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RESEARCH ARTICLE

Comparison Tests of Fossil Diesel Fuel and TBK-Biofuel

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Abstract
The objective of our measurements was to determine the most important properties of the TBK bio-diesel with relevance to ICE use and to evaluate its effects on the power output, fuel consumption, exhaust emissions of a CI engine in comparison with commercial diesel fuel. Thus the standardized diesel fuel was used as reference fuel, and it was compared with the newly developed biofuel called TBK. Based on our measurements its most important physical and chemical properties and its effects on combustion and exhaust gas emissions in ICE are presented in detail. Emissions mean on the one hand components which are regulated in the emission directives of the European Union for type-approval of vehicles or engines, and on the other hand, a detailed analysis of hydrocarbons. The evaluation was made on the basis of engine test bench measurements realized on a city bus engine typical for the Hungarian bus fleet.

Keywords
new type biofuel, CI engine, regulated and unregulated exhaust emissions, hydrocarbons, physical and chemical properties of biodiesel, exhaust gas analysis

1 Introduction

Biofuels can be defined as fuels derived from renewable sources like biomass and used in engines of road and non-road vehicles and in engines for energetically purposes. Using biofuels in increasing quantities for fuelling of road vehicles is an important tool for the EU member countries, also for Hungary, to decrease dependence on imported crude oil. It improves the security of supply of energy sources on a middle and long term, and it helps to decrease the emission of greenhouse gases. Biofuels can be used either in pure form or in blended form instead of fossil fuels. There are additional benefits like job creation in agriculture, using of agricultural overproduction and using of uncultivated lands.

The diesel fuel is the fuel of CI engines traditionally. Use of CI engines in Heavy Duty Vehicles and in other machines is almost autocrat against the SI engines thanks to their better efficiency and higher specific power. In the last time resulting from the apace development of technology can be observed the always bigger penetration of CI engines in passenger cars (MOL, 2011). For our comparison tests commercial diesel fuel was used as a reference fuel, which was purchased from a filling station of MOL in Budapest, and corresponds to the standard. EN 590:2013.

With the rapid development of chemical industry recently some new biofuel were invented for instance GVL (Horváth et al., 2008; Tukacs et al., 2014, Fábos, Mika and Horváth, 2014), and TBK. The TBK biofuel was invented by three Hungarian engineers (János THESZ chemical engineer, Béla BOROS mechanical engineer, Zoltán KIRALY chemical engineer) and has enormous potential like GVL G. It is a biodiesel produced by a new esterification process from vegetable oils. The invention was granted protection under patent number HU 226873 (2010) from the Hungarian Intellectual Property Office. According to the new process, the vegetable oil is esterified partially with short-chain alkyl-carboxylates, preferentially with ethyl acetate. During this process, a certain part of the C16 – C22 acyl groups are replaced with acetyl (C2) groups, and at the same time alkyl-esters of displaced fatty acids are produced. As a result of this process, a two-component fuel is afforded. Components are modified triglycerides with reduced

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molecular masses and ensuing decreased viscosities, plus fatty acid (m)ethyl esters (FAME or FAEE). This means that glycerol is not generated, and on account of the incorporation of (m)ethyl acetate molecules, 15 – 20% extra fuel mass can be produced from one unit of vegetable oil, compared to conventional biodiesel processes.

This new second generation type of biodiesel has many advantages compared the conventional biodiesel as follows:

- All atoms of triglycerides derived from biomass are utilized as fuel (the glycerol backbone is retained),
- No washings, no sewage generation,
- The oxygen content of the fuel will be higher than that of conventional biodiesel, which can result in a lower emission of particulate matter,
- It has a lower iodine number compared to FAME, therefore TBK-Biodiesel is more stable,
- Because of its higher density (915-950 kg/m^3) the energy content based on volume is higher,
- More favourable cold-flow properties (lower point of congelation and cold filter plugging point, CFPP),
- This is a simple, environmentally friendly technology (no use of methanol and hydrogen, both derived from fossil sources, whereas ethyl acetate is of biological origin) (Thesz and Kondor, 2008; Thész et al., 2014).

Biofuels like pure oil, transesterficated oil have disadvantages in point of view of physical and chemical properties with relevance to ICE use (Lujaji et al., 2010; Laza et al., 2011; Zhou et al., 2013). These disadvantages can be compensated by decreasing in exhaust gas emission in point of certain components because of their adherent oxygen content (Guarieiro et al., 2014; Mrad et al., 2012; Lapuerta et al., 2010; 2008).

2 Used methods and engine

Basic physical and chemical properties

From among the basic physical and chemical properties of fuels with relevance to ICE use the

- density,
- kinematic viscosity,
- heating value,
- cetane number
- TG and DTG curves.

were determined by us based on the relating European standards.

The tested engine

The engine used for the tests is the property of KTI Institute for Transport Sciences Non Profit Ltd.

Its type and emission category is: RÁBA D10 UTSLL 160, EURO II

The rated parameters of the engine are the follows:

- rated torque: 920 Nm / 1300 RPM
- rated power: 160 kW / 1900 RPM

Test method

As regards the exhaust emission the measurements were carried out according to the ECE Regulations detailed in UN-ECE R-24.02 (UNECE, 1995) and UN-ECE R-49.02 (UNECE, 1993).

External parameters of engine

- Torque, power output, specific fuel consumption, effective efficiency.

Emission

- Regulated exhaust emission components (CO, HC, NO$_x$, PM, smoke),

Detailed emission

In addition to the above-mentioned regulated exhaust components, some important unregulated hydrocarbons (TPH (Total Petroleum Hydrocarbon), BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), PAH (Polycyclic aromatic hydrocarbon), Aldehydes) were measured, too. These measurements were aimed to evaluate the detailed effect of TBK-Biodiesel on the composition of hydrocarbons of exhaust emissions, as well as their carcinogenic and odour nuisance effects. Place of sampling for exhaust gas measurements was from the exhaust pipe downward of the silencer.

Measurement of TPH, BTEX was made according to *ISO 9487:1992*. The sampling was made intermittently by an adsorption tube (SKC 226-01) filled with active carbon.

Measurement of PAH was made according to *MSZ 21862-29:1988*. The sampling was made intermittently by an adsorption tube (SKC 226-30-05) filled with XAD2 polymeric adsorbent.

Measurement of aldehydes was made according to *MSZ 13-144:1989*. The sampling was made intermittently by an adsorption tube (SKC 226-119) filled with impregnated silica gel.

Measuring elements

The types of the measuring elements are presented in Table 1. The accuracy of the measuring elements is described in the relating regulation.

Table 1 The measuring elements and its type

MEASURING ELEMENT	TYPE
Test bench	SCHNECK W400
Gas Analysator	Pierburg AMA-2000 F
Opacimeter	AVL 439
Dilution	Full flow dilution tunnel
Scales	Sartorius M3P-000V001
Fuel consumption measurement	Froude FG100
Air flow meter	Rosemount

3 Results and evaluation

Physical and chemical properties of the tested fuels

Density, kinematic viscosity, heating value

On Table 2 can be seen the values of the most important physical parameters of three fuels. In case of TBK, they were determined by ÁMEI Zrt. (Petroleum Products Quality Inspection Company in Hungary) according to biodiesel standard. The limit values of diesel fuel and biodiesel fuel were taken from the relating standards.

Table 2 Important parameters of TBK-Biodiesel in comparison with the two other standardized fuels (Merétei and Szabados, 2010; MSZ EN 590:2013, 2014; MSZ EN 14214:2012+A1:2014, 2014)

Parameter	Measured values of TBK biofuel	Biodiesel (EN 14214) [11]	Diesel (EN 590) [10]
Density (15 °C) [kg/m^3]	915	860-900	820-845
Kinematic viscosity (40 °C) [mm^2/sec]	6.5	3.5-5.0	2-4.5
Lower heating value [MJ/kg]	36.5	-	43.00 (measured)
Cetane number [-]	48	>51	>51

Parameters of a Diesel-engine are influenced dominant by the parameters of the fuel used in the engine. These have an effect among others on atomization imagine, on scaling and size of fuel drops, and through these on the composition of the exhaust gas, finally on the efficiency of the engine. One of these parameters is density. The density of TBK is higher than that of conventional biodiesel and diesel fuel. Besides the density exists the same relationship in the case of kinematic viscosity as well. It can have a conclusion that the atomization will be worse and the combustion will have a worse efficiency. As regards density and kinematic viscosity based on the result can be made a conclusion that against the diesel fuel on case of the biofuel the combustion process will drag the exhaust emission will increase, but regarding certain components the increasing can be compensated by the more oxygen content of renewable fuel.

Work got during the expansion stroke consequently the torque and power of the engine are proportional to the heating value of the fuel. Based on the results above the conclusion can be made that the engine will have likely smaller power and higher specific fuel consumption running on TBK.

TG and DTG curves

TG and DTG curves give us very important information about fuels in connection with their evaporative property. The results are shown on Fig. 1 in case of the two tested fuels.

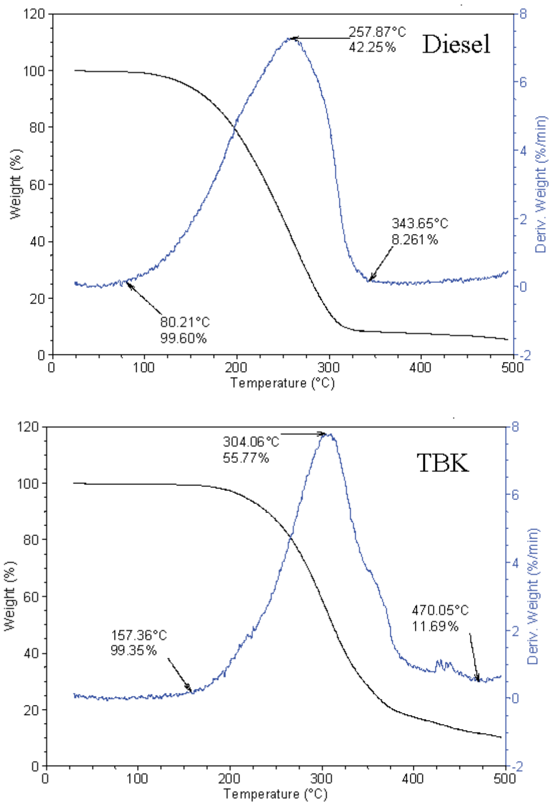

Fig. 1 TG and DTG curves of the two tested fuels (above: diesel fuel, under: TBK) (Szabados et al., 2014)

The thermogravimetry (TG) and the differential thermogravimetry (DTG) curves give information about the evaporation properties of the fuels as well. Evaporation is affected by many things, for example, the distribution of weight of the molecule, the polarity of molecules, chemical saturation, the phenomena of polarization. The diesel fuel is built up of molecules with nonpolar bonds which means a soft bond, and thanks to this the intensive evaporation begins previously opposite renewable fuels, which have molecules with polar, strong bonds and heteronuclear (oxygen). The measurements were carried out in air environment therefore in case of the biofuels can exist the polarization that decreases the evaporative tendency.

Based on the weight curves of the Fig. 1, it can be seen that the weight losses (in terms of percent) in function of temperature. The intensive evaporation of renewable fuel to the fossil one begins at a higher temperature by circa 100 °C. Based on the derived weight curves of the Figure are shown the velocities of the weight losses in function of the temperature. The maximum value of the velocity of weight losses of the renewable material is approx. at the temperature, which is by 40-45 °C higher than the same parameter of diesel fuel. As long as the fossil fuel reach the maximum point, the biofuel runs at a less value. By the time the diesel fuel is almost fully evaporated, at the same time the half of the TBK is evaporated regarding their mass.

External parameters of engine

Torque, power output, specific fuel consumption

Torque, power output, specific fuel consumption are so-called basic external parameters in case of every engine testing. With the help torque and power of the engine the dynamic characteristics of the vehicle can be calculated, the specific fuel consumption is a parameter for evaluation of economy. Results are summarized on the Figs. 2-4.

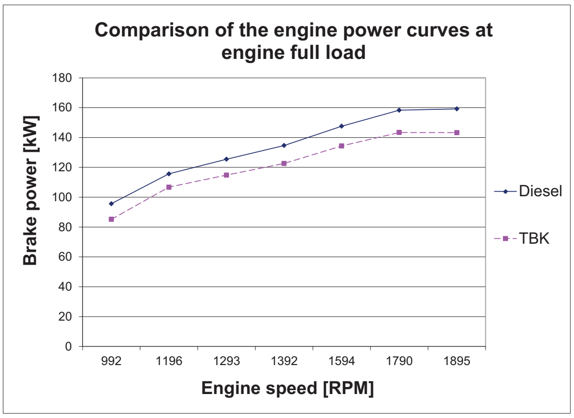

Fig. 2 Comparison of the engine power (Merétei and Szabados, 2010)

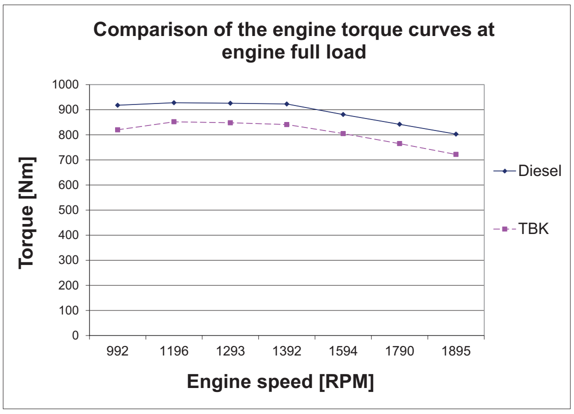

Fig. 3 Comparison of the engine torque (Merétei and Szabados, 2010)

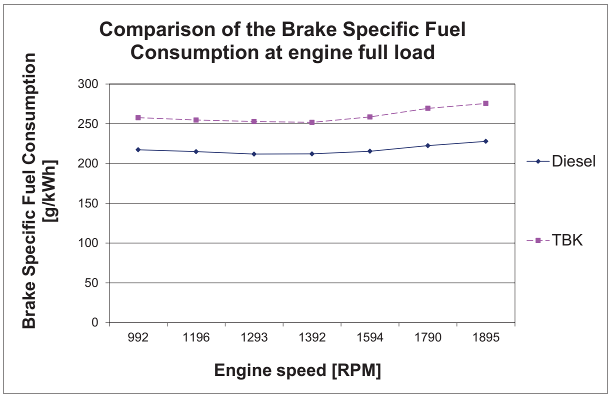

Fig. 4 Comparison of the engine specific fuel consumption (Merétei and Szabados, 2010)

The power output and torque values in the whole range of speed were less in case of TBK fuel than in the case of the commercial fuel. The 9-10% decrease of the torque and power output in case of the TBK is the consequence of its less heating value.

Weighted average of Brake Specific Fuel Consumption

The Brake Specific Fuel Consumption can be an appropriate indicator to characterize the efficiency of the engine. In case of the so-called 13 point test cycle, the final values of the emission components are determined with helping of weighting factors. A weighting factor belongs to each point. Among the 13 points there are 3, which are idle points. In case of idle of an engine, the specific fuel consumption will be immeasured and the effective efficiency of the engine will be zero. Weighting factors belong to these 3 points was divided to the other 10 points. Relating to this 10 points was determined the weighted average value of Brake Specific Fuel Consumption. These values can be seen in Table 3. In case of the TBK biofuel, the value is higher by 20 %. This means that to generate one unit of work the engine needs 20 % more fuel in terms of mass.

Table 3 Comparison of weighted average of Brake Specific Fuel Consumption (Merétei and Szabados, 2010)

	Weighted average of Brake Specific Fuel Consumption [g/kWh]
Diesel Fuel	240,8
TBK	292,9

Emission and detailed emission

Regulated exhaust emission components (CO, HC, NO_x, PM, smoke)

Smoke values were measured during the measuring process according to UN-ECE R-24.02. There are two methods. On one hand, it has to be measured under stationary circumstances, and the other hand under free acceleration. Results are summarized on Fig. 5, 6.

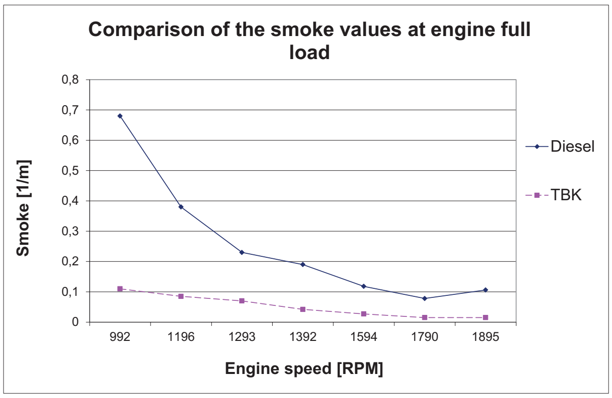

Fig. 5 Comparison of smoke values 1 (Merétei and Szabados, 2010)

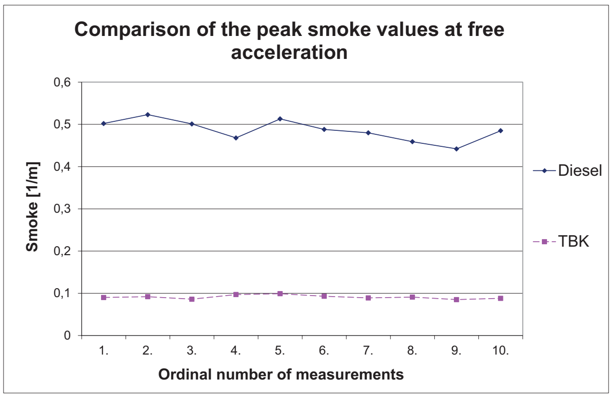

Fig. 6 Comparison of smoke values 2 (Merétei and Szabados, 2010)

Regulated components are measured according to the UN-ECE R-49.02, and the weighted average values listed in Table 4.

Table 4 Comparison of regulated emission components (Merétei and Szabados, 2010)

Emission components [g/kWh]	NO_x	CO	HC	PM
Diesel fuel	7,48	1,51	0,57	0,24
TBK	7,07	1,78	0,41	0,38

The average value of the smoke measurements at the free acceleration in case of the TBK (0,091 m^{-1}), is much less than that of the commercial diesel fuel (0,458 m^{-1}). Figure 5 shows the comparison of the smoke values measured at full load. The significant decrease of the smoke can be traced likely back to the coherent oxygen content of the biofuel.

The weighted average values of the regulated emissions are given in Table 2, which were calculated according to the UN-ECE R-49.02 Regulation. On the basis of these values the following conclusions can be drawn:

The NO_x-emission was decreased on an average by 5,5%, the HC-emissions were decreased on an average by 28%, the CO-emission was increased on an average by 18%, and the PM-emission was increased on an average by 58%. To explain the phenomena, that the smoke values lower and the PM value higher as the effect of TBK, it can be conceived, that the brake power decreased in case of TBK biofuel.

Hydrocarbons detailed (Aldehydes, TPH, BTEX, PAH)

Detailed hydrocarbons like aromatic and aliphatic components are listed in Table 5.

The measured hydrocarbons are given separately regarding the two different kinds of tested fuels in case of each of the investigated modes in μg/m^3 unit of measure.

The solid phase PAH-emissions at higher speed and load are slightly bigger in case of the TBK compared to the values measured using the commercial diesel fuel.

On the other hand, the liquid phase PAH-emissions were significantly less in case of all of the investigated modes regarding the TBK compared to the commercial diesel fuel.

Regarding the aliphatic hydrocarbons, their emissions were clearly less in case of TBK-Biodiesel compared to the commercial diesel fuel. These results correspond to the hydrocarbon emissions measured according to the Regulation using the FID exhaust gas analyser. But the benzene (benzol) emissions in all of the modes were bigger in case of TBK compared to the commercial diesel fuel. In case of the formaldehyde characteristic (mainly responsible) for the smell effect, the TBK produced less or bigger emissions depending on the speed and load compared to the commercial diesel fuel.

Summarising the before mentioned statements the following conclusions can be drawn:

In case of the TBK most of the hydrocarbon emissions clearly decreased. The emissions of carcinogenic and smelling not regulated hydrocarbons neither significantly decreased nor increased.

4 Conclusion

The objective of the test was the evaluation of effects of the TBK biofuel on the power output, fuel consumption, exhaust emissions, before this the comparison to the diesel fuel as regards the most important physical and chemical properties. In connection with exhaust emission were measured on one hand the components regulated in emission directives of the European Union for type-approval of vehicles or engines, and on the other hand a detailed analysis of hydrocarbons was made on the basis of engine test bench measurements investigating a city bus engine typical for the Hungarian bus fleet.

On the basis of the results of these tests the tested TBK-biofuel fuel can be considered as a nearly equivalent fuel compared to the commercial diesel fuel from points of view of the characteristic parameters and exhaust emissions of the test engine.

The measurements of this test do not provide opportunity to evaluate the effects of the tested TBK regarding durable operation (deposits, interactions with the lubricating oil, influence on lifetime expectation, cold-starting ability) as well as regarding the influences on function of the newest common-rail, very high pressure injection systems.

From the point of view of tested parameters, TBK could be better if their properties like density and kinematic viscosity were closer to those of commercial diesel fuel. Because of these things the engine has an over heat consumption. We propose a further development in order to its properties fit better the properties of biodiesel.

Table 5 Aromatic and aliphatic components (Merétei and Szabados, 2010)

Detailed hydrocarbons measured at different speeds and loads of the 13-Mode Test (UN-ECE R-49.02)												
Serial number of measurement	1		2		3		4		5		6	
Serial number in 13-Mode Test	1		2		4		5		6		8	
Load [%] / Speed (n) in the measured Mode	0% / n_{idle}		10% / n_{Mmax}		50% / n_{Mmax}		75% / n_{Mmax}		100% / n_{Mmax}		100% / n_{Pmax}	
Fuel	Diesel	TBK	Diesel	TBK	Diesel	TBK	Diesel	TBK	Diesel	TBK	Diesel	TBK
PAH (solid phase)	μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3	
Total naphtalene	0.721	0.792	1.063	0.909	4.356	1.675	1.050	1.737	2.786	0.829	2.481	0.885
Total PAH without naphtalenes	2.885	2.178	10.000	7.172	20.552	20.761	12.100	15.737	25.075	11.399	5.414	9.010
Total PAH	3.6	3.0	11.1	8.1	24.9	22.4	13.2	17.5	27.9	12.2	7.9	9.9
PAH (liquid phase)	μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3	
Total naphtalene	150.481	37.426	231.401	Not meausured	nd	109.645	nd	Not meausured	210.448	79.793	218.045	60.938
Total PAH without naphtalenes	5.913	1.040	8.213		15.092	17.056	10.650		11.741	19.637	11.880	12.865
Total PAH	**156.3**	**38.5**	**239.6**		**nd**	**126.9**	**nd**		222.4	99.5	230.1	74.0
Detection limit of the method (nd): 0.001 μg/sample for each species												
Accuracy of measurement: (±) 10%												
Aromatic and aliphatic species (BTEX)	μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3	
benzol	298.077	504.587	442.308	787.037	430.233	788.991	596.154	682.243	642.202	698.113	418.919	518.868
toluol	134.615	91.743	173.077	148.148	151.163	192.661	230.769	177.570	311.927	198.113	175.676	150.943
etil-benzol	38.462	18.349	57.692	27.778	46.512	36.697	57.692	28.037	45.872	37.736	40.541	18.868
xylenes	144.231	0.000	201.923	18.519	151.163	27.523	211.538	37.383	155.963	47.170	162.162	37.736
other aromatics	1096.153	0.000	1817.308	0.000	1290.691	0.000	1682.692	0.000	559.633	0.000	1135.135	0.000
Total aromatic	1711.5	614.7	2692.3	981.5	2069.8	1045.9	2778.8	925.2	1715.6	981.1	1932.4	726.4
Aliphatic C5-17	41634.6	5743.1	59326.9	11388.9	46162.8	10458.7	60384.6	13831.8	29266.1	17452.8	52432.4	14056.6
Detection limit of the method (nd): 0.2 μg/sample for each species												
Aldehyde species	μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3		μg/m^3	
formaldehyde	2087.379	5009.524	5524.752	4158.879	5230.769	2542.857	6000.000	3592.233	5066.667	6098.039	4478.873	5343.434
acetaldehyde	1038.835	493.333	1316.832	115.888	1910.256	156.190	656.566	499.029	2019.048	772.549	1746.479	1131.313
akrolein	273.786	102.857	203.960	nd	502.564	nd	68.687	79.612	401.905	31.373	321.127	117.172
other aldehydes	1312.621	1014.938	1423.762	598.131	2833.333	674.285	1131.313	1153.398	3097.143	1407.843	2205.634	1868.687
Total aldehydes	4712.6	6620.7	8469.3	4872.9	10476.9	3373.3	7856.6	5324.3	10584.8	8309.8	8752.1	8460.6
Detection limit of the method (nd): 0.05 μg/sample for each species												
Accuracy of measurement: (±) 10%												

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