

Estimating the Effect of Compression Ratio on Power, Knock, and Emissions of a CNG Engine Converted from a Diesel Engine

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ABSTRACT

This study examines the effect of compression ratio variation on the performance, fuel efficiency, and emissions of a single-cylinder diesel engine converted to operate on Compressed Natural Gas (CNG) using the AVL-Boost simulation software. The compression ratio was varied from 10 to 15 to evaluate key engine parameters. The results show that increasing the compression ratio improves thermal efficiency from 37.5% to 41%, enhances engine power from 13.2 kW to 14.3 kW, and increases torque from 58 Nm to 61.5 Nm. Additionally, specific fuel consumption decreases by approximately 6%, while CO and NO_x emissions are reduced by 0.15% and 134 ppm respectively. However, higher compression ratios also increase the required octane number, potentially inducing knock beyond a ratio of 15. An optimal compression ratio of 15 is identified, balancing improved performance, fuel efficiency, and emission control without exceeding knock limits. These findings provide valuable insights for the design of high-efficiency, low-emission CNG engines.

Keywords-compression ratio; CNG; diesel engine conversion; thermal efficiency; emissions

I. INTRODUCTION

Energy security is vital to economic stability and national resilience, closely linked to technological innovation and environmental sustainability. Diversifying energy sources and transitioning to cleaner alternatives are essential to mitigate the adverse effects of fossil fuel dependence. Concurrently, emissions from conventional fuel-powered transportation significantly contribute to environmental degradation [1-2]. A key strategy to address this issue is the use of alternative fuels

[3-6], which can reduce emissions while being compatible with current engine technologies. Compressed Natural Gas (CNG) has emerged as a promising alternative due to its environmental benefits and potential for broad application. Several studies have assessed the performance and emission characteristics of CNG engines. Authors in [7] evaluated how fuel composition affects efficiency and pollutant formation in CNG engines. Similarly, authors in [8] explored hydrogen supplementation in CNG engines, highlighting challenges like knock tendency and

output reduction. Authors in [9] examined hydrogen-enriched CNG blends in diesel engines, noting improvements in thermal efficiency and emissions, though dependent on load and substitution ratio. Authors in [10] analyzed dual-fuel combustion, showing that CNG improves efficiency but affects heat release patterns. Authors in [11] investigated injection timing optimization in dual-fuel engines, revealing trade-offs between NOx reduction and unburnt hydrocarbon emissions. While these studies confirm the benefits of CNG and its blends, most focus on fuel composition, injection parameters, and dual-fuel strategies. However, compression ratio—an essential factor affecting combustion efficiency, knock behavior, power output, and emissions—has received limited attention, especially for diesel engines converted to CNG. Recognizing this gap, the present study investigates how compression ratio influences power, knock resistance, and emissions in a single-cylinder diesel engine modified to run on CNG. Through numerical simulations, this research aims to identify the optimal compression ratio that balances thermal efficiency and environmental performance while mitigating knock risk. The findings will provide a foundation for optimizing CNG engine designs, supporting the broader goal of developing sustainable, high-efficiency, low-emission powertrains in line with global energy security and environmental objectives.

II. METHODOLOGY

A. Simulation Model Setup and Engine Specifications

Figure 1 shows the engine simulation model. To accurately analyze the impact of compression ratio variation on engine performance, AVL-Boost was employed, one of the most widely used one-dimensional (1D) simulation tools for internal combustion engine modeling. AVL-Boost is specifically designed to evaluate engine thermodynamics, combustion characteristics, and emission formation under different operating conditions [12-14]. The software allows to simulate the engine behavior before conducting physical experiments, thereby optimizing time and costs while minimizing the risks associated with prototype testing.

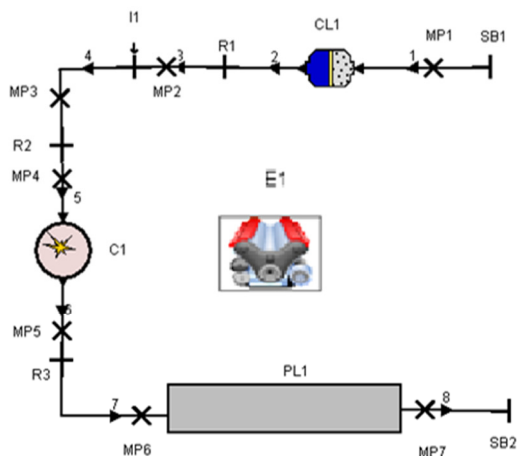


Fig. 1. Engine simulation model. E1: CNG-Engine, C1: Cylinder, I1: Injector, SB1 and SB2: System boundary, CL1: Air cleaner, R1, R2, R3: Restrictions, M1-M7: Measuring points, PL1: Plenum.

The engine was simulated at 2200 rpm, full load, with various compression ratios, and with an ignition advance angle of 14° Crank Angle Before Top Dead Center (CA BTDC). The intake valve advance angle is 10° CA BTDC, and the exhaust valve late angle is 7° CA ATDC. The heat transfer process from the combustion chamber to components such as the cylinder head, piston and cylinder wall is determined based on the Woschni heat transfer model:

$$Q_{wi} = A_i \alpha_w (T_c - T_{wi}) \tag{1}$$

where Q_{wi} is the heat transfer to the walls (cylinder head, piston, cylinder liner), A_i is the heat transfer area, α_w is the heat transfer coefficient, T_c is the cylinder refrigerant temperature, and T_{wi} is the wall temperature (cylinder head, piston, cylinder liner).

The experimental results show that the delayed combustion phase of the fuel-air mixture influences the knock phenomenon. The duration of this phase depends on the octane index of the fuel, as well as the temperature and pressure of the unburned mixture in front of the flame front in the combustion chamber. The delayed combustion time is calculated by:

$$\tau_{iD} = A \left(\frac{ON}{100}\right)^a p^{-n} \exp^{\frac{B}{T}} \tag{2}$$

where τ_{iD} is the ignition delay (ms), ON represents the fuel octane number, p is the pressure (atm), T is the temperature (K), and A, a, n, B are model constants.

If the ignition delay time (τ_{iD}) is greater than 1, detonation occurs. The engine’s specifications are presented in Table I.

TABLE I. ENGINE SPECIFICATIONS

| Parameters | Unit | Value |
|-------------------------|----------|------------------|
| Engine model | - | CNG |
| Number of cylinders | - | 1 |
| Compression ratio | - | 10-15 |
| Optimal ignition timing | Deg BTDC | 14 (at 2200 rpm) |
| Cylinder diameter | mm | 100 |
| Stroke | mm | 115 |

B. Simulation Model Validation

To validate the model, experimental data were utilized. The comparisons between the experimental and simulated results are illustrated in Figure 2. The black curves represent the simulated cylinder pressure results, while the red curves correspond to the experimental cylinder pressure results. The maximum difference of approximately 4.1% was observed at 420 CA and is considered acceptable. The simulated and experimental output data closely matched, demonstrating the high accuracy of the simulation model created with AVL-Boost software. Therefore, this simulation model can be reliably used for further studies.

III. RESULTS AND DISCUSSION

The observed improvements in thermal efficiency and emissions with increasing compression ratio are consistent with the findings of previous studies. For instance, authors in [9] demonstrated that hydrogen-enriched CNG fuels improved

thermal efficiency and reduced CO and NOx emissions in diesel engines, albeit with a different fuel blend approach. Similarly, authors in [7] reported enhanced fuel efficiency and reduced emissions when altering the CNG composition, which aligns with our results showing efficiency gains and emission reductions as compression ratio increases.

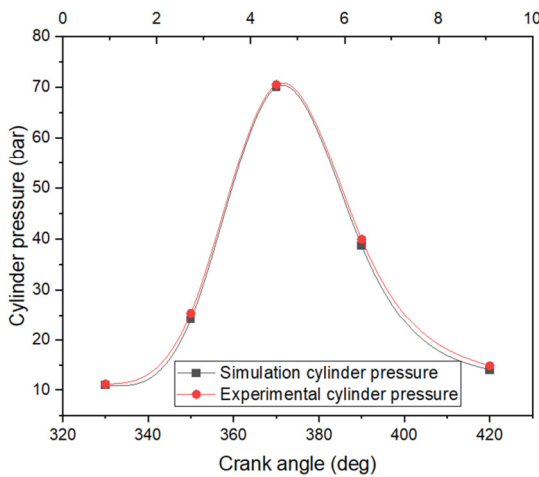


Fig. 2. Model validation.

Furthermore, authors in [10] emphasized the benefits of using CNG in diesel-gas mode, particularly in terms of improved combustion characteristics, which correlates with the improved combustion efficiency observed in our simulations at higher compression ratios. However, our research specifically highlights that while increasing compression ratio positively affects engine performance, it also leads to a significant rise in the required octane number, which can result in knock—a factor less emphasized in previous works.

Compared to earlier studies that often focused on dual-fuel systems or fuel injection strategies, the current study provides a targeted analysis of the effect of compression ratio in a dedicated CNG engine setup, offering clearer guidance on optimizing performance while maintaining engine durability. This detailed analysis bridges a gap in the existing literature by quantifying the trade-off between performance enhancement and knock tendency, which is crucial for practical engine design and fuel strategy decisions.

Figure 3 shows the relationship between thermal efficiency (η) and required octane number (ON) with compression ratio (ϵ) at 2200 rpm and full load. The results show that both thermal efficiency and required ON tend to increase as the compression ratio increases. When the compression ratio increases from 10 to 15, the thermal efficiency increases from 0.375% to 0.41%, while the required ON increases from 96 to 131. However, in a practical engine, the increase in compression ratio will be limited by the phenomenon of knocking. CNG fuel has a higher octane number than petroleum-based gasoline, so a compression ratio of $\epsilon = 15$ is considered the limiting compression ratio at a stoichiometric mixture ratio of $\lambda = 1$. The increase in thermal efficiency can be explained by optimized combustion, with the fuel burning

completely at high compression ratios. The required ON increases due to the increase in temperature and pressure in the cylinder at the time of ignition. Changing the compression ratio reduces the volume of the combustion chamber, causing the combustible mixture to be compressed at a higher pressure at the end of the compression stroke. Since temperature and pressure are two factors that vary inversely, the temperature at the end of the compression stroke also increases. The increase in pressure and temperature at the end of the compression stroke is the cause of the increase in the required octane number. At a compression ratio of $\epsilon = 10$, the required octane number is $ON = 94.02$ and increases to 130.42 when the compression ratio reaches $\epsilon = 15$, reaching the knock limit. The increase in the required ON with compression ratio can be calculated by:

$$\Delta ON = \frac{ON_{\epsilon=15} - ON_{\epsilon=10}}{ON_{\epsilon=15}} \times 100\% \tag{3}$$

$$= \frac{130.42 - 94.02}{130.42} \times 100\% = 27.91\%$$

The calculation of ΔON takes into account the influence of various factors on the occurrence of knocking.

Currently, the thermal efficiency of internal combustion engines is around 40%. Improving thermal efficiency obviously brings great economic and technical benefits. Increasing the compression ratio is one effective method to improve the thermal efficiency of internal combustion engines, however, it is limited by the octane number of the fuel. Therefore, it is necessary to focus on researching and developing suitable fuels for internal combustion engines, or finding alternative fuels with superior properties. Improving thermal efficiency will affect the working characteristics of the engine, and to better understand it, it is necessary to study the effect of changing the compression ratio on the performance of the engine.

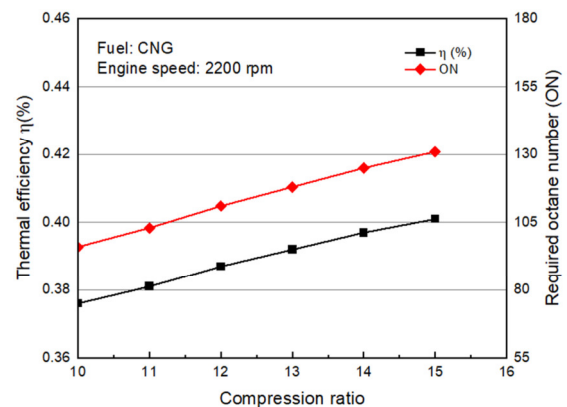


Fig. 3. Thermal efficiency and required octane number versus compression ratio.

Figure 4 shows the changes in maximum cylinder pressure (P_{max}), torque (M_e), and power (N_e) of the engine when the compression ratio increases. The pressure, torque, and power of the engine (with the condition of fixed engine speed at 2200

rpm, $\lambda = 1$, optimal ignition angle, and full load) all tend to increase when the compression ratio is increased. When the compression ratio increases from 10 to 15, the torque increases from 58 Nm to 61.5 Nm, the engine power increases from 13.2 kW to 14.3 kW, while the maximum pressure in the combustion chamber increases from 57 bar to 79.5 bar. The simulated P_{max} values align closely with experimental references, maintaining the error margin below 3%.

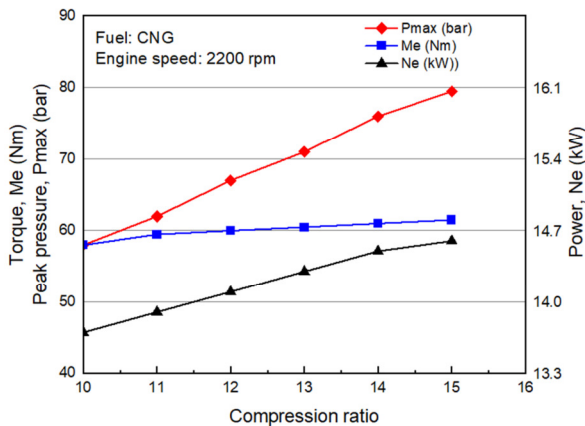


Fig. 4. Torque, peak pressure and power versus compression ratio.

However, the increase rate of torque and power in the range of ϵ from 10 to 15 is slower than the increase rate of maximum cylinder pressure, although the amount of mixture fed into the cylinder has decreased as the compression ratio increases. The reasons for the increase of P_{max} , M_e and N_e are different. P_{max} increases because the compression ratio increases without changing the piston stroke, which means that increasing the compression ratio increases the compression pressure and thus increases P_{max} . Meanwhile, the increase of M_e and N_e when increasing the compression ratio is due to the improvement of thermal efficiency, which helps compensate for the decrease in the amount of fuel and air mixture, and the main reason for this increase is that the combustion ability of the mixture is significantly improved when the compression ratio increases. To clarify this issue, simulations will be performed under the condition of keeping the amount of fuel supplied to a cycle unchanged and changing the compression ratio. The engine power is calculated according to:

$$N_e = \frac{p_e \cdot V_h \cdot i \cdot n}{30\tau} \quad (4)$$

where N_e is the effective power, p_e is the effective pressure, V_h is the work volume, i is the number of cylinders, τ is the stroke, and n is the engine speed.

The increase in engine power when the compression ratio is changed is mainly determined by the effective pressure. As the compression ratio increases, both the indicated pressure (p_i) and the mechanical loss pressure (p_m) increase. However, increasing the compression ratio will increase the thermal efficiency (Figure 3), and this causes the indicated pressure to increase at a higher rate. As a result, the effective pressure (p_e)

increases as the compression ratio increases, resulting in an increase in engine power. As the engine power increases, the engine torque also increases because power and torque are two positive functions when the engine speed is held constant.

Figure 5 shows the change in charging efficiency as the compression ratio varies under the engine's operating conditions: $n = 2200$ rpm and full load, with a constant fuel supply per cycle and the optimal ignition angle. The maximum pressure in the cylinder tends to increase sharply as the compression ratio increases. Meanwhile, the charging efficiency tends to decrease as the compression ratio increases, while the fuel amount remains constant. When the compression ratio increases from 10 to 15, the charging efficiency decreases from 0.71 to 0.7. As the compression ratio increases, the maximum pressure in the cylinder rises, leading to an increase in the pressure at the end of the exhaust stroke, as well as the pressure in the cylinder at the beginning of the intake stroke, which reduces the charging efficiency. Another reason for the reduction in charging efficiency is that the research engine uses an external air-fuel mixture with CNG fuel in the gaseous state. When the compression ratio increases and the fuel supply remains the same, a conflict between the fuel and air flows occurs during the intake process, leading to a decrease in volumetric efficiency.

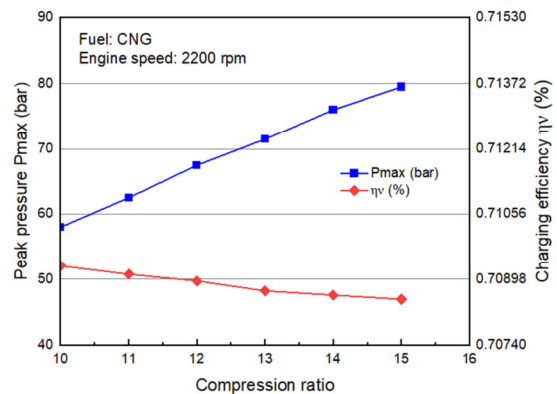


Fig. 5. Charging efficiency versus compression ratio.

Figure 6 shows the simulation results for fuel consumption rate (g_e) and thermal efficiency (η) as the compression ratio changes under the conditions: $n = 2200$ rpm and full load, with a constant fuel supply per cycle and the optimal ignition angle. In this simulation, the fuel quantity is kept unchanged across all compression ratios to examine the effect of the compression ratio on the combustion quality of the mixture. Observations from the Figure indicate that when the compression ratio increases from 10 to 15, the fuel consumption rate and thermal efficiency change in opposite directions. Thermal efficiency continues to increase, while the fuel consumption rate decreases sharply from 214 g/s to 201 g/s, despite the constant fuel supply. The increase in thermal efficiency with the compression ratio can be attributed to the increased complete combustion in the cylinder. As the compression ratio increases, both the pressure and temperature at ignition rise, which facilitates the combustion process and contributes to higher thermal efficiency. The sharp decrease in fuel consumption is

due to the increase in engine power as the compression ratio rises, even though the amount of fuel supplied remains constant across all compression ratios.

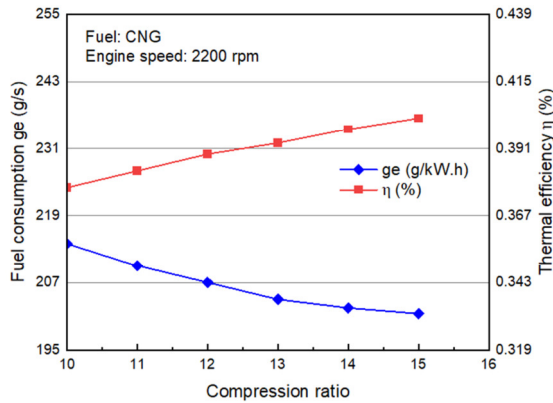


Fig. 6. Fuel consumption versus compression ratio.

Figure 7 shows the emissions of NO_x, CO, and HC as a function of the compression ratio under the engine operating conditions of $n = 2200$ rpm, full load, use of CNG fuel, optimal ignition angle, and $\lambda = 1$. Changing the compression ratio improved engine performance, leading to reduced emissions. Specifically, CO emissions decreased significantly from 1.86% (at $\epsilon = 10$) to 1.71% (at $\epsilon = 15$), a reduction of 0.15%. NO_x emissions also decreased from 1381.57 ppm (at $\epsilon = 10$) to 1247.44 ppm (at $\epsilon = 15$). However, HC emissions increased slightly from 177.16 ppm to 227.29 ppm when the compression ratio changed from 10 to 15. According to Figure 7, CO accounted for the largest proportion of emissions, while NO_x and HC levels were relatively low. The increase in compression ratio reduced the air and fuel flow into the cylinder, while the excess air factor $\lambda = 1$ remained unchanged, leading to a significant reduction in both CO and NO_x emissions.

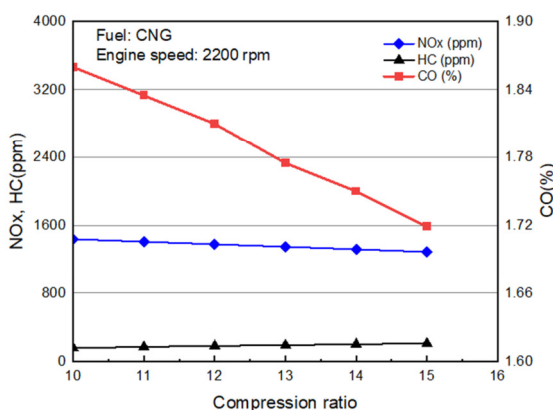


Fig. 7. HC, NO_x and CO emission versus compression ratio.

IV. CONCLUSION

This study investigated the impact of compression ratio on the performance, fuel efficiency, and emissions of a diesel

engine converted to operate on Compressed Natural Gas (CNG). Simulation results demonstrated that increasing the compression ratio from $\epsilon = 10$ to $\epsilon = 15$ led to significant improvements in thermal efficiency (from 37.5% to 41%), engine torque (from 58 Nm to 61.5 Nm), and power output (from 13.2 kW to 14.3 kW), while reducing specific fuel consumption by approximately 6%. Additionally, CO and NO_x emissions decreased by 0.15% and 134 ppm, respectively. However, the higher compression ratio increased the required octane number, raising the risk of knock, with $\epsilon = 15$ identified as the upper safe limit. The findings align well with previous studies [7-9], which highlighted the benefits of CNG in enhancing engine efficiency and lowering emissions. However, unlike prior experimental works that primarily focused on dual-fuel modes or fuel composition effects, this study provides a comprehensive numerical optimization specifically addressing the compression ratio for CNG-dedicated engines. The implications of these findings are significant: they offer a scientific basis for the design and optimization of high-performance, low-emission engines operating exclusively on CNG, contributing to sustainable energy solutions. Moreover, the results support the adoption of variable compression ratio technology to further improve engine adaptability while mitigating knock risks. These insights can guide future experimental validations and the development of practical engine modifications aimed at meeting stringent emission regulations and enhancing fuel economy.

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