EXPERIMENTAL INVESTIGATION OF FUEL CONVERSION ADAPTER USING BIOETHANOL AND GASOLINE BLENDS

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Abstract
The paper contains description of the working principles and evaluation of the operational parameters of the commercially available fuel conversion adapter, intended to adapt gasoline fuelled spark ignition (SI) engine for use of high ethanol content blended fuel, known as E85. Commercially available gasoline and E85 fuel were used as test fuels. Production automobile, equipped with 1.8 litre 4 cylinder SI port fuel injection (PFI) engine was tested on the roll-type eddy-current chassis dynamometer in wide open throttle (WOT) constant speed mode. High precision fuel consumption measurement system AVL KMA Mobile was used. Engine operating parameters, used for evaluation of the efficiency of the fuel conversion adapter was engine torque (T), engine brake power (P_b), air/fuel equivalence ratio (λ), specific fuel consumption (*SFC*) and engine thermal efficiency (η_t). Analysis of engine operational parameters showed successful operation of fuel conversion adapter with E85 fuel, resulting in increase of engine peak torque by 4.4%, increase of energy efficiency in whole tested engine speed range up to 6.1% but increase of specific fuel consumption by approximately 22%, when compared with the gasoline use.

Key words: Fuel conversion adapter, ethanol, biofuel, spark ignition engine.

Introduction

In ongoing search for sustainable human mobility, biofuels are rising particular interest. Biofuels are considered to have less severe influence on climate change. Use of biofuels reduces dependence on fossil oil supply and rises energy supply security (Usner and Mueller-Langer, 2009). According to the directive 2009/28/EC of the European Parliament and of the Council, target of 10% for energy from renewable sources in transport must be reached in the year 2020 by all Member States (Directive 2009/28/EC). The recently approved European directive 'On the promotion of the use of energy from renewable sources' 2009/28/CE and the stringent environmental regulations have favored the use of bio-fuels in all the energy sectors and especially in transport. In the European Community, fuel quality is regulated by different fuel standards. The EN228 normative establishes the specifications for gasoline fuels. Ethanol for blending with gasoline must meet the EN15376 standard (Armas et al., 2012). Current implementation of EN228 standard in Latvia defines the use of 5% ethanol in gasoline blend as standard fuel for automobiles with spark ignition (SI) engines. Modern automobiles are built to operate with such fuel blend. Another standardized fuel blend, colloquially known as E85, contains 85% of anhydrous ethanol and 15% of gasoline. Requirements and testing of E85 are established in standard CWA 15293. Using ethanol as a fuel additive to unleaded gasoline causes an improvement in engine performance and exhaust emissions. Ethanol addition results in an improvement in brake power, brake thermal efficiency, volumetric efficiency and fuel consumption; however, the brake specific fuel consumption and equivalence air-fuel ratio decrease because of lower calorific value of the ethanol. Using an ethanol-gasoline blend leads to a significant reduction in exhaust emissions of carbon monoxide (CO) and hydrocarbons (HC) for all engine speeds (Agarwal, 2006). Major automobile producers offer automobiles, compatible with E85 or even hydrous ethanol. Availability of such automobiles, known as FFV or Flexible-fuel vehicles, depends on market and marketing decision (Pirs and Malnicenko, 2010). Part of the existing automobile fleet can be converted from use of gasoline to E85. Application of E85 fuel for powering the automobile built for use of gasoline requires evaluation of material compatibility (Baena et al., 2012). Lower vapour pressure and the lower combustion heating values of ethanol leads to requirements for a higher fuel injection quantity, and results in higher fuel consumption. The use of ethanol is associated with cold start problems (Jiang et al., 2009). To overcome these difficulties, conversion adapters exist in the market. There is lack of research results on the conversion adapter design, requirements and testing. This study focuses on detailed analysis of the typical fuel conversion adapter, offered in the European market. The aim of the study is to evaluate performance of fuel conversion adapter, its ability to ensure safe operation of petrol engine operating on E85 fuel. Engine power, torque, air/fuel equivalence ratio, specific fuel consumption and engine thermal efficiency will be measured and compared using petrol and E85 fuel, and with and without fuel conversion adapter.

Materials and Methods

Engine operating parameters, used for evaluation of the efficiency of the fuel conversion adapter are engine brake power (P_b), air/fuel equivalence ratio (λ), specific fuel consumption (*SFC*) and engine thermal efficiency (η_t).

Commercial gasoline of standard EN228, identified as A95 and gasoline-ethanol blend of standard CWA 15293, identified as E85 were selected for this study. Properties of the test fuels are presented in Table 1. Technically both fuels are gasoline/ethanol blends. Pure gasoline is not commercially available for consumers in Latvia. Fuels were purchased in Statoil fuel stations in Latvia. Properties of test fuels were obtained from the certificates provided by fuel supplier. Lower heating value of the test fuels was estimated from basic values available in Biomass Energy Data Book, 2011.

Table 1

Properties of test fuels

Property	A95	E85
Density, kg m^3 at 15°C	740.0	786.9
Research octane number RON	95.4	106.5
Motor octane number MON	85.9	91.1
Ethanol content, volume %	4.8	84.5
Lover heating value Q_{LV}, MJ kg^{-1}	44.0	28.9
Air/ fuel ratio	14.7	9.8

Testing was performed on production vehicle Volkswagen Passat with a port fuel injection (PFI) spark ignition (SI) engine. Technical characteristics of the automobile are presented in Table 2.

Table 2

Technical characteristics of the test automobile

Model	Volkswagen Passat
Identification number	WVWZZZ3BZWE103686
Date of production	27.07.1997
Engine	Type ADR, 4-cylinder 20-valve
Compression ratio	10.3
Displacement volume	1781 cm^3
Bore	81.0 mm
Stroke	86.4 mm
Engine control system	Bosch Motronic M3.8.2
Gearbox	Type DHZ, 5-gear manual

Automobile was additionally equipped with fuel conversion adapter RMG-Rapsol B5. Installation was performed according to the manufacturer instructions. Conversion module was electrically connected to engine control unit (ECU) and fuel injectors, interrupting existing connections, and connected to chassis ground and power feed. Additionally, a conversion module was connected to the vehicle original oxygen sensor and throttle position sensor. Module uses its own coolant temperature sensor. The diagram of connection is shown in Fig. 1.

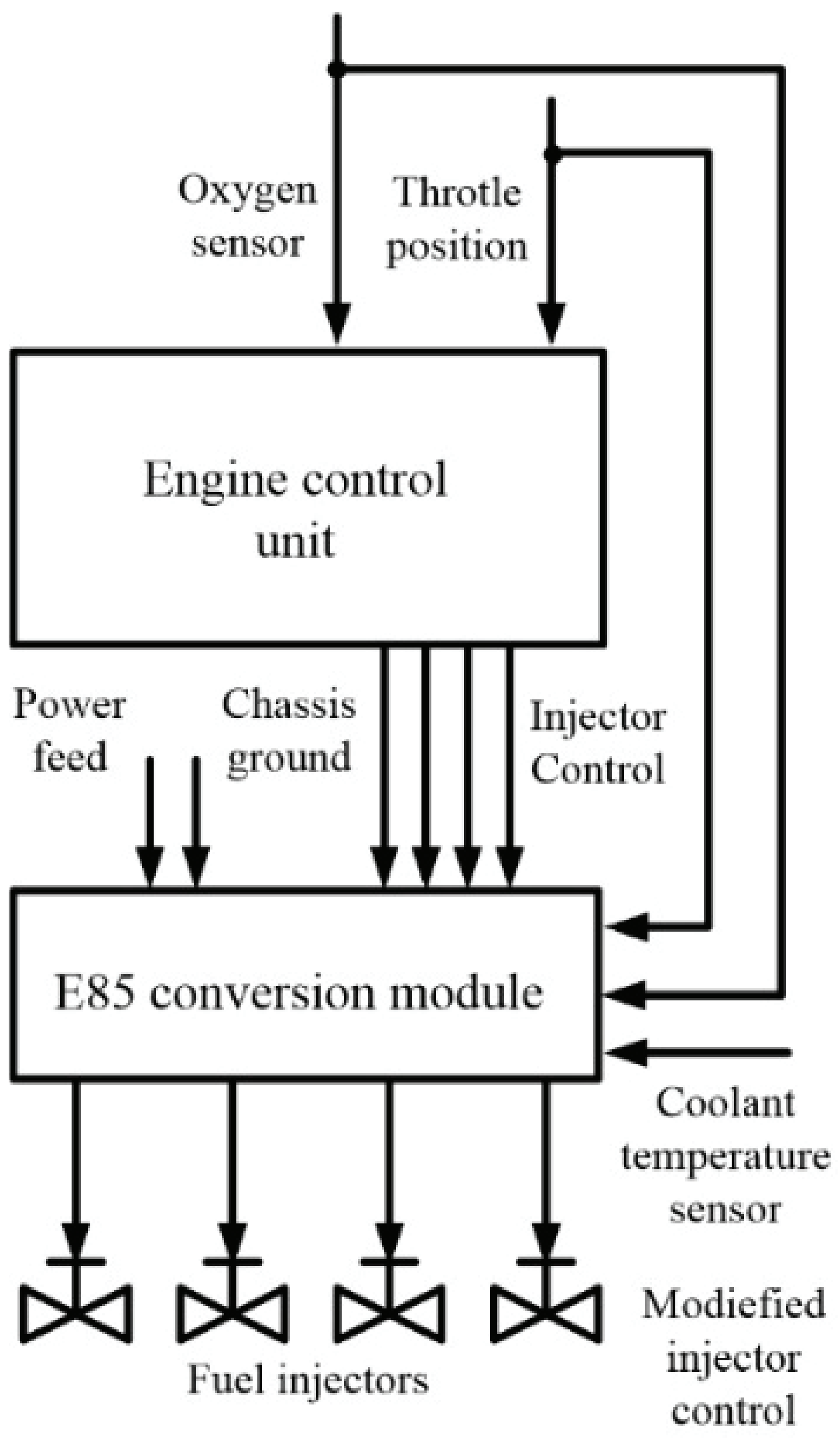

Figure 1. Connections of conversion module.

Testing was performed on roll-type eddy-current chassis dynamometer Mustang MD1750. Dynamometer applies specific load and measures torque on roll shaft. By knowing roll speed and engine speed of the tested vehicle, relative engine torque (T) can be calculated. Engine brake power (P_b) in kW is the product of engine torque (T) in Nm and rotational speed (ω) in rad s^{-1}:

$$P_b = T \cdot \omega. \tag{1}$$

Air/fuel equivalence ratio, λ, is relationship between actual and stoichiometric air/fuel ratio. At stoichiometric ratio all fuel and oxygen present in combustion chamber theoretically can react completely. Air/fuel equivalence can found using following equation:

$$\lambda = \frac{(A/F)}{(A/F)_s} = \frac{(\dot{m}_a/\dot{m}_f)}{(\dot{m}_a/\dot{m}_f)_s}; \tag{2}$$

where $\dot{m}_a$ and $\dot{m}_f$ are engine intake air flow rate and fuel flow rate, respectively (Costa et al., 2010).

Specific fuel consumption, *SFC*, in kg kW h^{-1}, as defined by Costa et al., 2010, is the fuel amount consumed per unit of power produced, and can be found by following equation:

$$SFC = \frac{\dot{m}_f}{P_b}. \tag{3}$$

The engine thermal efficiency η_t is a measure in percentage (%) of the fuel conversion efficiency, given by the relationship between the energy available at the engine output and the fuel energy content (Costa et al., 2010; Melo et al., 2012):

$$\eta_t = \frac{P_b}{\dot{m}_f \cdot Q_{LV}} = \frac{P_b \cdot 3.6}{FC \cdot Q_{LV}}; \quad (4)$$

where Q_{LV} is fuel lower heating value in MJ kg^{-1} and FC is fuel consumption in kg h^{-1}.

Air temperature in test room was 19 °C. Dynamometer control unit was used to calculate engine brake power and to register air/fuel ratio and exhaust gas temperature. Air-fuel ratio was measured using Bosch LSU 4.2 wideband oxygen sensor, connected to LM-1 Digital meter. Exhaust gas temperature at manifold exit was measured using K-type thermocouple. No corrections relative to the mechanical losses were applied to engine torque and power measurements. Measurements of fuel consumption were performed, using AVL KMA Mobile system. Fuel consumption was measured in volume domain. Fuel was supplied from external tank, cooled to 15 °C. When the fuel type was changed, fuel system was flushed three times to avoid influence of previously used fuel. Fuel flow was maintained by AVL KMA Mobile system internal fuel pump. Testing on chassis dynamometer was performed in constant speed mode. Using dynamometer control software, specific fixed roll speed steps were set, corresponding to the engine rotation speed from 1000 to 5500 rotations per minute (min^{-1}), by increasing step 500 min^{-1}. Each step lasted 20 seconds. Gearbox was set in 4th gear. Engine was tested in wide open throttle mode, limiting rotational speed at each measurement point by chassis dynamometer. The Motronic ECU works according to the proprietary algorithms, some of which are constantly adapting injection and ignition map values to maintain certain engine output characteristics. To avoid effect of ECU fuel trim adaptation, which can alter repeated measurements in unpredicted way, ECU adaptations were reset before each test drive. Value of ECU adaptation was monitored using Bosch KTS 570 diagnostic tool. Test results were excluded, if value of the ECU fuel trim adaptation exceeded 0%. Ignition advance correction was performed automatically, according to the ECU strategy, and recorded using Bosch KTS 570 diagnostic tool. Testing was performed with the vehicle set in four different configurations. Tests performed with the vehicle in production setup was identified A95 and E85, depending on the used fuel. Tests with the vehicle, equipped with fuel conversion adapter, were identified A95B and E85B. Each test was repeated 5 times and average values used as results. Data in results section is presented with error bars of 95% confidence intervals. Layout and principal connections of the testing equipment are shown in Fig. 2.

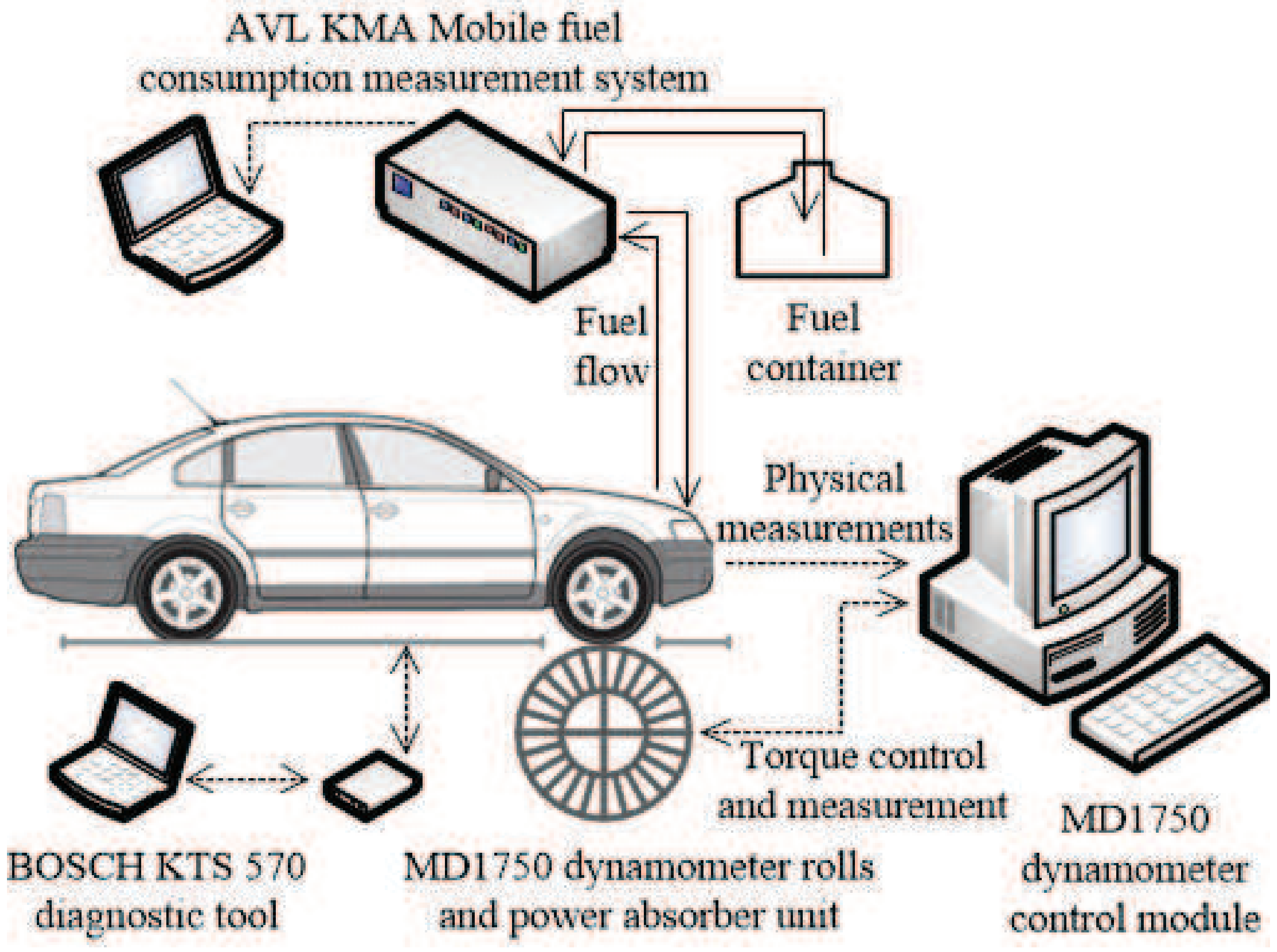

Figure 2. Test equipment setup.

Results and Discussion

Fuel conversion adapter RMG Rapsol B5 works by extending fuel injector control impulse which is supplied by ECU. ECU injector control circuit is isolated from the fuel injector solenoid coil. According to the information supplied by the producer of the fuel conversion adapter, amount of the correction of the injector opening impulse depends on engine temperature, throttle valve position and most of all, air/fuel ratio supplied by the oxygen sensor. Original and modified control impulse is shown in Fig. 3.

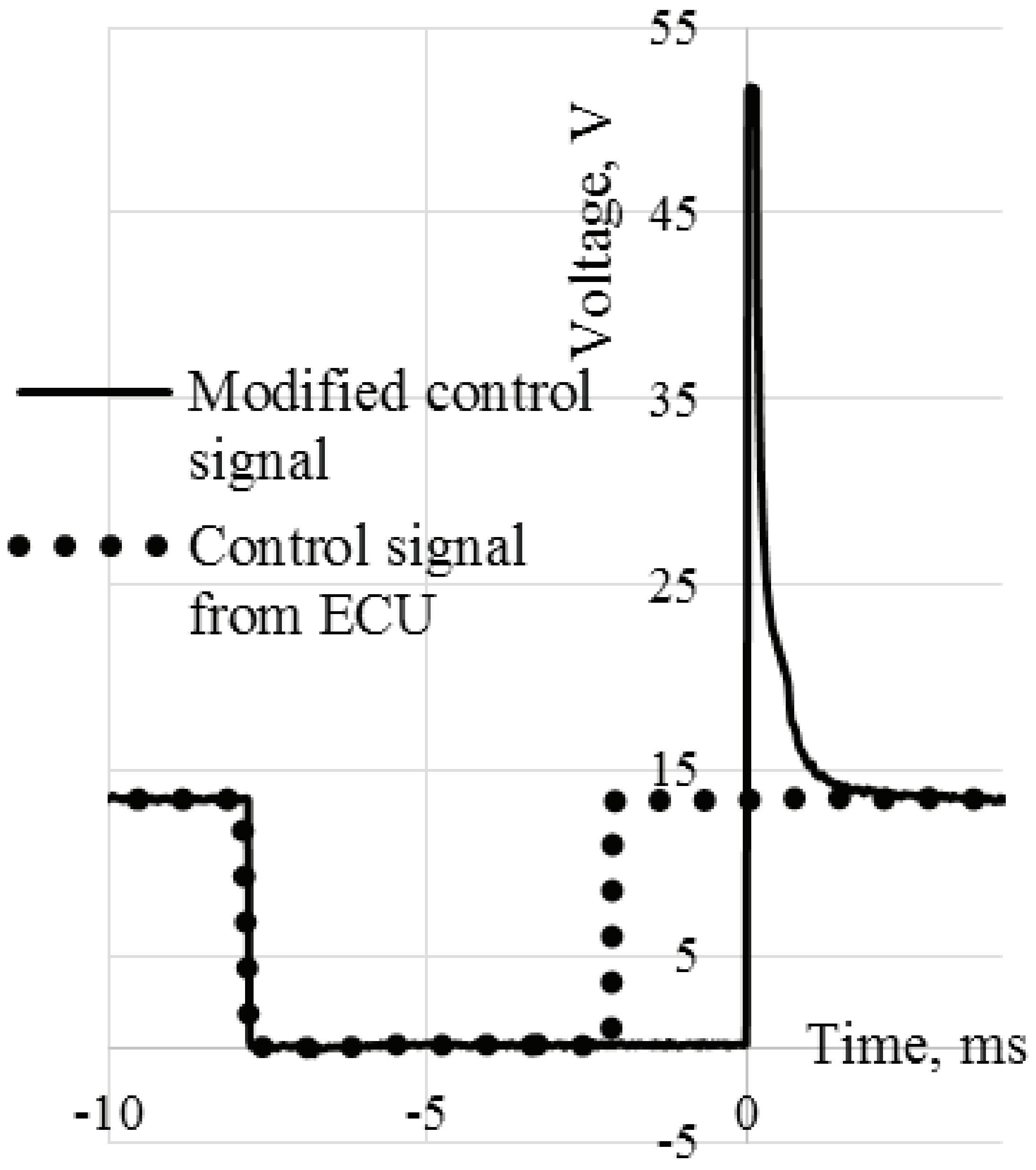

Figure 3. Injector control impulse.

Air/fuel equivalence ratio is presented in Fig. 4. In chosen test conditions, with the wide open throttle, ECU operates in an open loop mode. In the open loop

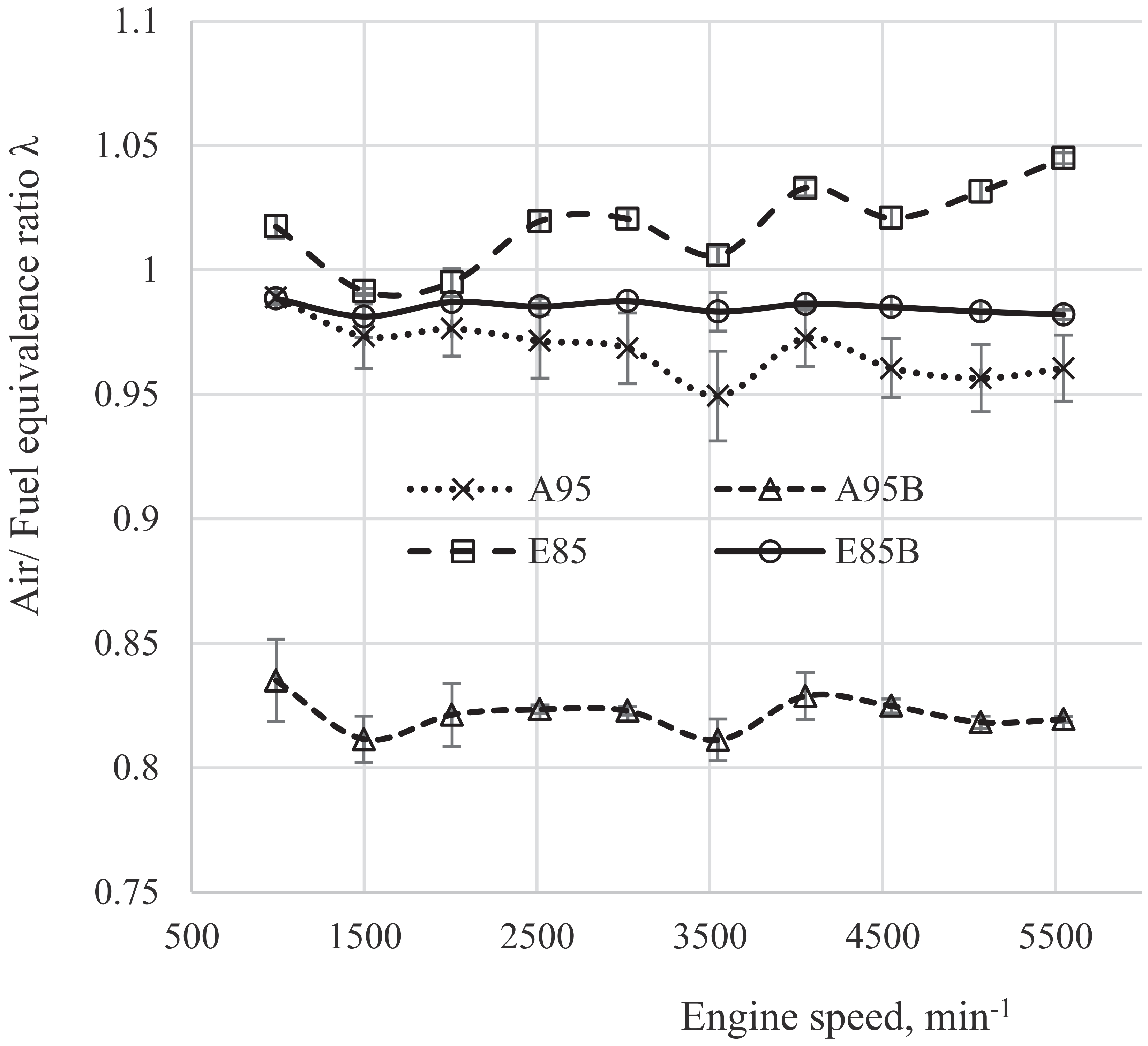

Figure 4. Fuel and conversion adapter influence on air/fuel equivalence ratio.

mode, feedback from the oxygen sensor is not used and air/fuel mixture is being prepared according to the pre-set map. That explains lean mixture in E85 test conditions, when unmodified fuel system works on E85 fuel. As the pre-set map was prepared for standard fuel (gasoline), but the stoichiometric ratio of the E85 is different, mixture is incorrect. Such operation conditions can lead to high temperature in combustion chamber and following engine damage. In test conditions A95B, when gasoline is used with an active fuel conversion adapter in place, air/fuel mixture is too rich. The reason for that can be long reaction time to fuel change or technical shortcomings of the particular conversion adapter. Tests performed in conditions A95 and E85B return satisfactory results of air/fuel mixture preparation during operation with the wide open throttle.

Diagrams of the engine torque and brake power are presented in Fig. 5. At engine speed range from 1500 to 3500 min^{-1} gasoline/ethanol blend in conditions E85B produced higher torque compared to the gasoline in conditions A95. At a low engine speed, around 1000 min^{-1}, the use of gasoline or gasoline/ethanol blend produced approximately the same torque. According to Costa et al., 2010, higher heating value of the gasoline is responsible for higher torque at low engine

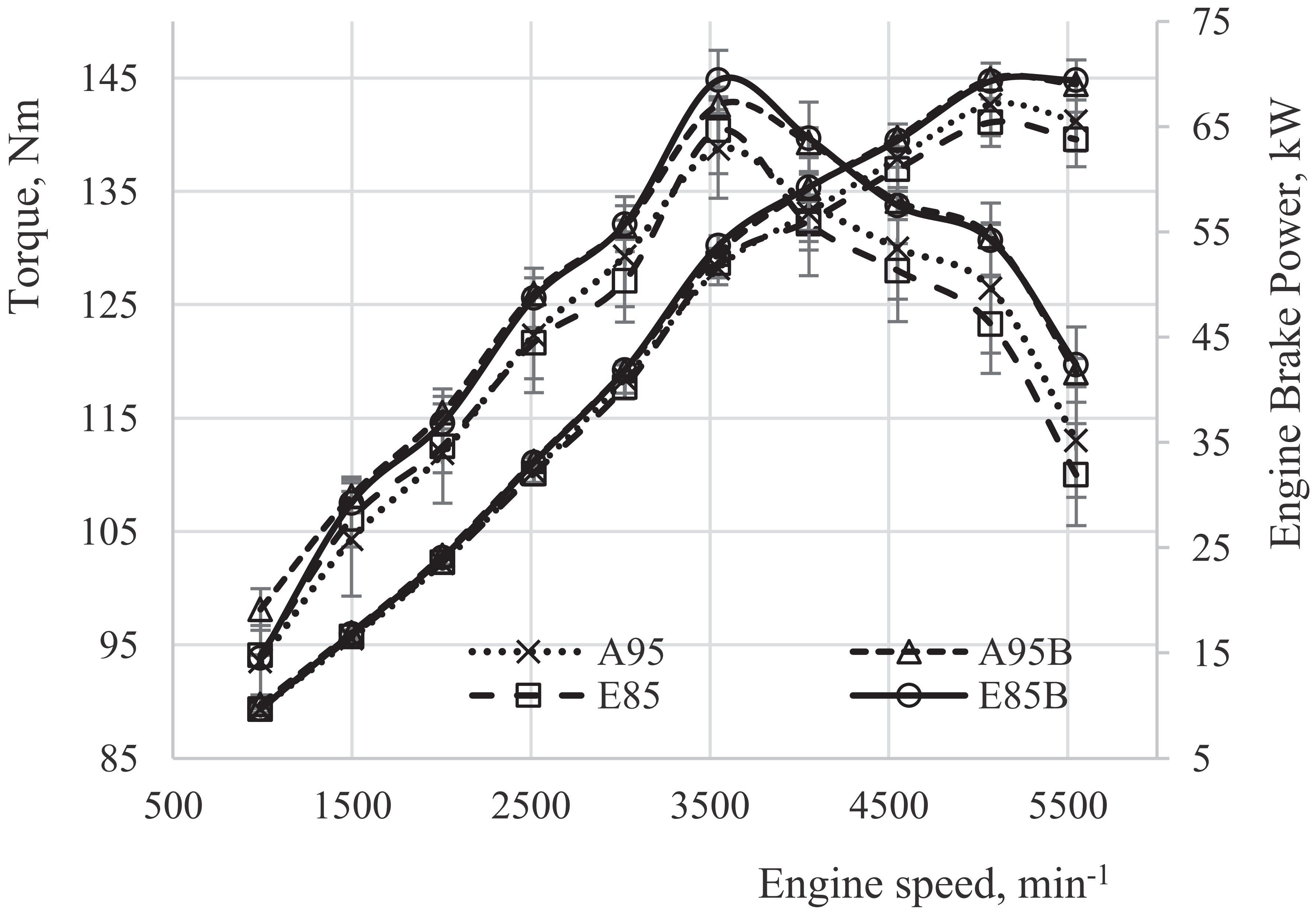

Figure 5. Fuel and conversion adapter influence on engine power and torque.

speeds. For higher engine speeds, faster flame velocity and higher resistance to detonation gives advantage to gasoline/ethanol blend E85 to produce higher torque, compared to gasoline (Costa et al., 2010; Jiang et al., 2009; Shifter et al., 2011). According to Szybist et al., 2010, a charge cooling effect is another factor which increases engine power. Latent heat of vaporization is 0.85 MJ kg^{-1} for E85 fuel and 0.35 MJ kg^{-1} for gasoline (Aleiferis et al., 2010). The charge cooling effect is created when fuel is sprayed into the intake air charge. During vaporization of the fuel, the air is cooled, reducing the specific volume of the intake charge. Since the latent heat of vaporization is significantly higher for E85 fuel, comparing to the gasoline, E85 is more effective at cooling the intake charge than gasoline.

Use of E85 fuel and conversion adapter produces maximal torque 144.8 Nm at 3547 min^{-1}, an increase

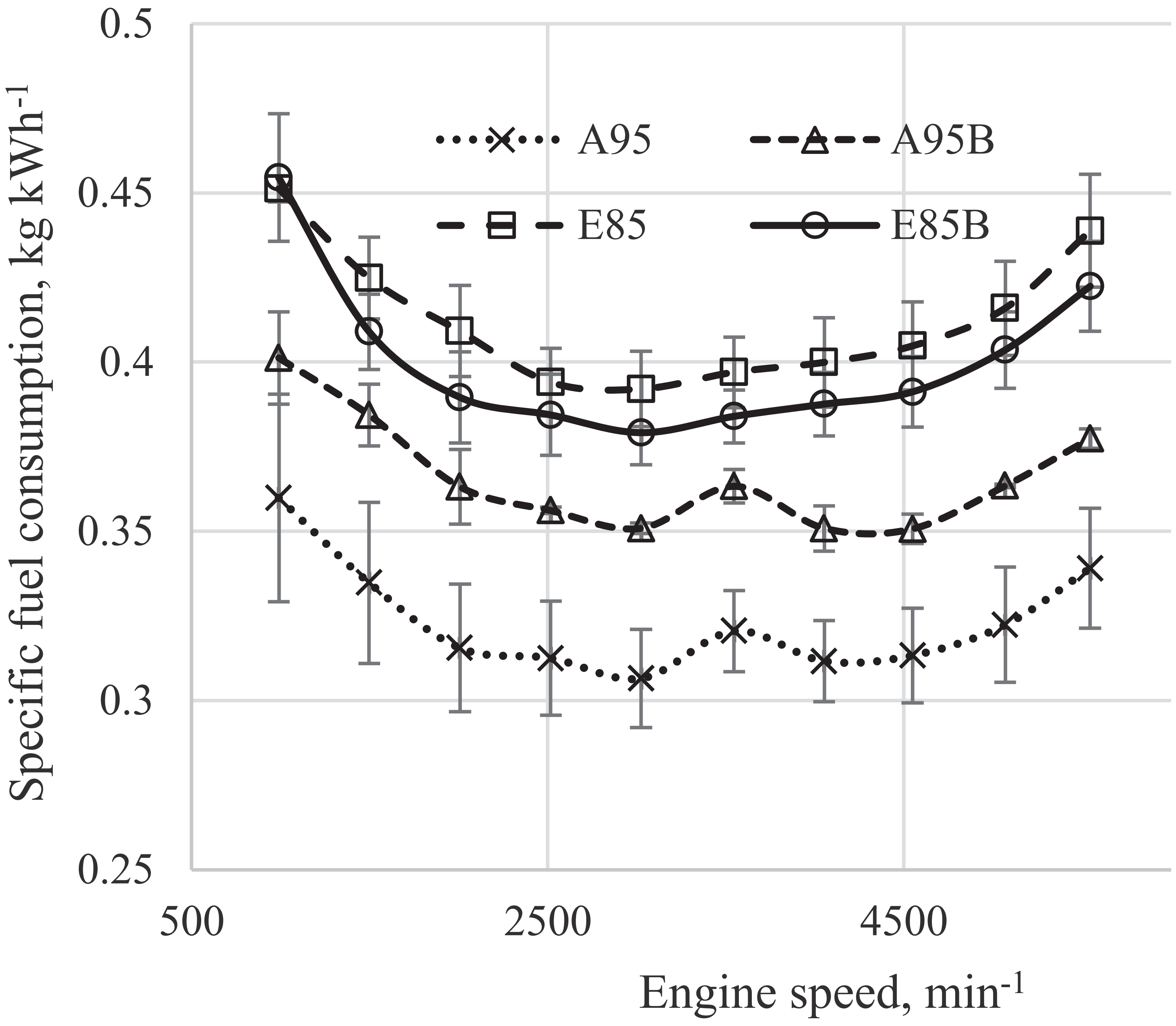

Figure 6. Fuel and conversion adapter influence on specific fuel consumption.

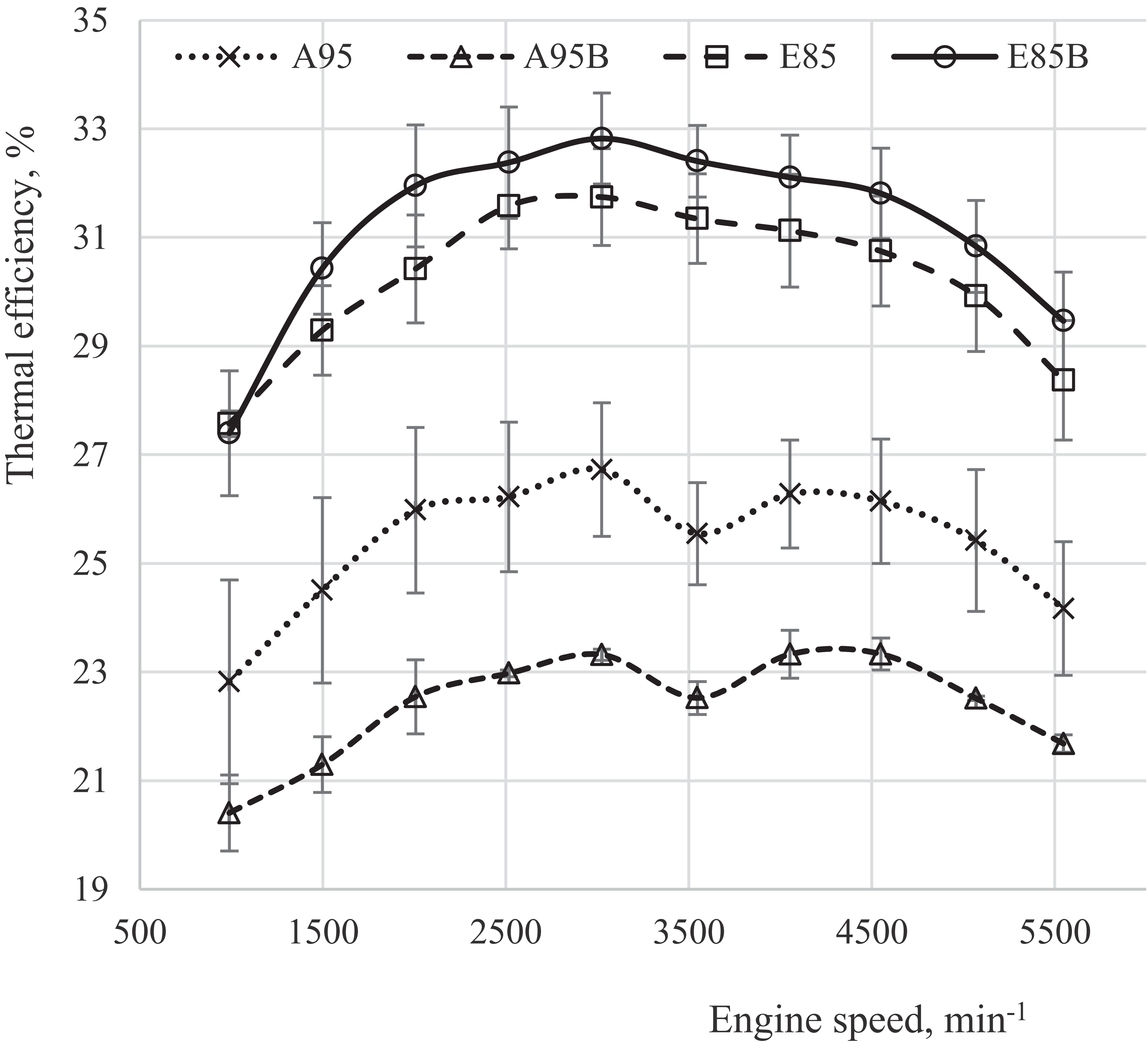

Figure 7. Fuel and conversion adapter influence on thermal efficiency.

by 4.4% compared to gasoline A95 and maximal power 69.3 kW at 5000 min^{-1}, an increase by 3.3% compared to gasoline.

Specific fuel consumption of E85 fuel, shown in Fig. 6, reached lower value 0.38 kg kWh^{-1} at 3000 min^{-1}. It was 22.6% increase for producing equivalent power, compared with the consumption of the gasoline. An increase can be explained with lower heating value of E85 fuel caused by higher content of the ethanol as shown in Table 1.

The engine thermal efficiency, calculated according to Eq. 4 is shown in Fig. 7. The lowest thermal efficiency and highest specific fuel consumption were observed when the engine equipped with conversion adapter was operated using gasoline. The engine thermal efficiency for E85 fuel was increased in all tested engine speed range Maximal thermal efficiency using E85B test setup reached 32.8% at 3000 min^{-1}, from 26.7% for gasoline in A95 test. Contributing factors of increased thermal efficiency of E85 compared to gasoline are the same that were mentioned earlier at engine power analysis - faster flame velocity, higher resistance to detonation and charge cooling effect. Based on the test data analysis, it can be stated that difference in engine operating parameters depending on used fuel - E85 or gasoline is in agreement with Agarwal, 2006; Costa et al., 2012 and Jiang et al., 2007. Consequently, it can be concluded that the conversion adapter RMG-Rapsol B5 provides normal operation of the engine using E85 fuel.

Conclusions

1. Fuel conversion adapter RMG-Rapsol B5 generates fuel injector control impulse based on ECU injection timing and ECU sensor readings.
2. Operation of the unmodified gasoline SI engine with E85 fuel in wide open throttle mode will lead to a lean air/fuel mixture and is not recommended, as the engine damage may take place.
3. Fuel conversion adapter RMG-Rapsol B5 provides adequate air/fuel mixture when E85 fuel is used, but fails to adapt when engine works on petrol.
4. The use of E85 fuel and conversion adapter give an increase of engine peak torque by 4.4% compared to gasoline, producing 144.8 Nm at 3500 min^{-1}, and maximal power 69.3 kW at 5000 min^{-1}, an increase by 3.3% compared to gasoline.
5. Specific fuel consumption is 20-23% higher, when E85 fuel with a conversion adapter is used, comparing with the gasoline use in the unmodified engine.
6. The thermal efficiency is increased in all tested engine speed range, when the engine is operated with E85 fuel instead of gasoline.
7. The peak thermal efficiency of the engine working with a conversion adapter and E85 fuel reaches 32.8% at 3000 min^{-1}, resulting in 6.1% increase, compared to the gasoline use.
8. The fuel conversion adapter RMG-Rapsol B5 provides basic optimization of air/fuel preparation system for using gasoline/bioethanol blend E85 in production PFI SI engine designed for the gasoline use.

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