

## Experimental Investigation of Dual-Fuel Operation with Biomethane and various Pilot Fuels using different Compression Ratios

Brautsch, M.<sup>1,2,3\*</sup>, Lechner, R.<sup>1,2</sup>, Röhl, A.<sup>1</sup> and O'Connell, N.<sup>2</sup>

<sup>1</sup>Technical University of Applied Sciences Amberg-Weiden, Centre of Competence for CHP-technologies, Amberg, Germany

<sup>2</sup>Institute of Energy Technology at the Technical University of Applied Sciences Amberg-Weiden, Amberg, Germany

<sup>3</sup>Jiangsu University, Zhenjiang, Jiangsu Province, China

\*Corresponding author email: [m.brautsch@oth-aw.de](mailto:m.brautsch@oth-aw.de)

### ABSTRACT

Dual-fuel engines can be an interesting option for efficient supply of heat and power in combined heat and power (CHP) systems, using a variety of both liquid and gaseous fossil and biogenous fuels. Within the scope of ongoing research at the Competence Centre for CHP technologies two different dual-fuel configurations derived from the same base engine were tested with biomethane as gaseous fuel, using heating oil and various biofuels as pilot fuel. Procedure 1, referred to as “flexible dual-fuel mode”, features a compression ratio of 19:1. Procedure 2, referred to “pilot ignition mode”, features a reduced compression rate of 16:1. This configuration allows for significantly higher biomethane ratios than Procedure 1, but limits the applicable liquid fuel quantities. Compared to Procedure 1 (flexible dual-fuel mode) Procedure 2 (pilot ignition mode) shows lower values of electric efficiency under light load, identical values under mid load and significantly better values at high loads. It allows for the highest gas ratios combined with the best electrical efficiencies at full load and is thus the optimum configuration when gaseous fuels are to be used as primary energy source. In flexible dual-fuel configuration the best efficiency was reached in liquid fuel operation, while in pilot ignition configuration the best efficiency was obtained in dual-fuel operation with maximum share of gas. In both procedures high electric efficiencies of more than 42 % could be achieved, along with power coefficients of about 1, which proves the good exergetic efficiency of the investigated CHP engines.

**KEYWORDS:** Biofuels, CHP, Dual-Fuel, Efficiency

**COLLOQUIUM: IC ENGINE AND GAS TURBINE COMBUSTION.**

### 1. INTRODUCTION

Combined heat and power (CHP) generation can reach all the essential factors for sustainable energy solutions according to [1]. Cogeneration units in different applications can be used in industrial plants [2] [3], communities [4], housing societies [5] [6], hospitals and private households [6] in many different ways. In combination with fluctuating energy systems like wind turbines and solar power plants, cogeneration systems can work as base-load units and can be operated with renewable primary energy sources in the forms of solid, liquid and gaseous biomass. There are different conversion routes to obtain renewable liquid and gaseous fuels by thermochemical conversion, biochemical conversion, chemical conversion or physical conversion [7] and there are different possibilities of internal combustion in diesel engines [8], dual-fuel engines [9] and spark-ignited gas engines [10] [11].

Dual-fueling of Diesel engines can be an attractive possibility to reduce the dependence on diesel and to reduce harmful diesel emissions to a sustainable fuel market with lower carbon emissions [12]. Diesel engines can be used under liquid as well as dual fuel operation with negligible technological modifications. The dual fuel process is especially appropriate for CHP units with weak gases and low methane values (wood gas, landfill gas) and lean air-to-fuel ratios as the liquid fuel injection enables a steady ignition with further energy input throughout the injection process.

Different dual fuel operation modes using common rail, direct injection or pre chamber injection systems are described in literature with different combinations of liquid fuels (bio diesel, diesel) and gaseous fuels (natural gas, hydrogen [13], biogas). Pre chamber engines are rugged designed and show less fault liability with lowest efficiencies. Direct injection engines with common rail injection systems are appropriate for dual fuel processes as they allow the accurate control of the liquid fuel injection and the pilot injection can optimize the dual fuel combustion process [14].

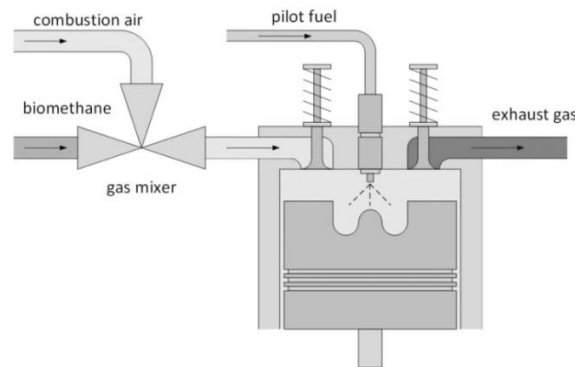
Sunmeet, S.K. et.al. [15] did experimental investigations on a Kirloskar single cylinder diesel engine in dual fuel mode with compression ratio 19.5:1. The injector opening pressure is described with 250-260 bar. Biodiesel was used as pilot fuel in two load categories with 2 kW and 5 kW. Biogas was simulated by blending carbon dioxide (CO<sub>2</sub>) with natural gas and was injected through two electronic controlled injectors, mounted on the engines intake manifold. The biogas share varied from 0 % (100 % liquid fuel operation) to 80 % and the CO<sub>2</sub> percentage of the biogas varied from 30 % to 50 %. It was carved out that the engine's efficiency decreased at 5 kW load from 32.6 % (liquid fuel operation) to 31.3 % (48 % biogas energy share) [15].

Barik, D. and Murugan, S. [16] also tested a Kirloskar single cylinder diesel with varying gas shares of up to 71.01 % and observed highest efficiencies at full load categories and significant higher efficiencies in liquid fuel operation (30.3 %) compared to dual fuel operation [16].

Hongyuan W., et.al. [17] modified a 6 cylinder common rail diesel engine with 247 kW power to diesel/methanol dual fuel mode. Methanol was injected continuously to the inlet duct by three methanol injectors with a pressure of 4.2 bar. During the experiments the main injection was at 1 degrees crank angle (°CA) before top dead center with a pressure of 800 bar. It is revealed that the application of pilot injection could improve the combustion stability and efficiency, but an increase of pilot injection quantity and the advance of pilot injection timing cause increasing cylinder temperatures and pressures before main combustion [17].

In order to optimize the injection timing and compression ratio of a raw biogas powered dual fuel diesel engine, Bhaskor, J.B., et.al. [18] modified a 3.5 kW single cylinder diesel engine with direct injection and a variable compression ratio into a biogas dual fuel diesel engine by connecting a venturi gas mixer at the inlet manifold. The pilot fuel injection of 29 °CA before top dead center and a compression rate of 18:1 brought a maximum efficiency of 25.44 % and a liquid fuel replacement of 82.67 %. The authors conclude that the optimization of the injection timing along with a high compression ratio is an important requirement for high dual fuel efficiencies [18]. In a further research project the authors tested rice bran oil methyl ester, pongamia oil methyl ester and palm oil methyl ester as pilot fuels of a dual fuel diesel operated with biogas engine [19]. At all load categories the biodiesel dual fuel mode had significant lower efficiencies than the diesel dual fuel mode. The maximum efficiency at full load with 19.97 % was observed with rice bran oil methyl ester/biogas in comparison to 18.4 % for pongamia oil methyl ester/biogas and 17.4 % for palm oil methyl ester/biogas. The liquid fuel substitution rate was 79 %, 78 % and 77 %. [19] At the same test bench the authors investigated the influence of different compression ratios in the rice bran oil methyl ester/biogas mode. The tests were realized at compression ratios of 18:1, 17.5:1 and 17:1 at a fixed beginning of injection. The highest efficiency of 20.27 % was observed at the highest compression rate. [19]

Within the scope of this paper the diesel ignited gas engine (c. f. Figure 1) will be further investigated. In this type of dual-fuel engine, a lean premixed mixture of gas and air is fed into the engine and a direct injection of liquid fuel into the combustion chamber ignites the compressed charge [20]. The investigations are part of an ongoing research project on fuel-flexible operation of CHP systems carried out within the framework of the Competence Centre for CHP technologies at the Technical University of Applied Sciences Amberg-Weiden. In the first step, which is presented in this paper, the electric and thermal efficiency in dual fuel operation was determined, using biomethane as gaseous fuel and different liquid biofuels as pilot fuels. Two different compression ratios and two different modes of operation (pilot injection mode and flexible dual-fuel mode) were applied.



**Figure 1.** Schematic of a Diesel Ignited Gas Engine (modified picture from [21]).

## 2. THE EXPERIMENTAL SETUP AND PROCEDURE

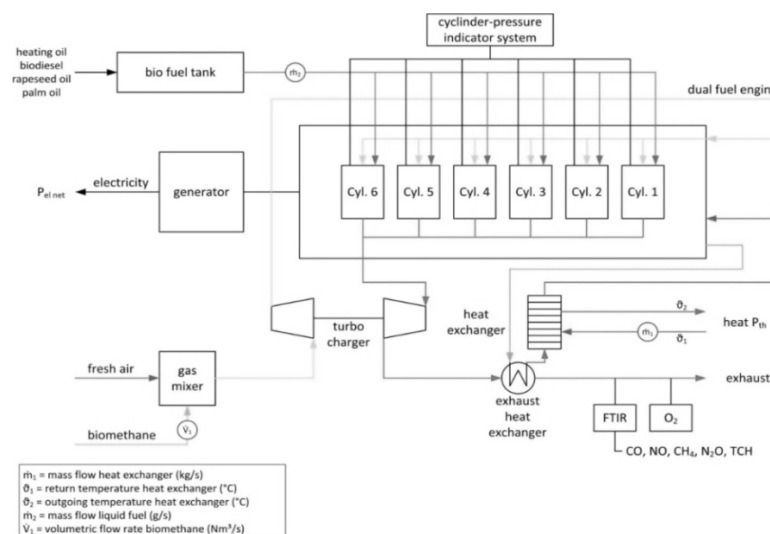
### 2.1 The experimental Setup

The experiments were carried out on a CHP test bench (c. f. Figure 2) equipped with a MAN D26 6-cylinder diesel engine (technical specifications c. f. table 2). The MAN engine was modified for dual-fuel operation and can be equipped with two different sets of pistons in order to achieve compression ratios of 19:1 and 16:1 respectively. The engine can be operated in two different modes. In “flexible dual-fuel mode” with compression ratio 19:1 the engine can be operated with variable shares of gaseous and liquid fuel, limited only by engine knock. This mode is intended for flexible conversion of both liquid and gaseous fuels in variable ratios. In the configuration with compression ratio 16:1 the engine is operated in “pilot ignition mode”, which means that the main energy input comes from the gaseous fuel and only a small portion of liquid fuel is used for ignition of the compressed charge. This mode is intended for efficient conversion of mainly gaseous fuels.

By applying pre-defined electric loads ranging from 80 to 240 kW of electric power, the electric and thermal efficiency were determined. The main indicators measured on the test bed were the electrical power, the thermal power, the fuel power input from gaseous fuels  $P_{\text{gas}}$  and/or liquid fuels  $P_{\text{liquid}}$  and the power coefficient. The power coefficient represents the ratio of electric power output to thermal power output and is an important indicator for the exergetic efficiency of CHP units, provided that all heat produced is utilized. A high power coefficient indicates that the CHP system has a high electric efficiency and thus, due to the higher exergetic value of electricity compared to heat, a good exergetic efficiency. Generally CHP units with a power coefficient near to unity can be considered as highly efficient.

The liquid fuel consumption (heating oil, biodiesel, rapeseed oil, soybean oil, palm oil) was determined gravimetrically with a Kern DS60KO.2 scale. The biomethane consumption expressed as the volumetric flow rate was recorded via a calibrated gas meter with pressure and temperature compensation. Based on the fuel consumption and the calorific values of the respective fuels the fuel power input was calculated. The generated electricity  $P_{\text{el, net}}$  was measured with a clamp-on electrical power and energy meter, (Hioki HiTester 3169-20). The auxiliary electrical energy demand for fuel pumps, water pumps and the ventilation system was subtracted from the generator’s power output before. The amount of heat supplied to the heating system was measured with a Flexim F601 energy meter consisting of an ultrasonic clamp-on flow sensor and Pt100 sensors for the outgoing and return temperature of the CHP plant (inlet and outlet temperature of the heat sink).

In order to determine the maximum cylinder pressures and the knock-limit, engine indicating with individual pressure measurement for each cylinder was carried out. "Indicating" refers to an analysis of the cylinder's pressure profile in combustion engines as a function of the piston position, which is determined by the crank angle. From the data of the cylinder pressure analysis, it is possible to determine information as the peak combustion pressure, the pressure increase rate and the heat release rate, which allows an assessment of combustion behavior. Within the scope of this work only the peak pressure and the pressure traces were evaluated as indicator for engine stress. For determination of the crank angle an optical sensor AVL 365C was used, which was mounted on the crankshaft of the engine. The top dead center (TDC) was determined by means of a capacitive sensor in towed operation. For cylinder pressure measurement IMES sensors type CPS-01 with a measuring range from 0 – 300 bar were used. To determine the base line for the cylinder pressure, low-pressure sensors (Kistler 4049A) were installed in the intake manifold. In order to detect the activation of the fuel injectors, the current flow in the supply line to the injector was measured with a current probe.



**Figure 2.** The installation of the test bed for the experimental procedure – modified picture from [21].

## 2.2 Experimental Procedure

The experimental work was divided into two different procedures summarized in Table 1. In Procedure 1 the CHP system was equipped with the MAN D 26 Diesel engine with a compression rate of 19:1 and liquid fuel operation as well as dual fuel operation with different gas ratios were investigated (flexible dual-fuel mode). Since engine knock due to the high compression ratio proved to be the limiting factor for gas admixing in Procedure 1, the compression was reduced to 16:1 in Procedure 2 in order to be able to investigate higher gas ratios with a fixed injection quantity of liquid fuel (pilot ignition mode).

For the experiments a total of five different liquid fuels were used, with heating oil as the reference fuel, followed by biodiesel, rapeseed oil, soybean oil and palm oil. As gaseous fuel "biomethane" was used. The term biomethane represents methane from biogenous sources, usually biogas, which is purified and segregated into pure methane and carbon dioxide to meet the standards of the public natural gas grid. Biomethane is injected into the public gas grid at the place of production and extracted at the place of consumption based on a balancing mechanism. Physically biomethane is equivalent to natural gas from the public grid, but it is produced from renewable sources and thus has a considerably smaller carbon footprint.

**Table 1.** Experimental Procedures.

	<b>Procedure 1</b>			<b>Procedure 2</b>		
<b>op. mode</b>	MAN D26 common-rail dual-fuel flexible mode			MAN D26 common-rail pilot ignition mode		
<b>fuel</b>	<b>liquid fuel</b>	<b>dual fuel</b>	<b>liquid fuel</b>	<b>liquid fuel</b>	<b>dual fuel</b>	<b>dual fuel</b>
	heating oil	heating oil	biomethane	heating oil	heating oil	biomethane
	palm oil	palm oil	biomethane	palm oil	palm oil	biomethane
	soybean oil	soybean oil	biomethane	soybean oil	soybean oil	biomethane
	biodiesel	biodiesel	biomethane	biodiesel	biodiesel	biomethane
	rapeseed oil	rapeseed oil	biomethane	rapeseed oil	rapeseed oil	biomethane
<b>compr. ratio</b>	19:1	19:1		16:1	16:1	
<b>electrical load</b>	80 to 240 kW	80 to 240 kW		80 to 200 kW	80 to 240 kW	

**Table 2.** Technical and mechanical data of the investigated CHP systems [22].

<b>base engine</b>	MAN D 26
working process	4-stroke diesel/dual-fuel, turbocharger with 2-stage intercooler
displacement	12.4 liter
bore	126 mm
stroke	166 mm
rotational speed	1500 rpm
injection system	common-rail direct injection with solenoid injectors
cooling	water-cooled with exhaust gas heat exchanger
<b>generator</b>	Leroy Somer LSA 47.2 M8
type	synchronous
cooling system	air cooled
maximum power rating	550 kVA
voltage	400 V
frequency	50 Hz
cos phi	1
efficiency	96%

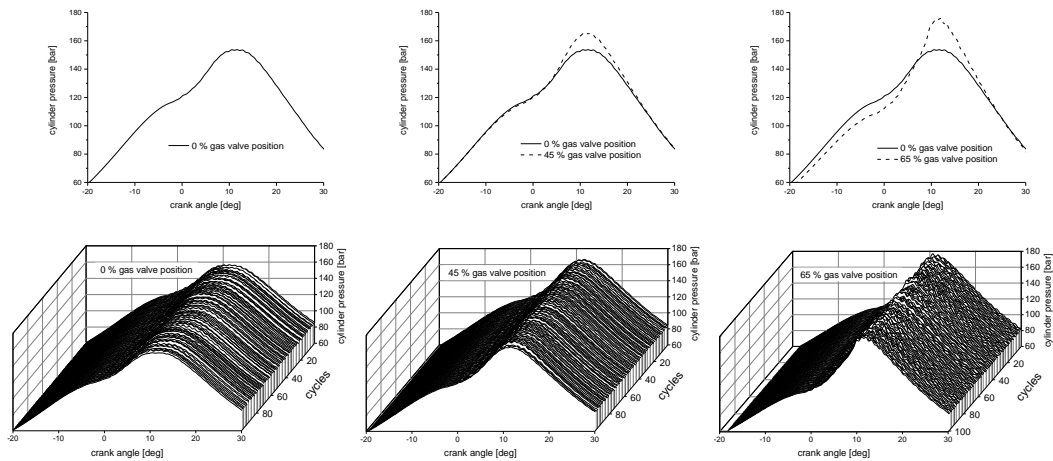
### 3. EXPERIMENTAL RESULTS

#### 3.1 Experimental Results Procedure 1

In Procedure 1 the CHP engine was configured as a flexible dual-fuel engine allowing different ratios of liquid to gaseous fuels, using a compression ratio of 19:1 and applying loads from 80 kW to 240 kW electric power output (minimum applicable load up to full load). The main application of this mode is to enable gas admixing whenever it is available on-site, but still keeping a fully functional diesel engine with a compression ratio and piston geometry optimised for diesel combustion. The engine essentially operates in diesel mode with 100 % liquid fuel and 0 % gaseous fuel, moving to gas-engine combustion with increasing admixture of gaseous fuel.

In this configuration the amount of gas that can be admixed to the intake air is primarily limited by the peak pressure and engine knock at higher loads. This effect is illustrated in Figure 3 for cylinder 4, which showed to be most prone to knock in the investigated engine configuration. The pressure traces presented in Figure 3 correspond to full load operation with 240 kW electric power output, heating oil as liquid fuel and biomethane as gaseous fuel. The gas ratio was increased from 0 % (liquid fuel operation) up to the individual maximum considered as safe for each operating point, which in this case was 65 %. The gas admixture is expressed as percentage of the gas valve position, where 0 % corresponds to a closed gas valve and 100 % corresponds to the gas valve being fully open.

It has to be noted that the dependency between the gas-valve position and the amount of gas in the compressed charge is not linear. Hence, in the following discussions the amount of gas admixed will be represented by its energy content expressed as fuel power input in kW. The maximum gas valve position of 65 % presented in Figure 3 corresponds to a fuel power input from biomethane  $P_{\text{gas}}$  of 141 kW and a fuel power input from heating oil  $P_{\text{liquid}}$  of 431 kW. All presented results refer to a liquid fuel injection timing of  $8^\circ$  crank angle before top dead centre, which in preliminary experiments was identified as optimum considering both efficiency and safe operation.



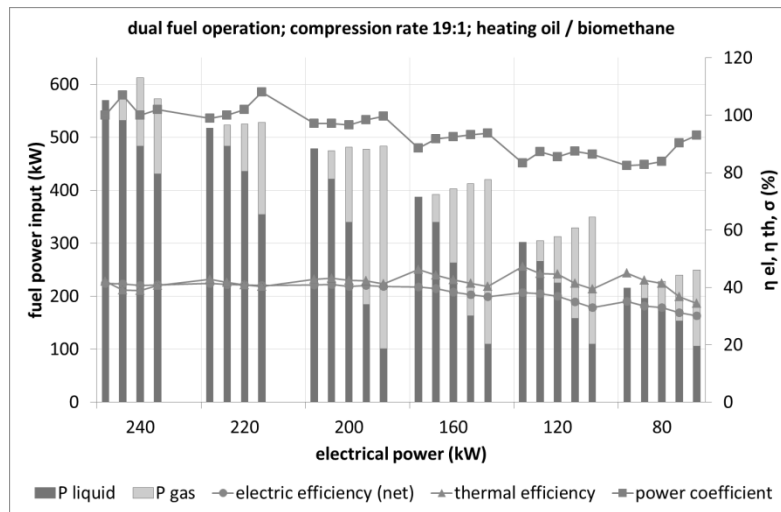
**Figure 3.** The cylinder pressure as function of the crank angle (cylinder 4) at 240 kW electrical load, heating oil / biomethane dual fuel operation, compression rate 19:1. In the lower line 100 single cycles are illustrated. The upper line shows the equivalent mean values.

In Figure 4 and Figure 5 the fuel power input, electric and thermal efficiency and power coefficient in flexible dual-fuel operation with heating oil and rapeseed oil and varying gas ratios are shown for electric loads from 80 kW to 240 kW.

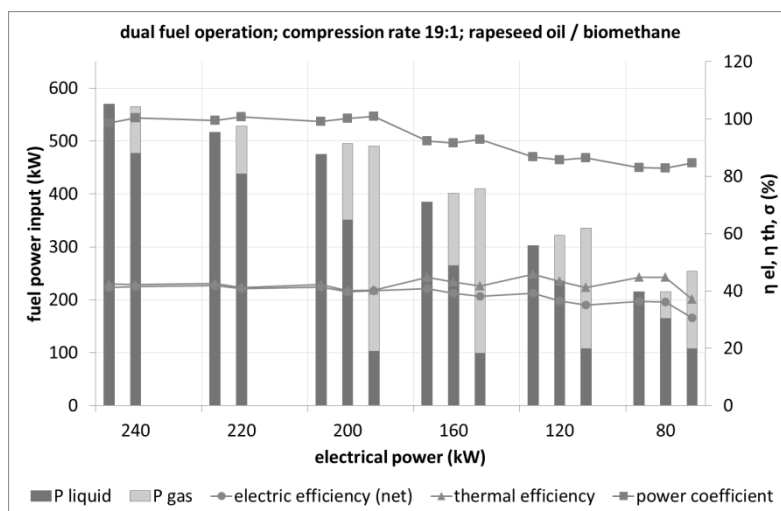
The highest admixture of gas could be achieved a medium loads. At high loads engine knocking and peak loads present the limiting factor, as described above, both with heating oil and biofuels. At low engine loads the limiting factor for gas admixture is the minimum injection quantity of liquid fuel, which was fixed at approximately 100 kW fuel power input. This minimum amount was set in the flexible dual-fuel configuration in order to ensure proper and stable operation under all conditions, even in case of gas supply failure.

Generally heating oil operation allows for slightly higher biomethane ratios compared to biogenous liquid fuels under full load. At all load categories, increasing biomethane ratios require a higher total fuel power input and lead to lower electric efficiencies. The maximum electric efficiencies were achieved with biodiesel and palm oil in liquid fuel operation (42.2 % and 42.1 % respectively), while the lowest electric efficiency was observed at minimum load and maximum gas ratio with heating oil and soybean oil (30.2 % and 30.5 % respectively). The power coefficient was in the range of 0.8 (minimum load with soybean oil) to 1.07 (full load with heating oil).

As an overall result it can be concluded that Procedure 1, the flexible dual-fuel mode with compression ratio 19:1, is suited for variable ratios of gaseous and liquid fuels with good electric efficiency in a considerably wide range, especially at mid loads. It is the preferred choice when flexible operation is required and liquid fuels are the primary fuel source, while allowing to additionally using gaseous fuels whenever available.



**Figure 4.** Fuel power input ( $P_{gas}$  and  $P_{liquid}$ ), electric ( $\eta_{el}$ ) and thermal efficiency ( $\eta_{th}$ ) and power coefficient ( $\sigma$ ) in flexible dual-fuel mode with heating oil and heating oil/biomethane.



**Figure 5.** Fuel power input ( $P_{gas}$  and  $P_{liquid}$ ), electric ( $\eta_{el}$ ) and thermal efficiency ( $\eta_{th}$ ) and power coefficient ( $\sigma$ ) in flexible dual-fuel mode (compression rate 19:1) with rapeseed oil and rapeseed oil/biomethane.

### 3.2 Experimental Results Procedure 2

In Procedure 2 the CHP engine was configured for pilot ignition operation with a compression rate of 16:1 and a fixed injection quantity of liquid fuel equivalent to about 40 kW of fuel power input.

Firstly, different liquid biogenous fuels were investigated and the CHP system was operated with 100 % liquid fuel. Heating oil was again used as reference fuel. The maximum power was limited to 200 kW in liquid fuel operation due to the smaller pressure rating of the 16:1 pistons, which does not allow cylinder peak pressures as high as in Procedure 1. The results show decreasing electrical efficiencies from 41.8 % (200 kW) to 35.2 % (80 kW), regardless of the type of liquid fuel. The thermal efficiencies were nearly constant at 43 % (from 200 kW to 80 kW), thus the power coefficients decreased from nearly 1.0 to 0.8, regardless of the used fuels. Compared to the

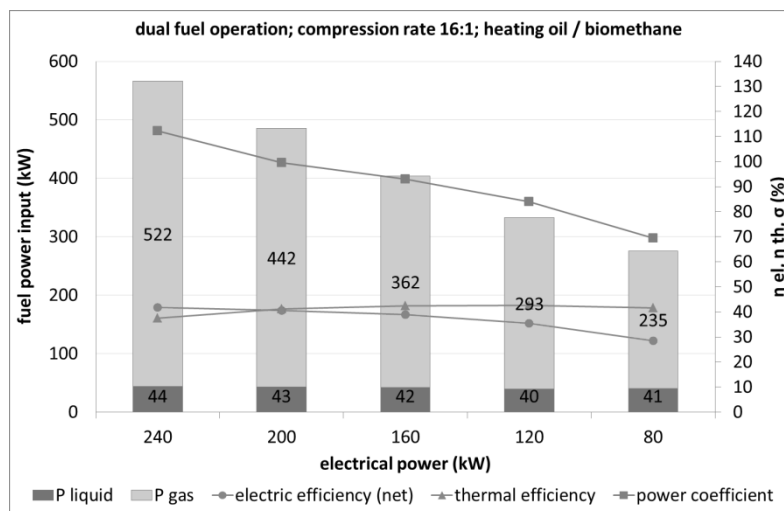
compression rate of 19:1 (Procedure 1), there is no significant efficiency disadvantage in the observed range of performance, although the compression ratio had been reduced to 16:1.

Secondly, biomethane was admixed to the intake air and the amount of liquid fuel was reduced to the pre-defined minimum of 40 kW (pilot injection). As shown in Figure 6 the pre-defined liquid fuel ratio is constant at all loads in heating oil/biomethane dual fuel operation. As a consequence, the additional fuel power input  $P_{\text{gas}}$  is provided from biomethane and increases up to 522 kW at 240 kW electrical load. Under full load operation the electrical efficiency is 41.8 % and decreases down to 28.4 % at the minimum applicable electric load of 80 kW.

The results when using biofuels as pilot fuel were almost equivalent to heating oil, showing a slight advantage in electric efficiency for the pure plant oils over biodiesel (c. f. results for rapeseed oil in Figure 7). The respective values of electric efficiency at full load and minimum load were 40.8 % / 28.9 % (biodiesel/biomethane), 41.6 % / 29.3 % (rapeseed oil/biomethane), 42.3 % / 29.6 % (palm oil/biomethane) and 41.8 % / 29.5 % (soybean oil/biomethane). Part load efficiency of the pure plant oils compared to heating oil and biodiesel was generally slightly better, especially at medium loads.

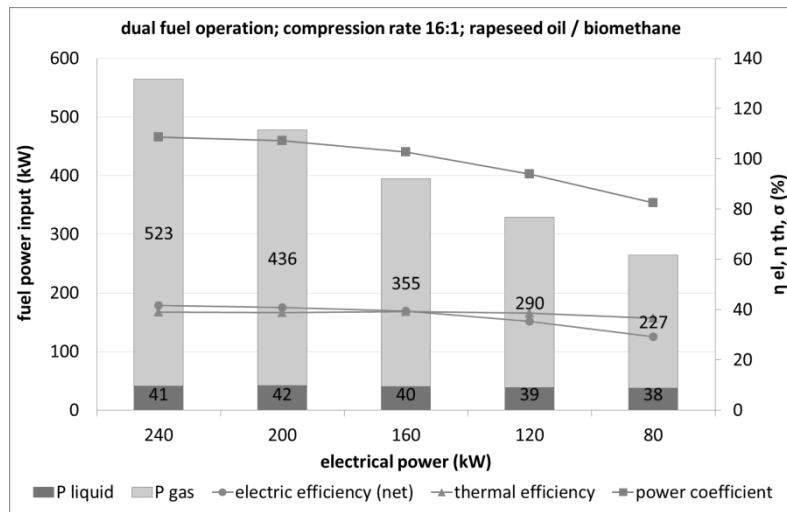
The power coefficients were 1.12 at maximum (heating oil/biomethane) and 0.69 at minimum (heating oil/biomethane), with a slight advantage for the pure plant oils at part load, for which the power coefficient decreased only down to 0.82 (rapeseed oil/biomethane). However, it should be noted that measurement of the thermal power output, which influences the power coefficient, depends on the inlet and outlet temperatures of the heat sink, which in the considered case is a district heating system. Thus at least some part of the effect has to be assigned to ambient conditions. This has to be better accounted for in future experiments.

As an overall result it can be concluded that Procedure 2 allows significantly higher biomethane ratios than Procedure 1, because of the reduced compression rate of 16:1, which effectively reduces peak pressure and knock, without sacrificing efficiency. Compared to Procedure 1 (flexible dual-fuel mode) the pilot ignition mode shows lower values of electric efficiency under light load, identical values under mid load and significantly better values above 200 kW. It allows for the highest gas ratios combined with the best electrical efficiencies at full load and is thus the optimum configuration when gaseous fuels are to be used as primary energy source.



**Figure 6.** Fuel power input ( $P_{\text{gas}}$  and  $P_{\text{liquid}}$ ), electric ( $\eta_{\text{el}}$ ) and thermal efficiency ( $\eta_{\text{th}}$ ) and power coefficient ( $\sigma$ ) in pilot injection mode (compression rate 16:1) with heating oil/biomethane.





**Figure 7.** Fuel power input ( $P_{\text{gas}}$  and  $P_{\text{liquid}}$ ), electric ( $\eta_{\text{el}}$ ) and thermal efficiency ( $\eta_{\text{th}}$ ) and power coefficient ( $\sigma$ ) in pilot injection mode (compression rate 16:1) with rapeseed oil/biomethane.

#### 4. SUMMARY AND OUTLOOK

Dual-fuel engines can be an interesting option for efficient supply of heat and power in CHP systems, using a variety of both liquid and gaseous fossil and biogenous fuels. Within the scope of ongoing research at the Competence Centre for CHP technologies two different dual-fuel configurations derived from the same base engine were tested with biomethane as gaseous fuel, using heating oil and various biofuels as pilot fuel.

Procedure 1, referred to as “flexible dual-fuel mode”, features a compression ratio of 19:1 with piston geometries optimized for diesel combustion and proved to be suitable for variable ratios of gaseous and liquid fuels with good electric efficiency in a considerably wide range, especially at mid loads. It is the preferred choice when flexible operation is required and liquid fuels are the primary fuel source, while allowing to additionally using gaseous fuels whenever available. Procedure 2, referred to “pilot ignition mode”, features a reduced compression rate of 16:1 and piston geometries optimized for gas engine combustion, helping to effectively reduce peak pressure and knock, without sacrificing efficiency. This configuration allows for significantly higher biomethane ratios than Procedure 1, but limits the applicable liquid fuel quantities. Compared to Procedure 1 (flexible dual-fuel mode) the pilot ignition mode shows lower values of electric efficiency under light load, identical values under mid load and significantly better values above 200 kW. It allows for the highest gas ratios combined with the best electrical efficiencies at full load and is thus the optimum configuration when gaseous fuels are to be used as primary energy source. In flexible dual-fuel configuration the best efficiency was reached in liquid fuel operation, while in pilot ignition configuration the best efficiency was obtained in dual-fuel operation with maximum share of gas. In both procedures high electric efficiencies of more than 42 % could be achieved, along with power coefficients of about 1, which proves the good energetic efficiency of the investigated CHP engines.

The presented results are the basis for further research which will focus more in detail on combustion behaviour and pollutant emissions from dual-fuel engines as well assessment of the ecological impact. Additionally it is planned to investigate further combinations of gaseous and liquid biofuels, concentrating especially on fuels derived from organic residues.

## REFERENCES

- [1] Dinçer, I., Zamfirescu, C. Advanced power generation systems. Amsterdam, Netherlands: Elsevier; 2014.
- [2] Brautsch, M., Lechner, R., Meierhofer, T. Innovatives Energieversorgungskonzept für den Standort Weiherhammer: Wissenschaftlich begleitetes Demonstrationsvorhaben der BHS Corrugated. Wellpappe 2008(6):17–20.
- [3] Brautsch, M., Meierhofer, T., Lechner, R. Ganzheitliche Optimierung durch Ringleitungsnetz. Blockheizkraftwerke 2009. Euro Heat & Power;2009:22–5.
- [4] Brautsch, M., Hofer, R. Alternative zum IKSK - Energienutzungspläne als Schlüssel zur Energieeffizienz in der Kommune ? Change 2013(7):2–7.
- [5] Brautsch M. Energieeffizienz und Klimaschutz in Wohnungsunternehmen: Ökonomisch sinnvolle Lösungen als Resultat eine wissenschaftlich neutralen Handlungskonzeptes. wohnen;2012(102):204–7.
- [6] Meyer, B., Scholz, R., Daschner, R., Binder, S., Jakuttis, M., Hornung, A., Brautsch, M. Mikro KWK Systeme in Wohnanlagen - Analyse verschiedener Betriebsstrategien. Euro Heat & Power;September 2013:30–6.
- [7] Pant, K. K., Pravakar, M. Biomass, Conversion Routes and Products - An Overview. In: Andreas Hornung, editor. Transformation of Biomass Theory to Practice: Wiley; 2014, p. 1–30.
- [8] Bialkowski MT. Theoretical and Experimental Investigation of a CDI Injection System Operating on neat rapeseed oil - feasibility and operational studies. Edingburgh; 2009.
- [9] Hornung A., Apfelbacher A., Neumann J., Jäger N., Schmitt N., Dascher R. Combined heat and power generation from solid biomass derived bioliquids and syngas by TCR - Upgrade of TCR-liquides by hydrodeoxygenation: Paper presented at 24th European Biomass Conference and Exhibition, EUBCE 2016, Amsterdam, 6-9 June. European Biomass Conference and Exhibiton (EUBCE), 2016.
- [10] Ouali, M., Yang, Y., Hornung, A. Engines for Combined Heat and Power. In: Andreas Hornung, editor. Transformation of Biomass Theory to Practice: Wiley; 2014, p. 159–173.
- [11] Grünig G. Zündstrahlmotoren: Effiziente Verbrennung von Biogas und Schwachgasen in Blockheizkraftwerken. Landsberg/Lech: Verl. Moderne Industrie; 2010.
- [12] Hegab, A., La Rocca, A., Shayler, P. Towards keeping diesel supply and demand in balance: Dual-fuelling fo diesel engines with natural gas. Renewable and Sustainable Energy Reviews <http://dx.doi.org/1016/j.rser.2016.11.249>.
- [13] Chintala, V., Subramanian, K.A. A comprehensive review on utilization of hydrogen in a compression ignition enging under dual fuel mode. Renewable and Sustainable Energy Reviews 2017;70:472–91.
- [14] Husberg, T., Denbratt, I., Karlsson, A. Analysis of advanced multiple injection strategies in heavy - duty diesel engine using optical measurements and CFD-simulations. SAE paper 2008;01-1328.
- [15] Sunmeet, S.K., Subramanian, K.A. Effect of simulated biogas on performance, combustion and emissions of a bio-diesel fueled diesel engine. Renewable Energy 2017;106:78–90.
- [16] Barik, D., Murugan, S. Experimental investigation on the behavior of a DI diesel engine fueled with raw biogas-diesel dual fuel at different injection timing. Journal of the Energy Institute 2016;89:373–88.
- [17] Hongyuan, W., Chunde, Y., Wang, P., Guopeng, H., Zhancheng, D., Taoyang, W., Meijuan, L., Bin, W., Jian, G., Chao, C., Junjie, S. Experimental investigations of the effects of pilot injection on combustion and gaseous emission characteristics of diesel/methanol dual fuel engine. Fuel 2017;188:427–41.
- [18] Bhaskor, J.B., Ujjwal, K.S. Optimisation of injection timing and compression ratio of a raw biogas powered dual fuel engine. Applied Thermal Engineering 2016;92:111–21.
- [19] Bhaskor, J.B., Ujjwal, K.S. Comparative assessment of a biogas run dual fuel engine with rice bran oil methyl ester, pongamia oil methyl ester and palm oil methyl ester as pilot fuels. Renewable Energy 2015;81:490–8.
- [20] Eder L, Kiesling C, Pirker G, Wimmer A. Development and Validation of a Reduced Reaction Mechanism for CFD Simulation of Diesel Ignited Gas Engines. In: Leipertz A, editor. Engine Combustion Processes (XIII. Congress): Current Problems and Modern Techniques; 2017, p. 299–312.
- [21] Lechner R., O'Connell N., Brautsch M. Identifikation von Einsatzmöglichkeiten und Potentialen der Zündstrahltechnologie zur Verbesserung der Anlageneffizienz und Wirtschaftlichkeit von BHKW-Anlagen mit experimenteller Überprüfung der Vorteile an einer Pilotanlage unter realen Bedingungen im Praxisbetrieb. Stuttgart: Fraunhofer-IRB-Verlag; 2015.
- [22] Burkhardt GmbH, Energy and Building Technology, Kreutweg 2, 92360 Mühlhausen Germany.