`Computation of Thermodynamic Cycle for Novel Detonation Aircraft Engine

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The paper presents several methods of computing the thermodynamic cycle for a novel detonation based, aircraft engine. The research effort presented herein is part of the Framework Programme 7 research project no. 335091 - TIDE, funded by the European Commission.

The interest of the scientific community on the research and development of pulse detonation engine has grown in the last few years, due to the potential gain in specific power. Very rapid species and energy conversion happens during detonation. This rapid conversion rate, which could be 2 or 3 orders of magnitude faster than in a flame, can lead to several advantages for propulsion application, first of all being the higher efficiency, which can be reached by constant volume combustion, compared to a constant pressure process. Detonation differs from other combustion processes in the way in which the physical phenomenon evolves. The detonation is formed by a leading shock wave which propagates in the explosive mixture. The propagating shock wave triggers the chemical reactions and thus, the heat release. The detonation wave rapidly propagates inside the chamber resulting in a nearly constant volume heat addition process that determines a high pressure in the combustor and provides the thrust. Due to the rapidity of the process, the equilibrium state in pressure cannot be reached and the process thermodynamically behaves as a constant volume process. The latter is more efficient than a constant pressure process, typical of conventional propulsion systems.

The paper presents three different methods of computing the thermodynamic cycle for a detonation based engine, presented in more detail elsewhere [1]. The engine consists of a centrifugal compressor that admits atmospheric air and delivers it at low speed into a group of detonation chambers, guided by the compressor blades and splitters. The admission of air in the detonation combustors is controlled by the aerodynamic forces occurring in the engine. Fuel is injected in the combustor and mixed with the high pressure air, and a high frequency detonation process occurs, providing a sudden increase in pressure and temperature. The detonation exhaust gas is, then, evacuated through supersonic nozzles aimed at converting the high gas pressure into thrust. The exhaust nozzles are designed such that a shock-free, low loss flow is obtained.

The thermodynamic cycle starts from **state 1*** defined by the standard atmospheric pressure and temperature. The specific volume is, then, determined by the equation of state for air, and the enthalpy and the entropy at 1 bar are determined as functions of temperature using curve fitting functions existing in the literature [2].

The gas evolution in the compressor (**1* - 2***) is described using two approaches: firstly as an isentropic adiabatic compression (state 2^*_{id}), and secondly as a non- isentropic adiabatic compression (state 2*). The total pressure at the end of the compression process is assumed known, since it is one of the main design parameters of the engine. Since the entropy is constant for the isentropic compression, and determining the entropy at the same temperature and at 1 bar using the equation:

$$s_{p_{atm},T} = s_{p,T} + R ln\left(\frac{p}{p_{atm}}\right) \tag{1}$$

where s is the entropy, p is the pressure, p_{atm} is the atmospheric pressure, and R is the air gas constant, the temperature T and, subsequently, the enthalpy, can be determined using the above mentioned curve fitting equations [2], and the specific volume using the equation of state for air. For the non-isentropic compression, estimations of centrifugal compressor loss coefficients existing in the literature [2] are used to determine the real compression work, W_c, required to raise the pressure at the specified value, and, hence, the real enthalpy, h_2^*:

$$h_2^* = h_1^* + W_c \tag{2}$$

where h_1^* is the enthalpy at state 1*. With the enthalpy known, the temperature can be determined using the above mentioned curve fitting equations [2] and the specific volume using the equation of state for air. With the known temperature and pressure, the entropy at state 2* is determined using the curve fitting equation and Equation (1).

The detonation evolution (**2* - 3***) is computed using three different models [3]: the Humphrey cycle, the Fickett - Jacobs cycle, and the Zeldovitch - Neumann - van Doring cycle. For all cycles, an ideal and a real state can be defined. In the ideal case, the detonation temperature is assumed to be the adiabatic flame temperature for the selected fuel. For the real state heat losses due to heat transfer through the combustion walls and incomplete combustion are considered, so the temperature is decreased by a temperature loss coefficient estimated form the literature [2].

For the ***Humphrey cycle***, a constant volume heating, is describing the detonation. The pressure is determined using the equation of state for burned gas, and the enthalpy and the entropy are determined using the curve fitting equations together with Equation (1).

For the ***Fickett - Jacobs cycle***, the detonation is modelled a compression with heat addition process. Under the Chapman - Jouguet theory the heat release through detonation is assumed instantaneous, and the process is identical to a Rayleigh heating and the process can be regarded as being in local thermodynamic equilibrium [3]. Thus, the pressure and the temperature after detonation are the coordinates in the *p-v* plane of the point defined by the intersection of the reactive Hougoniot curve corresponding to the selected fuel adiabatic flame temperature (real or ideal) with the tangent raised from the point defining the state before the detonation (state 2*) to the same reactive Hougoniot curve [3]. It is important to know that even if the equation of state remains valid in state 3*, the actual gas constant is not known, as its value changes throughout the detonation process from the value for air, to the value for exhaust gas. A mean value can be determined by applying the equation of state with the now known values for temperature, specific volume, and pressure after the detonation. The enthalpy and the entropy are determined using the curve fitting equations together with Equation (1), using the previously determined mean gas constant value.

For the ***Zeldovitch - Neumann - van Doring cycle***, the detonation is modelled via a two stage process: fist a shock wave compression along the inert (no heat addition) Hugoniot curve (path **2* - 3'***), followed by a Rayleigh heating (path **3'* - 3***). Thus, the pressure and the temperature of the intermediate state 3'* are the coordinates in the *p-v* plane of the point defined by the intersection of the inert Hougoniot curve corresponding to state 2* with the tangent raised from the point 3* determined for the Fickett - Jacobs cycle (under the Chapman - Jouguet theory) to the reactive Hougoniot curve corresponding to the selected fuel adiabatic flame temperature (real or ideal) [3]. The temperature of the intermediate state is determined using the equation of state for air. The enthalpy and the entropy are determined using the curve fitting equations together with Equation (1). The parameters characterizing state 3* are identical to state 3* in the Fickett - Jacobs cycle, since the heat addition follows the Rayleigh model.

The expansion evolution (**3* - 4***) takes place both in the combustor, and in the exhaust nozzle and can be, again, regarded as either an isentropic (state 4^*_{id}), or a non-isentropic expansion (state 4*). The total pressure at the end of the expansion process is assumed atmospheric. Since the entropy is constant for the isentropic compression, the temperature at state 4^*_{id} can be determined using the curve fitting equations, and the specific volume using the equation of state for combustion gas. For the non-isentropic compression, estimations of the exhaust nozzle energy loss coefficients existing in the literature [2] are used to determine the real exhaust gas energy, W_e, and, hence, the real enthalpy, h_4^*:

$$h_4^* = h_3^* - W_e \tag{3}$$

where h_1^* is the enthalpy at state3* (either according to the Humphrey cycle, or according to the Fickett - Jacobs and the Zeldovitch - Neumann - van Doring cycles). With the enthalpy known, the temperature can be determined using the curve fitting equations and the specific volume using the equation of state for combustion gas. With the known temperature and pressure, the entropy at state 4* is determined using the curve fitting equation and Equation (1).

The cycle is closed by a fictitious 1 bar isobar.

The final paper will present the actual calculations of the cycle, using the presented approach, the corresponding *p-v* and *T-s* diagrams, as well as the theoretical cycle efficiency and the useful work provided by the engine.

References:

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