THE POSITIVE INFLUENCE OF CO₂ IN FUEL ON ENGINE PARAMETERS

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SHRNUTÍ

Odstranění CO₂ jako nežádoucí příměsi z plyných paliv je současný trend. Na rozdíl od tohoto trendu prezentovaný článek popisuje přínosy přítomnosti CO₂ v plyném palivu na základní parametry motoru jako je střední indikovaný tlak, indikovaná účinnost, teplota výfukových plynů a produkce oxidů dusíku. Vliv oxidu uhličitého v palivu na parametry motoru je teoreticky ověřen, extrapolován a zobecněn. Článek detailně analyzuje vztah mezi součinitelem přebytku vzduchu, předstihem zážehu a hmotnostním podílem CO₂ v palivu.

KLÍČOVÁ SLOVA: PLYNOVÝ SPALOVACÍ MOTOR, BIOPLYN, OXID UHLIČITÝ, STŘEDNÍ INDIKOVANÝ TLAK, INDIKOVANÁ ÚČINNOST, PRODUKCE OXIDŮ DUSÍKU, SOUČINITEL PŘEBYTKU VZDUCHU, PŘEDSTIH ZÁŽEHU, HMOTNOSTNÍ PODÍL CO₂

ABSTRACT

The removal/clearing of CO₂ considered as an adulterant from gaseous fuels is a contemporary trend. Contrary to this trend the paper that is presented describes the benefits of CO₂ fuel content on basic engine parameters such as indicated mean effective pressure, indicated efficiency, exhaust temperature and NO_x production. The influence of carbon dioxide in fuel on engine parameters is theoretically validated, extrapolated and generalized. The paper analyses the trade-off between air excess, ignition timing and CO₂ fuel mass fraction in detail.

KEY WORDS: SI GAS ENGINE, BIOGAS, CARBON DIOXIDE, INDICATED MEAN EFFECTIVE PRESSURE, INDICATED EFFICIENCY, NO_x PRODUCTION, AIR EXCESS, IGNITION TIMING, CO₂ MASS FRACTION

1. INTRODUCTION

At present the world fossil fuel resources indicate an urgent need to use alternative resources as fuel. Biogas is one such alternative resource. Biogas is widely used in the area of combined heat and power production. The use of biogas for the propulsion of city buses and utility trucks is indispensable too but the presence of carbon dioxide in fuel decreases the vehicle range, increases the fuel tank volume and vehicle weight.

Carbon dioxide is a significant component of biogas. The content of carbon dioxide can reach 70 % of the mass fraction [1–3]. This component is considered as the adulterant and there is intensive effort to remove it from gaseous fuel [4–8]. Carbon dioxide has properties as an extinguisher and decreases flammability, combustibility and burning rates [9]. Carbon dioxide decelerates the combustion process in internal combustion engines due to these properties. The combustion deceleration causes cylinder fuel afterburning during the

exhaust valve open phase of the working cycle. This afterburning increases exhaust temperatures in the exhaust system and these higher temperatures cause intensive degradation of the whole exhaust system (including exhaust valve, manifold and turbine housing and exhaust pipe) [10–13]. Without any optimizations the combustion deceleration deteriorates the gross indicated efficiency and decreases the gross indicated mean effective pressure [9]. It is important to note that engine specific emissions of carbon dioxide do not influence the global warming index of the whole chain of production and utilization. The carbon dioxide that is removed is released into the air.

During the period when the author worked on development of stationary gas engines, he carried out a large number of experiments with biogas-fuelled lean-burn engines and optimized dozens of stationary biogas engines for the specific

gases of diverse origin. These experiments were unsystematic with regards to the influence of carbon dioxide assessment on engine parameters. These experiments were focused on the influence of the specific biogas on engine parameters. The basic parameters of engines were researched. The following conclusions were drawn which surprisingly differ from previously mentioned generally acknowledged statements:

- increasing the content of CO_2 in fuel considerably increases engine power and decreases total efficiency with a constant NO_x emission level, air excess and ignition timing are changed,
- optimized content of CO_2 in fuel increases engine power and total efficiency with a constant NO_x emission level,
- increasing the content of CO_2 in fuel increases exhaust temperature.

The constant NO_x emission level was maintained with the help of a change of air excess and ignition timing parameters. The conclusions from the experiment show that there is no justification for requiring the removal of carbon dioxide. This contribution describes the theoretical validation of these experimental conclusions.

2. APPROACH

The 1D mathematic model GT-Power/GT-SUITE [14] was used for the theoretical validation of the influence of CO_2 content in fuel on engine parameters. The engine model was created in this commercial software. This software describes the behaviour of the engine as well as providing a correct model of the carbon dioxide influence. To simulate the influence of carbon dioxide the heat release iterative regression model [15] derived by the author has been used. The main function of the heat release iterative regression model is to determine the HR pattern depending on the operation parameters and fuel composition. The operation parameters have been chosen according to the Csallner-Woschni method and these parameters are ignition timing α_{12} , air excess λ , engine speed RPM, residual gas content RGC, in-cylinder temperature T_{VA60} and in-cylinder pressure p_{VA60} 60 degree BTDC. The heat release pattern influences the engine working cycle and this cycle influences the engine parameters.

3. ENGINE DESCRIPTION

The modelled engine is derived from an existing SI turbocharged engine fuelled with natural gas. It was rebuilt from a diesel engine especially for laboratory purposes as a representative of a spark-ignited engine. Turbocharger match has been applied to generate boost pressure as it is typically used in stoichiometric engines. A powerful water-cooled intercooler has been installed

as part of the engine peripheries. The basic engine features of the modelled engine are shown in Table 1.

TABLE 1: Basic engine features
TABULKA 1: Základní parametry motoru

ENGINE PARAMETER	
Bore [mm]	102
Stroke [mm]	120
Compression ratio [1]	12:1
Turbocharger	YES – UNCONTROLLED
Cylinder number	4
Valves per cylinder	4
Cylinder arrangement	IN-LINE
IVO [°]	350
IVC [°]	588
EVO [°]	136
EVC [°]	368

4. GT-SUITE MODEL DESCRIPTION

GT-SUITE software is used for modelling the turbocharged engine. The GT-SUITE engine model is derived from [16]. The engine model has been created and calibrated according to the experimental results. The CO_2 influence is investigated with the aid of the parametrical study. The engine model was tested for different CO_2 fuel content. The remaining fuel component is always CH_4 . Air excess and ignition timing were the next variable engine parameters to keep a constant NO_x emission level. The NO_x emission level is represented by the TA-Luft limit. Other engine parameters and ambient conditions were the same. The in-cylinder conditions depend on the cylinder model which has been calibrated by three pressure analyses. The turbine speed depends on the turbocharger model. The intake temperature depends on the intercooler model.

The engine model is arranged and utilized for the purpose of heat release iterative regression model verification. The engine model is coupled with ENGCOMBUSER – user combustion model. The fuel composition parameters, ignition timing α_{12} and engine speed RPM are introduced directly into this user combustion model. The other parameters such as cylinder pressure p_{VA60} , cylinder temperature T_{VA60} , air excess λ and residual gas content RGC for each cylinder are introduced into the user combustion model with the aid of Wiring Harness part. The result of the iterative regression model is a modelled HR pattern. The fuel composition is imposed as a Composition Item in the EndEnvironment GT-SUITE object. The standard GT heat transfer models have been replaced by a user heat transfer model with implemented Eichelberg equation.

The burned fuel fraction (BF) pattern is more important as input to the GT-SUITE main procedure because the new versions of GT-SUITE are able to respect the combustion chemistry in a better way, using zone models and local chemical equilibrium of combustion products. For this reason, the HR pattern is corrected to the BF pattern. The BF correction is achieved with the aid of a burned rate correction procedure [15].

The GT-SUITE engine model layout is displayed in Figure A1.

5. RESULTS

Figure 1 shows the dependence of air excess on ignition timing and CO₂ mass fraction in fuel for a constant NO_x emission level [17]. The generally known dependence between ignition timing, air excess and NO_x emission level is shown for zero content of CO₂ in fuel. The graph shows the influence of CO₂ in fuel, increasing the CO₂ mass fraction and likewise decreasing the ignition timing makes it possible to enrich the mixture for a constant NO_x emission level.

Figure 2 shows the dependence of indicated mean effective pressure on ignition timing and CO₂ mass fraction in fuel for a constant NO_x emission level. Increasing the CO₂ mass fraction

FIGURE 1: Air excess dependence
OBRAZEK 1: Závislost součinitele přebytku vzduchu

FIGURE 2: Indicated mean effective pressure dependence
OBRAZEK 2: Závislost středního indikovaného tlaku

and decreasing the ignition timing makes it possible to obtain a higher indicated mean effective pressure for a constant NO_x emission level.

Figure 3 shows the dependence of indicated efficiency on ignition timing and CO₂ mass fraction in fuel for a constant NO_x emission level. This dependence is more complicated and demands effort to find an optimum. It is possible to find the optimum.

Figure 4 shows the dependence of exhaust temperature on ignition timing and CO₂ mass fraction in fuel for a constant NO_x emission level. Increasing the CO₂ mass fraction and decreasing the ignition timing increases exhaust temperature for a constant NO_x emission level.

Figure 5, Figure 6, Figure 7 and Figure 8 are used to give a more complete insight into the problem. They describe the behaviour of the engine working substance during the engine working cycle in a more comprehensive way. Two regimes (which are different in CO₂ mass fraction, ignition timing and air excess) are shown for a constant NO_x emission and imep level. The indicated efficiency is better for a regime with a high CO₂ mass fraction (37,7% vs. 35,3%).

FIGURE 3: Indicated efficiency dependence
OBRAZEK 3: Závislost indikované účinnosti

FIGURE 4: Exhaust temperature dependence
OBRAZEK 4: Závislost teploty výfukových plynů

FIGURE 5: In-cylinder pressure pattern
OBRÁZEK 5: Průběh tlaku ve válci motoru

FIGURE 7: HR pattern
OBRÁZEK 7: Průběh vývinu tepla hořením

FIGURE 6: LogP-LogV diagram
OBRÁZEK 6: LogP-LogV diagram

FIGURE 8: In-cylinder temperature pattern
OBRÁZEK 8: Průběh teploty ve válci motoru

6. CONCLUSION

The detailed theoretical research into the influence of CO_2 in fuel on engine parameters corresponds with and verifies experimental conclusions. As long as the emission of NO_x has to be limited taking into account the legislative requirements, surprising results can be obtained from the aforementioned research. An increase in the CO_2 mass fraction in fuel increases engine power and when properly optimized it can even increase total efficiency. The increased amount of CO_2 in fuel leads to increased exhaust gas temperature which enables an increase of the boost pressure and on the other

hand enhances the danger of the exhaust system and turbine overheating.

The influence of CO_2 in fuel on engine parameters is similar to the effect of EGR. A reason for this similarity may be the fact that EGR has a considerable fraction of CO_2 .

The next step in the author's efforts in this area is to compare the effects of CO_2 and EGR on the engine parameters to each other exactly; especially taking into account the indicated mean effective pressure and the indicated efficiency for a constant NO_x emission level.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

α_{12}	ignition timing [°BTDC]
BF	burned fuel fraction [1]
CH ₄	methane
CO ₂	carbon dioxide
EVC	exhaust valve close [°]
EVO	exhaust valve open [°]
η_i	indicated efficiency [1]
HR	heat release fraction [1]
imep	indicated mean effective pressure [bar]
IVC	intake valve close [°]
IVO	intake valve open [°]
λ	air excess [1]
p_{VA60}	cylinder pressure in compression stroke at 60° BTDC [bar]
NO _x	nitrogen oxides
RGC	residual gas content [1]
RPM	engine speed [1/min]
T_{VA60}	cylinder temperature in compression stroke at 60° BTDC [K]
TT1	exhaust temperature before turbocharger [K]

FIGURE A1: Engine model layout
OBRÁZEK A1: Struktura modelu motoru