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Amiruddin, Hilmi
Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia

Wan Mohd Faizal Wan Mahmood
Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia

Abdullah, Shahrir
Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia

Mohd Radzi Abu Mansor
Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia

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Hilmi Amiruddin[1,*], Wan Mohd Faizal Wan Mahmood[2,*], Shahrir Abdullah[2], Mohd Radzi Abu Mansor[2]

[1]Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia

[2]Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Malaysia

*Author to whom correspondence should be addressed:
E-mail: hilmi@utem.edu.my and faizal.mahmood@ukm.edu.my

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Abstract: The present paper assesses the empirical performance of a four-cylinder CNGDI engine with a vaned diffuser turbocharger compressor. This evaluation was performed to compare injection timing operating characteristics of engines coupled with vaneless and vaned diffuser turbocharger. Numerous start of injection (SOI) have been investigated, ranging from advanced SOI (300°CA to 180°CA bTDC) during the intake stroke to retarded SOI (180°CA to 120°CA bTDC) during the compression stroke. This experiment was conducted at a wide-open throttle (WOT) condition and the air fuel ratio is set at a stoichiometric condition. Study outcomes indicate that the vaned turbocharger increases boost pressure by an average of 50% compared to the vaneless variant. In comparison, a CNGDI engine equipped with a vaned diffuser turbocharger compressor increased brake torque by 3.66%, brake thermal efficiency (BTE) by 12.90% and volumetric efficiency by 4.75% when compared to a vaneless variant. Furthermore, a comparison of vaneless and vaned turbochargers indicates that brake specific fuel consumption (BSFC) reduced by 9.43%.

Keywords: injection timing; CNGDI; turbocharger

1. Introduction

The pursuit for alternative fuels like biodiesel[1,2], biomass[3], ethanol[4] and natural gas[5] has been of extensive interest because of energy crisis[6] and heightened environmental concern[7]. Natural gas can reduce CO_2 emissions compared to gasoline because it has a relatively higher hydrogen-to-carbon (H/C) ratio. Settling for natural gas as an alternative fuel will assist in the battle against anthropogenic CO_2-production climate change, environmental damage and energy sustainability[8]. Moreover, natural gas provides several benefits like reduced BSFC, enhanced BTE, capable for higher compression ratios engine[9], higher octane number, lower combustion temperature and lesser NOx pollution[10] as compared to other conventional fuels.

Despite the numerous benefits of the port fuel injection (PFI) natural gas engine, there is a probable decrease in thermal efficiency to the tune of 1% to 3% compared to the natural gas engine using direct injection[11]. This phenomenon is caused by a loss of cooling evaporation of injected gaseous fuel, which causes incoming intake air to be displaced. Hence, these factors lead to reduced volumetric efficiency[12].

Several researchers have studied the injection and ignition timing, combustion strategies and advanced boosting system of natural gas engine. A CNGDI volumetric efficiency can be enhanced by using retarded injection fuel or injecting after the inlet valve closes (IVC). This is due to the fact that when fuel is injected after IVC, the engine's air breathing capacity is not disturbed by the incoming fuel[13,14]. Chala et al.[7] stated that using different injection strategies for a CNGDI engine at speeds ranging from 2000 to 5000 rpm resulted in different outcomes. There were three SOI timing used: advanced injection (300°bTDC), intermediate injection (180°bTDC) and retard injection (120°bTDC). As a result, they discovered that retard injection led to optimal outcomes considering most of the operating conditions. Also, advanced injection provided enhanced performance when engine speed was relatively high. Aljamali et al.[15,16] also assessed the influence of various injection timing on the performance and emissions of four-cylinder stratified CNGDI engine. The authors indicated stratified combustion strategies corresponding to SOI 120°bTDC were associated with high torque, power and brake mean effective pressure.

Presently, turbocharging is extensively used for addressing the increasing need for more efficient engines, stricter emission control and enhanced fuel economy[17]. Knocking challenges lead to restricted turbocharger use for gasoline engines, specifically those having high compression ratios[18]. There has been a recent increase in interest concerning spark ignition (SI) boost for dedicated natural gas engine[19] or dual-fuel natural gas engines[20], primarily because of superior knock resistance against traditional gasoline engines. The use of boosting system for CNG engines can offset the volumetric efficiency loss caused by gaseous fuel displacing incoming intake air[21].

Turbocharger compressors are centrifugal compressors with three major components: impeller, inlet and diffuser. The diffuser is an important part of the conversion of the kinetic energy imposed by the impeller over a wide range of flows into pressure energy. Compressor with vaned diffuser application can achieved of about 4% peak efficiency over the vaneless configuration[22]. Several other researchers have evaluated and developed centrifugal compressors vaned diffuser experimentally and numerically[23,24]

Hence, the present study used a vaned diffuser turbocharger compressor to assess CNGDI engine performance using metrics like brake torque, thermal efficiency, volumetric efficiency and brake specific fuel consumption. Several SOI timings were evaluated to measure the increase in engine performance.

2. Experimental procedure

2.1 Engine Test Setup

Figure 1 represents the experimental arrangement schematic for the CNGDI turbocharged engine. Table 1 lists the engine specifications. The turbocharger compressor is fitted with a vaned diffuser and the specification can be obtained from the previous study[25]. This engine test uses the Kronos V4 software to obtain data from an Apicom FR250 eddy current dynamometer, whose details are listed in Table 2. Under steady state conditions, the engine was tested at WOT with a constant speed ranging from 1000 to 4000 rpm, with a speed increment of 1000 rpm.

Synerject produced the fuel injector for the CNGDI engine. CNG pressurised to 20 bar was injected into the cylinder. The present study used the same fuel composition chosen by several other researchers[26]. The indicative composition of CNG used for this study is indicated in Table 3. The Omega FMA-867A gas flow meter was used for measuring CNG mass flow rate. Concurrently, the inlet manifold pressure was determined using the boost meter model NRG Pro Series 2.5/90S.

Table 1. CNGDI turbocharged engine specifications

Parameter	Value
Number of cylinders	4
Displacement (cm^3)	1596
Compression ratio	12.5
Bore (mm)	76
Stroke (mm)	88
Intake valve opened, IVO (°CA bTDC)	12
Intake valve closed, IVC (°CA aBDC)	48
Exhaust valve opened, EVO (°CA bBDC)	45
Exhaust valve closed, EVO (°CA aTDC)	10

Table 2. Apicom FR250 engine dynamometer specifications

Parameter	Value
Maximum power (kW)	190
Maximum torque (Nm)	800
Maximum revolution (rpm)	12,000
Moment inertia (kgm^2)	0.15
Speed measurement accuracy (rpm)	± 1
Torque measurement accuracy (%)	0.2

Table 3. CNG composition[26]

Component	Volumetric (%)
Methane, CH_4	94.42
Ethane, C_2H_6	2.29
Propane, C_3H_8	0.03
Ethane, C_4H_{10}	0.25
Carbon dioxide, CO_2	0.57
Nitrogen, N_2	0.44
Others (H_20)	2

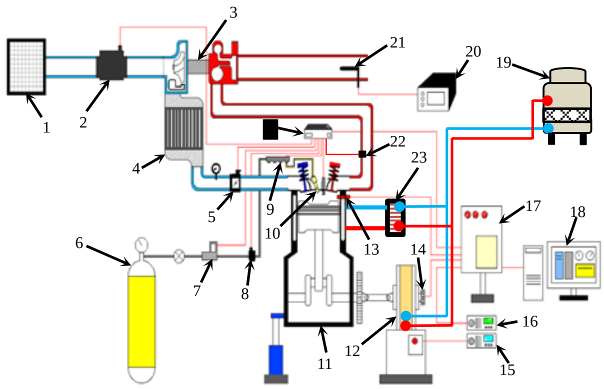

Figure 1: Experimental setup: 1. Air filter, 2. Air mass flow sensor, 3. Turbocharger, 4. Intercooler, 5. Throttle, 6. CNG tank, 7. CNG mass flow sensor, 8. Pressure regulator, 9. Fuel rail, 10. Injector, 11. CNGDI engine, 12. Dynamometer, 13. Pressure sensor, 14. Crank angle sensor, 15. Throttle controller, 16. Throttle controller, 17. Data acquisition setup, 18. Control panel, 19. Cooling tower, 20. Exhaust gas analyser, 21. Exhaust probe, 22. Oxygen sensor, 23. Heat exchanger.

2.2 Test Conditions

To ensure that a steady-state condition has been reached, the engine is heated to the optimal temperature, which is when the engine coolant temperature is around 70°C. The experiment is carried out in a laboratory temperature range of 29°C to 32°C, atmosphere pressure of 101.3 kPa and relative humidity of 70% to 85%.

The MoTeC M800 programmable ECU was used for controlling engine parameters like injection and ignition timings and air-fuel ratio levels. In order to determine the maximum performance of the CNGDI engine, the air fuel ratio was set at the stoichiometric condition (λ=1). As depicted using Figure 2, three different SOI[27,28] timings were used: advanced (300°CA to 270°CA bTDC), intermediate (270°CA to 180°CA bTDC) and retard (180°CA to 120°CA bTDC). The intermediate and advanced injection SOI are similar to the port injection characterised by a homogeneous mixture. On the other hand, the retard SOI was associated with a stratified charged mixture. For each SOI, spark timings; 16° to 32° bTDC were adjusted to maintain maximum brake torque (MBT).

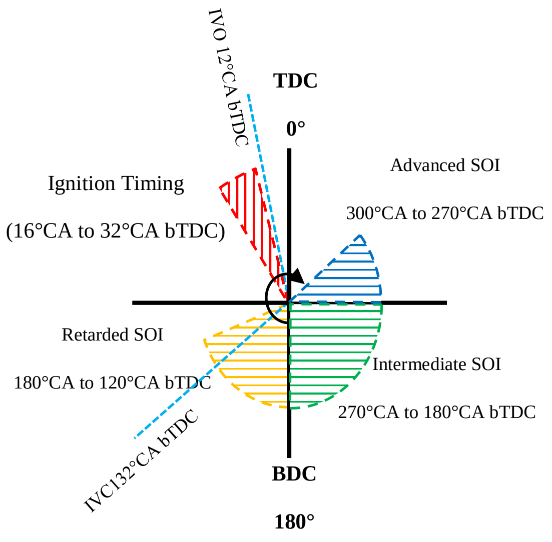

Figure 2: Injection and valve timing diagram

3. Results and discussion

3.1 Boost Pressure

Figure 3 shows the boost pressure change plot vaneless and vaned turbochargers. When the engine speed ranges between 1000 rpm and 3000 rpm, the vaned diffuser turbocharger outperforms the vaneless variant by producing an additional 0.05 bar boost. Both turbochargers produced maximum boost at 3000 rpm. The vaned and vaneless variants produced 0.35 and 0.30 bar boost pressure, respectively.

At 4000 rpm engine, both turbochargers produced identical boost pressure. Over the engine speed range, the vaned variant provided about 50% more boost than the vaneless turbocharger. When the diffuser of turbocharger compressor was augmented with vanes, there was an increase in boost pressure; consequently, CNGDI engine volumetric efficiency increased[29].

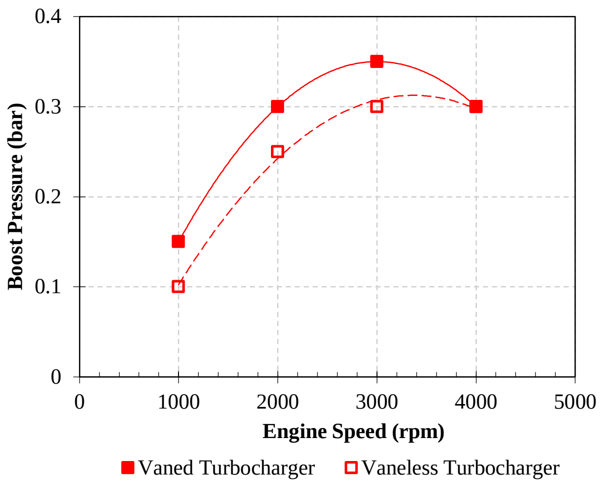

Figure 3: Boost pressure as a function of engine speed

3.2 Brake Torque

Figure 4 depicts maximum brake torque produced at different engine speeds for both (vaned and vaneless) CNGDI engine variants. The vaneless turbocharger equipped engine produced relatively less brake torque for the entire operating speed range using CNG fuel. Low engine speed in the 1000-2000 rpm range was associated with maximum brake torque for the retarded SOI timing with 160°CA bTDC and 140°CA bTDC for vaned and vaneless configurations, respectively. Therefore, combustion strategies for stratified mixtures and low engine speeds are associated with better brake torque than a homogenous mixture. Low engine speed is associated with reduced intake air volume during the intake stroke, thereby affecting output torque[30].

Nevertheless, higher engine speed in the 3000-4000 rpm range was associated with a contrasting outcome. Both turbocharger variants performed better at intermediate SOI timing, i.e., 240°CA bTDC and 260°CA bTDC. SOI timing for both turbocharger variants was identical throughout the tested speed range. Therefore, homogeneous mixture provide better torque results at high engine speeds as against stratified mixture. The reduced mixing time associated with the retarded SOI timng potentially leads to improper mixing that resulted in lesser brake torque. It should be noted that advanced SOI timing did not provide any benefits related to torque output. The potential cause for this phenomenon might be the CNG backflow to the intake manifold[31].

The vaned and vaneless turbocharger variants produced maximum brake torque values of 133.85 and 131.53 Nm at 3000 rpm engine speed. The torque output of the vaned turbocharger equipped CNGDI engine was approximately 3.66% higher for the entire speed window than the vaneless variant.

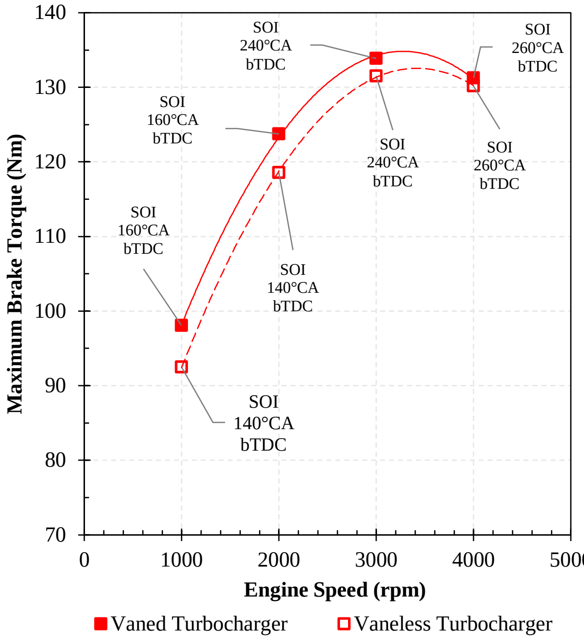

Figure 4: Maximum brake torque as a function of engine speed.

3.2 Brake Thermal Efficiency

BTE is plotted as a function of engine speed, as depicted in Figure 5. The vaneless turbocharger has comparatively lesser BTE for the entire speed range for CNGDI engine operation.

The retarded SOI timing produced the best BTE values at low engine speed ranging between 1000-2000 rpm. In contrast, high-speed operation in the 3000-4000 rpm range was associated with higher BTE using intermediate SOI timing. Both turbocharger variants produced maximum BTE at 3000 RPM; the corresponding values for vaned and vaneless turbocharger were 41.5% and 39.6%, respectively.

Moreover, the observations indicate that the vaned turbocharger outputs higher BTE for low-speed operation than high-speed operation. It can be attributed to the stratified charged combustion schemes used for low-speed operation associated with better volumetric efficiency[32]. For the tested engine speed range, the vaned variant produced about 12.9% more BTE than the vaneless variant.

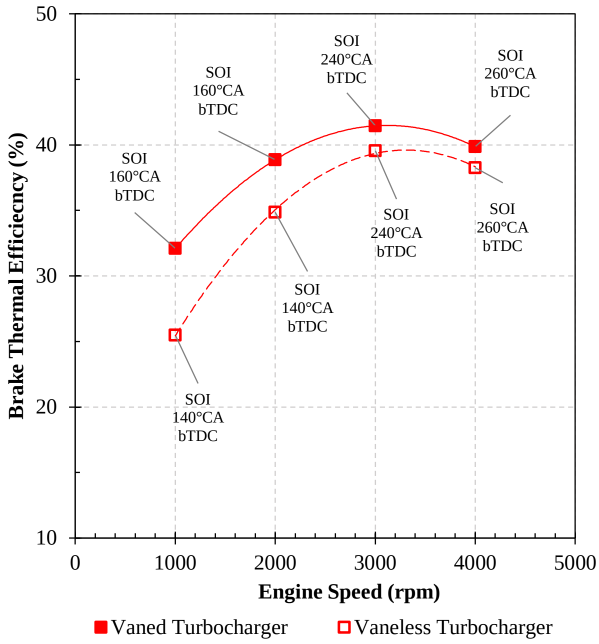

Figure 5: BTE as a function of engine speed

3.3 Brake Specific Fuel Consumption

The difference in BSFC for the 1000 -4000 rpm engine speed range is depicted in Figure 6. The outcomes suggest that the CNGDI engine operated using the vaned turbocharger had lesser BFSC compared to the vaneless turbocharger when the engine speed was within the 1000-3000 rpm range. It is understood that boost pressure in this speed range leads to a higher fuel economy. Additionally, the decrease in BFSC at 4000 rpm engine speed is attributed to lowered boost and volumetric efficiency.

The intermediate SOI timing was associated with the least BSFC for both turbocharged variants. The vaned and vaneless variants had BSFC values of 182.80 g/kW-h and 187.32 g/kW-h, respectively. This translates to a 9.43% drop in fuel requirement for the vaned turbochager.

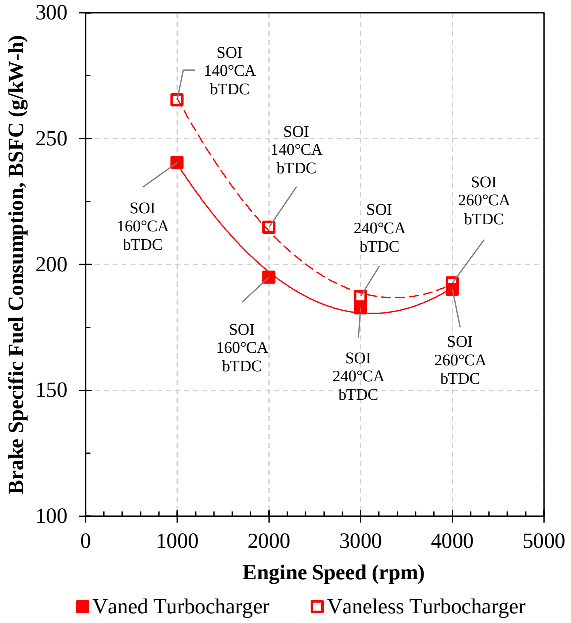

Figure 6: BSFC as a function of engine speed

3.4 Volumetric Efficiency

Volumetric efficiency is the primary reason behind the different torque produced by the CNGDI engine equipped with the two turbocharger variants. Volumetric efficiency is depicted as a function of speed using Figure 7. Typically, the engine having the vaned turbocharger produces better volumetric efficiency. The retarded SOI timing produced better volumetric efficiency in the low engine speed range, i.e., 1000-2000 rpm for both turbocharger variants. Moreover, retarded SOI provides better volumetric efficiency for stratified combustion because of reduced disturbance in air intake[31].

On the other hand, the higher engine speed range, i.e., 3000-4000 rpm, had contrasting outcomes. The intermediate SOI timing provided better volumetric efficiency in the higher speed band. The intermediate SOI timing allows for adequate mixing time; consequently, the engine produces optimal performance in the high speed band. The vaned turbocharger variant had a 4.75% average increase in volumetric efficiency compared to the vaneless variant.

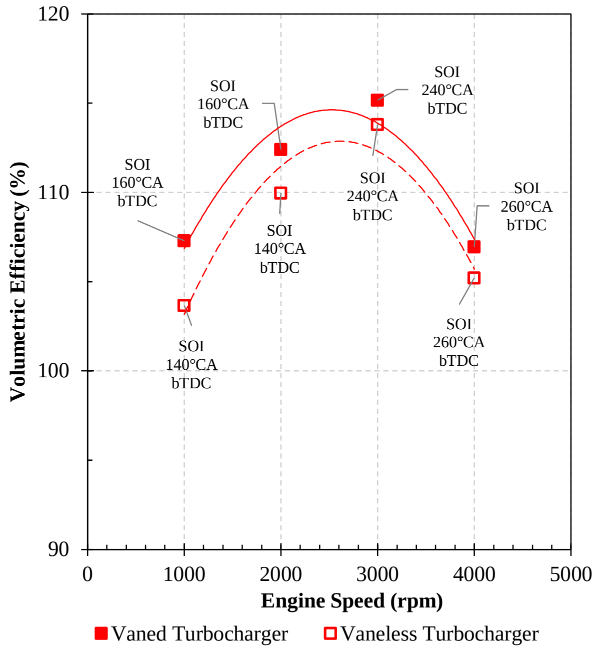

Figure 7: Volumetric efficiency as a function of engine speed

4. Conclusions

We conducted empirical research on multi-cylinder CNGDI engine performance augmented using two turbocharger variants and three SOI timing schemes. Study results suggest that a vaned diffuser turbocharger compressor is associated with a 50% increase in boost pressure or total pressure ratio. Consequently, there is a 4.75% increase in CNGDI engine volumetric efficiency. Additionally, brake thermal efficiency and brake torque for a vaned test engine demonstrated a 12.90% and 3.66% increase, respectively, compared to the vaneless variant. Moreover, the vaned turbocharger leads to a 9.43% reduction in brake specific fuel consumption compared to the vaneless variant.

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Nomenclature

aTDC	after top dead centre (-)
BTE	*brake thermal efficiency (%)*
CNG	compressed natural gas (-)
CNGDI	compressed natural gas direct injection (–)
bTDC	before top dead centre (-)
BDC	Bottom dead centre (-)
CA	crank angle (°)
ECU	engine control unit (-)
IVC	intake valve closed (-)

IVO	intake valve opened (-)
MBT	maximum brake torque (-)
PFI	port fuel injection (-)
SOI	start of ignition (-)
TDC	Top dead centre (-)

Greek symbols

λ	air to fuel ratio (–)

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