

Research Article

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Performance analyses of detonation engine cogeneration cycles

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Abstract: Aircraft engines such as gas turbines and detonation engines have very important attention by the researchers in the last decades. However, using detonation engines for producing electrical and heat power was not researched efficiently. In this study, gas turbine and pulse detonation engines cogeneration systems were analyzed and compared by using first and second laws of thermodynamics and exergy analysis method. Three different cycles, namely, basic gas turbine, Zeldovich–von Neumann–Döring (ZND) detonation engine and steam injected regenerative ZND detonation engine cogeneration systems were investigated. The performance analyses and the advantage of these three cycles were obtained and discussed. The performance analyses were done for different compression ratios (r), and the combustion outlet temperatures and pressures, exergy efficiencies, specific fuel consumption, electrical efficiency, exergy fuel consumption, electrical heat rates and other performance parameters of the three cycles were obtained and discussed. It is found that gas turbine cogeneration systems have some advantages and disadvantages in some conditions than ZND cycle. The steam injected regenerative ZND detonation engine cogeneration systems can compete with the Brayton cycle cogeneration systems.

Keywords: cogeneration, ZND, detonation engines, exergy

1 Introduction

The combustion processes are very important pollution source in the World. Research on combustion is conducted all over the World [1,2]. Subsonic combustion process called deflagration, in which flames obtained in subsonic

speeds with little decreases in pressure, are used in traditional gas cycles, like Diesel, Otto, Brayton cycles. Deflagration-based gas turbines are reaching the exergy efficiency limits, and increasing their performance efficiencies are becoming very difficult. One of the new promising technologies is pressure gain combustion (PGC), which has emerged because of its higher efficiency than the gas turbine systems. Detonative combustion is one of the primary methods to obtain and realize PGC. Detonation combustion provides 30% higher thermal efficiency than the conventional gas turbines. Detonation combustion is based on supersonic mode of combustion, which causes rapid burning that is thousands of times faster than the flames [3,4]. Detonation combustion process is more like a constant volume combustion than the constant pressure combustion, because there is no sufficient time for pressure equilibrium. The advantage of a constant volume combustion process is that it can produce a lower entropy rise of the working fluid than a constant pressure combustion process. There are four stages in the Pulsed detonation engine (PDE) cycles, namely, filling air fuel mixtures, combustion, blow down and purging [5,6]. Detonation is a shock front driven by energy releases. Detonation engines are very nicely explained by Zeldovich–von Neumann–Döring (ZND) cycle. In ZND cycle, the oxidant–fuel mixture comes from the injectors and is sprayed into the combustion chamber. Immediately after that, a spark igniter initiates the combustion and the flame proceeds subsonically as deflagration combustion.

The level of turbulence increases with the obstacles in the combustion chamber. The increase in the turbulence level causes the combustion to become detonation which is named deflagration to detonation transition [5,6]. The detonation wave at the combustion chamber outlet can be obtained. The exhaust gas is cleaned using an inert gas in the combustion chamber. The combustion chamber is ready for the next cycle. The minimum or the average frequency, for more efficient detonation than deflagration, has to be approximately 60–100 Hz. The flame moves at Chapman–Jouguet speed which produces good results when compared with the experimental studies using high frequency sensors. A detonation wave

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travels at supersonic speed. Temperatures are around 2,000–3,000 K according to the fuel heat value and the fuel–oxidant combination used in the front of the detonation. The ideal thermodynamic cycle with pressure gain combustion is ZND and Humphrey cycles. PDE and rotating detonation engine are the most favorable engines to use detonative combustion [5–7]. The main problems of PGC are the increasing entropy generation of combustion processes, pressure loss, blade cooling and other difficulties about the cycle's devices. The exhaust flows obtained in PGCs are defined with temperature and velocity fluctuations, and strong pressure. The main problem of PGC in gas turbines is to efficiently harvest work from the PGC exhaust gas. To solve these problems using a plenum after the combustion chamber or improved turbine designs to expand outlet flow of the PGC are discussed in literature. Obtaining maximum extraction from a PGC is still the real problem.

In this study, the performance analyses will be done for different compression ratios (r), and the combustion outlet temperatures and pressures, exergy efficiencies, specific fuel consumption (SFC), electrical efficiency, exergy fuel consumption, electrical heat rates and other performance parameters of the three cycles will be obtained and discussed. The ZND cogeneration systems advantages and disadvantages in some conditions will be shown.

In Figure 1, Brayton and ZND cycles' temperature–entropy (T – s) diagrams are given. In Table 1, the comparison of the basic parameters of deflagration and detonation combustions are given.

2 Materials and methods

Cogeneration plants include some components of which the main component is turbine. In those component chemical

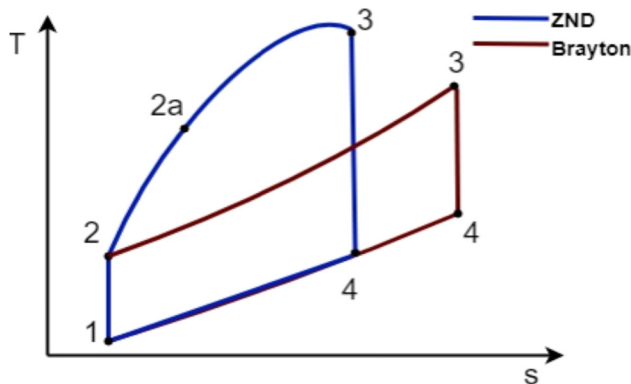


Figure 1: Brayton and ZND cycles temperature–entropy (T – s) diagram [4].

Table 1: Comparison of the basic parameters of detonation and deflagration combustion

Parameter	Deflagration	Detonation
Wave Mach number (Ma)	0.0001–1.04	1.1–5
Pressure ratio (p_1/p_0)	0.98–0.97	12–65
Temperature ratio (T_1/T_0)	5–16	8–20
Density ratio (ρ_1/ρ_0)	0.6–1.3	1.5–2.7

compositions, pressures and temperatures are changed. The assumptions made in the analyzing and the details can be found in literature [8–12].

The schema of a basic gas turbine cogeneration plant is given in Figure 2. From the figure, it is seen that air is taken into the compressor and after compressing, it is sent to the combustion chamber for combustion with methane. The mechanical energy obtained in a gas turbine from exhaust energies is transformed to the generator to produce electricity. The other energies of exhaust gas are transferred to an HRSG component to produce hot water or steam.

The schema of a ZND detonation engine cogeneration system is seen in Figure 3. Air is taken into the compressor and after compressing, it is sent to the PDC chamber for detonative combustion with methane. After the detonative combustion, the exhaust gas in high pressures and high temperatures is cooled, by producing steam in HRSG for the metallurgical reasons of the gas turbine. After the HRSG, the exhaust is available for the gas turbine to produce mechanical energy. After that, the exhaust is used in the HRSG to obtain steam again.

The schema of a steam injected regenerative ZND detonation engine cogeneration system is seen in Figure 4. Air is taken into the compressor and after compressing, it is sent to be heated in the HRSG for regeneration. The compressed and heated air is taken into the pulse detonation

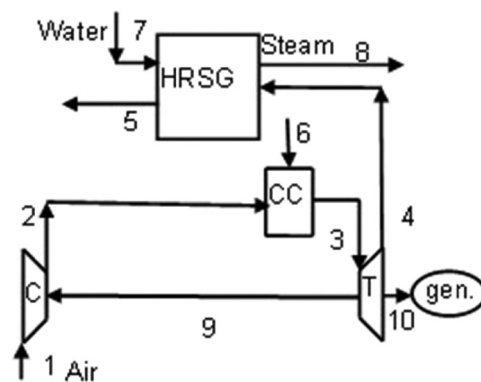


Figure 2: The schema of a basic gas turbine cogeneration plant.

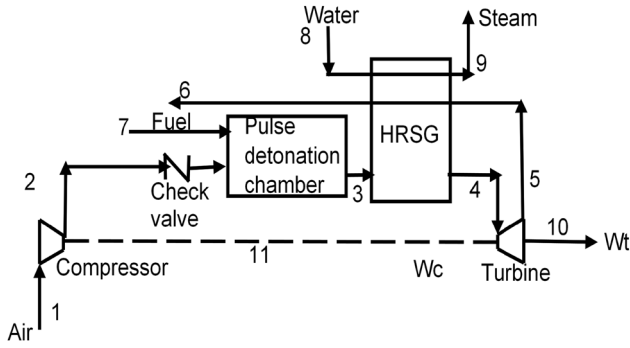


Figure 3: The schema of a ZND detonation engine cogeneration system.

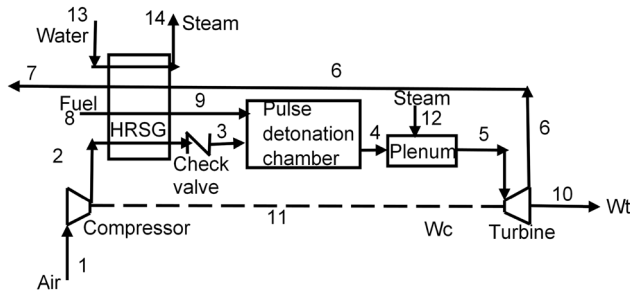


Figure 4: The schema of a steam injected regenerative ZND detonation engine cogeneration system.

combustion chamber for detonative combustion with methane. After the detonative combustion, the exhaust gas with high pressure and temperature are cooled, by injection steam in the plenum. The exhaust gas mass increases and their temperature decreases with steam and then exits from the outlet of the plenum to enter into the gas turbine. After the gas turbine, the exhaust gas is available to produce steam again and is sent to HRSG.

For steady state and open system, the energy equation is as follows:

$$\dot{Q}_{CV} - \dot{W}_{CV} + \sum_{in} \dot{m}_{in} \left(h_{in} + \frac{V_{in}^2}{2} + gz_{in} \right) - \sum_{out} \dot{m}_{out} \left(h_{out} + \frac{V_{out}^2}{2} + gz_{out} \right) = 0. \quad (1)$$

The law for steady state conservation mass is as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}. \quad (2)$$

Efficiency or the overall efficiency of the system is as follows:

$$\eta = \frac{W + Q_{steam}}{Q_{Fuel, inlet}}. \quad (3)$$

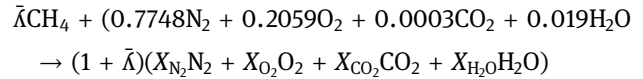
Electrical efficiency of the system is

$$\eta_{el} = \frac{W}{Q_{Fuel, inlet}}. \quad (4)$$

Heat efficiency of the system is

$$\eta_{heat} = \frac{Q_{steam}}{Q_{Fuel, inlet}}. \quad (5)$$

The chemical energy of fuel in combustion chamber is converted to thermal energy by chemical reaction. In the calculations, it is taken that the combustion is ideal and also complete. The chemical reaction in combustion chamber is as follows:



Stoichiometric value of air is the minimum value of air required to complete the combustion theoretically. However, to complete the combustion, more air is always used than the theoretical amount in Brayton cycle. Excess air ratio is the rate of real quantity of given air to theoretical air [12–14]. Availability is the theoretical maximum quantity of useful work. This can be obtained at the end of a reversible process, if equilibrium with environment is reached. Exergy has two components, physical and chemical [15,16]. For mixed substances, the physical exergy of ideal gas mixtures is as follows:

$$e_{phys} = (\bar{h} - \bar{h}_0)_{mixt} - T_0(s - s_0)_{mixt} = \sum_j x_j \left[\int_{T_0}^T \bar{c}_{p0j}(T) dT - T_0 \left(\int_{T_0}^T \frac{\bar{c}_{p0j}(T)}{T} dT - \bar{R} \ln \frac{P_j}{P_0} \right) \right]. \quad (6)$$

The chemical exergy for mixture of gases is as follows [17,18]:

$$\bar{e}_{chem, mix} = \sum_i x_i \bar{e}_{chem, i} + \bar{R} T_0 \sum_i x_i \ln x_i. \quad (7)$$

For a flow or control mass, the total exergy is as follows:

$$\bar{E} = \bar{E}_{phy} + \bar{E}_{chem}. \quad (8)$$

For open systems, the exergy equation is

$$\sum_i \dot{m}_i h_i - \sum_i T_0 S_i - \sum_j \dot{m}_j h_j + \sum_j T_0 S_j + \sum \dot{Q}_c - \sum \dot{Q}_c \frac{T_0}{T_c} - \dot{W} = \dot{E}_{loss}. \quad (9)$$

In Table 2, entropy, energy and mass equations for the devices for basic plant are shown. In Table 3, exergy

Table 2: Energy, mass and entropy equations of the devices for basic gas turbine cogeneration plant [12,13,16–18]

Devices	Mass equations	Energy equations	Entropy equations
Compressor	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1 \cdot h_1 + \dot{W}_C = \dot{m}_2 \cdot h_2$	$\dot{m}_1 \cdot s_1 - \dot{m}_1 \cdot s_2 + \dot{S}_{\text{gen},C} = 0$
Turbine	$\dot{m}_3 = \dot{m}_4$	$\dot{m}_3 h_3 = \dot{W}_T + \dot{W}_C + \dot{m}_4 h_4$	$\dot{m}_3 s_3 - \dot{m}_4 s_4 + \dot{S}_{\text{gen},T} = 0$
HRSG	$\dot{m}_4 = \dot{m}_5$ $\dot{m}_7 = \dot{m}_8$	$\dot{m}_4 h_4 + \dot{m}_7 h_7 = \dot{m}_5 h_5 + \dot{m}_8 h_8$	$\dot{m}_4 s_4 + \dot{m}_7 s_7 - \dot{m}_5 s_5 - \dot{m}_8 s_8 + \dot{S}_{\text{gen},\text{HRSG}} = 0$
Combustion chamber	$\dot{m}_2 + \dot{m}_6 = \dot{m}_3$	$\dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3 + 0.02 \dot{m}_7 \text{LHV}$	$\dot{m}_2 s_2 + \dot{m}_6 s_6 - \dot{m}_3 s_3 + \dot{S}_{\text{gen},\text{CC}} = 0$
Overall cycle	$\bar{h}_i = f(T_i)$ $\dot{m}_{\text{air}} h_{\text{air}} + \dot{m}_{\text{fuel}} \text{LHV}_{\text{CH}_4} - \dot{Q}_{\text{Loss,CC}} - \dot{m}_{\text{eg},\text{out}} h_{\text{eg},\text{out}} - \dot{W}_T$ $- \dot{m}_{\text{steam}}(h_{\text{water,in}} - h_{\text{steam,out}}) = 0$ $\dot{Q}_{\text{Loss,CC}} = 0.02 \dot{m}_{\text{fuel}} \text{LHV}_{\text{CH}_4}$ $\bar{s}_i = f(T_i, P_i)$		

efficiencies, exergy and evaluation criteria equations of the devices for basic plant are shown.

Temperature for ZND cycles

$$T = T^* \left(\frac{(\gamma + 1)M}{1 + \gamma M^2} \right)^2. \quad (10)$$

Entropy for ZND cycles

$$\Delta s = c_p \ln \left[M^2 \left(\frac{\gamma + 1}{1 + \gamma M^2} \right)^{\frac{\gamma+1}{\gamma}} \right]. \quad (11)$$

Data for the detonation combustion and the deflagration combustion of the fuel air mixtures, and exhaust gas properties are taken as temperature and pressure of the outlet combustion chamber, from the NASA CEA code <https://cearun.grc.nasa.gov/web> sites [19]. The average

approximation of the exhaust properties, by taking into account the experiments done in literature, was adopted for the exergetic analysis of this study [4,5,19–21].

3 Results and discussion

In this article, the normal conditions are taken as $P_0 = 101.3 \text{ kPa}$ and $T_0 = 25^\circ\text{C}$. For Brayton cycle, compressor's inlet air mass flow is $\dot{m}_{\text{air}} = 91.3 \text{ kg/s}$, fuel mass flow is $\dot{m}_{\text{fuel}} = 1.64 \text{ kg/s}$, isentropic efficiencies for turbines and compressors of the three cycles are taken as $\eta_{\text{izC}} = \eta_{\text{izT}} = 0.86$, the outlet temperature of the recuperative cycle is $T_{\text{recout}} = 850 \text{ K}$, the produced steam temperature is $T_{\text{steam}} = 485.57 \text{ K}$ and the outlet temperature of the HRSG is $T_{\text{exhaust}} = 426 \text{ K}$ [8,12,17].

Table 3: Exergy, exergy efficiency and evaluation criteria equations of the devices for basic gas turbine cogeneration plant [12,17,18]

Devices	Exergy equations	Exergy efficiencies
Compressor	$\dot{E}_{D,C} = \dot{E}_1 + \dot{W}_C - \dot{E}_2$	$\eta_{\text{ex},C} = \frac{\dot{E}_{\text{out},C} - \dot{E}_{\text{in},C}}{\dot{W}_C}$
Turbine	$\dot{E}_{D,T} = \dot{E}_3 - \dot{E}_4 - \dot{W}_C - \dot{W}_T$	$\eta_{\text{ex},T} = \frac{\dot{W}_{\text{net},T} + \dot{W}_C}{\dot{E}_{\text{in},T} - \dot{E}_{\text{out},T}}$
HRSG	$\dot{E}_{D,\text{HRSG}} = \dot{E}_4 - \dot{E}_5 + \dot{E}_7 - \dot{E}_8$	$\eta_{\text{ex},\text{HRSG}} = \frac{\dot{E}_{\text{steam,HRSG}} - \dot{E}_{\text{water,HRSG}}}{\dot{E}_{\text{in,exhaust,HRSG}} - \dot{E}_{\text{out,exhaust,HRSG}}}$
Combustion chamber	$\dot{E}_{D,\text{CC}} = \dot{E}_2 + \dot{E}_6 - \dot{E}_3$	$\eta_{\text{ex},\text{CC}} = \frac{\dot{E}_{\text{out,CC}}}{\dot{E}_{\text{in,CC}} + \dot{E}_{\text{fuel}}}$
Overall cycle	Electrical heat ratio SFC Exergy efficiency	$\text{EHR} = \frac{W_{\text{net}}}{Q_{\text{net}}}$ $\text{SFC} = 3,600 \cdot \frac{\dot{m}_{\text{fuel}}}{\dot{W}_{\text{net}}}$ $\dot{E} = \dot{E}_{\text{ph}} + \dot{E}_{\text{ch}}$ $\dot{E}_{\text{ph}} = \dot{m}(h - h_0 - T_0(s - s_0))$ $\dot{E}_{\text{ch}} = \frac{\dot{m}}{M} \{ \sum x_k \bar{e}_k^{\text{ch}} + \bar{R} T_0 \sum x_k \ln x_k \}$ $\eta_{\text{ex}} = \frac{\dot{W}_{\text{net},T} + (\dot{E}_{\text{steam,HRSG}} - \dot{E}_{\text{water,HRSG}})}{\dot{E}_{\text{fuel}}}$

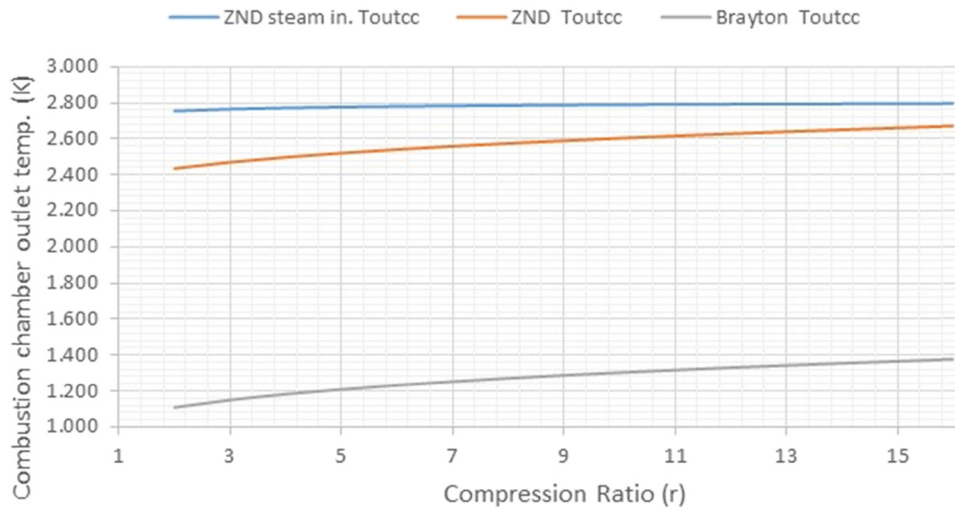


Figure 5: Variation in the combustion chamber outlet temperature with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems.

In Figure 5, variation in the combustion chamber outlet temperature with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems are given. From the figure, it is seen that the increase in the compression ratios, the combustion chamber outlet temperatures of the three cycles increase. This increase for Brayton cycle is 27.3%, for ZND cycle is 11.3% and for ZND steam injected cycle is 1.8%. The ZND cycles combustion chamber outlet temperatures are about 2,400–2,800 K so that the compression ratio is not effective and not needed.

In Figure 6, variation in the combustion chamber outlet pressure with compression ratio for ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems are given. As it is

clearly seen that increasing compression ratio increases the combustion chamber outlet pressure for ZND cycle by 380%, for ZND steam injected cycle by 733%, while it remains the same in Brayton cycle.

In Figure 7, variation in the exergy efficiency with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems are given. As it is seen this, increasing the compression ratio, increases exergy efficiency of gas turbine (Brayton), and steam injected regenerative ZND detonation engine cogeneration systems about 26 and 50%, respectively. For ZND cycle there is a maximum exergetic efficiency point at a compression ratio of about 5–7, which is the same as that found in the literature.

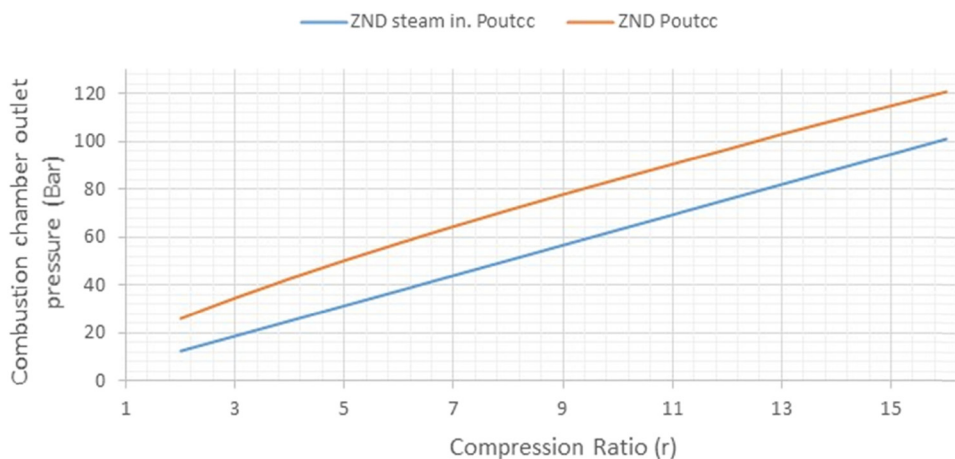


Figure 6: Variation in the combustion chamber outlet pressure with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems.

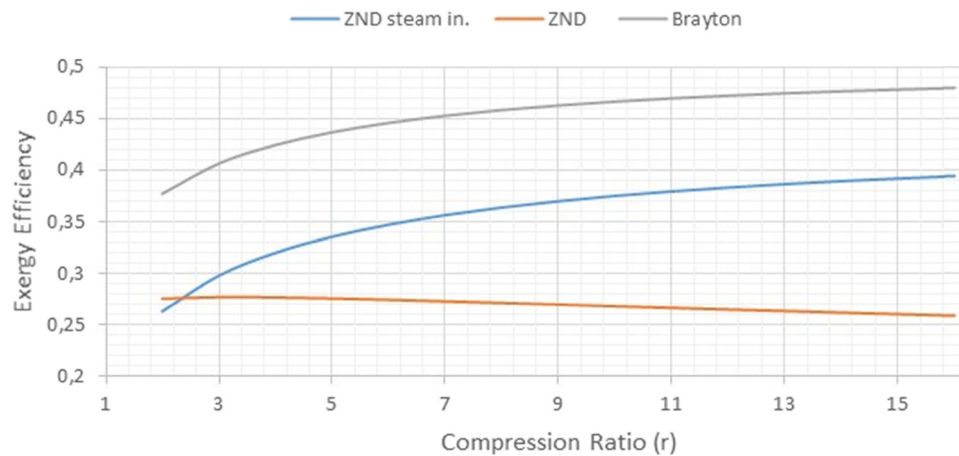


Figure 7: Variation in the exergy efficiency with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems.

In Figure 8, the variation in SFC with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems are given. This can be seen as there is a minimum point of the SFC for ZND cycle at a compression ratio of about 4–6. Over the compression ratio of 6, SFC increases rapidly. The SFC for gas turbine (Brayton) and steam injected regenerative ZND are better than ZND cycle. Gas turbine (Brayton) and steam injected regenerative ZND cycles can compete with each other.

In Figure 9, variation in the electrical efficiency with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems are given. Increasing the compression ratios increase the electrical efficiency of the gas turbine (Brayton) and steam injected regenerative ZND detonation engine cogeneration systems by about 106%,

and 190%, respectively. For ZND cycle, there is a maximum electrical efficiency point at a compression ratio of about 5–7, which is similar to that found in the literature.

In Figure 10, variation in fuel consumption for exergy with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems are given. It can be seen from the figure that increasing the compression ratio decreases fuel consumption for exergy of the gas turbine (Brayton) and steam injected regenerative ZND detonation engine cogeneration systems by about 21%, and 32%, respectively. For ZND cycle, there is a maximum electrical efficiency point at a compression ratio of about 5–7, which is the same as that found in the literature.

In Figure 11, variation in electrical heat rate with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND

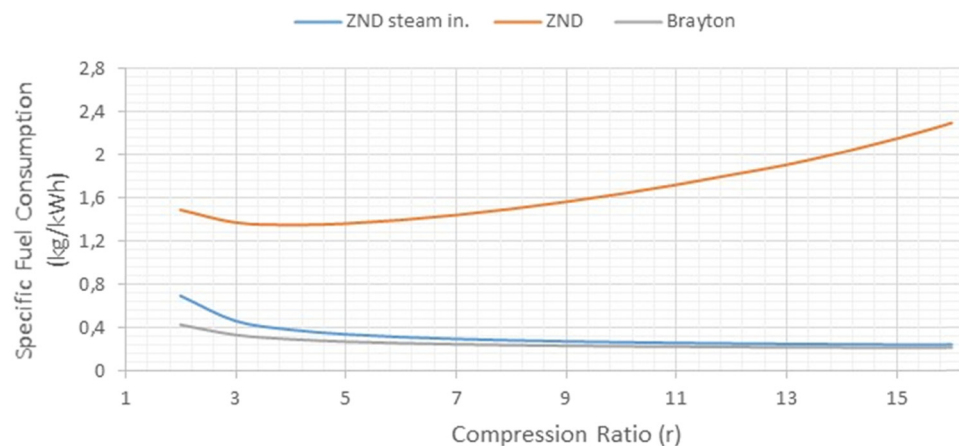


Figure 8: Variation in the SFC with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems.

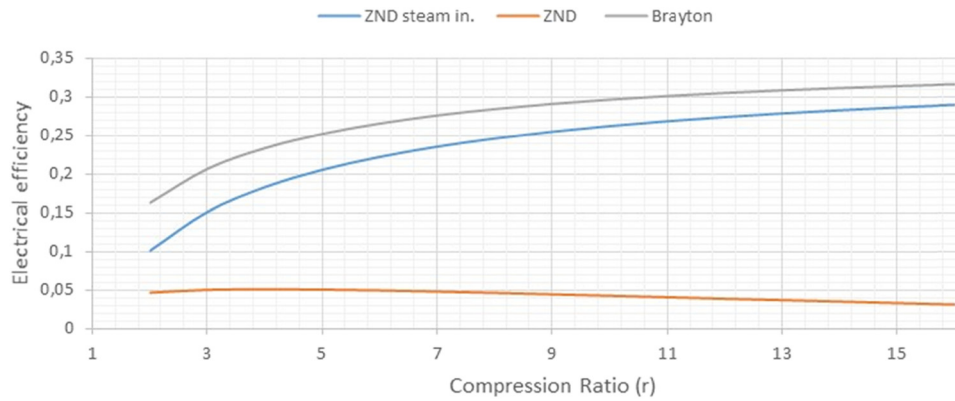


Figure 9: Variation in the electrical efficiency with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems.

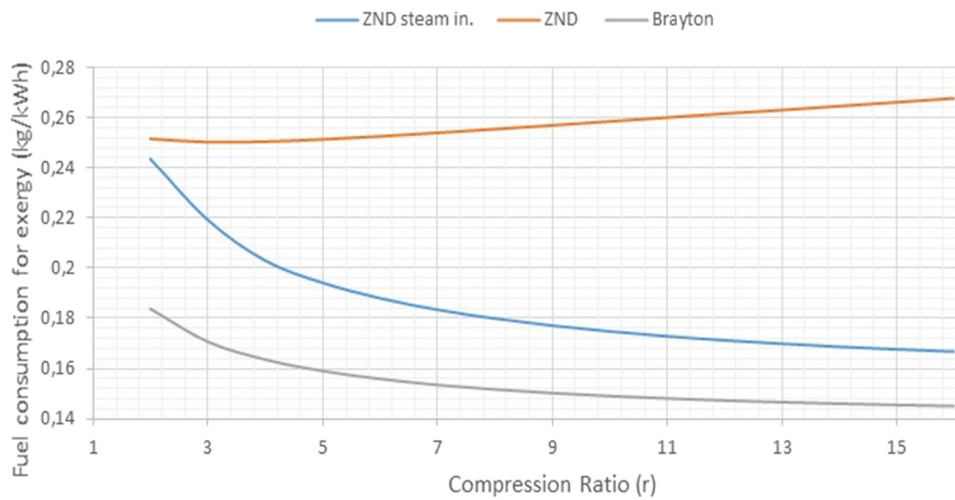


Figure 10: Variation in the fuel consumption for exergy with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems.

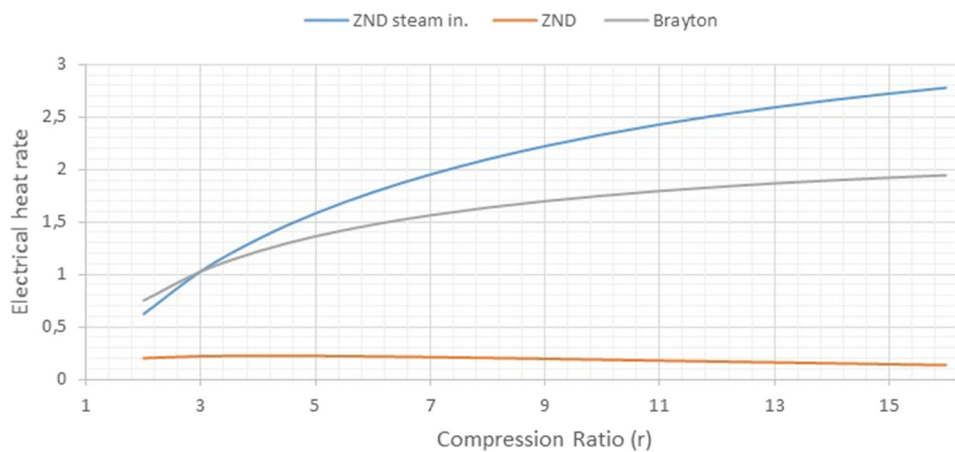


Figure 11: Variation in the electrical heat rate with compression ratio for gas turbine (Brayton), ZND detonation engine and steam injected regenerative ZND detonation engine cogeneration systems.

detonation engine cogeneration systems are given. As seen from the figure, an increase in compression ratios increase the electrical heat rate of the gas turbine (Brayton) and the steam injected regenerative ZND detonation engine cogeneration systems by about 143% and 367%, respectively. For ZND cycle there is a maximum electrical heat rate point at a compression ratio of about 5–7.

4 Conclusion

In this study, for different compression ratios (r), the gas turbine (Brayton), the ZND detonation engine and the steam injected regenerative ZND detonation engine cogeneration systems are analyzed. Increasing the compression ratios increase the combustion chamber outlet temperatures of the three cycles. The ZND cycles combustion chamber outlet temperatures are about 2,400–2,800 K so that the compression ratio is not effective and not needed to increase the temperatures. Increasing compression ratio increases the combustion chamber outlet pressure for ZND cycle by 380%, for ZND steam injected cycle by 733%, while it remains the same in Brayton cycle. Increasing the compression ratios increase the exergy efficiency of the gas turbine (Brayton) and the steam injected regenerative ZND detonation engine cogeneration systems by about 26%, and 50%, respectively. For ZND cycle there is a maximum exergetic efficiency point at a compression ratio of about 5–7, which is the same as that found in the literature. It was seen that there is a minimum point of the SFC for ZND cycle at about 4–6 compression ratio. Over the compression ratio of 6, SFC increases rapidly. The SFC for gas turbine (Brayton) and steam injected regenerative ZND are better than ZND cycle. Increasing the compression ratios increases the electrical efficiency of gas turbine (Brayton) and steam injected regenerative ZND detonation engine cogeneration systems by about 106%, and 190%, respectively. For ZND cycle, there is a maximum electrical efficiency point at a compression ratio of about 5–7, which is similar to that found in the literature. Increasing the compression ratios decrease the fuel consumption for exergy of the gas turbine (Brayton) and steam injected regenerative ZND detonation engine cogeneration systems by about 21% and 32%, and increases the electrical heat rate of the gas turbine (Brayton) and the steam injected regenerative ZND detonation engine cogeneration systems by about 143% and 367%, respectively. For ZND cycle, there is a maximum electrical efficiency and electrical heat rate point at a compression ratio of about 5–7.

In this article, the exergy and electrical efficiencies for the ZND cycles were compared with a deflagration-based Brayton cycle. For a compressor pressure ratio of 1, while

the Brayton cycle shows zero efficiency, the thermal efficiency of the two ZND cycles start at 25–30%. These findings support the theoretical advantage of PDEs over Brayton cycles. The advantage of the PDEs is that it only requires fans or few compressor stages. Also, the detonation engines are less complex and cost effective than other engines.

As a conclusion, gas turbine (Brayton) and steam injected regenerative ZND cycles can compete with each other. Improving ZND cycles by steam injection, regeneration, better designed gas turbines for PDE engines and PGC would make the ZND cycles superior over the gas turbine cycles.

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Conflict of interest: The author declares no conflict of interest.

Ethical approval: The conducted research is not related to either human or animals use.

Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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