Air-Fuel Mixture Temperatures with Light and Heavy Fuels for Effective Spark Ignition Engine Work

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Abstract:

This research resulted from military interest in finding methods to provide distributed electricity generation in order to support comprehensive state defence measures. The aim of the study was to investigate the effect of a heated air-fuel mixture on the combustion process of a spark ignition (SI) engine, and to highlight the maximum temperatures to be applied to air-fuel mixtures with different fuel fractions in order to avoid any detonation of the fuel mixture in the engine. Tests were carried out with a petrol engine generator (GENSET) so that an investigation could be conducted into the effect of the air-fuel mixture on the engine's combustion. It turned out that heating the air-fuel mixture permits the use of heavier fraction fuels than engine petrol in SI engines does, including diesel fuel and biodiesel fuel, and also that the use of heavy fraction fuels in SI engines is effective mainly under low and middle loads.

Keywords:

Abbreviations

ABP	after burning phase
AFM	air fuel mixture
AFR	air fuel ratio
ATDC	after top dead centre
BTDC	before top dead centre
EF	ethanol fuel
EP	engine petrol

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FDP   flame development phase
FSS   fuel supply system
GENSET   electrical generator with combustion engine
HEX   heat exchanger
HNS   host nation support
HRR   heat release rate
ICE   internal combustion engine
ICT   information communication technology
Jet   jet fuel
LoC   line of supply
MFB   mass fraction burnet
RBP   rapid burning phase
RHR   relative heat release
SI   spark ignition
TDC   top dead centre

1 Introduction

According to NATO's own principle, in the event of a military attack its member states must first ensure their own defence capabilities. This requires then to fight with limited resources until comprehensive joint operations can be launched. A full-scale launch of a NATO Article 5 response will take between two to three months. A military invasion is preceded by a gradual escalation into military action, forcing the country to use resources in advance. If those resources have been used prior to the commencement of battle operations and Host Nation Support (HNS) does not have military control of most of the country's territory, Article 5 response will not be launched. Nowadays, the management of state and military operations is based on electricity-consuming ICT (Information Communications Technology), and if there is no energy then there is no management. Regardless of war, peace, emergency, or a crisis situation, distributed ICT systems must be kept operational to ensure national security. Energy security is key, and it requires the production of the required amount of distributed off-the-grid electricity by all possible means. Assets are for peacetime tasks, but crisis reserves are mainly 'national' resources which are in the hands of businesses and individual citizens. The resources for mobile electricity production, independent of wind and the sun, cover engine petrol (EP) generators (GENSET) which can be requisitioned from warehouses, shops, and homes.

A simple and reliable means of generating electricity is a generator which is connected to an internal combustion engine. Small cubic GENSET with a carburettor fuel supply system (FSS) and spark ignition (SI) are widespread. A GENSET with a SI is ten times cheaper than the corresponding compression ignition (CI) engine. The use of EP or ethanol fuel (EF) additive EP only becomes a problem in times of crisis or war, as the fuel supply chains and lines of communication (LoC) are hindered or disrupted. In this case, it must be possible to use a wide variety of fuels in the SI engine, from heavy to light fuels, from fossil fuels to biofuels [1-4], as well as the NATO Single Fuel Concept Jet-A1 (Jet) [5, 6]. Mixtures of biofuels and fossil fuels in any ratio are also considered [7]. The introduction of liquid biofuels continues at an increasing pace, but liquid fossil fuels will certainly be in use for decades to come [8], as a well-functioning global production and distribution network has long existed for them [9].

An SI engine with a carburettor FSS can use EF, Jet without additives, and CI fuels such as diesel fuel (DF) and hydrogenated vegetable oil (HVO) if the air-fuel mixture (AFM) is heated [10]. The effect of heating heavy fraction fuels in the SI engine has been previously studied in carburettor and injection FSS´s. Research [11-20] focuses mainly on reducing the hazardous components that are contained within exhaust gases, solving cold start problems, and reducing the engine's fuel consumption rate, as well as on the combustion of various AFM's in the engine's cylinder. In addition, the use of heat energy in different heat exchangers (HEX) is something that has been studied in the past, but the research has focused more on the recovery of heat energy from exhaust gases and the study of cooled exhaust gases [21-28]. It is already accepted that heavy fuels result insufficient quality AFM in the formation of an AFM in an SI piston engine with a carburettor, because the heavy fuel fractions do not evaporate. The combustion of a low-quality AFM in the engine's cylinder is poorer and, as a result, the content of hazardous components (CO, CO_2, HC, and soot) in the exhaust increases, the engine oil gets polluted faster because portions of unburnt fuel enter the engine crankcase from the cylinder walls, and a rich air-fuel mixture results in the early combustion of the air-fuel mixture [29].

In addition, studies have also been conducted in terms of the effect of Jet and bi-odiesel and diesel fuel blends (20:80) on the small cubic SI engine. It has been found that the carburettor FSS should be replaced by an injection FSS because the carburised AFM is of insufficient quality and, therefore, the FSS is unable to maintain the correct air-fuel ratio (AFR) throughout the load mode of the piston engine [12-14]. The research has not indicated at which AFM temperatures different fuels can be used in the SI engine using the heated AFM method. Due to the different specific properties of the fuels, the AFM for various fuels has to be heated at different temperatures. This is due to several factors such as, for example, the air–fuel equivalence ratio (λ) affecting the ignition and combustion of the AFM. In addition, it is important to know what the combustion process is like in the engine when the AFM is being heated to a temperature which is above that at which detonation occurs in the engine. However, when using heavy fraction fuels, it is important to keep the temperature of the AFM as high as possible to ensure fuel evaporation.

The aim of this study was to investigate the effect of a heated AFM on the combustion process for a SI engine, and to identify the maximum temperatures to be used for AFM with different fractions in order to avoid any detonation of the AFM in the engine. In particular, this article analyses the effects of AFM temperatures when using engine petrol (EP), ethanol fuel (EF) (anhydrous), jet fuel Jet A-1 (Jet), diesel fuel (DF), and hydrogenated vegetable oil (HVO) on the SI engine's combustion process. The test subject was a GENSET equipped with a carburettor FSS. The broader aim of the research is to uncover solutions which will help to prevent an energy crisis which could arise in the event of war, emergency, or crisis situation, using different fuels in off-the-shelf petrol engine GENSET's.

2 Materials and Methods

2.1 Setting Up the Test

The test engine was a GENSET, which was equipped with a carburettor FSS. The maximum allowable load for the electric generator was 2.8 kW. During test preparations, the GENSET was loaded to 2.5 kW, but at this load the engine was able to run at

2 700 rev/min only, while the factory speed is 3 000 rev/min. To ensure the intended speed mode for the engine, the generator loads were selected to be 2.0 kW, 1.5 kW, and 1.0 kW. During the tests, the test engine was loaded with light bulbs. The motor's speed mode is important in terms of it maintaining a stable mains frequency. The technical details for the test engine and test equipment including tested fuels are given in Tab. 1.

Tab. 1 Test equipment and fuels

The data of experiment GENSET DB3500CL					
Strokes	4		Connection rod length		84.80 mm
Cylinder	1		Swept volume (V_d)		207.42 cm^3
Displacement	208 cm^3		Clearance volume (V_c)		28.28 cm^3
Engine power	3.6 kW		Total volume (V_t)		235.70 cm^3
Speed (n_e)	3 000 rev/min		Compression ratio (r_c)		8.00
Bore	70.00 mm		Bore to stroke ratio (R_{bs})		1.29
Stroke (l)	54.00 mm		Connection rod to stroke ratio (R)		3.14
FSS	Carburettor		Crankshaft radius (α)		27.00 mm
The weighing instrument CAS CI2001A					
Weight CI-2001, Digital			Measurement accuracy $\Delta m = 1$ g		
The combustion pressure measurement system AVL 621					
Signal amplifier AVL 2P2E					
SI engine pressure sensor ZF43			Measurement accuracy 1.5 %		
The air consumption measurement system AVL					
AVL Flowsonix Air 100			Measurement accuracy < ± 1 %.		
The fuels					
Parameter	Unit	EP*	EF*	Jet A-1*	DF*	HVO*
Molecular composition	—	C$_5$-C$_{11}$	C$_2$	C$_7$-C$_{16}$	C$_{15}$-C$_{23}$	C$_{15}$-C$_{23}$
Density at 15 °C	kg m^{-3}	700-750	789	787	765	775-785
Viscosity at 40 °C	mm^2 s^{-1}	0.6	0.80	0.94	2.0	2.5-3.5
Octane[1] - Cetane number[2]	—	87-97[1]	108[1]	30-40[1]	15-25[1]	~80-99[2]
Boiling point at atm	°C	25-220	78.37	147-230	160-360	269-313
Flash point	°C	−45	17	35-51	50-65	78
Calorific value	MJ kg^{-1}	43.5	26.8	43	45.4	44
AFR		14.6/1	9/1	15.6/1	14.6/1	14.6/1

* [30-42]

The time taken to measure fuel consumption was seven minutes. Fuel consumption was measured every sixty seconds using a CAS CI2001A weighing instrument. Combustion pressures were measured using an AVL 621 and fifty operating cycles were recorded for each test. Combustion pressures were averaged out, and the heat release rate (HRR) and relative heat release (RHR) were calculated. The heat release rate (HRR), in relation to the rotational angle of the crankshaft, is expressed as follows [43, 44]:

$$\frac{dQ_n}{d\varphi} = \frac{\gamma_{hr}}{\gamma_{hr}-1} P_c \frac{dV_c}{d\varphi} + \frac{1}{\gamma_{hr}-1} V_c \frac{dP_c}{d\varphi} \tag{1}$$

where P_c – cylinder pressure; γ_{hr} – isentropic exponent; V_c – cylinder volume; $d\varphi$ – crank angle.

The combustion process was divided into three phases [44]: 1) a flame development phase (FDP); 2) a rapid burning phase (RBP); and 3) an after-burning phase (ABP). The spark angle for the test engine was 48° BTDC.

In order to obtain the required reference data, the efficiency and economy parameters for the test engine were first measured at the aforementioned loads. An AFM heating unit was then added to the engine and additional measurements were taken in order that an investigation could be carried out into the effects the unit may be having on the engine's output parameters. The construction and operation of the AFM heating unit are presented below in the form of a separate subsection.

In the tests on different fuels, the temperature of the AFM was raised as high as possible until detonation occurred in the engine cylinder. The temperature of the AFM was then reduced until stable engine operation could be achieved, along with the non-detonated combustion of the AFM. The tests were then carried out. Since the process of heating the AFM serves to change the speed and timing of the combustion phases, the tests were carried out with the heated AFM at a spark angle of 31° BTDC.

The fuel that was used in the experiment was EP, EF, Jet, DF and HVO. The most important chemical and physical properties of those fuels which were used in the tests are given in Tab. 1, and this is something which must be taken into account when heating the AFM. A carburettor nozzle with a nozzle opening of 0.8 mm was used for all fuels except EF, for which the nozzle orifice diameter was expanded to 1.2 mm.

2.2 Operating Principles for the AFM Heating Unit

To be able to study the effects of the heated AFM, an AFM heating unit based on a process of heat exchange was added to the SI piston engine, which allowed the residual heat energy of the exhaust gases to be transferred into the AFM. The arrangement of the heating unit between the carburettor and the intake manifold is shown in Fig. 1. The cross-sectional area of the AFM channel which was used in the heating unit increases towards the intake manifold due to the expansion of the heated AFM. Tab. 2 reveals the parameters for the most important components of the heat exchanger (HEX) which was added to the FSS.
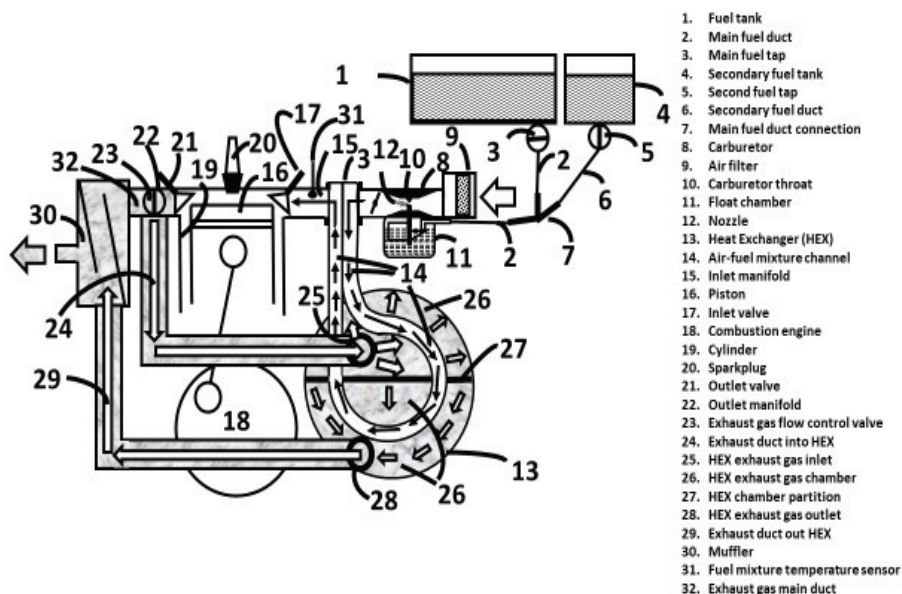

1. Fuel tank
2. Main fuel duct
3. Main fuel tap
4. Secondary fuel tank
5. Second fuel tap
6. Secondary fuel duct
7. Main fuel duct connection
8. Carburetor
9. Air filter
10. Carburetor throat
11. Float chamber
12. Nozzle
13. Heat Exchanger (HEX)
14. Air-fuel mixture channel
15. Inlet manifold
16. Piston
17. Inlet valve
18. Combustion engine
19. Cylinder
20. Sparkplug
21. Outlet valve
22. Outlet manifold
23. Exhaust gas flow control valve
24. Exhaust duct into HEX
25. HEX exhaust gas inlet
26. HEX exhaust gas chamber
27. HEX chamber partition
28. HEX exhaust gas outlet
29. Exhaust duct out HEX
30. Muffler
31. Fuel mixture temperature sensor
32. Exhaust gas main duct

Fig. 1 Schematic diagram of the engine equipped with AFM heating unit

The air-fuel mixture is directed to the HEX 13 and from the HEX 13, the AFM moves into AFM channel 14, where it is additionally mixed and heated up due to the heat being transferred from the exhaust gases. After that, the additionally-mixed and heated AFM moves from the HEX 13 to intake manifold 15, and from there to the engine. Exhaust gases from the engine are directed either to muffler 30 or the HEX 13, where the heat energy from the exhaust gases is transferred into the AFM. According to the engine load, the temperature of the AFM is regulated by exhaust gas flow control valve 23. If the AFM mixture is not heated, exhaust gas control valve 23 remains in the open position; when heated, valve 23 is in the closed position. To be able to achieve a higher AFM temperature, the exhaust gas flow through the HEX must be increased.

Tab. 2 Basic data of the technical components of heating unit

Technical component	Unit	Value
HEX AFM channel operating part length	cm	21
Cross-sectional area of exhaust gas inlet and outlet ducts	cm^2	2
The volume of the exhaust chamber of the HEX	cm^3	400
AFM inlet openings cross-sectional areas	cm^2	3.15
AFM outlet openings cross-sectional areas	cm^2	4.7
AFM channel cross-sectional maximum area	cm^2	6.05
The volume of the HEX AFM channel	cm^3	100
The HEX AFM channel heated part	cm^3	80

3 Results and Discussion

In the following data tables, the most important data of the experimental environment, are shown, such as carburettor nozzle orifice diameter (A_n), ambient humidity (r), ambient temperature (t_{env}), air-fuel mixture temperature in the inlet manifold (intake), and detonation starting temperature (t_{deto}). In addition, the theoretical amount of energy directed into the cylinder per cycle (E_{teor}), fuel consumption (B_f), and air consumption (B_a) are presented.

Fig. 2 displays the HRR in graphical terms, and Tab. 3 displays the most important details from the test environment and the tests at a load of 1.0 kW. Based on the information contained in Tab. 3, the duration of the FDP using an unheated EP relative AFM is 64°. Fig. 2 shows that the HRR's progress is smooth. The RBP lasts for 68° and the total duration of the combustion process is 132°. When unheated EF is used, the FDP is 63° and the RBP is 70°. The duration of the total combustion time for AFM is 133°. Fig. 2 shows that the transition of HRR from one phase to another is smooth. With Jet, the FDP lasts for 65° and the RBP lasts for 63°. Fig. 2 shows that the HRR's progress is smooth. The total combustion duration is 128°.

EP, EF and Jet can be used in an unmodified engine but in case of the Jet, the AFM used is rich due to the high viscosity of the Jet. The high viscosity prevents the fuel from being effectively carburised, and a lean relative AFM prevents the ignition of the AFM in the cylinder because there is not enough evaporated fuel drops in the AFM. Therefore, in order to use Jet more efficiently, it is important to ensure the more efficient evaporation of the fuel. The HRR graph is similar for all fuels because, based on the theory, the combustion efficiency at lambda values of 0.7 to 1.1 is similar.
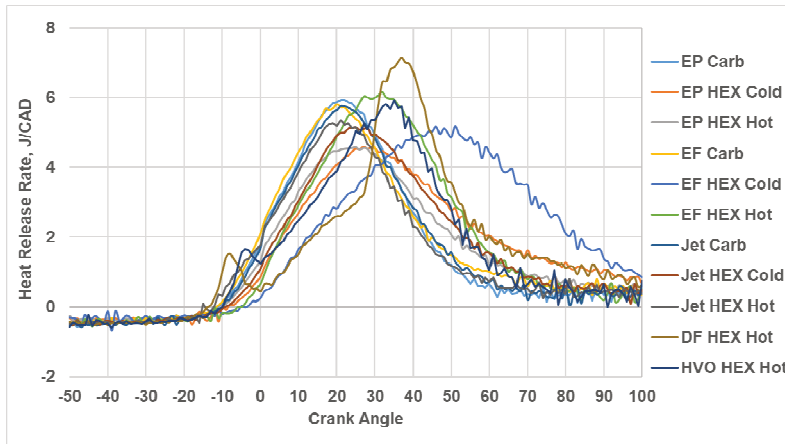
Fig. 2 HRR at load 1.0 kW

Tab. 3 Test data at load 1.0 kW

Parameter	Unit	EP Carb	EP HEX Cold	EP HEX Hot	EF Carb	EF HEX Cold	EF HEX Hot	Jet Carb	Jet HEX Cold	Jet HEX Hot	DF HEX Hot	HVO HEX Hot
A_n	mm	0.8	0.8	0.8	1.2	1.2	0.8	0.8	0.8	0.8	0.8	0.8
R	%	26	44	44	24	51	30	24	24	24	40	52
t_{env}	°C	24	16	18	22	24	27	21	18	20	26	24
t_{intake}	°C	26	30	112	33	20	140	13	12	117	120	106
t_{deto}	°C			120			145			125	125	115
BTDC	deg	48	48	31	48	48	31	48	48	31	31	31
t_{oil}	°C	81	75	90	77	82	102	74	77	85	74	80
n_e	rpm	3 000	2 925	3 011	3 011	3 000	3 000	3 006	2 987	3 025	3 026	3 019
λ	—	0.98	1.06	1.12	0.90	1.17	1.0	0.7	0.97	1.22	0.60	0.93
E_{teor}	J	286.1	317.1	278.4	312.7	303.3	294.0	394.2	280.6	217.9	523.2	379.8
B_f	kg/h	0.56	0.62	0.54	1.01	0.98	0.95	0.83	0.59	0.46	1.10	0.80
B_a	kg/h	8.12	9.68	8.88	8.20	10.3	8.56	8.50	8.43	8.30	9.76	11.0
FDP	deg	−48-16	−48-20	−31-17	−48-15	−48-15	−31-21	−48-17	−48-21	−31-16	−31-27	−31-22
RBP	deg	17-84	20-100	17-90	16-85	16-85	22-72	18-80	22-83	17-88	28-91	23-73
ABP	deg	85-141	101-145	91-139	86-138	91-139	73-140	81-140	84-141	89-138	92-139	74-141
MFB 10 %	deg	16	20	17	15	29	21	17	21	16	27	22
MFB 50 %	deg	29	43	35	30	53	37	30	37	30	43	37
MFB 90 %	deg	84	100	90	85	90	72	80	83	88	91	73

In EP tests with a cold HEX, the FDP is 68°. Fig. 2 shows that the HRR's progress is smooth, although when compared to the test without HEX, the combustion of the AFM takes place at a later point in the process. The RBP lasts for 80° and the overall combustion duration is 148°. When using EF fuel with a cold HEX, the FDP is 78°. The HRR's progress is smooth and comparable to the use of EP. When compared to a conventional engine test, combustion takes place significantly later. The duration of the RBP is 61°. The general combustion duration of the AFM lasts for 139°. With the Jet, the FDP lasts for 69°. The HRR graph shows that the HRR is steady but is later than with a factory engine setting. The RBP is 62°. The total burning time is 131°. In conclusion, the onset of combustion for the EP AFM with a cold HEX takes place somewhat later and its duration is longer. When using EF, the FDP is nine degrees longer than in an engine which is still using the factory settings, but the RBP is nine degrees shorter. In the case of a cold HEX and a Jet AFM, the combustion process is somewhat later than in an engine which still has its factory settings. When comparing with and without a HEX, it can be seen that the use of a HEX prolongs the FDP and postpones the onset of energy release in the EP and Jet fuel combustion process. This is due to the formation of a leaner AFM in the cylinder. When looking at the MFB50 data in the Tab. 3, it appears that the AFM's ignition and combustion processes are delayed when using all forms of fuel along with a HEX, as compared to the engine which has the factory settings. In theory, the AFM combustion has an MFB50 of 5° to 7° ATDC [44]. In the case of the engine that was being tested, delayed combustion is caused by the fact that the spark angle cannot be set for different loads, so instead it is set primarily for high loads being place on the engine.

The combustion of the heated EP AFM has a FDP of 48° and a RBP of 73°. The conversion of enthalpy to an endothermic exothermic reaction is smooth, and is similar to the results for the cold HEX test. The general combustion phase has a duration of 121°. The heated EF AFM has a FDP of 52°. The RBP phase lasts for 51°. HRR progress is similar to that for the use of EP. However, the maximum value of the HRR is higher when compared to a cold HEX and the use of EF. The total combustion duration is 103°. The heated AFM of Jet has a FDP of 47° and the RBP is 72°. The total combustion duration is 119°. When compared to a cold AFM of Jet, the combustion duration for the AFM is around twelve degrees shorter. As a result, the timing of the combustion phases has also changed.

The heated DF AFM has a FDP of 58° and a RBP of 64°. The overall combustion duration is 122°. The values for the HRR graph are significantly higher than for other fuels which were used as a comparison. This can be attributed to the chemical and physical properties of the fuel. Heavy fuel fractions do not burn in the cylinder. At the same time, it is important that enough fuel is directed into the cylinder to ensure the AFM's ignition and combustion in the cylinder. With a heated HVO AFM, the FDP is 53°, the RBP is 51°, and the combustion duration is 104°. When using both HVO and DF, the HRR graph shows a clear difference in combustion phases, which is something that is characteristic of CI engines. The HRR graph has a premixed combustion phase at −20 to zero degrees of crankshaft rotation for DF, and at −12 to zero degrees for HVO. This is due to the different fuel fractions for the DF and HVO, where the light fractions evaporate and combust rapidly and thereafter the ignition of heavy fractions takes place. In conclusion, fuels with heavy fractions combust somewhat differently in the SI engine when compared to EP and EF. In the DF and HVO combustion process, different phases are formed (the pre-mixed controlled and mixing controlled phases), which are not characteristic of the SI engine.

Fig. 3 shows the HRR in graphic form, whereas Tab. 4 shows the most important test information for a GENSET load of 1.5 kW.
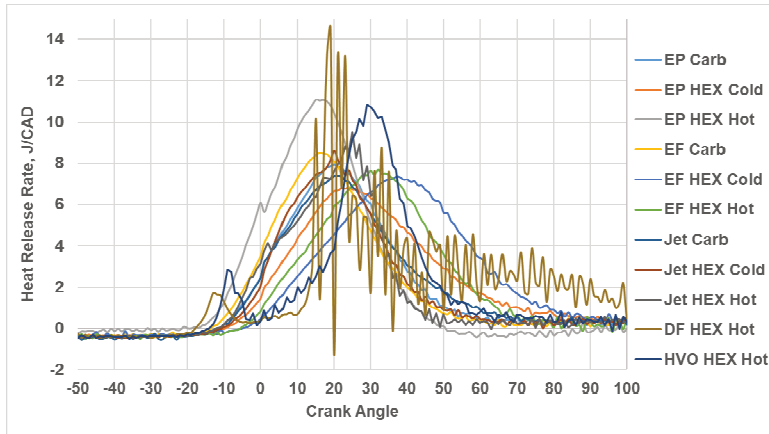

Fig. 3 HRR at load 1.5 kW

Tab. 4 Test data at load 1.5 kW

Parameter	Unit	EP Carb	EP HEX Cold	EP HEX Hot	EF Carb	EF HEX Cold	EF HEX Hot	Jet Carb	Jet HEX Cold	Jet HEX Hot	DF HEX Hot	HVO HEX Hot
A_n	mm	0.8	0.8	0.8	1.2	0.8	0.8	0.8	0.8	0.8	0.8	0.8
r	%	25	45	44	24	51	32	24	24	24	40	35
t_{env}	°C	24	18	18	22	24	26	21	19	20	26	25
t_{intake}	°C	30	26	107	34	20	100	16	14	61	80	58
t_{deto}	°C			115			110			68	87	65
BTDC	deg	48	48	31	48	48	31	48	48	31	31	31
t_{oil}	°C	88	81	91	83	86	104	77	77	88	82	83
n_e	rpm	3 008	3 060	2 976	3 019	3 001	3 011	3 026	3 057	3 000	3 020	3 019
λ	—	0.93	1.13	0.93	0.918	1.06	1.03	0.617	1.14	1.48	0.98	0.73
E_{teor}	J	363.5	332.5	348.0	368.7	350.0	312.7	580.5	308.2	229.3	415.7	473.0
B_f	kg/h	0.71	0.65	0.68	1.19	1.13	1.01	1.22	0.65	0.48	0.87	0.99
B_a	kg/h	9.73	10.88	9.32	9.84	10.88	9.42	11.08	10.90	10.46	12.62	10.70
FDP	deg	−48-11	−48-15	−31-1	−48-8	−48-22	−31-19	−48-12	−48-12	−31-11	−31-18	−31-22
RBP	deg	12-58	16-70	2-30	9-51	23-69	20-59	13-59	13-58	12-59	19-90	23-64
ABP	deg	59-138	71-138	31-50	52-136	70-140	60-139	60-135	59-137	60-137	91-141	65-139
MFB 10 %	deg	11	15	1	8	22	19	12	12	11	18	22
MFB 50 %	deg	25	32	16	21	41	35	27	24	24	42	33
MFB 90 %	deg	58	70	30	51	69	59	59	58	59	90	64

Based on the data in Tab. 4, the duration of the FDP when using an unheated EP AFM is 59°. Fig. 3 shows that the HRR's progress is smooth. The RBP lasts for 47° and the total combustion process has a duration of 106°. When unheated EF fuel is used, the FDP is 56° and the RBP is 43°. The overall duration of combustion for the AFM is 89°. Fig. 3 shows that the progress of HRR from one phase to another is smooth. The FDP for Jet lasts for 60° and the RBP lasts for 47°. Fig. 3 shows that the HRR's progress is smooth. The overall combustion duration is 107°. Combustion with EP and Jet AFM was relatively similar and no major differences in combustion phases were detected. EF differs from test data in terms of rapid combustion and energy release. Due to the high viscosity of Jet, a rich and less volatile fuel mixture with low quality evaporation is formed. Therefore it is important to ensure the more efficient evaporation of the fuel for the more efficient use of the Jet fuel.

In EP tests with a cold HEX, the FDP is 63°. Fig. 3 shows that the HRR's progress is smooth and, when compared to the test without HEX, the combustion of the AFM is delayed. The RBP lasts for 55° and the overall combustion duration is 118°. When using EF with a cold HEX, the FDP duration is 70°. The progress of HRR is smooth, and is comparable to the use of EP without the HEX test. When compared to the engine with factory settings, combustion is significantly delayed. The duration of the RBP is 47°. The total combustion duration of the AFM lasts for 117°. With the Jet AFM, the FDP lasts for 60°. The HRR graph shows that the rapid energy release is smooth, and is similar to the use of EP and Jet in engine with factory settings. The RBP is 46°. The overall combustion duration is 106°. The combustion of an EP AFM with a cold HEX is somewhat delayed, and its duration is longer. With an EF AFM, the FDP is 11° longer than it is when using the engine with factory settings, but the RBP is of the same length (47°). In the case of a cold HEX and Jet AFM, the combustion process is the same as with the use of EP and Jet in an engine with factory settings. When comparing with and without a HEX, it appears that the use of a HEX prolongs the FDP and postpones the onset of heat release in the combustion process for EP and EF. This is due to the formation of a leaner AFM in the cylinder. When looking at the MFB50 data in the Tab. 4, it appears that the AFM's ignition and combustion take place later when using a HEX with EP and EF, when compared to the results seen in the use of the engine's factory settings. When comparing Jet with tests which use heat exchange and those which do not use heat exchange, the combustion process is similar. In the case of this engine, delayed combustion is caused by the fact that the spark angle cannot be set for different loads, so the spark angle is set according to the optimal loads for the engine. Additional air mixing with Jet in the HEX after carburetting did add combustion efficiency.

The combustion of a heated EP AFM has a FDP of 32° and a RBP of 29°. The HRR's graph is smooth, but the increase in heat release is sharper when compared to the engine using factory settings. The general combustion phase lasts for 61°. The heated EF AFM has a FDP of 50°. The RBP lasts for 40°. The HRR's progress is similar to EP in an engine with factory settings, but occurs somewhat later. The overall combustion duration is 90°. The heated Jet AFM a FDP of 42°. The RBP is 48°. The overall combustion duration is 90°. For Jet, the combustion duration of the AFM is comparable to that of EF. EP's combustion duration is around 30° shorter than that of Jet and EF.

The heated DF AFM has a FDP of 49° and a RBP of 72°. The overall combustion duration is 121°. Fuel consumption is significantly higher than when using other fuels. The progress of the HRR's graph is uneven and the energy release is also uneven. This

is due to the formation of combustion zones in the AFM. Similar to the light load test, two combustion phases are distinguishable. This can be attributed to the chemical and physical properties of the fuel. With a heated HVO (58 °C) AFM, the FDP is 53° and the RBP is 42°. The combustion duration is 95°. When using both HVO and DF, the HRR's graph shows a clear differentiation of combustion phases, which is characteristic of CI engines. For DF, there is an increase in HRR at crank angle degrees of −20 to −5, and for HVO, the same thing occurs at crank angle degrees of −12 to −3. This is due to the different fuel fractions of DF and HVO, where the light fractions evaporate and combust rapidly and only thereafter do the heavy fractions ignite.

Heavy fraction fuels burn differently in the SI engine than do EP and EF fuels. In the combustion processes for DF and HVO, differentiable phases are formed (pre-mixed controlled and mixing controlled phases), which are not characteristic of the SI engine. The ignition and combustion of the DF and HVO AFM in the engine's cylinder is rapid and the heat release is short. The differences in the combustion processes of DF and HVO are due to the temperature of the AFM. Because HVO's cetane number is significantly higher when compared to DF, the HVO AFM cannot be heated as much as the DF AFM can. At the same time, the high cetane figure for the fuel improves the duration of the combustion process and the release of heat, which means that HVO releases energy evenly during the combustion process. The combustion of DF is uneven and cyclic when compared to HVO fuel. Based on the available data, no tests were carried out with DF and HVO fuel at a load of 2.0 kW because detonating combustion would take place in the cylinder at this spark angle. To be able to use DF and HVO at higher loads, an additional setting of the spark angle is necessary in order to prevent detonation during the combustion of the AFM. In the case of EP and EF, heating the AFM makes it possible to change the timing of the combustion phases and therefore to slightly improve the combustion efficiency of the AFM.

Fig. 4 shows a graphic representation of the HRR, while Tab. 5 shows the most important test information for a GENSET load of 2.0 kW.
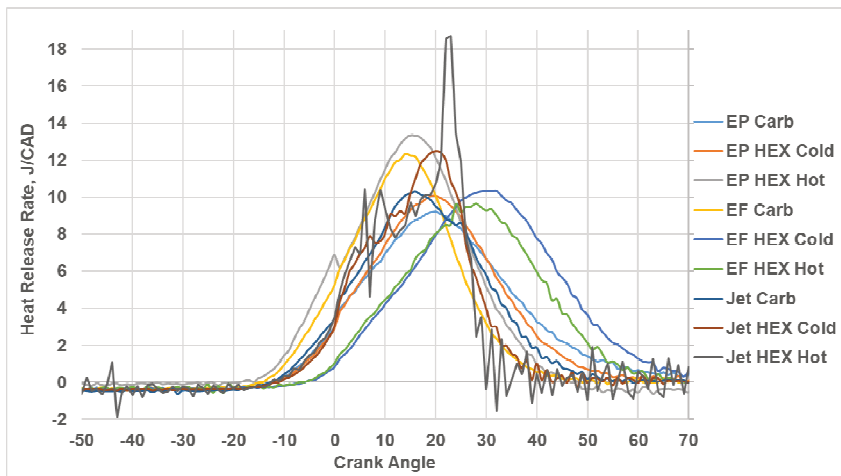

Fig. 4 HRR at load 2.0 kW

Based on the data in Tab. 5, the duration of the FDP when using an unheated EP AFM is 56°. Fig. 4 shows that the progress of HRR is smooth. The RBP lasts for 40° and the total combustion process has a duration of 96°. When using unheated HEX

and EF, the FDP is 53° and the RBP is 27°. The overall duration of combustion for the AFM is 80°. Fig. 4 shows that the transition of HRR from one phase to another is smooth. The FDP for Jet lasts for 56°, and the RBP lasts for 30°. Fig. 4 shows that the progress of HRR is smooth. The overall combustion duration is 96°. Jet can be used in an unmodified engine, but the AFM is rich, which is due to the high viscosity of Jet. High viscosity prevents the efficient carburisation of the fuel, and a lean AFM prevents the ignition of the AFM in the cylinder because the AFM does not contain enough evaporated fuel. Different AFM's burned stably in the engine.

Tab. 5 Test data at load 2.0 kW

Parameter	Unit	EP Carb	EP HEX Cold	EP HEX Hot	EF Carb	EF HEX Cold	EF HEX Hot	Jet Carb	Jet HEX Cold	Jet HEX Hot
A_n	mm	0.8	0.8	0.8	1.2	1.2	1.2	0.8	0.8	0.8
r	%	25	46	45	24	51	31	24	24	24
t_{env}	°C	24	18	18	24	24	26	21	19	20
t_{intake}	°C	23	23	42	26	37	50	23	30	35
t_{deto}	°C	32	28	53	33	18	50	16	13	45
BTDC	deg	48	48	48	48	31	31	48	48	48
t_{oil}	°C	93	85	90	86	87	105	78	82	85
n_e	rpm	3 009	2 945	2 986	3 004	3 014	3 038	3 038	3 095	3 085
λ	—	0.87	1.13	0.86	0.84	1.13	1.03	0.68	1.129	1.4
E_{teor}	J	425.3	348.0	425.3	448.0	354.7	374.3	587.7	365.5	293.8
B_f	kg/h	0.83	0.68	0.83	1.44	1.14	1.20	1.23	0.77	0.62
B_a	kg/h	10.66	11.30	10.58	10.94	11.68	11.16	12.34	12.79	12.79
FDP	deg	−48-8	−48-9	−31-17	−48-15	−48-15	−31-16	−48-8	−48-8	−31-8
RBP	deg	9-48	10-42	17-29	16-85	16-85	17-47	9-38	9-33	9-31
ABP	deg	49-139	43-140	30-48	86-138	91-140	48-139	39-138	34-138	32-130
MFB 10 %	deg	8	9	1	5	17	16	8	8	8
MFB 50 %	deg	23	22	15	16	32	30	20	19	19
MFB 90 %	deg	48	42	29	32	53	47	38	33	31

In EP tests with a cold HEX, the FDP is 57°. Fig. 4 shows that the progress of the HRR is smooth, and it is similar to the factory settings for the engine (using EP). The RBP lasts for 33° and the overall duration of combustion is 90°. When using EF, the duration of the FDP is 65° when applying a cold HEX. The progress of HRR is smooth, but when compared to the factory settings for the engine, combustion occurs significantly later. The RBP lasts for 36°. The duration of general combustion for the AFM is 101°. With a Jet AFM, the FDP lasts for 56°. The graph for the HRR shows

that heat release is steady but more rapid when compared to the engine's factory settings. The RBP lasts for 25°. The overall combustion duration is 81°. The combustion process for an EP and Jet AFM with a cold HEX is similar to that for the engine when using the factory settings. With EF fuel, the FDP is 10° longer than in an engine with the factory settings, but the RBP is 4° shorter. When looking at the MFB50 data in the table (Tab. 5), it appears that the EP and Jet values are similar when compared to the factory settings and to the cold HEX tests. The ignition and combustion of the EF AFM are both late when using a HEX, when compared to the results with the engine with factory settings.

The combustion of the heated EP AFM (53 °C) has a FDP of 32° and a RBP of 28°. The progress of the HRR is smooth. The general combustion duration lasts for 60°. With the heated EF AFM (50 °C), the FDP is 47°. The RBP lasts for 31°. The HRR progresses smoothly. The overall combustion duration is 78°. The heated Jet AFM has a FDP of 39° and the RBP is 23°. The overall combustion duration is 62°. The progress of HRR is uneven and a sudden release of energy occurs in the range of 20-25 CAD in the combustion process, which characterises detonating combustion in the cylinder. Therefore it is recommended that the spark angle of the engine be set somewhat later to ensure a more stable heat release in the cylinder. Based on MFB50 data, heating the AFM accelerates the FDP and the RBP in the combustion process of the fuels.

The above results show that the use of heavy fuel fractions in the SI engine is effective mainly at low and medium loads. At high loads, the combustion of fuels causes problems due to the chemical and physical properties of the heavy fuel fractions.

The preheating system allows to use different fuels in the spark ignition engine, but in practical use, following aspects are important:
- the combustion of the heated fuel mixture is faster and the ignition timing needs to be delayed, which depends on the used fuel,
- when diesel fuel is used, the fuel flow must be limited,
- in order to control the heated fuel mixture temperature accurately, the heat exchanger must be isolated.

4   Conclusions

In the course of the research, tests were carried out in order to see the effect of a heated AFM on the SI engine's combustion process. Heating the AFM permits the use of heavy fraction fuels in SI engines, such as diesel or biodiesel. The engine tests were carried out and the results were as follows:

At a load of 1 kW: In the unmodified engine, Jet can be used in addition to EP and EF, but the AFM is rich under such circumstances, which is due to the high viscosity of Jet. High viscosity prevents the efficient carburisation of the fuel, and a lean AFM prevents the ignition of the AFM in the cylinder because the AFM does not contain enough evaporated fuel. Therefore, in order to use Jet more efficiently, it is important to ensure the more efficient evaporation of the fuel. The onset of the combustion of the EP AFM with a cold HEX occurs later and its duration is longer. With EF, the FDP is nine degrees longer than in an engine which is still using the factory settings, but the RBP is 9° shorter. In the case of a cold HEX and a Jet AFM, the combustion process takes place somewhat later than it does in an engine which has its factory settings intact. When comparing systems with and without a HEX, it can be seen that the use of a HEX prolongs the FDP and postpones the onset of heat release in

the combustion process when using EP and Jet. This is due to the formation of a lean AFM in the cylinder. Based on the MFB50 data, it appears that the AFM's ignition and combustion phases are delayed with all fuels when using a HEX, when compared to an engine with its factory settings. In the case of the engine that was tested, delayed combustion is caused by the fact that the spark angle cannot be set for different loads, so the spark angle had to be set for high engine loads alone.

When comparing the tests between hot and cold EP and EF AFM´s, the use of a heated AFM serves to delay combustion. This is due to the use of a leaner AFM when heating. When compared to the tests that were carried out with a hot and cold Jet AFM, the combustion duration of the AFM is about 12° shorter. Consequently it can be concluded that the timing of the combustion phases changes when the AFM is heated. Heavy fraction fuels burn somewhat differently in the SI engine than they do with the EP and EF fuels. In the combustion process for DF and HVO, differentiable phases are formed (in the premixed controlled and mixing controlled phases), which are not characteristic of the SI engine.

At a load of 1.5 kW: In the case of an engine with a normal setting, the combustion of EP and Jet AFM`s is relatively similar and no major differences were detected in combustion phases. In the test data, EF is characterised by faster combustion and heat release. Due to the high viscosity of Jet, a rich and less volatile AFM is formed. Therefore, in order to use Jet more efficiently, it is important to ensure a more efficient evaporation of the fuel. The combustion start of EP with a cold HEX takes place later and lasts longer. With EF, the FDP is 11° longer than it is in an engine which is using the factory settings, but the rapid-burning phase has the same length (47°). In the case of a cold HEX and a Jet AFM, the combustion process is similar to the use of EP and Jet in an engine with factory settings. When comparing the systems with and without a HEX, it appears that the use of a HEX prolongs the FDP and postpones the onset of heat release in the combustion process using EP and EF. This is due to the formation of a leaner AFM in the cylinder. Based on MFB50 data in the table, it appears that the AFM's ignition and combustion are delayed with EP and EF when using a HEX, when compared to the engine with factory settings. When comparing Jet with and without a HEX, the combustion process is similar. In the case of the engine that was tested, delayed combustion is caused by the fact that the spark angle cannot be set for different loads, so the spark angle has to be set for optimum engine loads instead. Additional AFM with Jet fuel after carburetting in a HEX added combustion efficiency. This is also confirmed by the value of the λ, which is significantly higher when compared to the test without a HEX.

For Jet, the combustion duration of the heated AFM is comparable to that of EF fuel. EP's combustion duration is around 30° shorter than that of Jet and EF. Heavy fraction fuels combust differently in the SI engine at this load when compared to EP and EF fuels. In the combustion process for DF and HVO, differentiable phases are formed (premixed controlled and mixing controlled phases), which are not characteristic of the SI engine. The ignition and combustion of DF and HVO AFM in the engine's cylinder are rapid, and the heat release phase is short. The differences in the combustion processes for DF and HVO are due to the temperature of the AFM. As the cetane figure for HVO is significantly higher than that of DF, the HVO AFM cannot be heated as much as the DF AFM can. At the same time, the high cetane figure for the fuel improves the speed of the combustion process and the heat release, so that HVO releases heat evenly during its combustion. The combustion of DF is uneven and cyclic by comparison with HVO. Based on the data, no tests were carried out with DF

and HVO fuel at a load of 2.0 kW because detonating combustion would take place in the cylinder at such a spark angle. To use DF and HVO at higher loads, an additional setting of the spark angle is necessary in order to prevent any detonation during the combustion of the AFM. In the case of EP and EF, heating the AFM makes it possible to change the timing of the combustion phases and thereby to slightly improve the combustion efficiency of the AFM.

At a load of 2 kW: Jet fuel can be used in an unmodified engine, but the fuel mixture used is rich, which is due to the high viscosity of Jet. High viscosity prevents the fuel from being effectively carburised, and a lean AFM prevents the ignition of the AFM in the cylinder because the AFM does not contain enough evaporated fuel. Different AFM-s burned stably in the engine. The combustion process for an EP and Jet AFM with a cold HEX is similar to that of the engine with the factory settings. With EF, the FDP is 10° longer than it is in an engine which has the factory settings, but the RBP is 4° shorter. Based on MFB50 data, it appears that the values for EP and Jet are similar to those of the factory settings and the cold HEX tests. The ignition and combustion of the EF AFM are delayed when using a HEX, in comparison with the engine at its factory settings. With the heated Jet AFM, the HRR's progress is uneven and there is a sudden release of heat in the combustion process, which illustrates a detonating combustion in the cylinder. Therefore it is recommended that the engine's spark angle be set somewhat later to ensure a more stable heat release in the cylinder. Based on MFB50 data, the heating of the AFM accelerates the FDP and the RBP in the combustion process for the fuels.

Acknowledgement

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