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Accelerating Low carbon Industrial Growth through CCUS

Deliverable No. D4.2.4

Final validation test run of stationary engine for peak-power production by CCU-DME

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Report summary

Efforts to reduce our carbon emissions are increasing around the globe in order to reach the set targets of the Paris Agreement in 2050. Reaching zero CO_2 emissions by solely reducing the carbon emissions is highly unlikely. Reducing the emitted CO_2 by capture and Storage (CCS) and reusing (CCU) carbon are very promising technologies for decreasing the CO_2 in our atmosphere and thus preventing a global warming of more than 1.5°C.

Synthesizing dimethyl ether (DME) is one possibility of reusing carbon atoms, produced with H_2 and CO_2 in a synthesis unit. DME has a cetane number higher than 55 and is a Diesel substitute. A diesel engine can run on DME with some minor changes mainly regarding the fuel supply system, since DME is gaseous under atmospheric conditions. The tank is pressurized with 5 to 8 bar depending on the surrounding temperature. Because of the high oxygen content of the fuel and no direct C-C connections, the combustion in an internal combustion engine produces almost no soot, hence nullifying the Soot-NO_x-tradeoff resulting with the introduction of exhaust gas recirculation (EGR).

In this task a 7.2l Deutz generator engine is modified to run on DME and produce electricity, thus closing the CCU chain, enabling CO_2 as a resource in modern society instead of a waste product.

With the DME operation the maximum power of the diesel operation could be reached with a similar fast responding behavior on power demand, which is necessary for a peak power generator, providing electricity for a hospital or other applications. All measured emissions, but NO_x emissions could be reduced for all load points at 1500 1/min corresponding to the German power grid frequency. The thermal efficiency was on average 2-3 percentage points better than the diesel operation.

In the following report the main results of the thermodynamic investigations are presented and discussed.

Table of Contents

1 Introduction

Using a synthetic fuel like dimethyl ether (DME) a compression ignition engine bears challenges especially for the fuel system. DME is usually stored as a liquefied gas in a pressurized tank (5-8 bar). The much lower kinematic viscosity of DME compared to diesel also demands some changes to the fuel system, for example the high-pressure fuel pumps have to be lubricated with oil. Despite the costs of these changes in the fuel system there are advantages in using DME instead of conventional diesel.
DME has no direct C-C bindings and has a relatively high oxygen content of 35 m%, thus producing almost no detectable soot (see Figure 1.1). Therefore, diminishing the influence of the soot-NOx-tradeoff regarding the use of exhaust gas recirculation (EGR) and enabling the possibility of a simpler exhaust gas aftertreatment system and increasing the engines overall efficiency simultaneously.

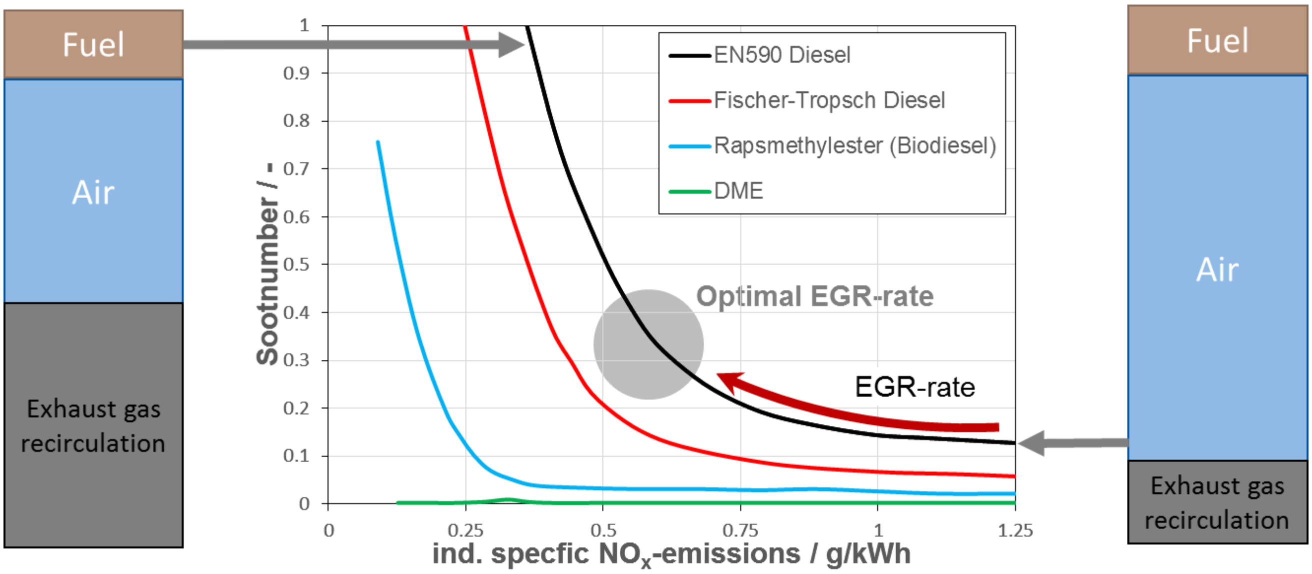


Figure 1.1: Soot-NOx tradeoff

The injection behavior is different as well compared to Diesel. For example, the Liquid Penetration Length (LPL) and the Lift Of Length (LOL) are clearer separated than with Diesel. Thus, resulting in better mixture formation and a more efficient combustion.

2 Thermodynamic investigations

For the application of DME on a diesel engine and to quantify the above-mentioned potential and to derive the necessary changes of the calibration thermodynamic investigations were carried out. These investigations include variations of load, injection timing, injection pressure, introducing pilot and post injections etc. In the following the main steps for the thermodynamic investigations as well as the main results are presented.

2.1 Engine Setup

The main technical data of the Deutz TCD 2013 L06 V4 engine for diesel operation is summarized in Table 2.1.

Table 2.1: Technical data of the DEUTZ TCD 2013 L06 V4 in diesel operation

Technical data	
Emission norms	EU IIIA, US T3
Number of cylinders	6
Bore	108 mm
Stroke	130 mm
Displacement	7.2 l
Length	1865 mm
Width	1046 mm
Height	1322 mm
Weight	870 kg
Typical generator power at 50 Hz/ 1500 rpm	
Typical generator power (COP)	226 kW
Typical generator power (PRP)	238 kW
Typical generator power (LTP)	251 kW

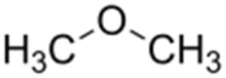
The engine was operated in three different setups:
- Standard diesel setup
- DME setup with DME optimized injector and standard piston bowl
- DME setup with DME optimized injector and optimized piston bowl

The standard diesel setup was measured as a baseline, for engine performance, consumption and emission characteristics. Since the standard injectors are not capable of injecting DME the optimized injectors had to be used for the first operation with DME. In order to verify the impact of the piston bowl optimized by Computational Fluid Dynamics (CFD) on the DME operation the standard piston bowl was used for the first measurements with DME. The third setup included the optimized piston bowl and with this setup the final calibration was accomplished. The test bench setup as well as the main measurement results and the comparison between the three setups are shown and explained in the following.

2.2 Test bench setup

The Deutz TCD 2013 L06 V4 engine was run at the Center for Mobile Propulsion (CMP) a modern research center of the RWTH Aachen University. The test bench facility is managed by Prof. Dr.-Ing. (USA) Stefan Pischinger of the internal combustion institute Aachen (VKA), within the facilities 16 institutes are working on an interdisciplinary approach for modern mobile propulsion systems.
For the use of an alternative synthetic fuel such as dimethyl ether the test bench setup has to be adapted. The test bench has to be equipped with a DME detection system and an explosion proof ventilation system. Since DME is gaseous under atmospheric conditions and heavier than air, DME could otherwise during a malfunction accumulate an explosive mixture inside the test bench. The Engine adaptions mainly concentrate on the fuel system since DME is a liquefied gas and has significant differences regarding the chemical properties compared to diesel as shown in Table 2.22.

Table 2.2: Chemical properties of DME and diesel

Property	**Unit**	**DME**	**Diesel**
Chemical structure			
Molar mass	g/mol	46	170
Carbon content	mass%	52.2	86
Hydrogen content	mass%	13	14
Oxygen content	mass%	34.8	0
Carbon-to-hydrogen ratio	-	0.337	0.516
Liquid density	kg/m³	667	831
Cetane number	-	>55	>51
Auto-ignition temperature	K	508	523
Stoichiometric air/fuel mass ratio	-	9	14.6
Lower heating value	MJ/kg	27.6	42.5
Kinematic viscosity of liquid	cSt	<.1	3

The schematic design of the DME fuel system is shown in Figure 2.1. The diesel fuel filter is exchanged with a 5 µm ceramic membrane, three heat exchangers cool down the DME to ensure liquefied DME in the fuel system. The Low Pressure (LP) pump sufficiently provides pressurized DME for the LP system. The pressure in the LP system is set to 30 bar and controlled with a pressure limiter. A pressure of 30 bar is necessary in order to keep DME in liquid state up to a temperature of 95°C.

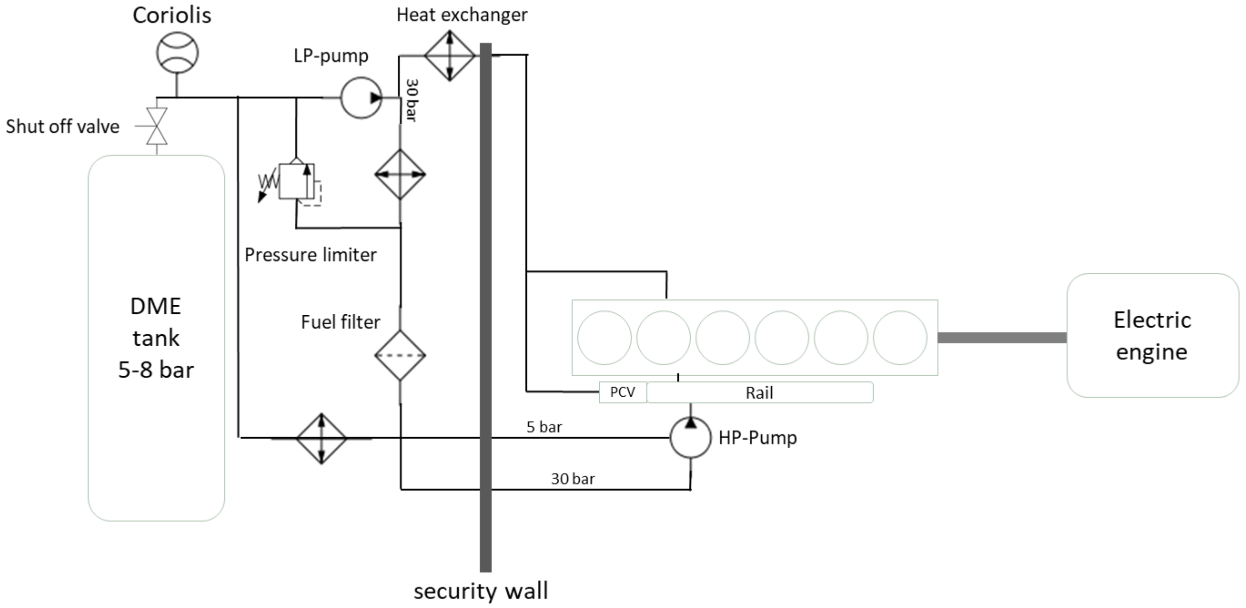


Figure 2.1: Schematic of the DME fuel system

The Fuel Control Unit (FCU) for diesel operation is implemented with a metering unit limiting the amount of fuel pumped into the high-pressure system and a pressure limiter valve at the rail.
For the use of DME the FCU has to be modified. Hence cavitation at the entrance of the high-pressure pumps has to be avoided in order to prevent damaging the fuel pumps. Therefore, the metering unit cannot be used for DME and the pressure limiter valve is replaced with a Pressure Control Valve (PCV). The PCV controls the pressure in the rail with the help of a Proportional-Integral-Derivate (PID) controller. The input for the PID controller is the measured rail pressure from the ECU and the control variable is the desired pressure set by the ECU. Since the ECU is not capable of regulating a PCV unit, it is necessary to use an autonomous controller.
With this setup, the injection pressure can be set to desired values ranging from 300 bar to 1000 bar and its influence can be investigated.

2.3 Test bench results

In this section the main results of the test bench investigations will be presented. The low Lower Heating Value (LHV) of DME compared to diesel as well as the lower density could be compensated by a higher injector flow rate and longer injection durations, as Figure 2.2: Overview of power, cylinder pressure, consumption and efficiencyFigure 2.2 shows the maximum power of P_{max}=250 kW at M=1600 Nm and n=1500 1/min was reached with both DME setups. The maximum cylinder pressure at low and medium torque was higher for DME due to a different injection strategy. The diesel operation used a pilot-, main- and post injection for all lower and mid load points, as well as a relatively late injection start. The DME operation used only a main injection. In high load points the diesel operation as well as the DME operation used only one main injection. The Brake Specific Fuel Consumption (BSFC) is as expected higher for DME due to the lower LHV.

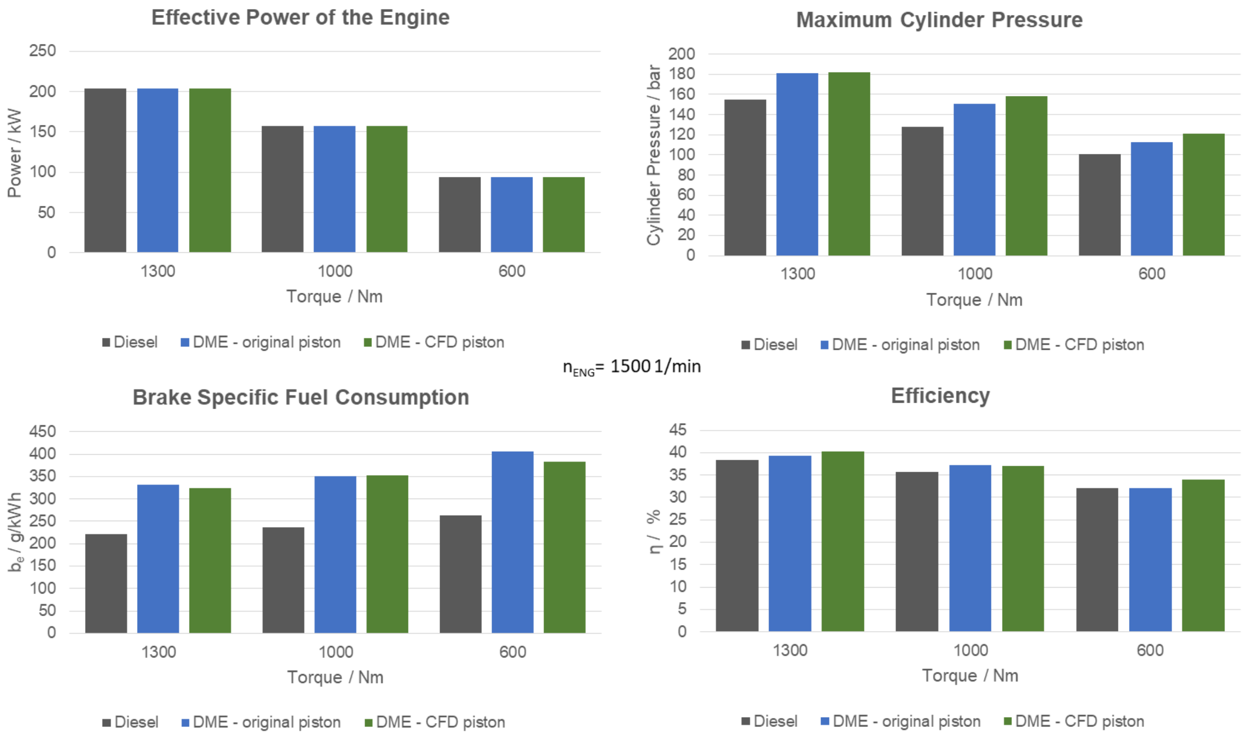


Figure 2.2: Overview of power, cylinder pressure, consumption and efficiency

At higher loads above M=1400 Nm the used Coriolis measurement device for the fuel flow caused a high pressure drop in the low pressure fuel system with DME, causing the DME to partially gasify and therefore the measurement of the fuel flow was inconclusive. The efficiency for the DME operation showed a better performance compared to diesel. The CFD piston setup in particular was on average 3-4% percentage points more efficient than the diesel setup. The increase in efficiency can be explained with the higher burn rate and earlier start of combustion of DME compared to the diesel operation. The position of the burned mass fraction of 50% (XMB50) of both DME setups was set to the same value for all load points, this allows for a good comparison of the results regarding the performance and emissions of the changed piston bowl. Comparing the two DME setups the optimized CFD piston shows an increase in burn rate for all operating points, indicating a more efficient combustion. The main set target for the CFD optimization process was a higher air utilization, which results in a faster and more efficient combustion. Therefore, the analysis of the burned mass fraction indicates a successful CFD optimization of the piston bowl and the injector cone angle.

Figure 2.3 shows an overview of the most important engine out emissions in parts per million (ppm) without any filter or other exhaust gas after-treatment system. The Filter Smoke Number (FSN) is zero for DME at all operation points, this is due to no direct carbon to carbon (C-C) bonds and the high oxygen amount in DME.

The higher NO_x emissions of DME compared to diesel can be explained with the faster burn rate and therefore higher temperatures inside of the combustion chamber, this effect is intensified by the higher air utilization of the CFD piston. High combustion temperatures are one of the main reasons for the production of NO_x emissions. The combustion temperature can be decreased with the integration of exhaust gas recirculation (EGR), which is considered mainly as an inert gas. In diesel operation higher EGR-rates result in an increase of soot emissions, this behavior is also known as the Soot-NO_x-tradeoff, where a balance between soot and NO_x emissions has to be found by optimizing the EGR-rate. However, with DME emitting almost no soot this effect is nullified and the EGR-rate can be increased to lower NO_x emissions without impact on soot emissions. This was unfortunately not possible for the DEUTZ LCD 2013 L06 V4 engine, since the EGR path is retrofitted and only allowed relatively small EGR rates. The pressure difference

between the exhaust gas after the EGR cooler and the fresh air before entering the engine is essential for the feasible amount of EGR, as it provides the driving force for the EGR. At this engine the pressure difference was very low for all measured operation points, only the implemented reed valve ensured a small amount of EGR of less than 10%. There are different possibilities to increase the EGR for this engine, but they include hardware changes such as changing the turbocharger or introducing a throttle in the fresh air path, which entail major changes to the application and calibration and could therefore not be considered.
The CO emissions were also significantly lowered with the use of DME, in part load the emitted CO was more than halved and stayed below 100 ppm. Only for maximum torque the CO emissions started to rise, but never reached the diesel level. The CO emissions of the CFD piston showed lower values at nominal power and higher torques, also indicating a more complete combustion and good air utilization.
The hydrocarbon (HC) emissions are low for all three scenarios, but DME shows especially for low torques better HC emissions than diesel. The lower HC emissions for the CFD piston also indicate an improved air utilization and overall more complete combustion in particular for higher loads, where the DME operation with the standard piston bowl has a small increase in HC emissions the CFD piston shows a steady decline.

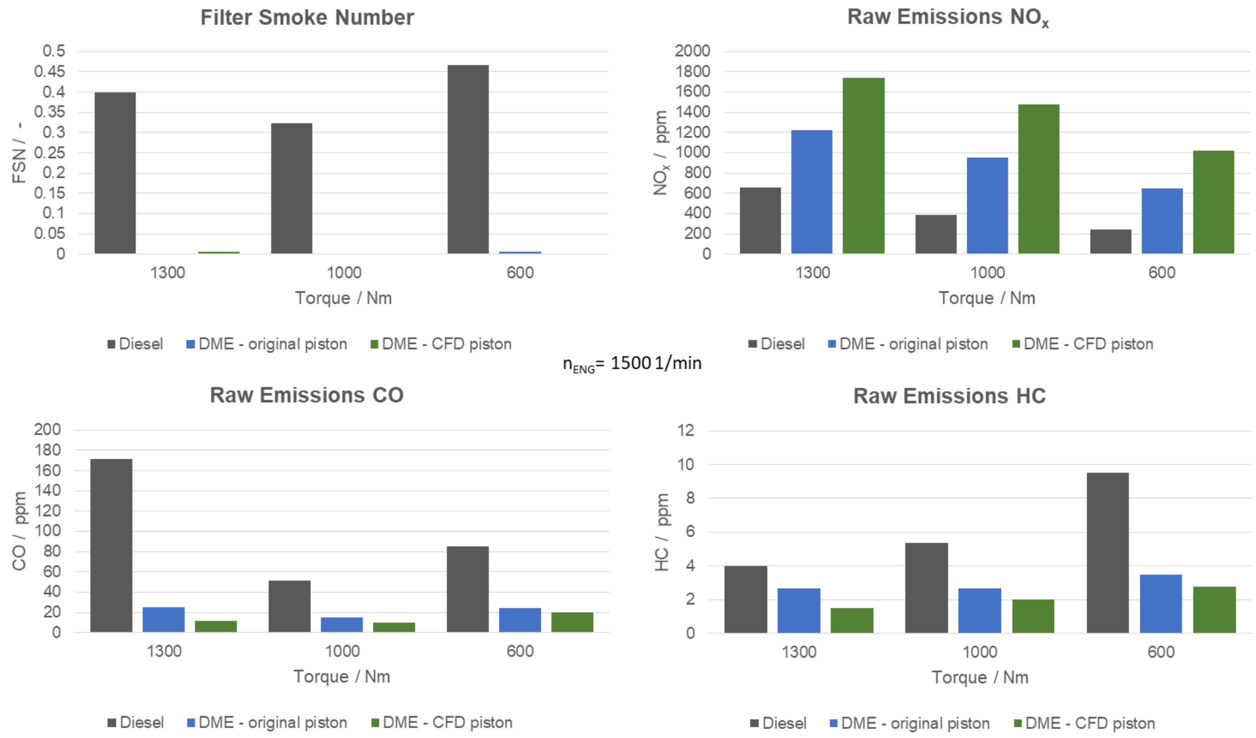


Figure 2.3: Emissions overview

After the main investigations and calibrations were finished the cylinder head was exchanged as planned, since installed temperature measurements had to be removed before the engine was handed over to RWE and implemented in the CCU plant in Niederaußem. During the exchange small damages in the CFD piston bowl surface were detected (as seen in Figure 2.4). The small cracks at the edge of the steps are all in line with the spray cones of the injectors and therefore most likely caused by the spray burning very hot at the surface of the piston. Since DME has more than 30% of oxygen content, it can burn in more rich areas as diesel. For the final application of the engine and the further use in the project the original pistons were reinstalled and the maximum torque was limited from 1600 Nm to 1300 Nm in order to prevent reoccurring damages. Furthermore the clean surface of the piston in Figure 2. needs to be addressed, there are no soot deposits visible and thus illustrating the soot free burn behavior of DME.

Figure 2.4: CFD piston after the measurement program at CMP

After the finished engine adaptation and calibration for the use of DME, the engine was tested regarding its performance and endurance similar to typical peak-power engine tests. The engine was successfully operated for more than 8 hours continuously with a permanently changing demand in power emulating the use of many different electric customers.

3 Summary and conclusion

The LCD2013 V06 V4 was successfully adapted for the use of DME, by changing several parts in the fuel system. The level of performance of the diesel engine was reached with DME while keeping within the given engine limits. The CFD optimized combustion chamber (injector cone angle and piston bowl) gave good results regarding the optimized parameters. For further DME projects in compression ignition engines pistons with higher temperature resistance such as steel pistons as well as injector-needles with more holes instead of bigger holes should be investigated in order to prevent similar damages on the piston bowl surface.

The overall emissions of the DME operation decreased in all categories but NO_x. Since DME combustion produces almost no soot thus eliminating the Soot-NO_x-tradeoff, the NO_x emissions could be reduced with increasing the EGR rate, but with the retrofitted EGR path on this engine EGR rates higher than 10% were not possible. The main engine performance results used for the life cycle assessment for the CCU chain are shown in Table 3.1. The lower CO_2 emissions of DME despite of the higher fuel consumption can be explained by the higher H/C ratio of DME compared to diesel.

Table 3.1: Main engine performance results for DME and diesel

Fuel	Torque	Effective power	Fuel consumption	Combustion Noise Level	Filter smoke number	Particle mass	Particle number	NO_X emissions	CO emissions	HC emissions	CO_2 emissions
-	Nm	kW	g/kWh	dB(A)	1	g/kWh	#/kWh	g/kWh	g/kWh	g/kWh	g/kWh
DIESEL	1300	204	220.7	80.1	0.4	0.21	3.10E+11	5.14	0.66	0.08	711.97
DME	1300	204	332.0	78.8	0	1.50E-05	1.05E+10	9.40	0.10	0.02	635.60