Review of Research on the Application of CNG Fuel in Vehicle Engines: Research Bibliography 2017–2021

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Abstract Compressed Natural Gas (CNG) is an alternative fuel used to solve cleaner exhaust emissions, global warming, and limited world fossil oil production problems. It emits cleaner gases during combustion, is economical, can be applied to light/heavy vehicles, and has good adaptability to diesel/petrol engines. This research reviews the application of CNG in vehicle engine articles published from 2017 to 2021. There were 82 articles on CNG, while 38 were on CNG as vehicle fuel. The articles reviewed were classified in several focus areas of research, such as the development of the ignition system on the CNG engine, the injection method, the application of Exhaust Gas Recirculating (EGR) technology, variations in the compression ratio of the CNG engine combustion chamber, the application of Reactivity Controlled Compression Ignition Engine (RCCI) on CNG machine, system modeling, mixer and method. The results showed a lack of research on the development of CNG that integrates intelligent control systems. Therefore, further research is suggested to explore the potential effect of the next period.

Keywords CNG · Vehicle · Article · Engine

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1 Introduction

Compressed Natural Gas (CNG) is an alternative fuel significantly utilized due to its ability to produce cleaner emissions, economical price, adaptability to gasoline/diesel engines, and application to light/heavy vehicles. It also helps solve the problem of increasing energy consumption due to the rise in the number of vehicles [1] and the limited fossil energy production globally [2, 3]. Therefore, the application of CNG as an alternative fuel is essential to produce vehicles with cleaner emissions and high economic value.

The application of CNG continues to be developed sustainably with various fields of research, especially regarding its engine performance. This alternative fuel improves engine performance by several aspects, such as injection, setting the ignition system, applying EGR, modifying the combustion system, and utilizing various mixing methods, hence it more homogeneous. Meanwhile, multiple studies have been carried out to determine the CNG modeling in terms of pressure in the reducer/fuel line, flow regulation approach, and a mixer.

The CNG setting with injection is designed to regulate the fuel entering the engine (4,5). Yuvenda [4] developed an injection timing system, which improved the CNG entering the engine. Meanwhile, Duc [5] designed an injection system by adopting the single-hole injector technology. However, both studies focused on developing an injection technology without creating an Engine Control Unit (ECU) to control the Air-to-Fuel Ratio (AFR) between CNG and air. Muhssen [6] and Kar (7) then achieved AFR stoichiometry values, while Muhsessen [6] and Kar [7] developed a CNG engine with an AFR stoichiometry approach oriented toward a range value of 17.2–17.4. This research, somehow, was unable to set AFR, which is oriented toward achieving high fuel efficiency/savings.

Ignition system settings are developed by determining the most suitable method, which leads to the use of lasers to reduce the particle content in exhaust emissions [8]. Intelligent Dual Sequential (IDS) is applied by igniting the spark plug 2 times in 1 engine cycle, therefore, the fuel content entering the exhaust manifold due to the engine flushing step can be burned to achieve cleaner emissions [9]. Correct calibration of the CNG engine ignition system is the key to power production, using the multiplexed extremum method [10]. However, the studies above have not developed an ignition system to improve fuel economy.

Another increase in CNG engine performance is by applying Exhaust Gas Recirculation (EGR). According to Mahla [11], this technique helps to reduce NOx gas in the exhaust manifold of CNG engines and focuses on achieving cleaner emissions. Besides the content of Nox gas, Kontses et al. [12] stated that the Particle Number (PN) in the exhaust gas is a concern after comparing CNG with other alternative fuels. A unique way to reduce emissions is to observe the driving style, such as Gha [13] research using 60 CNG vehicles. Modification of the CNG engine combustion with RCCI [14] and variations in the compression ratio has been developed to increase engine performance [15]. This research focused on the search for the most optimal combustion modification by analyzing the power generated by the CNG engine without discussing efforts to increase vehicle savings.

CNG engine modeling is the best method for predicting its engine capabilities. Computational Fluid Dynamics (CFD) software can be used to simulate the mixer design [16]. Sadah [16] observed the process of mixing CNG with air to obtain the most optimal mixture. Meanwhile, Alper and Do (9) used CFD to achieve variable torque generated by CNG engines. Dual sequential ignition was observed on the change in torque of the CNG engine. However, these two modeling research have not discussed the ECU development modeling to save fuel.

The development of CNG study has been developed with several variables. Still, several variables have not been discussed, including the development of AFR, which is oriented toward increasing fuel economy appropriately. CNG ignition system calibration that considers the fuel consumption factor. The application of EGR considers fuel consumption. CNG engine modeling considers the fuel use factor. Therefore, this article provides an overview of research trends to determine opportunities for developing and improving the application of CNG engines in vehicles.

2 Method

Reviews from studies on the application of CNG fuels were traced from 2017 to 2021 through "Science Direct". A total of 82 articles were found, with only 38 on CNG application to vehicle engines. Improved engine performance was the most discussed theme. The research reviewed was divided into several themes, namely ignition system, EGR application, mixer, injection method, compression ratio variation, RCCI application, CNG modeling, and other applications. The distribution of research themes on the application of CNG engines to vehicles and per year is shown in Figs. 1 and 2, respectively. Furthermore, approximately 5, 2, 2, 15, 3, 4, 1, and 6 articles were found on ignition system research, EGR application, mixer, injection method, compression ratio variation, RCCI application, CNG modeling, and other applications, respectively. Imran [17] previously conducted a review on CNG application in vehicles from 1991 to 2016. The themes discussed include its safety systems, the environment, the addition of hydrogen, vehicles with bi-fuel, fuel injection/combustion characteristics, engine performance, control system design, and economic aspects. The distribution of the research themes reviewed is presented in Figs. 1 and 2.

Environmental friendly and energy-efficient vehicles motivate the development of spark ignition engines [18, 19] since global energy availability is a major concern [20]. Even worse, there is a continuous rise in energy demand in the transportation sector along with an increase in the number of vehicles. The development of injection technology is one of the efforts to realize energy-efficient vehicles [21]. Lee [21] developed dual port injection technology, which led to a fair good fuel economy. Furthermore, Hydraulic Variable Valve Actuation (HVVA) was introduced to increase fuel efficiency [22]. The element of flexibility and application of genetic

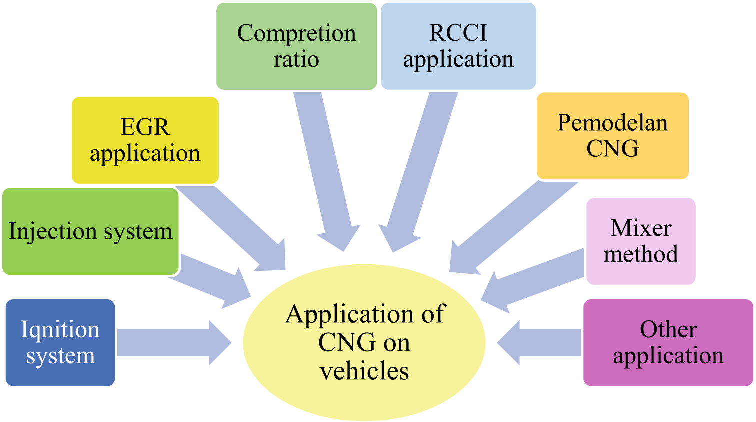

Fig. 1 Distribution of research themes on the application of CNG engines to vehicles

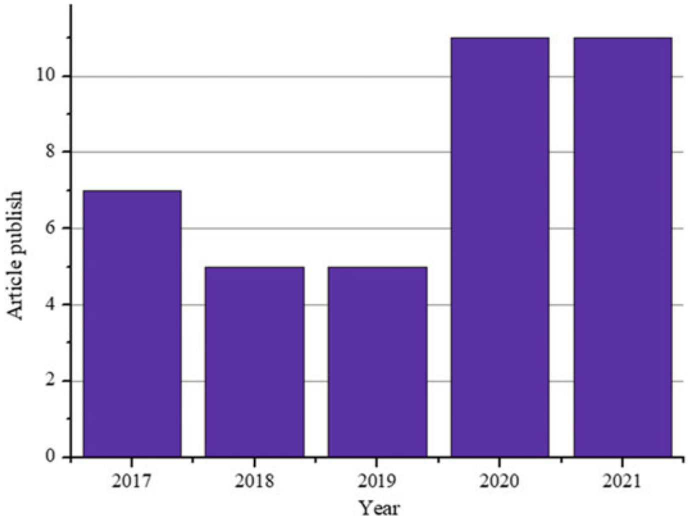

Fig. 2 Number of articles published on the application of the CNG engine

algorithms were also considered in this study. The results were quite interesting, with about 13% achievement of fuel economy, but both studies did not include steering operation as a control element.

Electronic Control Unit (ECU) is a fuel system control module in vehicles, continuously being developed to improve internal combustion engines. Meanwhile, Air-to-Fuel Ratio (AFR) is the main element to increase fuel economy, which is a driver's need [23–25]. It has three ranges of values, including lean AFR above 14.67, stoichiometry of 14.67, and rich below of 14.67 [26]. Currently, the realization of stoichiometry values is the focus of the AFR controller. The stoichiometry is generally maintained at the ideal value of 14.67.

Recently, artificial intelligence (AI) is being applied as a controller in the fuel control system [10, 11]; an example is fuzzy logic [27–29]. Furthermore, this study used fuzzy logic to control AFR but is yet to consider steering operation. Therefore, there is a need for further studies using the intake manifold pressure variable as an AFR clustering with neuro-fuzzy. The output would be in the form of a fuel injection control system. Another study used oxygen sensors to control AFR [30]. Besides fuzzy logic, the neural network is an AI that can be used for control systems [31–33]. Therefore, there is a continuously increasing number of studies on neural networks as a fuel control system [34]. Arsei [34] utilized the Recurrent Neural Network (RNN) to achieve the AFR value in the stoichiometry range. However, the study has not considered steering operation.

2.1 Literature Review

a. **Ignition System**

Research to improve the performance of CNG engines with variable ignition systems was carried out with several variations. Singh [8] stated that the laser method has the ability to reduce the particle content in exhaust emissions, thereby leading to cleaning emissions. Meanwhile, the Intelligent Dual Sequential (IDS) method is able to provide information stating that the performance of CNG is better in terms of gas emission. It allows the spark generated by the plug to be ignited 2 times in 1 cycle, including the compression and exhaust cycle [9]. Furthermore, the multiplexed extremum model is used to calibrate the CNG ignition system, which showed the ability to use proper adjustment to improve the fuel efficiency of CNG engines [10].

b. **Injection System**

The injection system developed with several varied methods, such as dual injection (Direct injection-DI, Port Fuel Injection–PFI), pilot injection, Start of Injection (SOI), timing, and CNG jets, is used to improve engine performance. According to Ramasamy [35], the dual injection method combines CNG and other fuel engines to produce an optimal mixture of 65% CNG and 25% gasoline. Lee [36] utilized EGR combined with a dual injection system, where the CNG rate was controlled by 70–80% flow, thereby indicating thermal efficiency. Furthermore, dual injection added with hydrogen gas by experimental DI technology on CNG engines showed an increase in brake thermal and engine power efficiency with a decrease in its fuel consumption [37]. Although these three studies discussed the dual injection method of the CNG fuel system, none analyzed the development based on an intelligent control system.

Song [38] compared the volumetric efficiency between CNG-DI and CNG-PFI to determine the injection system using DI/PFI type technology. Subsequently, CNG-DI can produce higher volumetric efficiency and fuel conversion efficiency than CNG-PFI. Furthermore, [36] researched the development of the DI type integrated with the turbocharger through experimental DI technology, which was compared between gasoline and CNG engines. The outcomes indicated that DI-CNG has the ability to improve thermal efficiency at full load by increasing the spark time due to its higher octane number. Research conducted by Melaika [39] compared the efficiency of CNG engines with gasoline/gasoline-DI(GDI), CNG-PFI, and CNG-DI types, where CNG-DI was set at stoichiometry conditions. The rate of heat release of CNG obtained is lower than gasoline fuel, however, the stable combustion process of DI-CNG provides additional benefits, and the efficiency of the CNG engine is quite high. Kar [7] compared GDI and CNG-DI to determine how the engine works with charge dilution. The results showed that the highest efficiency was obtained on CNG-DI with the lean burning operation and AFR stoichiometry with charge dilution. Although these four studies compared the volumetric efficiency of the CNG fuel system, none analyzed the development based on an intelligent control system.

Verma [40] designed a pilot injection to spray CNG with low load injection timings set at 32, 29, and 26°BTDC showing energy efficiencies of 8.5%, 11.1%, and 11.9% for biogas, CNG, and hydrogen operations, respectively. According to Meng [41], this method is also used to determine the throttling effect by applying it to the diesel-type CNG engine. Meng stated that dual fuel (diesel–CNG) engines are more advantageous for increased efficiency and emissions at low loads. However, both studies led to good engine performance, not developed a pilot injection capable of increasing fuel saving based on the engine's external control system.

Yuvenda [5] sets injection time from 70° to 150° ATDC and CNG from 70° to 150°CA with intervals of 20° at low load. Subsequently, the CNG engine is able to produce the highest cylinder pressure and Heat Release Rate (HRR) values by slowing down the CNG injection time (130° ATDC). Injection Timing (TI) settings measure Brake Thermal Efficiency (BTE) on CNG machines with different loadings. The results showed that advancing the injection time increases BTE earlier in time [42]. Channappagoudr [43] experimented with the injection time on a BIO-CNG engine and concluded an enhanced performance at 29° BTDC. The three research have tried to use the injection time variable to improve CNG performance but have not linked the injection time to the external engine variable.

Other variations of CNG injection methods include testing engine brake power, pilot fuel Start of Injection (SOI), and the CNG jet method. Duc et al. (2019) Duc [4] increased the engine performance by improving the injection method tested for the engine's brake power. This method decreases up to 19%, increasing brake-specific energy consumption (BSEC) by 14% (4). SOI is controlled for dual fuel engines, namely diesel-CNG, with a pressure of 7.5 bar from the Indicated Mean Effective Pressure (IMEP) and a mixture of B10CNG60 and B20CNG60 [41]. Presently, there is a massive application of the jet/CNG jet method globally. A Schlieren photograph was used to observe the characteristics of CNG injection, and the results showed that the increase in axial jet penetration is strongly influenced by room pressure [44].

These three studies have explored various improvements to the CNG engine with different variations of methods without discussing the development of the ECU to control CNG with variables from environmental aspects.

c. **EGR Application**

EGR as a method of reducing NOx gas in CNG engines has numerous advantages, therefore, it continues to be pursued. Mahla [11] added Bio-Diesel/B20 (castor oil) to the CNG engine, integrating EGR and B20 used as pilot fuel. This method is able to reduce NOx at engine load without damaging the combustion characteristics [11]. Another method is to apply EGR to a CNG-diesel engine with a certain mixture used to decrease the movement of BTE and BFSC under full loading conditions. Although Mahla [11] and Kumar [45] applied EGR to CNG engines, they have not yet developed CNG EGR controlled by an intelligent control system to provide better regulatory effects.

d. **Compression Comparison Variations**

The performance of the CNG engine is carried out by varying its compression ratio. Srivastava and Agarwal [15] observed a compression ratio from 9.9 to 11.8 with laser ignition on a CNG-air mixture. This method is used to determine lean mixtures and find a suitable compression ratio for CNG engines. The result showed the lean flammability limit from 1.62 to 1.76 and also sheds light on laser ignition that can be used with CNG-air lean mixtures [15]. Research conducted by Sahoo [46] controlled the compression ratio to reduce detonation in CNG engines. The compression ratio of 12 produces the highest engine beats. Meanwhile, Bhasker and Porpatham [47] observed the impact on the compression ratio of CNG engines 12.5:1, which increased brake power output and thermal efficiency.

e. **RCCI Application**

RCCI is a strategy used to reduce emissions with a control system by promoting cleaner combustion. Sunmeet [14] used biodiesel (B100) to inject pilot fuel into the engine with the addition of CNG and 18% HCNG to reduce emissions. Therefore, HC, CO, and smoke emissions in all parts of the HCNG energy are less than that of basic CNG. However, NOx emissions increased slightly with HCNG and less than basic biodiesel.

Another research used RCCI in diesel engines with CNG as the main fuel and a mixture of diesel and Karanja biodiesel (BD20) as pilot fuel. Furthermore, 10 ms CNG induction with 90% Energy Share (ES) and BTHE (Brake Thermal Efficiency) experienced the highest rate of 24.2% and the smallest BSFC 0.3 kg/kW-hr. According to Wategave [48], low Reactive Fuel is better than diesel at 60% ES. RCCI is also applied with injection timing settings at pressures of 500, 750, and 1000 bar. The integration of loading, injection time, and pressure can improve engine performance with optimal conditions at a 750 bar [49].

2.2 Synthesis

A summary of several research articles that focus on discussing the application of CNG in vehicle engines is given in Tables 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10.

3 Conclusion

The literature review on the application of CNG as a fuel in vehicles has two periods, including 1991–2016 and 2017–2021. The first period focused on the research of regional experiences with CNG vehicles, Economic Aspects, Engine Design, Control and Performance, Combustion and Fuel Injection Characteristics, Diesel Dual Fuel Operation, Hydrogen Enriched CNG Vehicles, Environmental Aspects, and Safety Aspects. Meanwhile, for the second period, the focus was on improving the performance of CNG engines. The most widely carried out research themes with more than 70% were a modification of the ignition system, injection adjustment, RCCI application, CR investigation, EGR design, etc. However, research on CNG mixer modeling using CFD has started to be developed.

In the first and second periods, the literature review on the application of CNG as a vehicle fuel did not imply the development of control systems associated with intelligent control systems. Therefore, this literature review becomes a potential for future research development because this field has not been widely examined previously. Moreover, it is interesting to develop an external engine system and CNG control with smart sensors in a control system considering environmental aspects.

Table 1 Research articles about CNG fuel system development part one

No	Author	Research focus	Method	‘Analysis of results	Finding
1	[50]	Improvement of engine performance	Hydrogen + CNG mixing investigation with a dynamic system	This research examines the mixing of hydrogen + CNG (HCNG). The 30HCNG mixture has the most optimal conditions, which provides information on the most optimal blending method but does not cover how to mix HCNG with air	Mixture of HCNG with 30% yields better performance than basic CNG
2	[47]	Improvement of engine performance	Observing the impact on the compression ratio of CNG engines	Bhasker is used to set the compression ratio for CNG engines. The result signified that the CNG engine is capable of working on ultra-lean combustion. However, it has not considered the engine loading aspect	The ratio of 12.5:1 is proven to increase brake power output and thermal efficiency
3	[35]	Improvement of engine performance	Using dual injection CNG and gasoline	Ramasamy applied a dual injection system between CNG and gasoline to enhance engine performance. However, no research has been conducted on the stoichiometry mixing process	The most optimal dual injection blend is at 65% CNG and 35% gasoline

Table 2 Research articles on CNG fuel system development part two

No	Author	Research focus	Method	‘Analysis of results	Finding
4	[44]	Improvement of engine performance	Experimenting with jet characteristics on CNG	Erfan used Schlieren photography to observe CNG injection with the jet method. Although the results were the most optimal conditions with the jet method, the research has not been applied to vehicle engines	The results provided information on the strategies needed to increase the penetration of the axial jet, which is strongly influenced by room pressure
5	[38]	Improvement of engine performance	Developing DI and PFI injection system and timing	The results of comparing the volumetric efficiency between CNG-DI and CNG-PFI had numerous advantages. However, the research has only been carried out at 1700 rpm engine speed yet with various rotations	CNG-DI has the ability to have higher volumetric efficiency and fuel conversion efficiency than CNG-PFI
6	[14]	Improvement of engine performance	Developing a clean combustion strategy to reduce emissions	Sunmeet used biodiesel (B100) as pilot fuel in its CNG engines and 18% HCNG to reduce emissions. RCCI was also integrated into the research. The results tend to reduce emissions. However, studies on mixing with the AFR method have not been considered to enhance fuel economy	HC, CO, and smoke emissions in all parts of HCNG energy are less than basic CNG. However, NOx emissions increased slightly with HCNG and are still less than basic biodiesel
7	[40]	Improvement of engine performance	Using pilot injection on the CNG-Biogas-Hydrogen engine	Verma compared the efficiency of dual fuel (DF) CNG–biogas–hydrogen in diesel engines. This research provided recommendations on energy efficiency by mixing CNG–biogas–hydrogen. However, studies on mixing the air entering the engine have not been discussed	At low load, injection timings of 32, 29, and 26°BTDC demonstrated the highest energy efficiency of 8.5%, 11.1%, and 11.9%, respectively, for biogas, CNG, and hydrogen DF operations

Table 3 Research articles on CNG fuel system development part three

No	Author	Research focus	Method	‘Analysis of results	Finding
8	[15]	Improvement of engine performance	Implementing variable compression and laser ignition system–plasma	Srivastava observed the laser ignition of the CNG-air mixture to determine the lean mixture and find a suitable compression ratio for the engine. The result indicated that this method can increase the flammability limit of CNG machines. However, the uses of this flammability limit have not been discussed in detail	It obtained a lean flammability limit from = 1.62 to = 1.76 and increased the compression ratio from 9.9 to 11.8. Therefore, the CNG-air mixed laser ignition can be developed through a certain mixture
9	[51]	CNG model design	Creating a multi-zone thermodynamics model on a CNG engine	Baratta reproduced / interpreted data to gain insight into engine combustion processes and pollutant formation. Although the research considered kinematic chemistry, it has not considered the molecular type	The model-developed results were able to predict greater engine capability improvements
10	[10]	Improvement of engine performance	Using the multiplexed extremum model to calibrate the CNG ignition system	In this research, multiplexed extremum was used to determine the appropriate model to improve CNG performance. The designed system focused on the application of calibration accuracy without developing self-calibration	Experimental results exhibited that under proper tuning, the proposed controller can improve the fuel efficiency of CNG engines
11	[11]	Improvement of engine performance	Using EGR on CNG engines with added Bio-Diesel (castor oil)	Mahla used (EGR) on a diesel engine (CNG) with a blend of Jatropha biodiesel (B20) as pilot fuel. However, the results were cleaner emission reductions, and no research has been conducted on the power generated	The EGR method can reduce NOx in the engine load without changing the engine combustion characteristics

Table 4 Research articles on CNG fuel system development part four

No	Author	Research focus	Method	'Analysis of results	Finding
12	[9]	Improvement of engine performance	Using i DSI (intelligent dual sequential ignition) engine on bi-fuel (gasoline-CNG)	Alper and Do compared the performance of CNG-Gasoline engines with various engine loads. The i-DSI ignition system was applied to a bi-fuel engine (gasoline-CNG). Furthermore, the power and volumetric efficiency results were discussed in detail. However, the AFR between fuel and air has not been discussed	This method is able to state that the performance of gasoline is better than CNG in terms of power. However, in terms of CNG emissions, it is better
13	[4]	Improvement of engine performance	To improve the performance of CNG engines and the injection method	Experimental research on the performance of gasoline-CNG engines with injection ports denoted an increase in BSEC and a decrease in emissions. However, it has not measured the AFR between fuel and air	When fueled with CNG, the brake power of the test engine was reduced by 19%, while the brake-specific energy consumption (BSEC) was increased by 14%
14	[52]	Improvement of engine performance	Using pilot fuel Start of Injection (SOI) on the engine (diesel-CNG)	Meng used SOI to increase Indicated Thermal Efficient (ITE) and reduce emissions optimally. However, it has not included the aspect of power generated by the engine. This condition would be better variable power discussed	At a pressure of 7.5 bar, the Indicated Mean Effective Pressure, B10CNG60, and B20CNG60 ITE increase with a decrease in emissions
15	[53]	Improvement of engine performance	Addition of hydrogen to reduce emissions in CNG engines	This research assessed the emission of gasoline, CNG, and HCNG engines. The most optimal mixture of HCNG acquired is approximately 18%, with the ability to reduce emissions drastically. However, it has not used artificial intelligence to regulate the mixing method	The lowest emission was achieved in HCNG with a mixture of 18%

Table 5 Research articles on CNG fuel system development part five

No	Author	Research focus	Method	'Analysis of results	Finding
16	[54]	Improvement of engine performance	Developing CNG engine modeling with CFD	Garg designed a CNG engine modeling with CFD. The results showed that the overall engine efficiency increases when the case of pre-mix stoichiometry is compared with the lean stratified condition. However, the power generated has not been revealed	The coated casing exhibits 30% lower NOx emissions when compared to pre-mixed casings at the same engine load
17	[5]	Improvement of engine performance	The time setting of the CNG injection that enters the engine	Yumenda optimized the CNG injection time. The results revealed that a late injection time leads to a high heat release rate and low emissions. However, it has not discussed the increase in CNG savings by setting the injection time	By slowing down the injection time of CNG (130° ATDC), the highest cylinder pressure and heat release rate (HRR) is produced
18	[55]	Improvement of engine performance	Using a pilot injection system to determine the effect of throttling	Meng examined the effectiveness of increasing throttling on efficiency and emissions in dual fuel combustion modes numerically. As an outcome, the pin reduction numerical calculation can significantly improve combustion efficiency and emissions. However, the research discussed on combustion efficiency has not discussed fuel efficiency	Engines with dual fuel (diesel–CNG) with the pilot injection method are more profitable for increased efficiency and emissions at low loads
19	[56]	Improvement of engine performance	Optimization of diesel injector injection with CNG substitution	Lee used a CNG rate at 70–80% flow to enhance thermal efficiency with varying EGR. The computational indicated that a 25% smaller diameter nozzle (150 m) with continued ROI increased the mean effective pressure by 3.4%. However, this research has failed to reveal the power generated by the engine and fuel efficiency	This research used a CNG rate of up to 80%. The results obtained can increase the thermal efficiency of the engine and reduce CO_2 in the exhaust gas

Table 6 Research articles on CNG fuel system development part six

No	Author	Research focus	Method	‘Analysis of results	Finding
20	[43]	Improvement of engine performance	Modifying the injection timing setting on the BIO-CNG engine	This research modified the diesel engine into BIO-CNG. The accomplishment showed an increase in engine performance and emissions. However, the set injection time has not been able to increase fuel efficiency	The injection time can improve the performance of the Bio-CNG engine at 29° BTDC
21	[37]	Improvement of engine performance	Experimenting with DI technology and the addition of hydrogen to a CNG engine	Hydrogen was added to the CNG engine with DI technology to observe the engine performance. The results have the ability to improve thermal brake efficiency and engine power, reducing specific fuel consumption. However, it has not discussed the AFR setting on the addition of hydrogen	This method is able to increase the efficiency of brake thermal and engine power while decreasing its specific fuel consumption
22	[36]	Improvement of engine performance	Conducting experimental DI technology on gasoline and CNG engines	Lee compared DI technology in gasoline and CNG engines with the addition of a turbocharge. Subsequently, CNG increases the thermal efficiency under maximum load conditions by raising the spark time. However, it has not used AFR to measure engine performance	DI-CNG improves thermal efficiency at full load by increasing the spark time, with a rise in the octane number
23	[8]	Improvement of engine performance	Developing laser ignition system	Sigh used a laser ignition system on a CNG–hydrogen engine. Consequently, using CNG–hydrogen with a laser ignition system reduces the particle content in the exhaust gas. However, it has not enhanced fuel economy	The combination of CNG–hydrogen and increasing ignition timing improves CNG engine performance

Table 7 Research articles on CNG fuel system development part seven

No	Author	Research focus	Method	‘Analysis of results	Finding
24	[12]	Improvement of engine performance	Observing the Particle Number (PN) produced by gasoline-PFI, diesel-DPF, hybrid, LPG-PFI, and CNG-PFI fuels	In this research, the effect of PN on vehicles with gasoline-PFI, diesel-DPF, hybrid, LPG-PFI, and CNG-PFI fuels was compared. Subsequently, PN can be significantly reduced on LPG and CNG engines. However, this research has not linked the resulting PN to the engine during acceleration and deceleration	Significant PN reduction potential was observed with LPG and CNG versus gasoline by up to 93% and 90%, respectively
25	[13]	Improvement of engine performance	Analyzing changes in emissions from CNG-fueled vehicles on driver behavior	Gha tested private vehicles/ taxis with CNG engines based on driving patterns. Consequently, emissions increase with the rise in vehicle speed. However, changes in emissions to environmental changes have not been observed	For CO, gas increases depending on vehicle speed, while for HC, it decreases
26	[57]	AFR control	Observing the robust stochastic system for the AFR setting	This research proposed setting AFR with robust stochastic on CNG machine. The result showed the AFR control in the closed loops, whereof type CNG machine area, while the changes based on machine learning technology have not been observed	AFR application with robust stochastic can regulate AFR in the stoichiometry area, thereby improving engine performance
27	[6]	AFR control	Designing a mixer on a CNG machine	Muhssen designed the CNG Mixer previously customized in CFD. The results were in the form of a mixer design used to mix CNG with air to obtain a more homogeneous mixture. It has not been tested with various engine load variations	The mixer design results can help achieve AFR CNG in the stoichiometry area

Table 8 Research articles on CNG fuel system development part eight

No	Author	Research focus	Method	'Analysis of results	Finding
28	[46]	Improvement of CNG engine performance	Observing the Compression Ratio (CR) aspect to knock on CNG engines	Sahoo used CR to determine the knock effect on a CNG engine. The results exhibited that the CR 12 gasoline engine produced the highest knocking, while the CNG engine can work on CR 16 and is more resistant to knocking symptoms. However, it has not added CNG to other fuels	On the CR 16, the CNG engine is still able to operate without knock-out effects
29	[39]	Improving CNG engine performance	Injection method control	This research compared the efficiency of GDI, PFI-CNG, and DI-CNG systems using stoichiometry conditions. Although the results implied that DI-CNG has the highest efficiency and reduced emissions, the applied injection method has not considered the application of an intelligent control system to improve the engine performance further	The application of DI-CNG provides better engine performance
30	[42]	Improving CNG engine performance	Injection method control	Rai used timing injection (TI) settings to determine the performance of CNG engines with different loadings. Subsequently, IT applications are evidenced to reduce NOx and increase smoke. However, the intelligent control system has not been considered for IT control	The results showed that increasing the injection time leads to a rise in BTE over time
31	[7]	Improving CNG engine performance	Injection method control	Kar compared GDI and DI-CNG to determine how the engine works with charge dilution. The results indicated that the lean burn strategy led to higher brake thermal efficiency than stoichiometric operation. However, research has not been carried out on environmental conditions	EGR/lean burn application increases the total CO_2 equivalent emissions relative to stoichiometric operations without dilution

Table 9 Research articles on CNG fuel system development part nine

No	Author	Research focus	Method	‘Analysis of results	Finding
32	[49]	Improving CNG engine performance	Injection method control	This research used an RCCI set with injection time at 500, 750, and 1000 bar pressures. The results showed that 750 (Bar) injection pressure and the injection time (BTDC) of 12.5 led to the most optimal engine performance. However, this research has not considered the input from the environment/intelligent control system	By integrating loading, injection time, pressure and increasing engine performance under optimal conditions at an injection pressure of 750 bar
33	[45]	Improving CNG engine performance	Use of EGR	Kumar used dual fuel to increase the performance of the CNG engine. The results showed that BTE and BSFC decreased at a higher load of 2–3% under all loading conditions compared to diesel. However, no research has been carried out on applying an intelligent control system to control mixing in a dual fuel system	In dual fuel mode, NOx is decreased by 21%–18%, and under all loading conditions, BTE reduces by 1–2%, and BSFC decreases at higher loads by 2–3% compared to diesel
34	[48]	Improvement of engine performance	Using reactivity controlled compression ignition (RCCI)	Watagave set fuel operating limits to reduce CNG engine noise and provided cleaner combustion. The results showed that 10 ms CNG induction with 90% ES was the operating limit of the CNG engine, while the 60% CNG content produced the cleanest combustion. However, it has not observed AFR CNG restrictions related to rough sound and combustion quality	In 10 ms CNG induction with 90% energy share (ES), and BTHE experienced the highest 24.2% and the lowest BSFC 0.3 kg/kW-hr. Low Reactive Fuel is better than diesel at 60% ES

Table 10 Research articles on CNG fuel system development part ten

No	Author	Research focus	Method	‘Analysis of results	Finding
35	[58]	Improvement of engine performance	Using RCCI and CR	Aydin used a variation of CR to enhance the performance of the CNG engine. The analysis proved that CNG with biodiesel increases BTE and BSEC, while BSFC experienced a decrease in biodiesel/CNG RCCI and various CR operations	With this variation of the CR method, BTE tends to control BTE, BSEC, and BSFC
36	[59]	Improvement of engine performance	Using RCCI and CBG	Harari applied RCCI with a combination of CNG and Compressed Bio Gas (CBG). The analysis indicated that D + CNG gave better results in terms of performance and emission characteristics. However, in AFR, CNG with CBG has not been observed	This method is able to increase (BTE) at a loading flow of 75%
37	[60]	Improvement of engine performance	Using laser system ignition on CNG engines	Alper compared CNG engines to conventional laser and ignition systems	The results obtained with the laser system reduced the propagation time and kernel flame formation as well as NOx gas
38	[16]	CNG Simulation	Simulating the mixer on the CNG reducer design with CFD	Laser ignition is confirmed to reduce propagation time, Kernel flame formation, and NOx. However, studies on the relationship between AFR and CNG engine laser ignition have not been conducted	The CFD simulation better predicts the CNG engine capability at 10 injection holes in the mixer

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