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# Nanoparticles size distribution in wood combustion

Francesca HUGONY[1], Senem OZGEN[2], Carmen MORREALE[1], Stefano SIGNORINI[2], Stefano CERNUSCHI[2], Angela MAGGIONI[1], Gabriele MIGLIAVACCA[1], Sergio MARENGO[1], Michele GIUGLIANO[2], Giovanni LONATI[2], Giovanna RIPAMONTI[2]

1Innovhub-SSI, Stazione Sperimentale per i Combustibili

2 Politecnico di Milano, DIIAR – Environmental Engineering section, Italy

e-mail: **hugony@ssc.it** ; Website: **http://www.ssc.it**

## Introduction

The use of biomass as a fuel for domestic heating appliances spread in the last years as a consequence of both rising fossil fuel prices and major concerns about global warming. However, despite its importance as an energy source, wood combustion may lead to worsening local air quality characteristics given the high emissions in terms of particle matter, observed especially from residential-scale batch-combustion appliances.

The study aims to investigate nanoparticle emissions from a commercially available closed fireplace fed with beech wood, focusing on particle size distribution.

The emissions from the closed fireplace were characterized by the dominant presence of nanoparticles (NP: particles with diameter < 50 nm) and particle size distribution was observed to be in a strict relationship with combustion conditions.

## Material and Methods

The sampling and measurement of nanoparticles were carried on a commercially available closed fireplace with the nominal heat output of 11 kW. The fuel used for the tests was beech wood which is the reference fuel for the European standard for closed fireplace type testing [1]. The flue gas exiting the fireplace was pre-diluted with local ambient air in a dilution tunnel set up (Figure 1). A sample flow is extracted from the preliminary dilution tunnel with a heated probe bearing a PM2.5 cyclone and further diluted with a two-stage dilution apparatus (FPS-4000, Dekati Ltd., Finland), employing a first stage perforated tube and a second stage ejector dilution with particulates-, humidity-, and organics-free dilution air; operable with hot and cold dilution conditions. Real-time number concentration and size distribution of particles were measured in parallel with an Electrical Low Pressure Impactor (ELPI - Dekati Ltd., Finland) and with a Fast Mobility Particle Sizer (FMPS – TSI 3091). CO, $CO_2$, $O_2$ and non methane hydrocarbons (NMHC) were measured in continuous to monitor combustion phases. For the instantaneous qualitative measurement of PM concentration a fast-response system based on light scattering was used..

The fire box was fed with 2.4kg of beech wood and the refueling period was about 40 minutes. 15 tests were performed and the emission measurements have been carried out including initial, intermediate and final combustion phases.

The initial phase starts just after the fuel loading and regard the ignition of the fuel. This stage is characterized by pyrolysis process with high emissions of CO and NMHC and it is highlighted by

the first CO peak. The intermediate combustion phase begins when gases and char oxidation rate becomes predominant. This phase is characterized by low CO and NMHC concentrations and by a visibly good flame; combustion quality is the best of the entire cycle. When char oxidation rate decreases and the incomplete combustion products start to increase again, the combustion cycle is in the final phase. In Figure 2 visual images of the three combustion phases are represented.

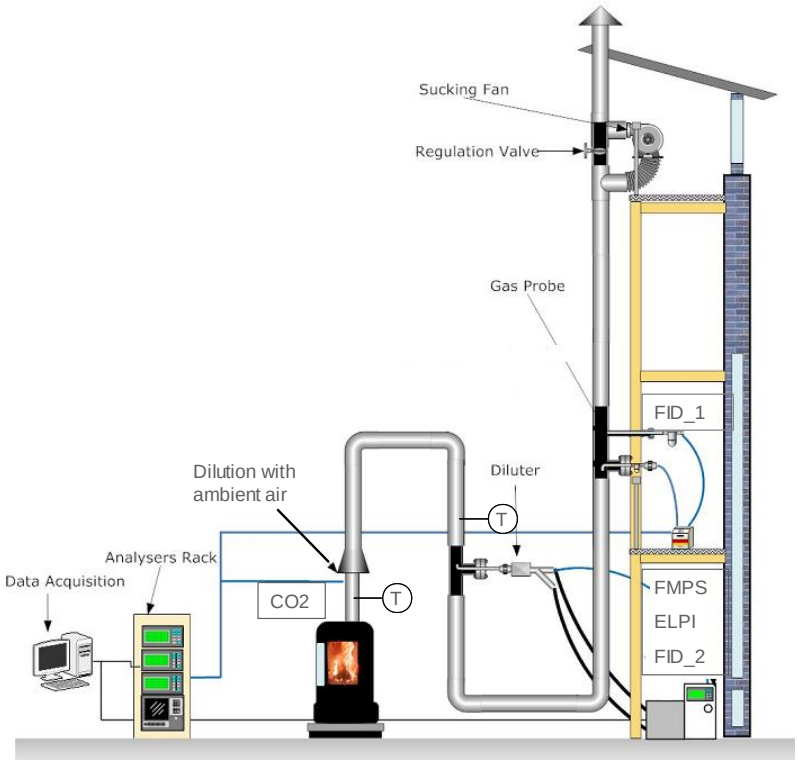


**Figure 1. Schematic of the experimental test rig**

**Figure 2. Visual images of the three combustion phases**

## Results and conclusions

The comparison between the two different nanoparticle analysers gave good results, in fact in Figure 3a shows a good accordance, with very similar trends of number concentration of particles below 50nm . Nanoparticle concentrations, detected by both FMPS and ELPI, are also consistent with the trend of incomplete combustion products (Figure 3b).

The average concentration is around $1.0 \cdot 10^{8}$ $cm^{-3}$ at 13% of $O_2$, for both instruments (Figure 4). NP account on average for the 67% of the total particles measured (56% for ELPI). Mode particle diameter of the average size distribution is observed to be around 10 - 20 nm for both instruments (Figure 5).

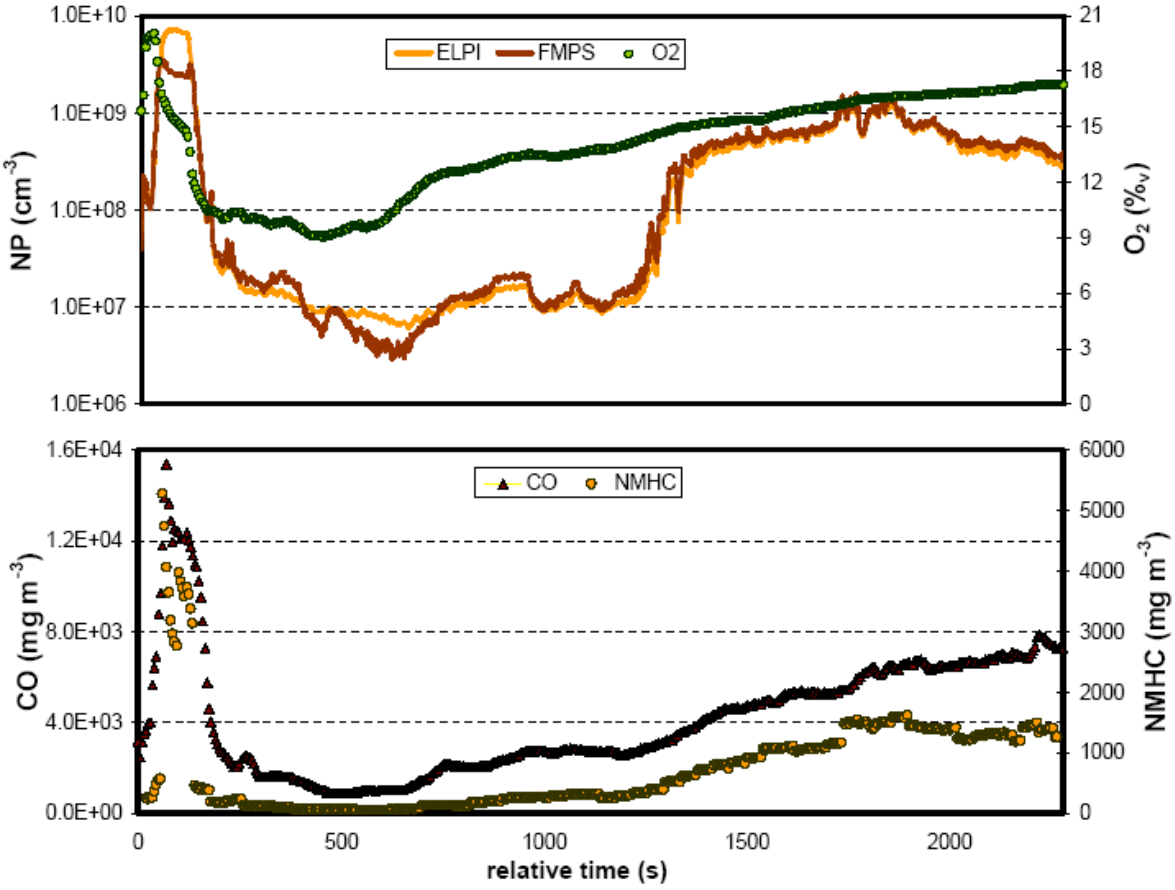


**Figure 3. Time profiles for a) NP number measurements and flue gas oxygen content, b) CO and NMHC concentrations**

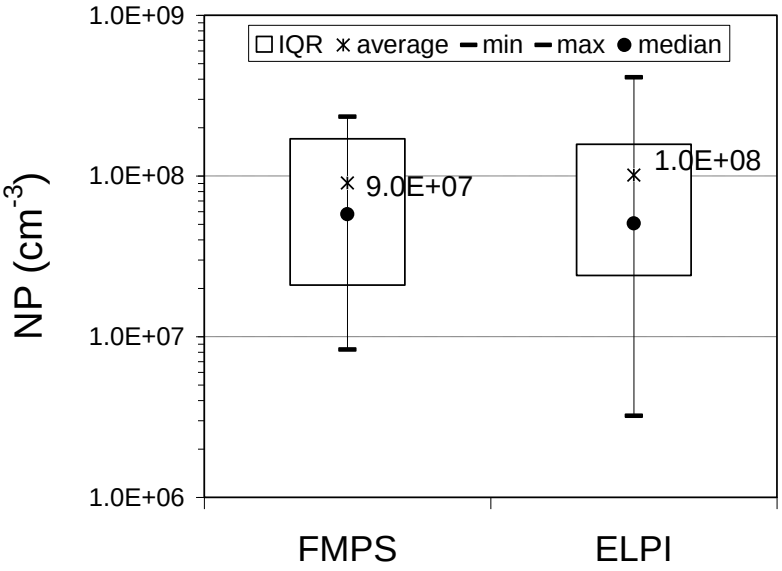


**Figure 4. NP number concentrations measured with FMPS and ELPI**

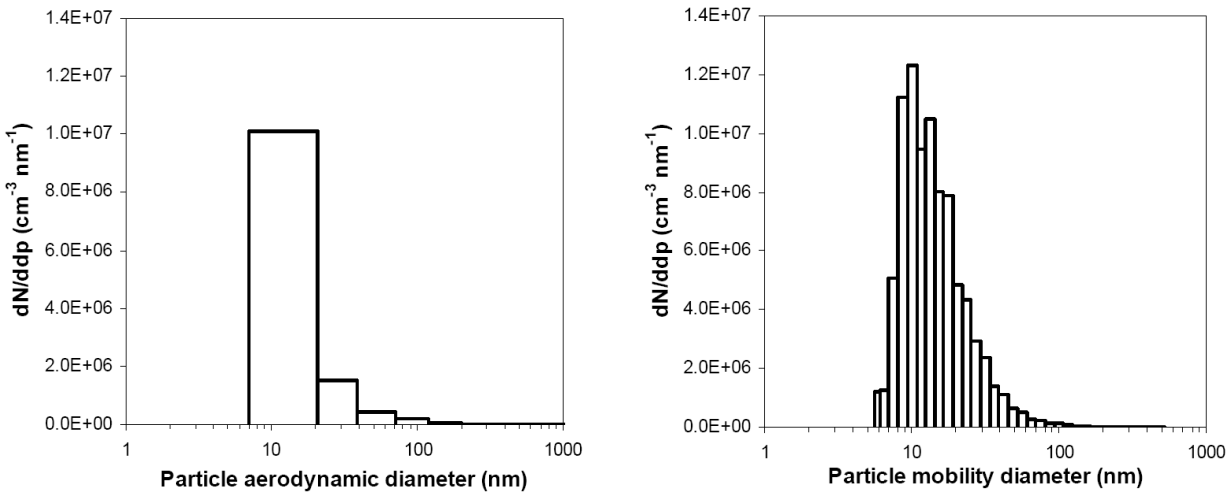


**Figure 5. Average size distribution given by ELPI (left) and FMPS (right)**

Figures 6 - 7 were obtained considering the FMPS results. In fact the instrument is capable of detecting more size classes than ELPI, and this allows having more details about the size distribution in the NP size fraction.

Regarding the phase resolved average size distributions, during the different combustion phases the mode particle diameter is observed to be around 10 nm – 20 nm. The initial wood combustion process, mainly dominated by pyrolysis process, produces high particles number concentration. During the proper char oxidation (intermediate phase), the more stable combustion condition decreases the formation of particles while the mode diameter is still around 10 nm. With the final stage (during the flame extinction), particle formation increases with a size distribution similar to the initial stage.

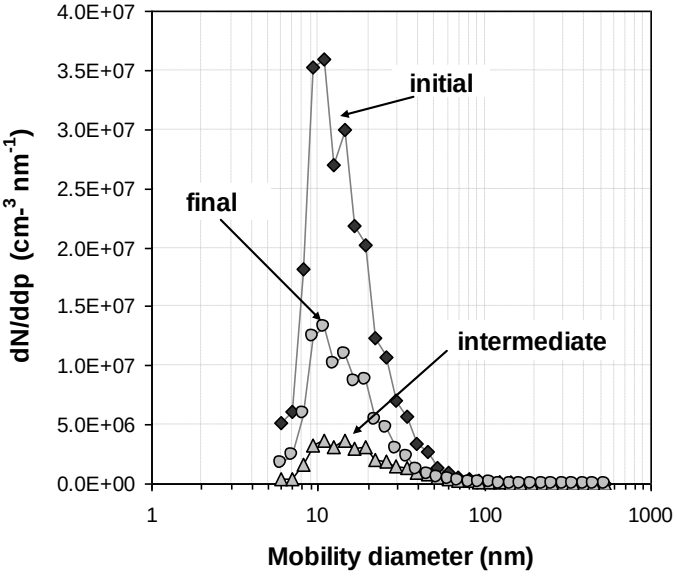


**Figure 6. Phase resolved average size distributions of particles**

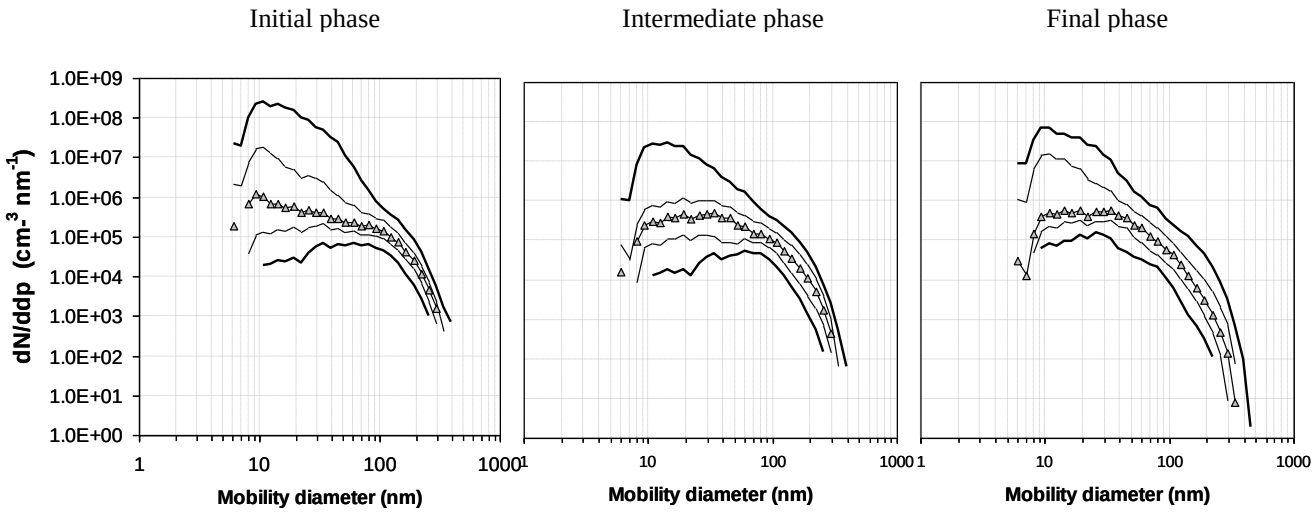


**Figure 7. Phase resolved size distributions of particles (5th, 25th, 50th, 75th, 95th percentiles)**

The analysis of the percentiles of the phase resolved particle size distributions (Figure 7) shows that larger particles (i.e., diameters larger than 100 nm) have a narrower IQR* with respect to smaller particles, implying a slightly changing distribution throughout the combustion cycle. The number concentration of these particles is two to three orders of magnitude lower than smaller particles.

Conversely, the small particles (i.e., diameters in the range of 5.6 - 100 nm) have a most dispersed data, in particular for the initial phase. This is because the presence of the NP in the flue gas is mostly dependent on the new particle formation processes triggered by the high concentration of NMHC in the diluted and cooled flue gas.

The correlation analysis points out that particles in the range of 100 - 316 nm have less or no correlation with the combustion conditions in the fireplace represented by the main combustion gases, however they are significantly correlated with the dust concentration in the flue gas during the intermediate phase which is characterized by flaming combustion, suggesting that these particles are likely primary soot particles which have undergone condensation in the diluted and cooled flue gas.

In conclusion, the particle size distribution is dominated by the dynamic changes occurring in the NP fraction due to dilution and cooling of the flue gas which superimposes on more or less stable size distribution throughout the combustion cycle represented by the slightly changing median distribution between the different phases.

## References

1- EN 13240. Roomheaters fired by solid fuel - Requirements and test methods.

* IQR: interquartile range=75° percentile-25° percentile

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*[1]Innovhub-SSI, Stazione Sperimentale per i Combustibili*
*[2] Politecnico di Milano, DIIAR – Environmental Engineering section, Italy*
***e-mail:*** hugony@ssc.it ***Website:*** http://www.ssc.it

## Objectives

Despite its importance as an energy source, wood combustion may lead to worsening local air quality characteristics given the high emissions observed especially from residential-scale batch-combustion appliances. The emissions from the closed fireplace are characterized by the dominant presence of nanoparticles (NP) (i.e., particles with diameter < 50 nm), and the particle size distribution is observed to be in a strict relationship with combustion conditions. The study aims to investigate nanoparticle emissions from a commercially available closed fireplace fed with beech wood, focusing on particle size distribution.

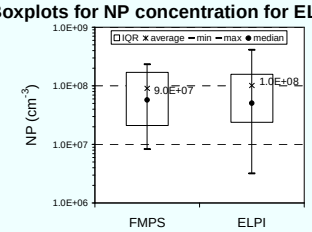
## Materials and methods

The sampling and measurement of particles were carried on a commercially available closed fireplace with the nominal heat output of 11 kW. The fuel used for the tests was beech wood which is the reference fuel for all the tests described in the European standards. The flue gas exiting the fireplace was pre-diluted with local ambient air in a dilution tunnel set up. A sample flow is extracted from the preliminary dilution tunnel with a heated probe bearing a PM2.5 cyclone and further diluted with a two-stage dilution apparatus (FPS-4000, Dekati Ltd., Finland), employing a first stage perforated tube and a second stage ejector dilution with particulates-, humidity-, and organics-free dilution air; operable with hot and cold dilution conditions. Real-time number concentration and size distribution of particles were measured in parallel with an Electrical Low Pressure Impactor (ELPI - Dekati Ltd., Finland) and with a Fast Mobility Particle Sizer (FMPS – TSI 3091). CO, $CO_2$, $O_2$ and non methane hydrocarbons (NMHC) were measured in continuous to monitor combustion conditions.

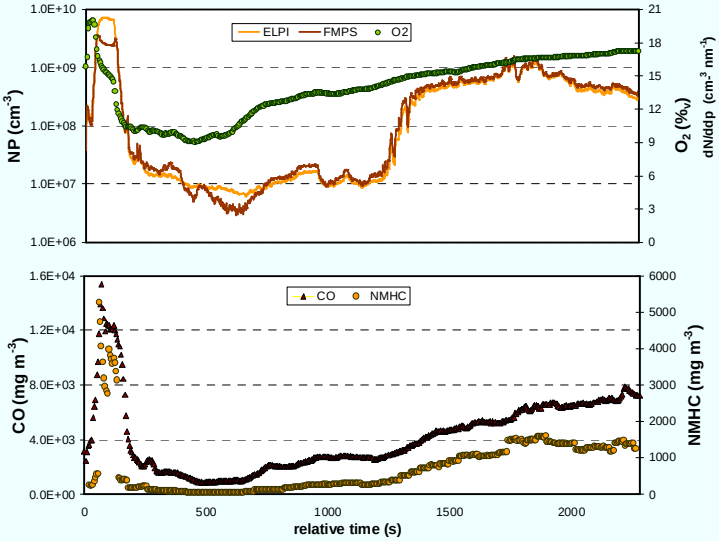
## Results and conclusions

Nanoparticle concentrations, detected by both FMPS and ELPI, show a similar trend with the incomplete combustion products. The average concentration is around $1.0 \cdot 10^8$ cm$^{-3}$ for both instruments. NP account on average for the 67% of the total particles measured (56% for ELPI). Average mode particle diameter is observed to be around 10nm.

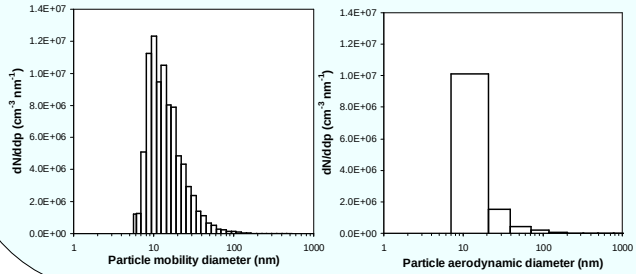
**Boxplots for NP concentration for ELPI and FMPS**




**Nanoparticle number concentration and incomplete combustion products emissions at 13% of oxygen concentration, during a combustion cycle**

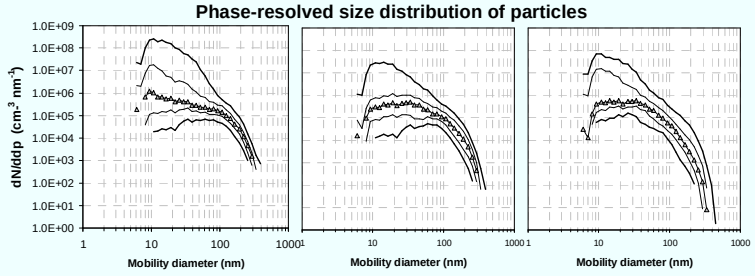



**Average size distribution of particles for FMPS (left) and ELPI (right)**




During wood combustion three different phases are detectable: an initial phase, which starts just after the fuel loading and is characterized by pyrolysis process with high emissions of CO and NMHC. This phase is represented by the first CO peak. The intermediate combustion phase begins when the gas and char oxidation rate increases. This phase is characterized by low CO and NMHC concentrations with good combustion conditions. When char oxidation rate decreases and the incomplete combustion products start to increase again, the combustion cycle is in the final phase.


**Phase-resolved size distribution of particles**




- The analysis of the percentiles of the phase resolved particle size distributions shows that larger particles (i.e., diameters larger than 100 nm) have a narrower IQR* with respect to smaller particles, implying a slightly changing distribution throughout the combustion cycle. The number concentration of these particles is two to three orders of magnitude lower than smaller particles.
- Conversely, the small particles (i.e., diameters in the range of 5.6 - 100 nm) have a most dispersed data, in particular for the initial phase. This is because the presence of the NP in the flue gas is mostly dependent on the new particle formation processes triggered by the high concentration of NMHC in the diluted and cooled flue gas.
- The correlation analysis points out that particles in the range of 100 - 316 nm have less or no correlation with the combustion conditions in the fireplace represented by the main combustion gases, however they are significantly correlated with the dust concentration in the flue gas during the intermediate phase which is characterized by flaming combustion, suggesting that these particles are likely primary soot particles which have undergone condensation in the diluted and cooled flue gas.
- In conclusion, the particle size distribution is dominated by the dynamic changes occurring in the NP fraction due to dilution and cooling of the flue gas which superimposes on more or less stable size distribution throughout the combustion cycle represented by the slightly changing median distribution between the different phases.

*IQR: interquartile range=75° percentile-25° percenti le