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METHODS FOR REDUCING EMISSIONS OF SMALL INTERNAL COMBUSTION ENGINES

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Abstract: *This study was motivated by the fact stated by European Commission regarding non-road mobile machinery that one hour use of a chainsaw equipped with a two-stroke engine produces as much emissions as driving for 2000 km with a modern passenger car. A carbureted small engine with a mechanical governor is quite inefficient and the emissions of such engines are significant. Fuel consumption and emissions of these engines can be reduced by electronic throttle control and retrofitting electronic fuel injection (EFI). A load testing rig was built to help measuring the emissions produced by the engine. The emissions were measured for both the carburetor and electronic fuel injection. Also the use of renewable fuel, ethanol with electronic fuel injection was examined.*

Keywords: electronic fuel injection, governor, spark ignition, engine, renewable fuel

1. INTRODUCTION

The current state of small internal combustion engines (ICE) is that they are often carbureted and generally governors and other methods of control are mechanically achieved. The problem is that a carbureted small engine with a mechanical governor is not very fuel efficient and the emissions of such engines are quite significant. [1,2,3] Electronic control for carburetor and ultimately electronic fuel injection (EFI) would reduce emissions and improve fuel economy. [2,4]

Additionally, improved governing of the engine rotation speed would prove useful in various applications such as small hydraulic logging trailer powered by a small internal combustion engine driving a hydraulic pump.

European directive for small internal combustion engine emissions has not been updated since the early 2000s’. Pressure for updating them is increasing as emissions level criteria have been updated. Currently the U.S. standard is stricter for new spark-ignition engines over 225 cc, the maximum permissible Carbon Monoxide (CO) level is 610 g/kWh and Hydrocarbon (HC) + Nitrogen Oxides (NOx) is 8.0 g/kWh and EU levels are 610 g/kWh and 12.1 g/kWh respectively. [5,6]

In this research it is studied, is it possible to reduce fuel consumption and emissions of carbureted engines by electronic throttle control and by retrofitting electronic fuel injection system. Also the use of a renewable fuel, ethanol, is studied by comparing emissions and to those generated by gasoline operation.

The goal is to design and fabricate such electronic throttle control system that hobbyists and enthusiasts can easily retrofit to their carbureted engines, and a fuel injection system that could be used in place of carburetor.

2. TEST SYSTEM

As the main purpose of this study is to discover how various improvements on a small internal combustion engine fuel delivery system affect the emissions produced by the ICE, environmental parameters are needed to be controlled.

Item	Specification
Frequency converter	0,55-250 kW, 230-690 V
Electric motor	7,5 kW, 35,8Nm, 2000 rpm
Engine	4-stroke, 1-cylinder, 7,5 kW, 330cc
Resistive load	20 Ohm

Table 1. Load testing rig specifications.

2.1 Testing rig

A load testing rig (Table 1) was built to help measure the emissions produced by the internal combustion engine. Controlled varying load, which is important factor in evaluating total emissions produced by the internal combustion engine, has been implemented with an electric motor combined with a frequency converter. Frequency converter is used to adjust the resisting torque produced by the electric motor. The engine is connected to the electric motor using a belt drive. The energy generated by the electric motor is fed to a resisting load and dissipated as heat. Combustion engine is started with the electric motor doubling as a starter and a load.

2.2 Electronic governor

Initial tested method for reducing emissions was replacing the mechanical governor with an electronic governor (Fig. 1) used in conjunction with carburetor. The component setup of the electronic governor is shown in Table 2.

Item	Description
Microcontroller	Arduino UNO embedded platform
Actuator	Stepper motor w/ controller
Sensor	Automotive hall effect sensor w/ 36-1 trigger wheel mounted on the crankshaft

Table 2. Components used in the electronic governor.

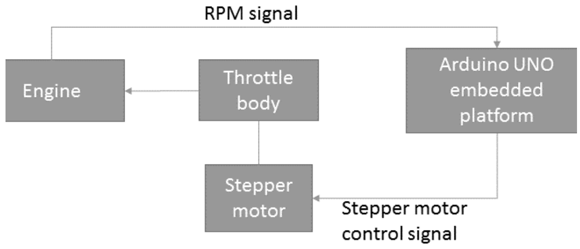

Fig. 1. Principle of electronic governor.

The adjustment of the throttle opening is done using stepper motor that is mechanically connected to the throttle plate axle on a modified throttle body. The controlling of the system is done using PID controller.

2.3 Electronic fuel injection

The primary emissions reducing method tested was electronic fuel injection. There are several types of fuel injection, such as port fuel injection (PFI) and direct in-cylinder injection (DI). Since the goal was to build a retrofittable fuel injection kit, the PFI system was chosen, since it requires less modifications to the engine than a DI system. [4]

The tested electronic fuel injection system (Fig. 2) consists of similar components as conventional fuel injection system. The fuel injection system comprises of fuel supply system, throttle body with fuel injector and electronic control unit (ECU).

To achieve constant fuel pressure at the fuel injector, a surge tank with a fuel pump and fuel pressure regulator is implemented. Throughout the test the fuel pressure is kept constant, at 300 kPa.

The ECU controls the injection quantity and injection timing based on sensor outputs. The tested EFI system is controlled by alpha-N control algorithm.

The control algorithm uses throttle position angle and engine rotation speed to read a value from volumetric efficiency (VE) chart to determine the correct fuel delivery. The volumetric efficiency values are stored in a 16x16 lookup table, which consists of experimentally determined VE values. [3,7] The fuel injectors are controlled with pulse

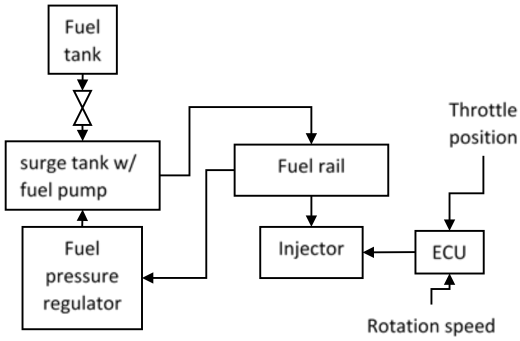

Fig. 2. Schematic layout of the tested EFI system.

width modulation (PWM). To determine correct fuel output the flow rate of the injectors are required. The fuel injection system comprised mainly of salvaged parts from a 600cc motorcycle. The data for the injectors was unavailable, so the injectors were characterized by measuring their output on various pressure levels and varying injection time. The data from the injector characterization is shown in Figure 3.

Even though the tested EFI system should have least possible amount of sensors, a few are still needed for correct operation of the EFI. Following values are obligatory for tested EFI system: throttle position and engine rotational speed. Throttle position sensor (TPS) is used to monitor the position of the throttle plate. The engine rotational speed is measured with an automotive hall-sensor, which measures the crankshaft position.

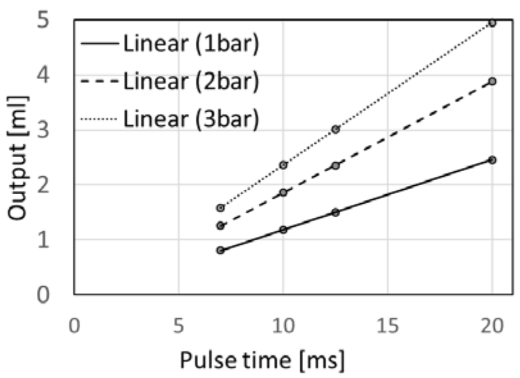

Fig. 3. Flow rate of the injector used in the EFI system.

In the experiments commercially available EN228 standard 95-octane gasoline fuel was used. It is the most widely used type of spark ignited combustion engine fuel in Finland. [8] Also the use of ethanol as fuel was studied. The RE85 85%-ethanol fuel meets EN15376 standard [9]. Allen Test Products 53-700 4-gas exhaust analyser was used to measure the emissions. The analyser measures CO (0-10%), CO_2 (0-20%), HC (0-2000 PPM) and O_2 (0-21%) contents. The emission levels were measured at various engine rotation speeds and various load conditions. Engine rotation speed was measured with automotive hall sensor used with EFI and electronic governor. Lambda value was measured with Tech Edge 2J2 wideband λ sensor and controller.

3. RESULTS

Tables 3 and 4 show exhaust emission levels of carburetor and EFI at lambda values at which the carburetor operated during measurements. Tables 5 and 6 show exhaust emissions of 95E10 and RE85 at lambda value 1.

RPM	Load [*W*]	CO_2	CO	HC	$\lambda \pm 0,1$
2000	1600	12,2	0,18	250	1,2
2000	2000	13	0,7	249	1,01
2000	3700	1,5	1,57	170	0,98
3000	1000	12,1	0,5	140	1,15
3000	2000	12,6	0,37	87	1,15
3000	3700	13,1	0,58	48	1,03
4000	1000	12,5	0,52	21	1,04
4000	2000	13	1	65	1,02
4000	3700	13,3	5,5	0	1,02

Table 3. Measured carburetor emissions in different static operating conditions. Weather conditions +0,8 °C 1009,1 hPa.

RPM	Load [W]	CO_2	CO	HC	$\lambda \pm 0,1$
2000	1600	12,6	0,12	130	1,2
2000	2000	14,3	0,3	138	1,01
2000	3700	14,3	0,8	100	0,98
3000	1000	12,8	0,28	22	1,15
3000	2000	12,9	0,25	26	1,15
3000	3700	14	0,21	45	1,03
4000	1000	14	0,3	14	1,04
4000	2000	13,9	0,4	20	1,02
4000	3700	14,1	0,4	15	1,02

Table 4. Measured EFI emissions in different static operating conditions with matching lambda values to carburetor measurement. Weather conditions +1 °C 1010,7 hPa.

RPM	Load [W]	CO_2	CO	HC
2000	1000	14,2	0,92	200
2000	2000	13,8	1,26	181
2000	3700	13,4	1,89	95
3000	1000	13,9	0,75	121
3000	2000	13,8	0,8	146
3000	3700	13,8	0,85	70
4000	1000	13,8	0,9	66
4000	2000	13,8	0,79	96
4000	3700	13,8	0,85	50

Table 5. Measured EFI with gasoline emissions in different static operating conditions with lambda value 1. Weather conditions +1 °C 1008,8 hPa.

RPM	Load [W]	CO_2	CO	HC
2000	1000	13,4	0,89	113
2000	2000	13,6	0,75	114
2000	3700	13,7	0,85	82
3000	1000	13	1	97
3000	2000	13,4	1,05	86
3000	3700	13,7	0,36	70
4000	1000	13,3	0,68	71
4000	2000	13,3	0,67	39
4000	3700	13,7	0,65	48

Table 6. Measured EFI emissions with ethanol in different static operating conditions with lambda value 1. Weather conditions +0,9 °C 1009,1 hPa.

4. DISCUSSION

It was found out that the electronic governor system had a small impact on HC-emissions on transient loading situations. Retrofitting the electronic fuel injection system had a larger effect on the emissions. The cold startability and general operability were improved significantly. In testing conditions, the engine fitted with carburetor had starting difficulties and severe problems to provide the engine with ignitable mixture on idle. Therefore, preheated intake air had to be used. The EFI ran without preheated intake air and had no operability issues. HC and CO emissions were reduced on all tested operating points with the EFI system. This could be accounted for lower manifold fuel condensation and better atomization of the fuel droplets in the intake air [10,11]. Especially HC emissions at lower RPM were reduced with EFI. As it can be seen when comparing table 3 and table 4, the engine with carburetor produces comparable HC-emissions with the EFI when operating in carburetors' designed RPM range. Retrofitting an EFI system to small IC-engines is an effective way to reduce the emissions and even more significant differences would be seen in transient condition measurements.

Further reduction of emissions can be seen when switching from pump gasoline 95E10 (Table 5) to ethanol fuel mixture E85 (Table 6). With ethanol, drop in CO and HC throughout the measured range when comparing to gasoline, shows that best emissions reduction on a small carbureted engine can be achieved by changing from pump gasoline to ethanol together with EFI conversion. Further reduction in emissions could be achieved by utilizing the larger ignition range of the ethanol fuel by running the engine on higher excess air ratio in part load conditions [11].

For further improvements, it is suggested that the electronic governor system should be improved in such a way that it is more easily retrofitted without major modifications to the engines. In addition, the durability of the system should be examined. The throttle body of the EFI system needs to be designed, in such way that it is more suitable for small engines. The current throttle body is designed for much larger airflow than needed for an engine of a size discussed in this paper.

5. REFERENCES

[1] Elfasakhany, A. Investigations on the effects of ethanol-methanol-gasoline blends in a spark-ignition engine: Performance and emissions analysis. Engineering Science and Technology, an International Journal, 2015, 713-719.

[2] Hayakawa, K., Yamazaki, S., Takenaka, S., Oshiba, H., Yang, K. C., & Worth, D. 125cc small engine fuel injection system with low emissions solutions SAE Technical Paper (No. 2004-32-0094), 2004.

[3] Karthikeyan, G., Ramajayam, M., Pannirselvam, A. Design and Fabrication of an Electronic Injection Kit for a Conventional Small Capacity SI Engine. International Journal of Engineering and Advanced Technology, 2013, **2**, 525-529.

[4] Hushim, M. F., Alimin, A. J., Selamat, H., Muslim, M. T. PFI Retrofit-Kit as Green Technology for Small 4-Stroke S.I. Engine. Applied Mechanics and Materials, 2013, 315, 453-457.

[5] European commission directive 2002/88/EY. Available: http://eur-lex.europa.eu/legal-content/FI/TXT/PDF/?uri=CELEX:32002L0088&qid=1452454470566&from=EN

[6] Electronic code of federal regulations, PART 1054—CONTROL OF EMISSIONS FROM NEW, SMALL NONROAD SPARK-IGNITION ENGINES AND EQUIPMENT. Available: http://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=9987fbe65063af0d43e04b79fc93cf7c&mc=true&n=sp40.33.1054.b&r=SUBPART&ty=HTML

[7] Dase, C., Falcon, J.S., Maccleery, B. Motorcycle control prototyping using an FPGA-based embedded control system. IEEE Control Systems, 2006, 26, 17-21.

[8] Finnish Petroleum and Biofuels Association, 2015. Available: http://www.oil.fi/fi/tilastot-3-suomen-oljymarkkinat/35-markkinaosuudet

[9] St1 Oy, Ethanol Fuel RE85 Product Data Sheet, 2014. Available: http://www.st1.fi/files/12697/RE85_tuotetieto_joulu2014.pdf

[10] Dietsche K, Klingebiel M. Automotive handbook. 7th , rev a exp ed. Plochingen: Robert Bosch; 2007. 1200 s. ISBN 978-0-470-51936-3

[11] Van Basshuysen R, Schäfer F. Internal combustion engine handbook: basics, components, systems, and perspectives. Warrendale, PA: SAE International, 2004. 950 s. ISBN 978-0768011395

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