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Technical Notes

Exergy Analysis of a Pulse Detonation Power Device

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Nomenclature

ε = second law efficiency
$\mathcal{M}$ = molecular weight
W = work

I. Introduction

TRADITIONAL gas cycles, such as the Otto, Diesel, and Brayton cycles [1], are based on the deflagrative mode of combustion for adding energy to the working fluid. A paradigm shift from deflagration-based cycles can be achieved by using detonations to develop thrust or power. A detonation wave travels at a few thousand meters per second [2] compressing the quiescent upstream reactive mixture to trigger chemical reactions. A simple planar model for the detonation wave that is convenient for thermodynamics studies is the Chapman–Jouguet (CJ) model [3,4].

This note seeks to provide a comparison between the deflagration and detonation combustion modes applied to a power generation device. The performance of such modes is presented in a parametric study where parameters such as precompression ratio, combustion chamber length and detonation frequency are analyzed. This comparison enables a distinction to be made as to the advantages of the detonation mode under certain circumstances. The exergy approach [1] has lately been applied to aerospace systems [5–8] and to detonation-based energy conversion systems [9]. In particular, [10] applied exergy methods to a hybrid pulsed detonation engine and suggested analysis of stationary power generation to such systems.

II. Pulsed Detonation Power Device

A conceptual hybrid pulsed detonation power device (PDPD) is shown schematically in Fig. 1. Air enters through a compressor or low-pressure fan from the left and is mixed with a gaseous hydrocarbon (GHC) in the detonation chamber. A check valve is necessary to prevent backflow into the air line during detonation. The fuel–air mixture is ignited by an electric spark within the detonation chamber. The flame accelerates from a deflagration to a detonation within the chamber, propagating to the right. This detonation wave then enters a plenum, driving a two-stage turbine, the first stage being used to drive the fan and the second a generator. Because there is no fuel addition to the plenum, the detonation will degenerate into a blast wave. The plenum is also used to condition the flow. Some experimental work has shown the efficacy and need of the plenum, especially for detonation that uses multiple combustion chambers [11,12]. While the conventional detonation cycle initiates combustion at ambient pressure, the hybrid PDPD, with the low-pressure compressor, increases the pressure in the detonation chamber which is expected to improve performance. Moreover, the compressor allows for self-aspiration.

III. Cycle Analysis

An exergy analysis of a pulse detonation engine designed for power production using methane (CH_4) and propane (C_3H_8) is presented. The exergetic efficiency for detonation using a Humphrey cycle with a compressed fuel–air mixture is compared against a deflagration-based power production system for different compressor pressure ratios. The exergetic efficiencies are also compared for different design parameters such as the cycle frequency and the detonation tube length. This analysis, besides showing the theoretical improvement of pulse detonation engines over gas turbines, serves as a starting point for refining the design of such a device for electric power production.

A. Exergy Analysis

The exergy method is concerned with how well the available work that is generated from the energy resources is used. Thus, the so-called second law efficiency differs from the first law efficiency by taking into account the maximum possible thermal efficiency under the same conditions. This efficiency measures how the energy is converted in the system and it is a better metric for evaluating the performance of the system since the first law efficiency makes no reference to the best performance available. With such information, the design process can be improved. It is applied here to provide a quantitative estimate of how well detonation-based systems compare against deflagration-based systems for power production.

For power production, the second law efficiency, based on the fuel available energy, can be written as

$$\varepsilon = \frac{\dot{W}/\dot{m}_f}{\bar{\xi}_f/\mathcal{M}_f} \tag{1}$$

where $\bar{\xi}_f$ is the fuel chemical exergy on a molar basis, $\dot{m}_f$ is the mass flux of fuel, and $\mathcal{M}_f$ is the molecular weight of the fuel.

B. Model and Approach

For the proposed PDPD shown schematically in Fig. 1, a precompressed uniform stoichiometric mixture of air and GHC is introduced into the combustion chamber. Any losses preceding the combustion, such as mixing, compressor, valve, and line losses are neglected. The compressor is run by the first-stage turbine while a second-stage turbine is used to run an electric generator. The calculations make use of ideal gas approximations and isentropic relations. Losses are introduced by the isentropic efficiencies for the turbines.

Data for deflagration and detonation of the fuel–air mixture are obtained from the NASA Chemical Equilibrium with Applications (CEA) code [13]. Because the detonation wave propagating from the closed-end of a tube comprises a sharp front followed by a Taylor expansion, causing a pressure, temperature and density decay [2] an average approximation for these properties was adopted for the present thermodynamic analysis. It is important to note that the averaging procedure depends on the tube length and pulse rate. The analysis follows that of [14,15]. This model is developed for a single-cycle pulse detonation engine and it is based on the CJ theory, as is the model adopted by the present authors.

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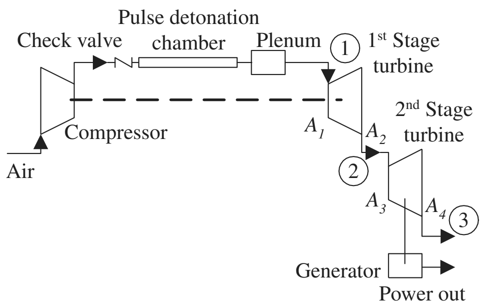

Fig. 1 Hybrid pulse detonation power device.

The velocity at the tube exit can be specified assuming that the Mach number at the exit is 0.4 and by assuming that the sonic velocity is based on the average properties of the cycle, as was done above for the pressure, temperature and density. The total or stagnation properties can then be calculated.

The first-stage turbine drives the compressor. Losses are introduced by assuming that the turbine isentropic efficiency as 85%. For this analysis, $A_2/A_1 = A_4/A_3 = 3$ (Fig. 1). The velocity drop v_3/v_2 in the second-stage turbine is taken as being 50% to conform to the exit conditions. The pressure at the turbine outlet is the ambient pressure. The work developed by the second stage is the output power available for power generation. The fuel availabilities are 74600 kJ/kg-mol for methane and 104680 kJ/kg-mol for propane, values obtained from the CEA code [13].

IV. Results and Discussion

The exergy analysis for power production is based primarily on the work developed by the system and the fuel exergy, as given by Eq. (1).

A. Performance Analysis

Calculations were performed for methane and propane fuels mixed stoichiometrically with air. The calculations assumed isentropic efficiencies for the turbine and compressor of $\eta_t = 85\%$ and $\eta_c = 75\%$, respectively, a fuel–air mixture flow rate $Q = 1.0\ m^3/s$, for a precompression ratio of three, a combustion chamber length of 1 m, a pulse rate of 100 Hz (or a period per detonation cycle of 0.01 s). The period per detonation does not include the fueling time, only the time after ignition [15], even though the fueling time is an important parameter for future design optimization.

The power developed by a system that uses detonation are 1.95 and 2.05 MW for methane and propane, respectively. The power developed by a system that uses deflagration are 1.35 and 1.38 MW for methane and propane, respectively. It can be seen that, for the same initial conditions, the power produced by the detonation-based system is considerably higher than that produced by a deflagration-based system. Because the energy stored in propane is higher than that stored in methane, the power developed by propane is also higher. The second law efficiency for a detonation-based methane and propane system is 38.3 and 79.1%, respectively. However, for a deflagration-based system with the same fuels, the second law efficiencies are 27.5 and 55.0% for methane and propane, respectively. The results show that detonation is the more efficient mode of combustion for power production when applied to the PDPD shown in Fig. 1.

B. Parametric Study

Figures 2–4 show the results of a parametric study for the precompression ratio, the combustion chamber length and the detonation frequency. The second law efficiency for the hybrid detonation-based system is compared against a deflagration-based system, the latter being constant for the parameters analyzed. This approach permits the determination of boundaries where deflagration becomes more efficient than deflagration, yielding potential thermodynamic advantages.

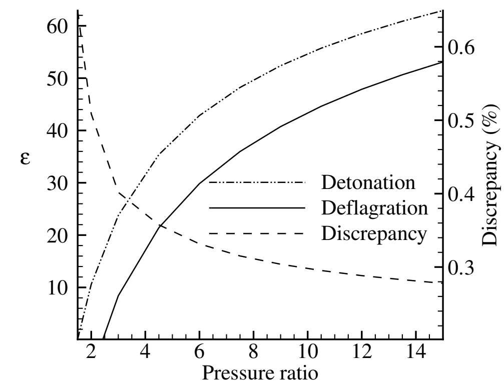

Fig. 2 Second law efficiency with increasing precompression for methane.

1. Precompression

The second law efficiency for different precompression ratio using methane is shown in Fig. 2. It can be seen that detonation is more efficient than deflagration for all range of precompression ratios here adopted. The higher the precompression ratio, the faster is the fuel/air mixture injection. Also the frequency of detonation increases. Faster detonation is obtained and hence the combustion produces more power. On the other hand, increasing the pressure will increase the fuel consumption, thus making the system less effective. A practical aspect to consider is the necessity to use high-pressure rating valves and lines, which would make the system more complex and more expensive.

2. Combustion Chamber Length

Figure 3 shows the efficiency for different combustion chamber lengths. It can be seen that the detonation processes for methane and propane become more efficient than deflagration at around the same tube length of 0.6 m, with the combustion using methane being more efficient in a slightly longer tube length than the combustion using propane.

Increasing the combustion chamber length brings an increase in the power of the system and guarantees that DDT can be achieved. However, increasing the combustion chamber length will also increase the weight and size of the engine. But unlike propulsion systems where weight and size are important concerns, these are not expected to be so for terrestrial power production.

3. Frequency

In Fig. 4, the second law efficiencies are compared for different detonation frequencies. The detonation processes become more efficient than deflagration at around the same frequency of 60 Hz. As the detonation frequency increases, the power produced by the

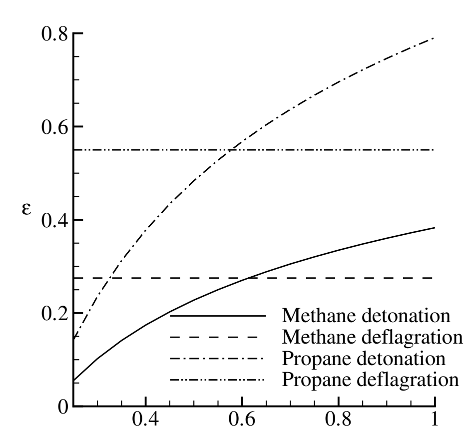

Fig. 3 Second law efficiency with different combustion chamber lengths.

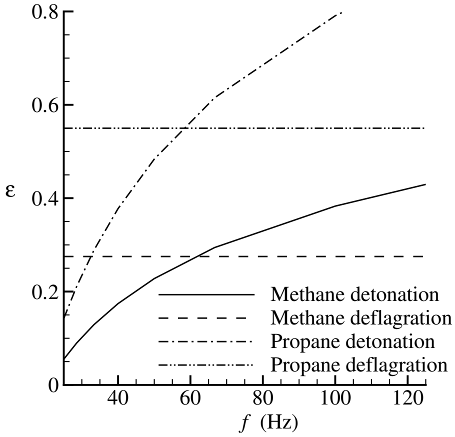

Fig. 4 Second law efficiency for different detonation frequencies.

combustion increases. Clearly there has to be a minimum frequency for which the detonation can be more efficient than deflagration. According to the results shown, such a frequency is approximately 60 Hz. This result agrees with what has been seen on the literature regarding experimental work using detonation for propulsion. Those studies claim that in order for the PDE cycle to be competitive with conventional turbojet/turboramjet systems, they will be required to operate in the 75–100 Hz range with near stoichiometric fuel–air mixtures. It is expected that for power production the range need not be the same but similar to that for propulsion [16].

V. Conclusions

The present work is a preliminary study of a PDPD. The purpose of this exergy analysis is to identify where improvements can be made to the PDPD. Another purpose is to address the design parameters that are necessary to build such a device and to confirm what other studies have shown: that detonation is a more efficient process than deflagration, in this case for power production. On analyzing the entire system, it is seen that the losses caused by the combustion process is far greater than the contribution of losses from the pump, valve, plenum, turbines, and generator. One of the differences between the first and second law efficiencies is the energy provided to the system: first law efficiency takes into account the energy release associated with the heating value of the fuel rather than the exergy of the fuel. In addition, Petela [17] showed that the exergy loss for deflagration combustion processes is larger than the exergy loss for detonation combustion processes, making the combustion process the main source of energy loss in the system.

The present results show that pulse detonation is an efficient combustion mode for power production when it reaches the CJ condition. The second law efficiency shows clearly that pulse detonation is much more efficient than deflagration for power production under certain circumstances. The parametric study shows that the critical design parameters are the frequency of detonation and the combustion chamber length, which are related to each other through the period per detonation cycle. It shows that there is an optimum value for the frequency and the combustion chamber length for which the detonation process is more efficient than the deflagration.

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