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# Comparison of performance end emissions of turbocharged CI engine fuelled either with diesel fuel or CNG and diesel fuel

*Abstract: In the course of the project on adaptation of turbocharged compression ignition engine produced by Andoria (Poland) to dual-fuelling with compressed natural gas (CNG) and diesel fuel (DF), performance and emissions of both: base engine fuelled with DF and dual–fuel fuelled with CNG and DF where measured. Some information on the project was published earlier; in this paper authors focused on comparison of performance and emissions of dual-fuel and base engine. It is shown, that carbon dioxide and smoke decreased, but hydrocarbon and carbon monoxide considerably increased. Also torque, power and brake fuel conversion efficiency of the engine for both modes of fuelling were compared.*

## 1. Introduction

Compression ignition turbocharged engine (CITE) produced by Andoria with common-rail system, with EGR, satisfying Euro 4 standards was adapted to dual-fuelling with CNG and diesel fuel [1]. CNG was injected to each of four inlet ports sequentially, when inlet valves were opened, and diesel fuel was supplied with factory common-rail system. When load was increased, diesel fuel dose was kept constant (as for the torque 20 Nm), whereas CNG dose was increased up to the limit, when cylinder pressure became as high as 100 bar and knocking combustion occurred. Then fractions of both fuels were changed: diesel fuel fraction was increased and CNG fraction decreased.

The course of experiment and some results, as performances, analysis of heat release rate and combustion pressure were presented in [1, 2].

In this paper the performance and emissions of base engine (fuelled only with diesel fuel) and dual-fuel engine were compared.

## 2. Test stand

**Schematic of base CITE engine is shown in Fig.1,** and its data in Tab.1. For dual fuelling with DF and CNG gas installation was installed. Its block diagram is shown in Fig.2.

**Table 1. ADCR engine data.**

| | |
|---|---|
| Engine type | Compresion ingition with common-rail turbocharged with intercooler |
| Cylinder number and configuration | 4, in-line, vertical |
| Cylinder diameter | 94 mm |
| Piston stroke | 95 mm |
| Swept volume | 2636 $cm^3$ |
| Compression ratio | ~17,5 |
| Power | 85kW at 3700rpm |
| Maximum speed | 3700 rpm |
| Maximum torque | 250 Nm at 1800-2200 rpm |
| Specific fuel consumption at max torque | 210 g/kWh |
| EGR system | Watercooled |
| Injection system | Common-Rail |
| Sequence of injection | 1-3-4-2 |
| Number of valves in each cylinder | 2 |
| Valve timing:<br>• Inlet valve:<br>- opening<br>- closssing<br>• exhaust valve<br>- opening<br>- closssing | <br><br>10 ± 4 deg BTDC<br>38 ± 4 deg ABDC<br><br>58 ± 4 deg BTDC<br>10 ± 4 deg ABDC |
| Homologation | Euro IV according to direct. 70/220 EEC + actual. |

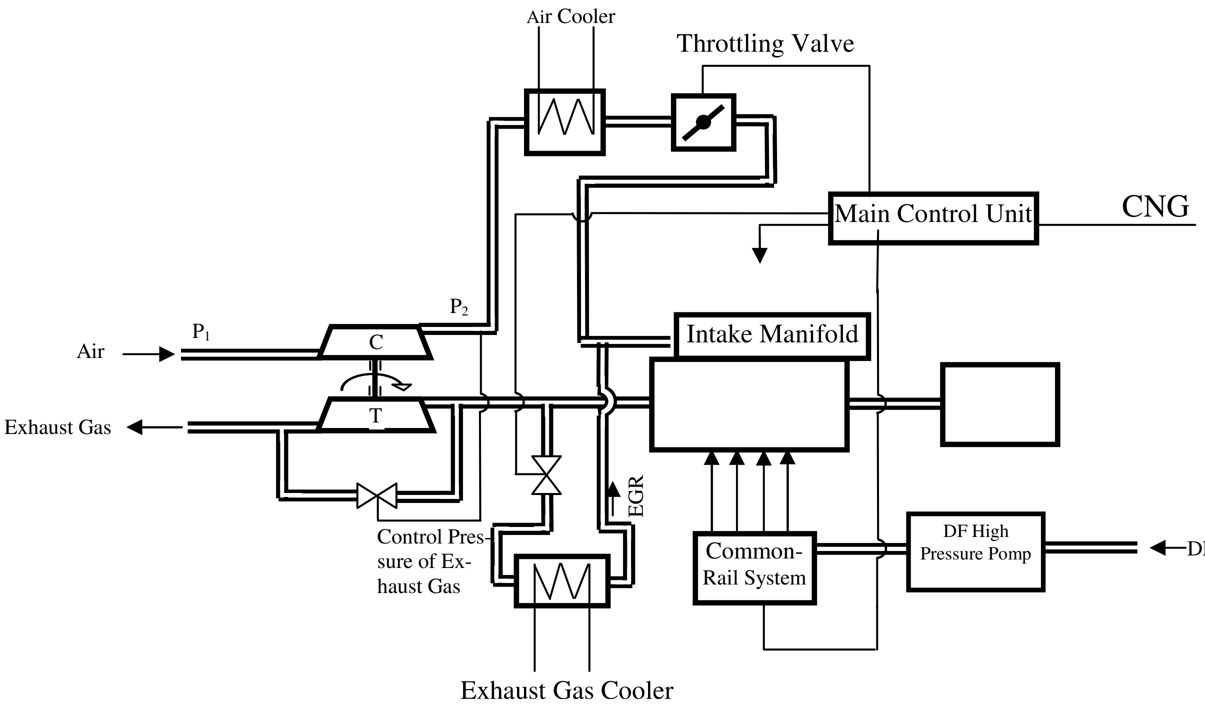


**Fig: 1. Schematic of ADCR engine adapted to CNG fuelling.**

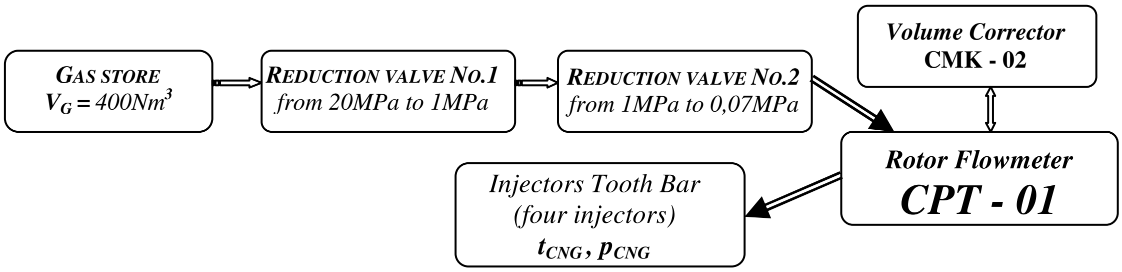


**Fig: 2. Block diagram of CNG installation of ADCR engine. $t_{CNG}$ – inlet gas temperature measurement, $p_{CNG}$ – inlet gas pressure measurement.**

Engine torque was measured with hydraulic torque meter Automex, diesel fuel flow - with laboratory balance Electromex, CNG flow - with rotor-gas meter CGR-01 DN 40G16PN16 supplied with volumetric corrector CMK-02. Emissions were measured as follows: $NO_x$ with Beckman 951 analyzer, HC, CO and $CO_2$ –with AVL analyzer model 465DiGas, smoke level-with Bosch smoke-meter. Pressure sensor Kistler 6043 Asp Ø8mm was used to measure pressure-time history in engine cylinder and knock sensor DR 190 BO 92-2F to detect onset of knocking combustion. For CNG fuelling system Zenit-6E/M344/FM was installed. CNG was injected into inlet duct of each cylinder with gas injectors. Diesel fuel was injected with standard common-rail system of base engine.

## 3. Concept of dual-fuelling mode

For each particular speed in the range of 1200-3200 rpm the torque was increased due to increase of gas flow, while DF dose was kept constant, but up to the moment, when cylinder pressure reached 10-11MPa. Then gas flow was decreased and diesel fuel increased-Fig.3.

Maximum engine speed for dual-fuelling was limited by heavy knock-its value was 3200 rpm.

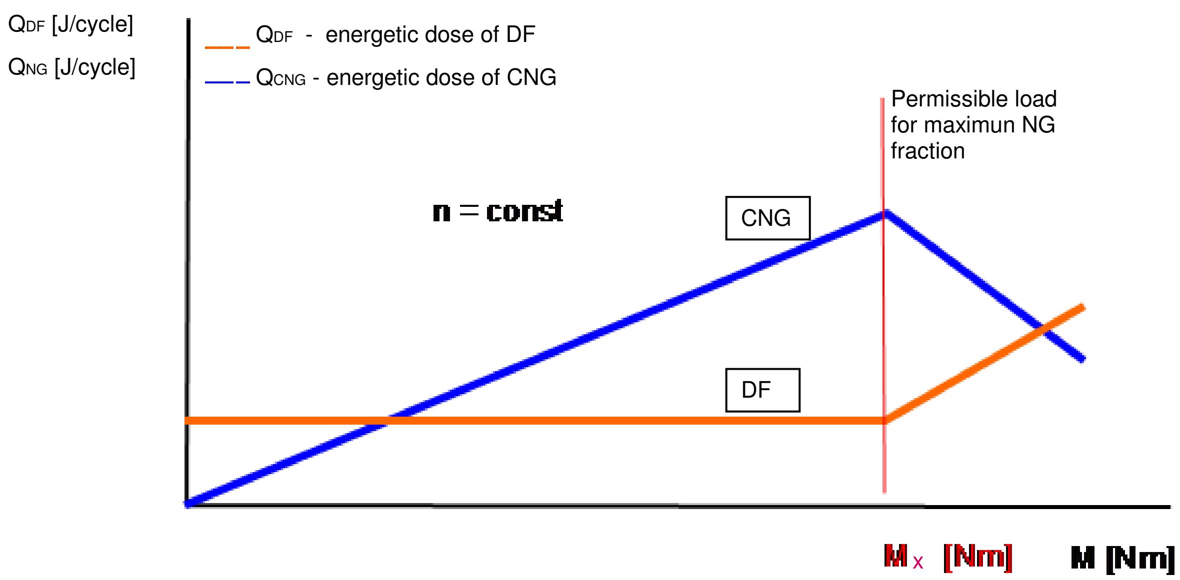


**Fig: 3. Idea of diesel fuel and CNG energetic charges selection in function of load for any constant speed of dual fuelling.**

## 4. Comparison of performance and emission for both modes of fuelling: only DF and DF+CNG

### 4.1 Results

Comparison is performed for maximum torque for each particular speed.
Results of investigation are shown in the Tab. 2 for both modes of fuelling.

*Table 2a: Performance and emissions of the engine fuelled with DF*

| Parameter | Mode of fuelling | n [rpm] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *1200* | *1400* | *1600* | *1800* | *2000* | *2200* | *2400* | *2600* | *2800* | *3000* | *3200* | *3400* |
| N, kW | DF | 18,85 | 27,86 | 35,69 | 47,1 | 51,73 | 48,38 | 51,77 | 62,62 | 58,64 | 65,97 | 60,32 | 62,31 |
| M, Nm | DF | 150 | 190 | 213 | 250 | 247 | 210 | 206 | 230 | 200 | 210 | 180 | 175 |
| CO [%] | DF | 0,11 | 0,07 | 0,02 | 0,02 | 0,01 | 0,01 | 0,01 | 0,01 | 0,01 | 0,01 | 0,01 | 0,1 |
| HC [ppm] | DF | 7 | 11 | 7 | 5 | 10 | 14 | 6 | 5 | 10 | 10 | 8 | 8,4 |
| $N0_x$ [ppm] | DF | 860 | 820 | 780 | 1120 | 875 | 270 | 650 | 1020 | 420 | 255 | 480 | 510 |
| D [-] | DF | 0,6 | 5 | 3,7 | 4,7 | 7,2 | 3,9 | 5 | 6 | 6,4 | 1,7 | 0,08 | 6,3 |
| $CO_2$ [%] | DF | 9,5 | 10 | 8,9 | 9 | 8,8 | 8,5 | 8,6 | 8,8 | 8,8 | 9,1 | 8,5 | 8,4 |

*Table 2b: Performance and emissions of the engine fuelled with DF+CNG*

| Parameter | Mode of fuelling | n [rpm] | | | | | |
|---|---|---|---|---|---|---|---|
| | | *1200* | *1400* | *1800* | *2200* | *2600* | *3200* |
| N, kW | DF+CNG | 11,69 | 19,6 | 31,1 | 46,08 | 200 | 56,97 |
| M, Nm | DF+CNG | 93 | 130 | 165 | 200 | 54,45 | 170 |
| CO [%] | DF+CNG | 0,16 | 0,06 | 0,12 | 0,07 | 0,22 | 0,17 |
| HC [ppm] | DF+CNG | 256 | 379 | 479 | 411 | 499 | 231 |
| $N0_x$ [ppm] | DF+CNG | 810 | 1050 | 1050 | 870 | 971 | 1400 |
| D [-] | DF+CNG | 1,1 | 0,2 | 0,2 | 0 | 0,2 | 5,2 |
| $CO_2$ [%] | DF+CNG | 4,6 | 6,8 | 4,3 | 6,3 | 4,4 | 6,2 |

For dual fuelling mode the injection angle of DF was optimized on account on maximum torque for particular speed. In high speed range the ratio of CNG/DF was also optimized. Additionally engine performance: power, torque and brake fuel conversion efficiency η vs engine speed are shown in Fig. 4 and 5. Mean values of emissions in the range of experiments are shown in Tab. 3.

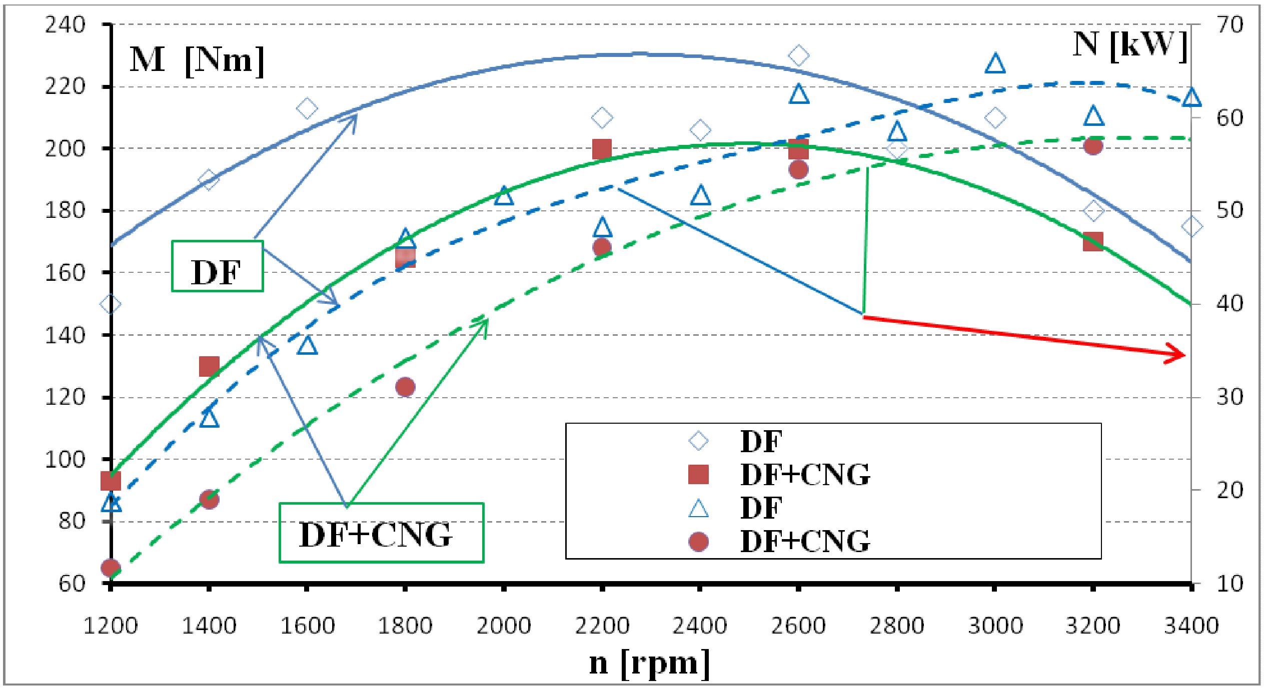


*Fig. 4. Torque and power vs engine speed for both modes of fuelling*

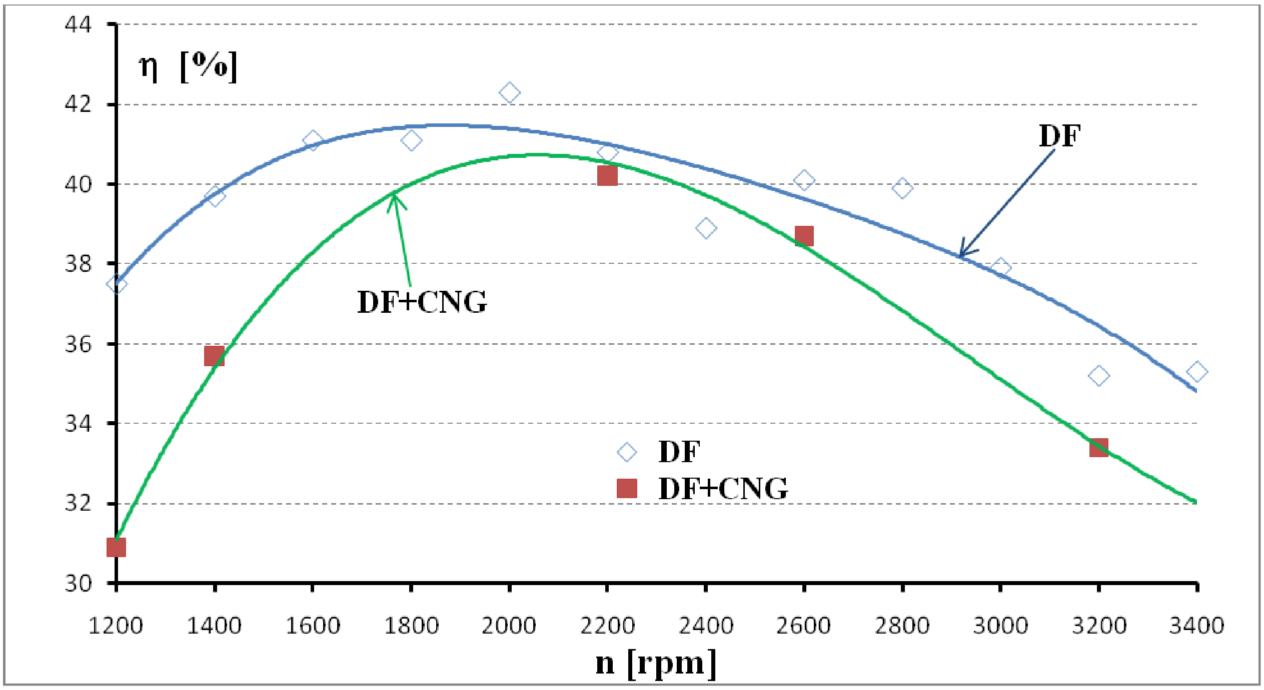


*Fig. 5. Brake fuel conversion efficiency vs speed for both modes of fuelling*

*Table 3: Mean values of concentration from each particular measurement in the range of the speed 1200 - 3200 /3700 rpm for both modes of fuelling*

| ***Parameter*** | ***Mode of fuelling*** | ***Mean concentration*** |
|---|---|---|
| CO [%] | DF | 0,03 |
| | DF+CNG | 0,13 |
| HC [ppm] | DF | 8,45 |
| | DF+CNG | 377 |
| $NO_x$ [ppm] | DF | 671 |
| | DF+CNG | 820 |
| D [-] | DF | 4,22 |
| | DF+CNG | 1,32 |
| $CO_2$ [%] | DF | 8,91 |
| | DF+CNG | 5,43 |

## 4.2 Discussion

As may be expected, emissions of carbon dioxide and smoke for fuelling with CNG and DF are lower than these for fuelling only with DF. On the other hand, emissions of carbon monoxide and hydrocarbons are much more higher. The first result is clear: natural gas consists mainly with methane, which has higher contents of hydrogen atoms than diesel fuel (in relation to lower heating value) and gas combustion emits less smoke and carbon dioxide than diesel fuel. High emissions of hydrocarbons and carbon monoxide result from incomplete combustion, which is caused by too less energy of diesel fuel dose for ignition of the gas in the whole volume of combustion chamber. Burning diesel fuel droplets do not reach distant parts of the chamber and - in the result of that - a lot of gas is not burnt. This process is assisted by the fact, that the gas displays oxygen in the atmosphere around the droplets, resulting in incomplete combustion (for CO rather than $CO_2$) and lower engine efficiency. Moreover, high emission of hydrocarbons resulted in valve overlap: the gas from inlet duct flows through open valves to exhaust duct and mixes with exhaust gasses, increasing HC emission measured in exhaust pipe [3].

Confirmation of this interpretation gives emissions of $NO_x$: when ratio of DF/CNG is enough high, $NO_x$ emission is higher for dual-felling due to complete combustion and high temperature, but when it becomes low, $NO_x$ decreases due to lower temperature caused by incomplete combustion.

Because for each particular speed for both modes of fuelling the torque (and brake power) were different, comparison was also prepared for emissions in ppm (except smoke) related to engine power, which was lower for dual-fuelling. Emissions related engine power are shown in Table 4 and mean values in Table 5.

*Table 4: Emissions related to engine power. Engine fuelled with DF and DF+CNG*

| **Parameter** | **Mode of fuelling** | **n [rpm]** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *1200* | *1400* | *1600* | *1800* | *2000* | *2200* | *2400* | *2600* | *2800* | *3000* | *3200* | *3400* |
| $\frac{CO}{N}\ \frac{\%}{kW}$ | DF | 5800 | 300 | 15 | 4 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | DF+CNG | 137 | 31 | ÷ | 39 | ÷ | 15,2 | ÷ | 40 | ÷ | ÷ | 30 | ÷ |
| $\frac{HC}{N}\ \frac{ppm}{kW}$ | DF | 0,372 | 0,394 | 0,196 | 0,106 | 0,193 | 0,289 | 0,116 | 0,08 | 0,17 | 0,152 | 0,133 | 0,135 |
| | DF+CNG | 21,9 | 19,88 | ÷ | 15,4 | ÷ | 8,92 | ÷ | 9,16 | ÷ | ÷ | 4,05 | ÷ |
| $\frac{NOx}{N}\ \frac{ppm}{kW}$ | DF | 2,42 | 1,06 | 0,61 | 0,5 | 0,32 | 0,12 | 0,24 | 0,26 | 0,12 | 0,06 | 0,13 | 0,13 |
| | DF+CNG | 5,93 | 2,89 | ÷ | 1,09 | ÷ | 0,35 | ÷ | 0,1 | ÷ | ÷ | 0,07 | ÷ |
| $\frac{D}{N}\ \frac{1}{kW}$ | DF | 0,372 | 0,394 | 0,196 | 0,106 | 0,193 | 0,289 | 0,116 | 0,08 | 0,17 | 0,152 | 0,133 | 0,135 |
| | DF+CNG | 21,9 | 19,88 | ÷ | 15,4 | ÷ | 8,92 | ÷ | 9,16 | ÷ | ÷ | 4,05 | ÷ |
| $\frac{CO_2}{N}\ \frac{\%}{kW}$ | DF | 0,5 | 0,36 | 0,25 | 0,19 | 0,18 | 0,17 | 0,16 | 0,14 | 0,14 | 0,07 | 0,14 | 0,13 |
| | DF+CNG | 0,393 | 0,357 | ÷ | 0,138 | ÷ | 0,137 | ÷ | 0,08 | ÷ | ÷ | 0,109 | ÷ |

*Table 5: Emissions related to engine power and their mean values in the experimental range of speed.*

| ***Parameter*** | ***Mode of fuelling*** | ***Mean emission*** |
|---|---|---|
| $\frac{CO}{N}\ \frac{ppm}{kW}$ | DF | 0,051 |
| | DF+CNG | 0,050 |
| $\frac{HC}{N}\ \frac{ppm}{kW}$ | DF | 0,19 |
| | DF+CNG | 13,22 |
| $\frac{NO_x}{N}\ \frac{ppm}{kW}$ | DF | 0,5 |
| | DF+CNG | 1,74 |
| $\frac{D}{N}\ \frac{1}{kW}$ | DF | 0,9 |
| | DF+CNG | 0,18 |
| $\frac{CO_2}{N}\ \frac{\%}{kW}$ | DF | 0,2 |
| | DF+CNG | 0,2 |

As may be seen from measurements, air flow rate for fuelling with only diesel fuel and dual-fuelling was almost the same, Table 6.

*Table 6. Air flow rate measurements with Bosch Flow meter [kg/h]*

| **Fuelling mode** | **Engine speed n, rpm** | | | | |
|---|---|---|---|---|---|
| | *1400* | *1800* | *2200* | *2600* | *3200* |
| DF | 138 | ÷ | 279 | 322 | 368 |
| DF+CNG | 127 | 200 | 254 | 322 | 365,6 |
| Difference in percent in relation to DF | 7,9 | ÷ | 2,9 | 0 | 0 |

Due to that, absolute value of each harmful emission in $m^3$ related to power unit, kW, may be compared. In this case $CO_2$ emission is the same for both fuelling mode. Perhaps it is due to that, that engine efficiency was lower for fuelling with both CNG+DF than this for DF only.

## 5. Summary

From the experiment the following conclusions may be drawn:
the dual-fuel engine in comparison with base one (fuelled only with diesel fuel) has

- lower torque and power
- a little lower brake fuel conversion efficiency
- much more higher CO and HC emissions

but has some advantages as

- lower $CO_2$ and smoke emission
- lower $NO_x$ emissions at higher load range.

Application of natural gas instead of petroleum fuels contributes to save resources of crude oil and to decrease greenhouse effect.

Further work would be necessary to optimize control parameters for increase of performance and decrease HC and CO emissions.


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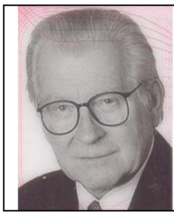

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