 1971, p. 45.
8. Bhaduri, A.A., Investigations on Pulsating Combustion, *Indian J.Technology*, 1968, vol. 6, pp. 80–82.