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# Comparing the Combustion Process and the Emission Characteristic of a Stationary Heating Device System and an Internal Combustion Engine with Experimental Investigation

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**Abstract**

Stationary heating devices can be used to warm up the coolant of an internal combustion engine or the cabin air of a vehicle. This kind of heat engine transforms the chemical energy content of liquid fuels into heat energy. The combustion process and the emission of such a device is in focus in this study, which would be the first part in a greater project in the field. Therefore, some relevant parameters have been established. Relevant cycles have been chosen for the kinds of heat engines. It means a normal mode cycle for the stationary device and a WLTC cycle in the case of the direct injection gasoline engine. Fuel used was the same for both. This heat transfer process is such, that the combustion seems to be quite simple and rough in the stationary device compared to that of in internal combustion engine. This means an inhomogenous combustion with non-premixed flame at a low combustion temperature. This situation affects the emission characteristic accordingly, so causes low $NO_x$ and relatively high particle relevant emission comes out from the device. As far as the device's particle relevant emission is concerned it would be suitable for further investigation described at the end of the article.

**Keywords**

flame temperature, particulate number, stationary heating device, non-premixed flame

## 1 Introduction

Internal combustion engines used for propulsion of road vehicles operate basically according to two cycles that are the Otto and Diesel cycle (Szendrő et al., 2012). Basic difference between the two theoretical cycles is the way of heat input. In the case of Diesel-cycle the heat is put in at a constant pressure while the volume can change. The heat input occurs during a constant volume process when pressure changes in engines with Otto-cycle (Heywood, 2018). Air-fuel mixture is formatted internally in Diesel-engines so the engine compresses air whose temperature will be higher than the autoignition temperature of the fuel at the end of the compression. Thus, mixture formation and combustion are heterogeneous and quite complex. Characteristic maximal flame temperatures and combustion peak pressure and lambda values are 2000-2700 °C, 200–250 bar, 1.5–5.5 accordingly as for the operation of a Diesel-engine (Jeon et al., 2013; Jeon and Park, 2015; Mollenhauer and Tschöke, 2010). Fuel for Diesel-engines is diesel which has to meet the required standard, i.e., described in a standard (EN 590:2005, 2005) for Europe. Otto-engines can be divided into two groups from which the first would be those that have external mixture formation and the second one those that operate with internal air-fuel mixture formation. The first one is the conventional one. The second solution is spreading nowadays, which is like that of Diesel-engines as for the mixture formation, so therefore it is heterogeneous and combustion will also be heterogenous. Therefore, emission component that are typical for a Diesel-engine will be typical for Otto-engines with internal mixture formation (Todoruț et al., 2020). Characteristic maximal flame temperatures and combustion peak pressure and lambda values are 2100-2500 °C, 50–100 bar, 0.8–5 respectively as far as operation of Otto-engines is concerned (Hershey and Paton,

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1933; Nabi, 2010; Reif, 2015). Otto-engine's fuel is gasoline that meets the requirements, described in the relevant standard (EN 228:2008, 2008) for Europe.

If we are approaching the heat input and combustion processes from flames point of view, processes developing in Diesel-engines are closely to non-premixed flames (Mastorakos, 2009). In Otto-engines with conventional (external) mixture formation the combustion process is similar to premixed flames (Bychkov and Liberman, 2000) while Otto-engines with direct injection i.e. internal mixture formation generate flames similarly to non-premixed ones (Mastorakos, 2009).

Processes described above occur with conventional fuel. There are many fuel alternatives for both cycles (Hergueta et al., 2018; Hsieh et al., 2022; Myung et al., 2009; Szabados and Bereczky, 2015) but this is not subject of this study to analyse those results.

Emission components that are generated in the engine are produced among different in-cylinder circumstances from which probably the most important parameters are temperature and excess air to fuel ratio (lambda). There are many ways in that NO is produced from which the thermal is dominant regarding internal combustion engines. Thermal NO is intensively produced from 1500 K. CO, HC are products of incomplete combustion. So from temperature point of view, they are produced where there is no flame and the temperature does not reach flame temperature (Dezsényi et al., 1990; Kalmár and Stukovszky, 1998). Components CO and HC have relatively high level in the range lambda lower than 1, at value lambda equal to 1 and higher than 1 emission of these components will be low. $NO_x$ raw emission has a peak value closely higher than lambda 1 and under and above this value it decreases. $CO_2$ goes inversely proportional to efficiency of combustion, so it has the highest value somewhere under but near lambda 1 (Bereczky and Varga, 2014; Boschán and Meggyes, 1993; Cordos et al., 2013).

Stationary heating devices are built in and used in cars and heavy-duty vehicles and are as well widespread all over the world. Based on their utilization they can be divided into two groups from which the first one is where they heat air for heating the air of cabin. Devices in the second group are connected to the coolant system of the engine and so they heat the coolant of the engine to reduce the warm-up phase of the engine, to save some harmful emission, to improve cold-start properties of engines as far as relevant parameters under cold-start like friction, wear, etc. are concerned. In some cases, they are used for heating the cargo space. Depending on the area of use these devices are used seasonally or during the whole year.

They operate as a stove, so they generate heat coming from burning fuel. Harmful emission which is a product of combustion in devices are not treated after, so they are emitted directly into the environment (Eberspächer, online; Exergy LLC, online; Webasto Group, online).

The manufacturers strive to adjust the device to minimize their emissions. In spite of this situation their operation, combustion process, exhaust emission of these devices has not yet been studied intensively by science.

### 1.1 Aim of current investigations

In the present research, the aim is to perform a mapping work with a chosen stationary heating device using gasoline as fuel. Firstly, how it is built up and operates. Which are characteristics for its combustion process and emission. Whether it is similar to those of an internal combustion engine's with direct gasoline injection from quantity and quality point of view? Thus, some combustion relevant parameters have been chosen and emission components have also been in focus. Results have been compared with those of an Otto-engine tested on engine test bench. This study and measurement series is the first part of a greater project.

## 2 Experimental setup

### 2.1 The stationary heating device

The chosen and tested stationary heating device is used for heating cabin air and uses gasoline so is generally used in cars where engine's fuel is gasoline. Table 1 shows the most important functional parameters of the chosen and tested stationary heating device.

To be able to see how the chosen stationary heating device is built up regarding the central energy conversation unit it has been mapped in a Computer Tomograph System type YXLON YCT Modular (Paulus et al., 1999; YXLON, 2021).

### 2.2 Measurement system for mapping the operation process of the device

For mapping the operation process of the device, it has been connected into a measurement system, where combustion

**Table 1** Technical parameters of the stationary heating device

| | |
|---|---|
| Nominal heat power | 5.5 [kW] |
| Type | cabin (air) heater |
| Fuel supply | by electric pump, pulsing |
| Injection | burner mesh |
| Evaporation | glow plug |
| Fuel | gasoline |

and emission relevant parameters have been measured and recorded. This measurement system is plotted in Fig. 1, and components of the system can be followed in Table 2. Every part in measurement system is calibrated based on either the annual calibration plan or the calibration conducted before and after the measurement series.

### 2.3 Measurement system for mapping the operation process of the device

The engine to be tested was a four-stroke, turbocharged engine with specs showed in Table 3. It is not presented, but

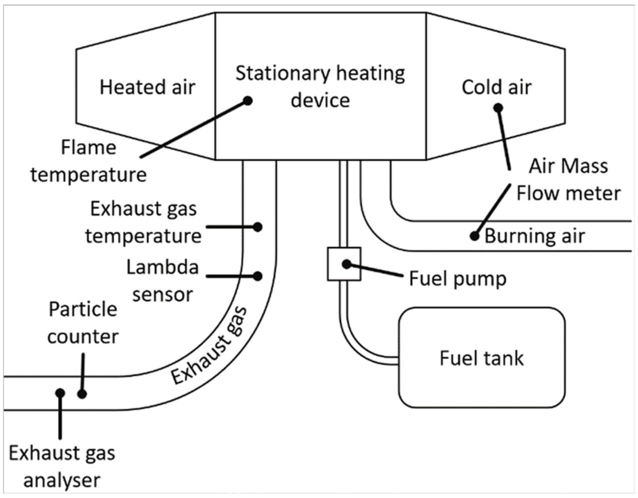


**Fig. 1** Measurement system regarding measurement of the stationary heating device

**Table 2** The parts of measurement system

| Path | Parameter | Instrument, device | Make, type |
|---|---|---|---|
| Air | Mass flow of burning air | Mass flow meter | Hitachi AFH70 25C Mass Air Flow (MAF) |
| | Intake air temperature | Thermo couple | K type sensor with QuantumX MX1609KB |
| Combustion | Flame temperature | Thermo couple | N type sensor with QuantumX MX1609B |
| | Lambda | Lambda sensor | Bosch LSU 4.9 wide band sensor with ETAS ES636.1 module |
| Exhaust | Exhaust temperature | Thermo couple | K type sensor with QuantumX MX1609KB |
| | Particle number | Condensation Particle counter (CPC) | AVL Particle Counter |
| | Gaseous exhaust components | Exhaust gas analyser | AVL SESAM i60 FT SII |

**Table 3** General parameters of the investigated internal combustion engine

| | |
|---|---|
| Displacement [$cm^3$] | 1.5 |
| Number of cylinders | 4 |
| Layout | inline |
| Compression ratio | 12.5:1 |
| Turbocharger | yes |
| Exhaust gas recirculation | yes |
| Fuel type | gasoline |
| Fuel system | direct fuel injection |
| Injection pressure [bar] | up to 350 |
| Rated torque [Nm] | 250 |
| Rated power [kW] | 110 |

the engine has been tested on an engine test bench. Exhaust temperature, lambda and emission parameters have been measured by the same tools as in the case of the heater device.

### 2.4 Methods

To investigate the internal combustion engine, firstly it has been installed onto an engine test bench. The test method chosen is the well-known WLTC (Worldwide Harmonized Light-Duty Vehicles Test Cycle) (Commission Regulation (EU) 2018/1832, 2018; United Nations Economic Commission for Europe, 2018), which is a test cycle for testing vehicles. The condition to run this cycle on engine test bench is firstly to run the cycle with a car on chassis dyno. During this vehicle testing one can gain data for control the engine on test bench according to the WLTC cycle.

As for the stationary heating device there are three optional modes that are Eco, Normal and Boost. A chosen mode determines the heat power in the stable working point of the device. Thus, the fuel consumption and exhaust emission change accordingly. The Normal mode has been chosen for our comparative measurement.

It has to be mentioned that the comparative test series have been conducted under laboratory conditions. From this point of view the environmental temperature is the most important parameter because it is 20–22 °C under laboratory circumstances. It differs from the real winter conditions but, this test bench is not a climate chamber so it is not capable to reach temperatures like in climate chamber test benches.

Operation and measurement periods are also determined in the same way in order to be able to compare the emission results on a time base.

Measurements and cycles of the heater device and the engine have been carried out separately. Because of the investigated heater is a cabin heater it was not possible to connect the device to the engine and test them together.

Calculation of emission has been conducted according to the relevant method established in the Commission Regulation (EU) 2018/1832 (2018).

Combustion temperature has been chosen as a basic parameter to make a simple evaluation about the combustion process taking place in both of the heat engines. On the one hand it has been measured in the heater device and it was intended to be calculated in the combustion engine. To do so a thermodynamic model had to be figured out. This thermodynamic model would have the following simplifications to calculate the peak temperatures in the combustion engine:

1. values of parameters like temperature and pressure of the intake air are known (they have been measured),
2. adiabatic exponent of the mixture must be taken (Velasco et al., 1998) and
3. if the compression ratio of the engine is known (Table 3) the end temperature of an adiabatic compression process can be calculated (Gresh, 2018). (It is known for the authors that compression ratio of an engine gives the relationship of volumes, exactly ratio of chamber volume plus displacement volume to chamber volume, but in the lack of in-cylinder pressure indication, this simplification must be taken to be able to indicate a combustion temperature range for the internal combustion engine).
4. the heat input develops under constant volume (Otto theoretical) where throughout the fuel introduced heat turns into rising the temperature from the compression end temperature to the combustion peak temperature. Values for the calculation elements (fuel's LHV, specific heat) can be found in (Rajput, 2007).

Fuel used in the test series was the same for both kinds of heat engine, which is the standardized gasoline according to the related Hungarian standard (Hungarian Office for Standardization, 2017).

## 3 Results and discussion

### 3.1 Structure of the energy conversation unit of the heater

The structure of the energy conversion unit can be seen in Fig. 2. The fuel is carried by an electric pump up to the burner mesh. This electric pump operates in pulsating manner so, this pulsating movement of fuel would be a substitution for the periodical injection of fuel in an engine. Fuel reaches the burner mesh. Burner mesh is a piece of metal with porous structure. Fuel has to go through the mesh which has the role to atomize the fuel. The quality of this atomization is not comparable with the atomization's quality in a modern engine. Probably because of low fuel pressure in the case of the heater and this porous metal piece the injection process cannot be compare to that of in an internal combustion engine. The glow plug can be found next in the way of the fuel which is used to heat up the atomized fuel drops to ignite the mixture to which air enters from side (signalized with arrow in Fig. 2) into the mixing and firing chamber. Is can also be seen that air-fuel mixture formation is an internal one and quite heterogeneous. After the igniting process, the combustion takes place continuously as long as fuel and air are available and transported into the chamber. The continuous combustion process takes place at pressure near to the environmental pressure, and the pressure is assumed to be more or less constant, where the gas can expand as long as there is volume available. If we consider that combustion process from the flame's point of view it is surely non-premixed flame. The gas moves on from the exhaust zone into the exhaust pipe. The heat transfer occurs in the exhaust zone, so the air needed to be heated will be heated up with the heat coming from the exhaust of the combustion.

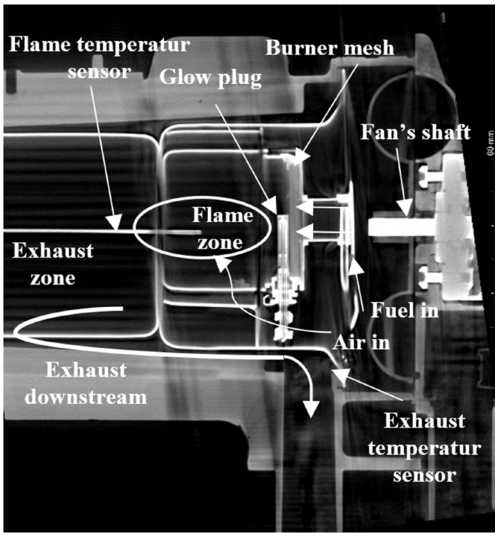


**Fig. 2** Structure of the energy conversation unit inside the heater

A temperature sensor has also been built into the unit which would be intended to measure the temperature of the flame during operation of the device. Flame temperature results will be introduced later in Subsection 3.3. It is known for the authors that there are complex methods to determine the flame temperature, the flame temperature-distribution, but this is not an aim in this research. In this case only a simple temperature parameter would be desirable from the core of the flame which serves as a base for comparative analyses.

As a summary of Subsection 3.1. i.e. how the energy conversation unit is built up and how the combustion process takes place, it can be established that the combustion process is similar to the Diesel combustion because of the constant pressure and changing volume and Diesel-similar heterogeneous mixture formation (which is also closely to the mixture formation of a direct gasoline engine), but with gasoline which is the fuel of Otto-process. So, from Diesel-similar heterogeneous combustion process, Diesel relevant emission characteristic can be expected if it is not considered that there can be differences in the composition of diesel and gasoline which may influence the emission characteristic.

### 3.2 An operation cycle of the device

The operation of heater, thus the useful heating time in a stable working point, depends on the user. A general operation cycle has been chosen to gain results about how it operates. Independently from the cycle modes (ECO, Normal, Boost) the sections in a cycle are the same. But the whole cycle from switch on to switch off can be divided into four operation part-cycles as it is plotted in Fig. 3. In our case the particulate number (PN) parameter gives the base to analyse this whole cycle.

After switching on the device, the first phase begins. This phase is the glowing phase, where the glow plug is switched into an electrical circuit and it heats up itself and its direct environment. At the same time fuel and air are carried in their path to the combustion unit. In the very first moment of this phase the PN emission reaches a very high value and when the combustion develops it reduces continuously. At a certain time, when device heating phase starts the air to be heated is introduced in the system, which means cooling air for the combustion thus PN begins to rise. It increases up to a local maximum and after that reduces till a thermal balance is established in the system. In this case it takes ca. 450 secs so 7–8 minutes, during which a high among of emission is realized. During the stable working point the particulate number is oscillating around a constant value. This time is selectable according to the demand, but it can be maximum 30 minutes in Boost operation mode, where the nominal heat power is available. After switching of the device, the fuel transport stops the combustion process is ending. The glow plug heats up the fuel residing in the burner mesh, which results in a very high peak in the particulate emission. About how this PN emission relates to the emission of the investigated engine can be read in Subsection 3.4.

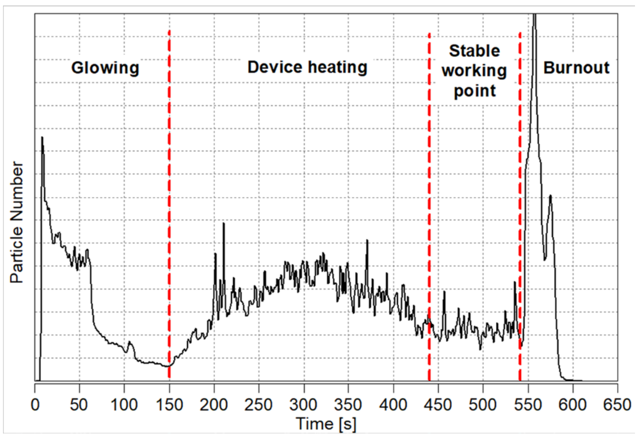


**Fig. 3** Operation cycle of the investigated stationary heating device based on the device's PN emission

### 3.3 Combustion relevant parameters

Lambda values of the investigated heat engines can be followed in Fig. 4. It shows that engine operates in a lambda 1 mode. Peaks with very high values mean lean mixture situations without injection during overrun periods of engine. Lambda range for the heater lies between values 1.38–1.51 which means a lean mixture operation. This range may be necessary to maintain the combustion process with this quality which the device has.

Flame temperature is determined by fuel properties, oxygen content available for combusting, and the beginning temperature of air inside the combustion chamber. Taking the fuel consumption as unit the quantity of the introduced air was higher in the case of the heater. From

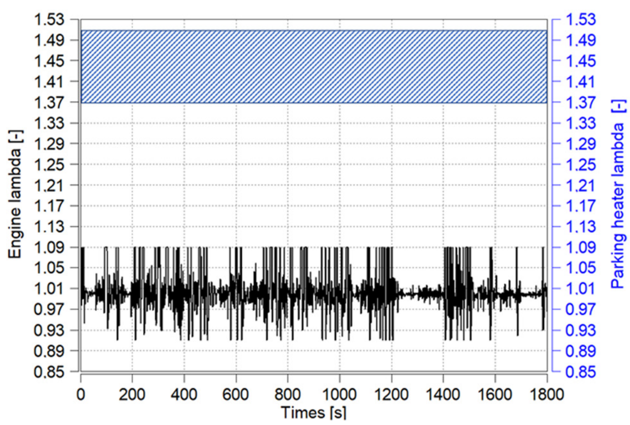


**Fig. 4** Lambda values of engine and the heater

this point of view itself the heater would operate with higher flame temperature, but in the case of the combustion engine there is a compression prior to the burning which rises the combustion beginning temperatures. And also, the injection quality in the engine is far higher which allows oxidizing more fuel molecules which is also a temperature rising process. Fig. 5 stands to show the temperature characteristics of the heat transformers over the time in the cycle. Flame temperatures and exhaust temperatures can be followed at the same time.

Upper part of Fig. 5 is about flame temperatures. Internal combustion engine has a higher range than the device. This range is between 1850 °C and 2700 °C which is a plausible range for an Otto-engine. This range is calculated according to the method described in the Subsection 2.4. 1250 °C is the flame temperature of the heater in the steady state operation mode. Temperatures in engine are almost twice as high as those of in the device which determines the quality of combustion and the quantity of various exhaust components. Exhaust temperature is measured ones before the turbine of engine's turbocharger, while the same temperature for the heater has been also measured at a point in the device's exhaust presented in Fig. 2. The heater's exhaust temperature is a constant 420 °C one during steady state. The temperature difference between flame and exhaust is 830 °C in the case of the heater. This would mean a heating efficiency of 66%. The same calculation for the engine may be carried out with combustion temperatures of 1940 °C and 2650 °C and with 600 °C – a cycle average of exhaust temperatures – but this is unusual calculation for internal combustion engines.

Based on the temperatures some projections can be made regarding the exhaust emission of the two investigated heat transformers. Higher temperature may cause higher $NO_x$ and at the same time lower particle emission

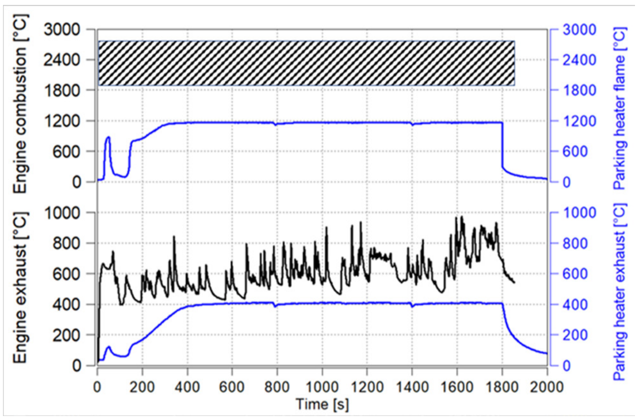


**Fig. 5** Flame and exhaust temperatures

coming out from the internal combustion engine compared to the heater's expected emission. The effect of the combustion relevant parameters on the exhaust emission will be analyzed in the Subsection 3.4.

### 3.4 Exhaust emission

Particulate number as particulate relevant parameter and other gaseous components like oxides of nitrogen, carbon dioxide and carbon monoxide have been included in the investigated emission components. Fig. 6 shows the particle number emission over the time in the case of stationary heating device (blue) and engine (black). The first two peaks in parking device's curve is concerning the glowing and device heating up phases introduced in Subsection 3.2. Particle number reaches the value of around 4E+7 #/ccm in the glowing phase. Under the steady state operation of the device a relatively low emission of number of particles can be detected. At the end of the cycle another peak can be seen which appropriates the burnout phase of the device's operation. Here is also a peak with value 2E+7 #/ccm. During the engine's WLTC cycle a lower peak can be seen at the beginning of the cycle and at any other places in the cycle particle number emission values are staying low.

Concrete emission values are indicated in Table 4. The results are shown in normalized form, where engine emissions were used as a basis. Particle number emission of the stationary heating device is around 5 times higher than that

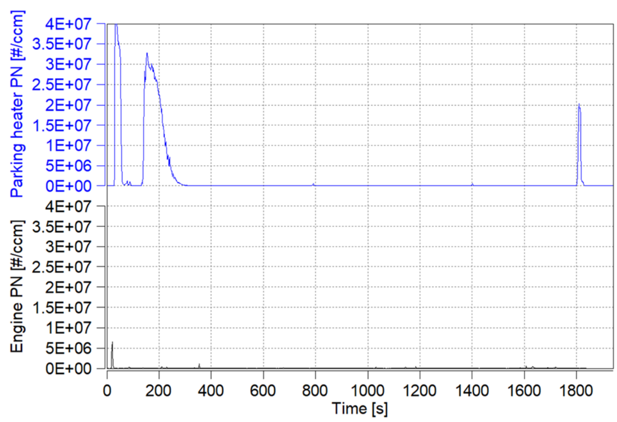


**Fig. 6** Particle number emission over the cycle

**Table 4** Exhaust emission of the investigated heat engines

| | PN | $CO_2$ | CO | $NO_x$ |
|---|---|---|---|---|
| Engine cumulative emission (WLTC) | 100% | 100% | 100% | 100% |
| Stationary heating device cumulative emission (Normal mode) | 552.6% | 19.8% | 0.23% | 1.44% |

of the engine's regarding the cumulative values over the cycles. This is also the case if specific values are analysed.

Here it must be mentioned that the exhaust mass flow was 50.81 kg/h for the engine while it was 15.0 kg/h in the case of the parking device. Specific fuel consumption values were 4.55 l/h and 0.73 l/h accordingly and $CO_2$ emission will change, respectively.

CO emission of a heat engine is a basic function of lambda and because of the situation stationary heating device operates with quite higher lambda than the engine its CO emission is also quite lower as it can be seen in Table 4. The difference in values is 3 orders of magnitude. Theoretically calculated and probably the real flame temperatures and peak temperatures are higher in the internal combustion engine which is a reason for the higher $NO_x$ emission of the engine compared the device's $NO_x$ emission. The differences here are in 2 orders of magnitude.

## 4 Conclusions

An analysing and comparing study has been introduced between the operation of a stationary heating device and an internal combustion engine concerning some combustion and emission relevant parameters. Based on the presented work conclusions can be made as follows:

- After analysing the structure and operation of the stationary heating device its mixture formation and combustion do not reach those qualities of the internal combustion engine.
- The flame temperature in the combustion engine is averagely higher (2 times) compared to temperature occuring in the device. This is advantageous for $NO_x$ formation, but it can cause a lower emission of particle.
- As for the lambda, the heater operates with higher air excess therefore CO can be quite lower.
- Cumulative and specific $NO_x$ values are lower in the case of the device. The flame temperature is behind which is around the NO formation beginning temperature.
- Higher particle number emission belongs to the heater which a consequence of the mixture formation and combustion with lower quality. Particle formation takes place, but the temperature is not enough for particle burnout. Particle count covers just a part of size and mass range of particle coming from an internal combustion engine. Other particle relevant parameters should be involved.
- Emission component CO is a trace element in the exhaust of the stationary heating device which is probably due to the excess air ratio of the device during the operation.

## 5 Aims for further investigations

There are many directions, question raised, that could be followed in this research project. They can be summarized as follows:

- To investigate and compare other particle relevant parameters like mass, FSN, relative mass with microsoot device. Because of the lower combustion quality of the heater greater emission of these parameters from the device can be expected.
- For analyzing the emission of ash formers mass spectrometry is going to be used.
- How it develops the emission of ash formers in the case of the heater if the fuel would be blended with lubricant.
- How it changes the emission coming from the device if renewable fuel would be added to the conventional one.
- What would be the emission relevant results if the stationary heating device would be tested for durability.

## Acknowledgement

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