Fuel quality sensors for HD engines

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Diesel Fuel Quality Sensors
MASTER THESIS

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Approved 2014-09-23	Examiner Andreas Cronhjort	Supervisor Andreas Cronhjort
	Commissioner SCANIA	Contact person Ola Stenlåås / Andrey Gromov

Sammanfattning

Under de senaste åren har de globala utsläpps standarder blivit mer stringenta när vi talar om Heavy Duty (HD) Dieselmotorer. Dessutom har varje region, eller land, sina egna regler med egna utsläppsnivåer för de huvudsakliga föroreningarna: CO, kolväten (HC), kväveoxider och partiklar (PM). Också, den verkliga användning, skiljer sig alltid från laboratorieförhållanden där motorerna testas för att klara lagkraven. För ett företag som Scania, som utvecklar och använder HD dieselmotorer och har ett intresse av att sälja sina produkter över hela världen, har olika utsläpps regler en direkt inverkan på den framtida produktutvecklingen. Dieselmotor utrustade HD lastbilar eller bussar kontinuerligt förbättras ständigt i syfte att uppfylla dessa lagkrav, antingen genom nya och komplexa motorkonstruktioner, förbränningskontrollstrategier eller avgasefterbehandlingssystem (t.ex. Catalyst, SCR, EGR, UDS, etc.). Men ingenting kan anpassa en dieselmotor för olika de bränsletyper som den kan träffa på under en resa från norra Sverige till södra Italien. Det är därför bränslekvalitet och bränslets egenskaper är viktiga aspekter när man talar om motorutveckling och utsläpp.

Denna avhandling föreslår en rad svar om bränslekvalitets mätningar. Först föreslås definitioner för de viktigaste bränsleegenskaperna. Deras påverkan på drift och utsläpp diskuteras också. För det andra presenteras en översyn av de för närvarande tillgängliga teknikerna på marknaden för mätning ombord. Dessa tekniker kan mäta och upptäcka dessa bränsleegenskaper. De inbyggda teknikerna är tänkta att införliva samma mätteknik som ett laboratoriet som används för analys av bränsleparametrar, erbjuda jämförbara resultat, större rörlighet och fordonsanpassningsförmåga. Till sist, föreslår avhandlingen tre sensorer som innehåller två innovative ombord mätnings tekniker, som kan upptäcka bränslets egenskaper. Dessa sensorer är testade med olika typer av bränslen, bränsleblandningar och förorenade bränslen. Testresultat är mer än överraskande och intressant, då varje sensor erbjuder annat än väntad prestanda och användbarhet. Stämgaffel teknik till exempel har två sensorer representerade och den minst lovande sensorn visade sig vara lite mer exakt än den andra. NIR-sensor som utvärderas i detta arbete, har jämförbara resultat med stämgaffelgivare, när vi talar om väldefinierade bränsletdensitets mätningar. Trots detta, andra mätningar som är specifika för denna typ av NIR-teknik, erbjuder den inte resultat på den förväntade nivån.

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Abstract

In recent years global emissions standards have become more in more stringent when we refer to Heavy Duty (HD) Diesel engines. Moreover, every region or country has its own regulations with own levels of emissions for the main pollutants: CO, hydrocarbons (HC), NOx and particulate matter (PM). Also, the real life usage, always differ from the laboratory conditions in which the engines are tested in order to pass regulations. For a company like Scania, that is developing and using HD diesel engines and has an interest in selling its products world-wide, different emissions standards have a direct impact on the future of product development. Diesel engines equipping HD trucks or busses are continuously being improved in order to align to these standards, either by new and complex engine designs, combustion control strategies or exhaust after treatment systems (e.g. Catalyst, SCR, EGR, UDS, etc.). However, nothing can adapt a diesel engine for different fuel types that it can meet on a trip from Northern Sweden to southern part of Italy. That is why fuel quality and fuel properties are important aspects to account for when talking about engine development and emissions.

This Thesis is proposing a series of answers regarding fuel quality measurements. First, definitions for some of the most important fuel properties are proposed. The impact on engine operation and emissions is also discussed. Secondly, a review of the current available on the market on board technologies is presented. These technologies are able to measure and detect these fuel properties. The onboard technologies are supposed to incorporate all laboratory measurement techniques capabilities used for analyzing fuel parameters, offer comparable results, a larger mobility and vehicle adaptability. At last, the thesis proposes three sensors that are incorporating two innovative measurement on board technologies, which are able to detect fuel properties. These sensors are tested with various type of fuels, fuel blends and contaminated fuels. Test results are more than surprising and interesting, with every sensor offering other than expected performance and applicability. Tuning fork technology for example has two representative sensors that are tested and the less expected sensor proves to be little more accurate than the other one. The NIR sensor that is evaluated in this work, has comparable results with tuning fork sensors, when we refer to well defined fuel density measurements. Nonetheless, other measurements specific to this type of NIR technology, do not offer at this level the expected results.

FOREWORD

This master thesis was implemented at Scania CV AB in Södertälje by NESC (Engine combustion control software group) and NEPE (Engine Electrical Components group). The work was carried out on Scania platform in collaboration with KTH and under the supervision of Dr. Ola Stenlåås, Dr. Andrey Gromov and docent Andreas Cronhjort.

I would like to acknowledge and thank for all the effort made by my supervisor Ola Stenlåås throughout the whole length of this thesis. His technical advices and continuous perseverance were more than inspiring and valuable in my success as a student and a future engineer. To Andrey Gromov I would like to thank for helping me understand the secrets of better engineering writing and to Andreas Cronhjort for all the support and belief that he had for me.

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NOMENCLATURE

Notations

Symbol	Description
ε	Dielectric constant
ρ	Density (g/cm^3 or kg/m^3)
N_A	Avogadro number
α	Electric polarizability
M	Molecular weight
ID	Ignition Delay (ms)
t	Time (s)
υ	Kinematic viscosity (mm^2/s or cSt)
η	Dynamic viscosity (mPa or cP)
C	Viscosimeter calibration constant (mm^2/s^2)
Y_S	FAME content (%(V/V))
X_S	FAME content (g/l)
Z	Impedance (Ω)
ω	Resonant frequency (Hz)
A	Constant that depends on tuning fork geometry
B	Constant that depends on tuning fork oscillation mode
I	Electrical current (A)
C_0	Mechanical compliance (m/N)
R_0	Mechanical loss
L_0	Mass inertia (kg)
C_p	Electrode capacitance (F)
T	Temperature (°C)
V	Volume (m^3)
m	Mass (kg)
β	Volumetric temperature expansion coefficient (/°F)

Abbreviations

ACEA	European Automobile Manufacturers Association
ASTM	American Society for Testing and Materials
*B***	Diesel-biodiesel blend with ** percentage biodiesel in the blend
CAN bus	Controller Area Network
*CF***	Contaminated fuel number **
CFPP	Cold Filter Plugging Point
C-H	Carbon – Hydrogen
CN	Cetane Number
CO	Carbon Oxide
DCN	Derived Cetane Number
Diesel MK1	Dieselolja Miljöklass 1 (Diesel oil Environment class 1)
ECU	Electronic Control Unit
*ED***	Etahnol-diesel blend with ** percentage ethanol in the blend
EGR	Exhaust Gas Recirculation
EMC	Electromagnetic compatibility
*EN***	European Standard number **
ESD	Electrostatic Discharges
ETBE	Ethyl tertio-butyl ethers
FAME	Fatty Acid Methyl Esters
FIS	Fuel Injection Systems
FQS	Fuel Quality Sensor
FT-NIR	Fourier Transform Near-Infrared
HC	Hydrocarbons
HCP	HydroCarbon Profiler
HD engine	Heavy Duty engines
HVAC&R	Heating, Ventilating, Air Conditioning and Refrigeration
ID	Ignition Delay
ISO	International Organization for Standardization
J1939	Standard real-time network for control and diagnostic information
LHV	Lower Heating Value
MEMS	Micro-electro-mechanical systems
MIR	Mid Infra-Red
MOEMS	Micro-Opto-Electro-Mechanical-System

Abbreviations (continuation)

MON	Motor Octane Number
MTBE	Methyl tertio-butyl ethers
NIR	Near Infra-Red
NOx	Nitrogen Oxides
O-H	Oxygen - Hydrogen
PCB	Printed Circuit Board
PM	Particulate Matter
PON	Road Octane Number
PZT	Lead Zirconate Titanate
RME	Rapeseed Methyl Esther
RON	Research Octane Number
SCR	Selective Catalytic Reduction
*SF***	Special fuel number **
SS	Swedish Standard
*TAC***	Total aromatic content fuel number**
UDS	Urea Dosing System
ULSD	Ultra Low Sulphur Diesel
UV-VIS	Ultraviolet–visible spectroscopy
WDXRF	Wavelength Dispersive X-ray Fluorescence

TABLE OF CONTENTS

1. INTRODUCTION

This chapter describes the background, purpose and delimitations of the current project. It presents the motivation behind choosing the subject of study, the desired result at the end of analysis and the restrictions the project had.

1.1. Background

Diesel engine is considered to be one of the most efficient thermal machines. Its efficiency is based mostly on fuel consumption which determines exploitation costs. Besides fuel efficiency, Heavy Duty (HD) diesel engine offers increased reliability and durability. Although it has more advantages compared to other engines, it has some disadvantages when it comes to commercial transportation. One of the biggest, is the exhaust gas content. Diesel exhaust is considered to have more toxic air contaminants with harmful health effects than any other fossil fuel engine [1].

According to the European Automobile Manufacturers' Association (ACEA), diesel becomes an increasingly popular fuel as more than half of the new registrations represents vehicles that are using diesel engines. And these numbers reflect only the European market. Looking at heavy duty engines, in 2013 ACEA announced over 550.000 new registered vehicles with HD diesel engines (231,662 units of over 16t heavy trucks, 304,333 units of over 3.5t trucks and 32,992 new buses and coaches) [2]. And these numbers do not cover all the other HD engines sold for industrial or marine purposes.

That is why, in the recent years global emissions standards have become more and more stringent when we refer to heavy duty diesel engines. Moreover, every region or country has its own regulations with own levels of emissions for the main pollutants: carbon oxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and particulate matter (PM). Additionally, the usage in real life always differ from the usage in laboratory conditions in which the engines are tested in order to pass regulations. For a developing-HD-diesel-engines company, that has an interest in selling its products world-wide, different emissions standards have a direct impact on the future of product development. HD diesel engines are continuously being improved in order to align to these standards, either by new and complex engine designs, combustion control strategies or exhaust after treatment systems (e.g. Catalyst, SCR, EGR, UDS, etc.). Still, no strategy nor engine design can predict engine behavior and its emission when equipping a truck or coach that travels through different geographic regions (e.g. northern Sweden to southern Italy, from Russia to Spain or Canada to southern USA).

Table 1. Part of diesel fuel specifications for different global regions.

	EN590:2013	Sweden MK1	US	Canada [winter / summer fuel]	China / Beijing	Australia 2009
Sulfur [mg/kg]	10	10	15	15	≤ 50 / 10	50
Cetane no.	51	50	40	40 - 45	47 - 51	42 - 46
Total aromatics [% m/m]	8	5	35	-	≤ 11	-
Density [kg/m^3]	820 - 845	800 - 820	-	810 - 870	-	820 - 880
T90/95 [°C]	360	285	288 - 338	290 - 360	-	360

The fuels used during its journey may vary in properties from country to country (see Table 1). All of these properties are able to impact engine operation and its emissions in a smaller or larger way. Furthermore, fuel properties might differ due to fabrication process features (e.g. US diesel has lower cetane number because American refineries are built for more gasoline production and thus the fuel contains more cracked components (bi-products)) [3]. Source and nature of raw fossil oils plays an important role in fuel properties, and final fuel combinations (e.g. diesel + kerosene) offers different resulting parameters for fuel as well.

Most of the fuel properties and their impact on emissions and engine operation have been long studied by many teams of researchers. Some of these findings related to fuel parameters are to be presented in Chapter 2.

1.2. Purpose

As already mentioned, throughout recent years, a lot of work and research has been spent by private research companies or by vehicle manufacturers in order to align their engine emissions to more strict emission legislation. Most of the work has been done to better understand the combustion process and thus to increase its efficiency so that less harmful gases leave the combustion room. Developing new after treatment systems and changing engine geometry or Fuel Injection Systems (FIS) have been other points of interest. All of these studies pointed towards a factor that was hard to control and predict: fuel quality. Although most of the research is performed with standardized fuel, the large number of fuels on the market lead to different engine behaviour in real life usage. Client complaints on engine operation and increasing quantities of harmful gases all over the world are also a result of different qualities when we talk about combustibles.

The main purpose of this study is to analyse the capability of fuel quality sensing systems to supply useful information to engine control units (ECU). For this scope, the current work will explain what are considered to be the most important fuel parameters that denote fuel quality. Additionally, a review of the available on-board technologies and sensors is going to extend the knowledge on this field.

What makes this work apart from others is the direct comparison of two different technologies. If one is mostly based on measuring fuel parameters, the other one analyses fuel composition and with the help of a deciphering algorithm it predicts the fuel type and thus its characteristics.

1.2.1 Goals

The specific goals of this paper are to describe and offer a good image off:

- the most important fuel properties which are defining a qualitative diesel fuel. Also present the way these parameters can affect engine operation and emissions according to previous studies and the way they are measured in laboratory conditions;

- the available on board technologies that can detect those previously described fuel properties;

- the available sensors that incorporate those on board analysing technologies and the best procedure to test their performance;

- analysis and final conclusions on sensor performances and their capabilities to adapt engine operation to fuel type.

1.3. Delimitations

A few thesis delimitations have been made for the current study:

- current paper is not going to make a thorough description and analysis of fuel chemical properties and fuel laboratory testing procedures;

- testing of sensors will not be done on engine rigs or vehicles because different types of fuel (e.g. ethanol, gasoline, different biodiesel concentrations, etc.) will be tested and it will consume too much time to adapt these engines to each specific fuel.

It is also considered to be a preliminary study project, and thus vehicle implementation is not yet taken into account;

- test with oxidized fuels will not be performed as time for getting aged fuel (3 to 6 months) exceeds the limit of the time frame of the thesis. It will be considered to be a future work topic;

- in-tank placement tests for each sensor will not be performed because the adaptation of the rig would have been challenging. Additionally, fire and security risks for the Class 1 fuels (e.g. ethanol, gasoline, toluene) would have been higher. Another reason is that one of the sensors was not adapted for this type of testing. This type of test will also be considered as a future work topic.

- physical environmental testing of sensors (e.g. different ambient temperature tests, endurance tests, electrical shock tests) are not going to be performed as it is not considered to be the purpose of a pre-study on sensor specific abilities to read fuel quality.

- the current study is only using two different onboard technologies as they were considered to be the most developed, precise and accurate when it comes to fuel properties sensing.

2. LITERATURE REVIEW

This chapter provides the theoretical issues that are considered to be the base for the current research. It briefly describes the most important fuel properties that define a qualitative fuel, technologies that are used to measure these fuel parameters and previously performed work related to fuel quality analysis.

2.1 Fuel properties

Fuels are elements with stored potential energy, which by combustion can be released and transformed into different types of mechanical energy. Even though they are met in all three states (liquid, gaseous and solid), the most used ones in vehicles are the liquid fuels. Some of the advantages of liquid fuels are that they can be easy to handle, transport and they can take the shape of any type of container. In order to be able to perform analysis on fuel quality, it is important to understand firstly what are the properties that define a qualitative fuel. With respect to that, a review of previous work on this subject was performed, and the results are shown in this chapter. It is generally acknowledged that fuels have a set of parameters. Lots of them are also mentioned in standards (e.g. EN590, ASTM 975) and legislated. Yet, in this chapter, just some of the parameters are described. They are the ones that are mostly representative when talking about fuel quality sensors ability to measure. These properties are what the current on-board technologies are able to interpret and give accurate and repeatable readings on, in the quickest way possible. Each of these parameters can be taken and analyzed independently. There are sensors that by combining two different readings (e.g. viscosity and density) with a prediction algorithm and a known fuel database, can provide information on other properties or fuel type / blend. Also, some of the sensing technologies claim to be able to enlarge on request, the total number of recorded fuel parameters. Finally, the impact of these properties on emissions and diesel engine operation has been described.

2.1.1 Fuel parameters

Cetane number

Cetane number (CN) is similar to the octane number for gasoline fuels, being the measure of fuel’s ignition delay [1]. Thus, along with other characteristics (e.g. pressure, temperature, air/fuel ratio) it has an impact on combustion quality. A high quality combustion is an efficient combustion, which occurs when most of the fuel stored energy is transformed into useful products. These products (e.g. heat, complete burned fuel, etc.) are then converted mainly into kinetic energy or other useful outputs. This takes place when most of the Carbon and Hydrogen compounds are completely burned in conditions of ideal fuel/air ratio, ideal turbulence, pressure and temperature, and in the optimal amount of time. CN is considered one of the most important parameters when talking about fuel quality.

When it comes to cetane number influence on emissions or engine operation, opinions are divided. This diversity of opinions are coming from the definition of efficient combustion itself, mentioned before. CN has a direct impact on ignition delay, but other factors like air/fuel ratio, pressure, temperature, etc., are influencing the test conditions and operating points. Different studies used different test parameters and some are performed for instance at low load operating points, while others at high load operating points. It can be seen as an example, in Lee et al. [3] and in 2009 Hochhauser [5] literature review on fuel quality and the Cetane Number's effect on emissions. They both state that opinions on CN influence are divided, but this is the result of different test conditions in their reviewed papers. A more recent study of De Ojeda et al. [6] confirms this statement. This study claims that CN has beneficial effects on HC emissions, but only for medium and high load conditions. De Ojeda also shows that during their experiments, lower CN fuels produced increased HC emissions at low load conditions. As it can be seen, different conditions (low, medium and high engine load) and different fuels (high and low CN fuels) have been tested and conclusions can be considered to be more pertinent.

When referring to CO, soot and Particulate Matter (PM) emissions, the opinions are relatively similar, stating that cetane number has little or no influence at all [3, 5, 6]. This is again due to the variety of conditions these tests were performed at. These explanations are also supported by a more recent paper which is in agreement with the fact that higher cetane number lowers soot/PM emission, however with a direct influence of in-cylinder pressure-rise rate $dp/d\theta$ [7]. These conclusions are also the result of tests performed in various test load conditions.

By its definition, higher cetane number fuels have a reduced premixed combustion due to a lower ignition delay [3, 4, 7, 8, 9]. This leads to lower combustion pressures and lower combustion temperatures, which has an impact on lowering NO_x emissions. Although the effects of cetane improvers were not entirely assessed, researchers tried to find out if these enhancers have an influence, especially on NO_x formation. And, as already mentioned, temperature and pressure influence the amount of NO_x emissions, rather than the CN improver. Still, in their 2011 study, De Ojeda et al. [6] delimited that for the same medium and high load conditions, fuels with high CN give worse results on soot-NO_x trade-off than the lower cetane fuels.

Relating to cetane number influence on combustion quality and engine performance, opinions are divergent again due to different test conditions. Claims like the ones of Rose et al. [10] that low CN increases the noise of diesel engines at high part loads or of De Ojeda et al. [6] that at low load conditions, low cetane number leads to really instable engine operation, cannot be fully attributed only to CN. In conclusion, one may say that there are a lot of other factors that influence combustion quality and emissions. Cetane number have an impact only on ignition delay factor. Factors like operating regime (load, engine revolution), fuel types used in the test process and engine configuration are the ones that makes every test distinct. Nevertheless, by knowing CN, engine operation strategy can be adapted for engine's maximum efficiency.

Fuel density

It is also an important fuel parameter that defines its quality. Density defines in a way, fuel economy and maximum power. This is due to the fact that a denser fuel will give more energy per unit of volume. It is a very important factor as fuels are purchased by volume.

In order to analyze density's influence on emissions, stable and constant conditions of engine power should be taken into account [3]. As in the Cetane Number case, different operating conditions are not able to provide an image on the fuel density's influence on different types of emissions. If this is the case, then NO_x emissions can be related to temperature and pressure peaks, whilst for other emissions, to the air/fuel mixture ratio. Emissions can be connected to density only if, for constant engine operation point a higher quantity of lower density fuel needs to be injected (when compared to same engine operating conditions and higher density fuel). All these connections are recognizable as hard to interpret by Hochhauser as well, in his 2009 literature review of fuel properties effects on vehicle emissions [5]. Talking about combustion performances, lower density fuels will have better spray dispersion and penetration. But these factors cannot be good for all types of engines as, what can be appreciated as positive for one type of engine configuration (combustion chamber geometry, compression ratio, type of turbulence, air/fuel ratio, etc.), can be harmful for other types. Thus, fuel density influences still have to take into account engine operation points, injection pressure, injector type or combustion chamber geometry in order to confirm their influence on emissions or engine performance [3]. Density is however one of the best characteristics to determine a certain type of fuel, and it's knowledge can have a positive impact on engine's operation strategy.

Fuel viscosity

Viscosity is an important parameter for fuels as it is an image of the fuel's resistance to flow. This means that if the fuel has a low viscosity the injection system might be prone to increased temperatures with a higher risk of wear and cavitation erosion. Low viscosity fuels are also more likely to leak. Fuels with higher viscosity (e.g. B100) will increase injection pressure in system that cannot self regulate the injection pressure. This is a phenomenon that can occur at high temperatures. Another effect of highly viscous fuels would be that larger droplets will form and thus, the spray pattern might change [13]. Specific studies on viscosity influence on emissions were not performed, but Pischinger et al. [11] paper for example, mentions that along with density, viscosity has an influence on soot emissions. Nylund et al. [4] mentions also that ignition delay and combustion duration are affected by density and viscosity. They both have a direct influence on droplet formation and chemical mixing.

Total Aromatics Content (TAC)

TAC represents the total numbers of C/H ratios present in the fuel, compounds with at least one or two benzene like ring structures (see Figure 1). Regarding aromatics influence on emissions, there have been long discussions and contradictions. Most of them were coming from the fact that total aromatics content have never had alone an impact on certain type of emission. They were always put together with cetane number and density influences on emissions [5, 12]. Rob Lee in his 1998 paper [3] also states that past studies did not had a clear image on aromatics influence on emissions.

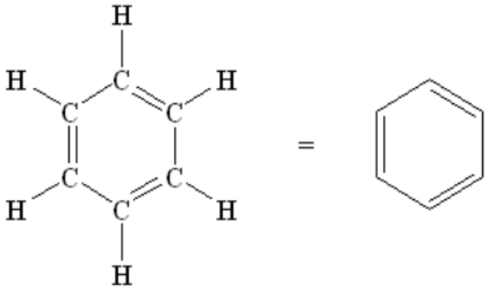


Figure 1. C_6H_6 benzene chemical structure [14]

Yet, according to the same paper, more recent work managed to separate other fuel properties influences from the aromatics influences on emissions. In 2011 two different studies used different approaches to show the well known fact that aromatics content influence soot/PM emissions. Pishinger et al. [11] used fuel with increased levels of aromatics which lead to more soot emissions, while Mizushima et al. [9] used a high Rapeseed Methyl Ester (RME) concentrated biodiesel fuel with no aromatics content and consequently less soot emissions. When it comes to NO_x most of the papers agree that decreasing aromatic content will also be beneficial for NO_x emissions. This is the result of the fact that lowering the aromatics C/H ratios, more H_2O will result and less CO_2. H_2O is less susceptible to dissociation at high temperatures (when related to CO_2) and thus to kinetic production of NO. Combustion temperatures will also be lower on lower TAC fuels, and this is considered to be the main reason for lower NOx[3]. Shankar et al. [8] are even more specific and state in their paper that at high loads (diffusion flame combustion, very high temperatures and pressures), increased aromatic content resulted in more NOx emissions, whilst at low loads (premixed mode combustion, low temperatures, fuel not entirely mixed with air), NOx decreases with elevated aromatics content.

FAME content

Fatty acid methyl esters (FAME) are the result of alkali-catalysis between fatty acids and methanol. Their origin is usually vegetable oils or animal fat and they are main components of biodiesel. Biodiesel has become, in the recent years, a good alternative fuel for HD diesel engines compared to fossil diesel fuel. This is the result of better lubricating properties and high cetane number. It has also proved to reduce fuel injection systems (FIS) wear and to have almost no sulphur content. Yet, it has a lower energy density, a higher mixing capability with absorbed water from condensation, it is more prone to oxidation and has a lower cloud point. From this last point of view (cloud point - the highest fuel temperature at which stable solid crystals can be observed in the cooled fuel), it is very important to know the amount of blend as higher FAME concentration fuels will have higher cloud points when compared to normal diesel fuels (e.g. soybean biodiesel cloud point (CP) is around 1°C, whereas the CP for No. 2 diesel is between -28°C and -7°C) [1]. When FAME is mixed with fossil diesel, the new fuel mixture is abbreviated as B**, where ** is the FAME volume-volume percentage (v/v %) in the mixture. (e.g. B20 is 20 v/v % FAME and 80 v/v % diesel). In Europe, according to the new emissions regulations, it is allowed to have up to 7 v/v % FAME content in the final diesel fuel mixture [17].

As in 1999 biodiesel was not that widely used, Lee et al. in their paper [3] drew no conclusions on its influence on emissions. One of the main ideas that suggests that the studies were in incipient phase, is the confidence that adding FAME with a higher level of oxygenates compounds to the fossil fuel has no impact on NO_x emissions. It was in 2009 when, with a similar paper (a literature study on fuel properties effect on emissions), Hochhauser concluded that for heavy duty (HD) diesel engines, higher amounts of FAME will reduce PM emissions but will for sure increase NO_x emissions. He also mentions that some of the studies showed that CO emissions were also lower along with HC ones. Yet, some of the results made him conclude that when talking about splash blended fuels, results should not be generalized [5]. His findings are also supported by more recent studies on biodiesel effect on emissions. Regarding NO_x emissions Mizushima et al. [9] and Robbins et al. [16] are also supporting the idea of increased values due to high FAME content. EPA’s 2001 document on diesel fuel properties correlation with emissions reflects biodiesel capabilities to reduce HC and CO emissions, idea supported by Rose et al. [10] and Robins et al. [16] papers. The last article also showed a reduction in PM emissions as a result of biodiesel usage.

Regarding combustion quality and engine performances it is hard to draw a clear conclusion. The main common opinion is that there is a large number of variants mixing biodiesel and diesel fossil fuels at different percentage. Usually there are different engine operation strategies and during development and testing of engines a certain type of blend is used. Combined with the fact that in real life, fuel usage extends to a larger variety of fuels and blends, it can be concluded that contradictions in reports and readings can occur. Thus, the amount of FAME content is a very important parameter to know as it is affecting not only the fuel properties in cold conditions, but its oxidation stability and control strategy for optimum engine operation.

Dielectric constant

Dielectric constant represents the absolute permittivity (ε) or the relative permittivity (ε_r). The relative permittivity denominate the ratio between the complex frequency-dependent absolute permittivity of the material and the permittivity value which was measured in vacuum.

Table 2. Dielectric constant values for some well known fluids [20]

Fluid type	Dielectric constant value [ε]	Temperature [°C]
Ethanol	24,3	25
Methanol	33,1	20
Benzene	2,3	20
Gasoline	2	21
Diesel	2,1	21
Kerosene	1,8	21
Water	80,4	20
Jet fuel	1,7	21

There are two things that have to be known when talking about dielectric constant: (i) its dependence on temperature variation and that (ii) there are two types of liquids: polar and non-polar liquids. The temperature dependence of the polar molecules is higher when compared to the non-polar ones. As a polar liquid example, water represents one of the most interesting, being one of the diesel fuel's contaminants. Other interesting fluids are the alcohols (e.g. ethanol, methanol). As they are both comprised of C-H and O-H bonds, they have both polar and non-polar behavior. They will mix very good either with water or with fossil fuels, and not only as an emulsion (like water-diesel mix). This might lead to interesting results in dielectric constant reading as a function of ethanol percentage and temperature. Different types of fuels (e.g. diesel, gasoline, kerosene, etc.) are considered to be non-polar liquids [21].

In 1992, Sen et al. [22] conducted a series of experiments at the end of which they proved the linear dependency of dielectric constant for simple molecules like n-alkenes on temperature (see Figure 2). Their team also observed that the dielectric constant is actually dependent on liquids density as well. Density is inversely proportional to the temperature and the dielectric constant is inversely proportional to the temperature. The best way to describe this relation, according to Sen et al. [22] is the Clausius – Mosotti relation [22]:

$$\frac{\varepsilon'-1}{\varepsilon'+2} = 4\pi\rho N_A \frac{\alpha}{3M} \quad (1)$$

where $\varepsilon'$is the dielectric constant, ρ the mass density of the fluid, N_A Avogadro's number, α represents the electric polarizability of the molecule and M is fluid's molecular weight.

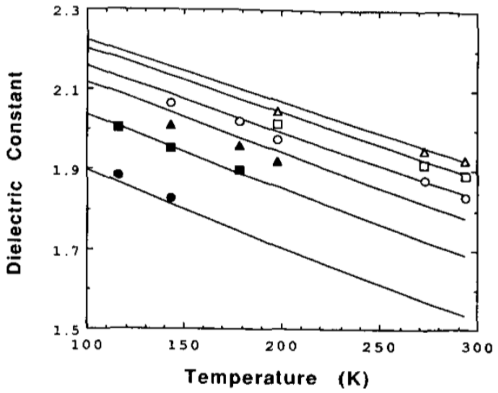


Figure 2. Dielectric constant variation with temperature for different simple molecules like the n-alkanes fluids; Δ - n-heptane, □ – n-hexane, ○ – n-pentane, ▲- n-butane, ■ – propane, ● – ethane [22]

By comparing equation pattern with experiment results, they showed that the model has an accuracy of ±0.3% above 0°C and ±1% below 0°C.

The trend is considered to be the same for higher C-H bonds fluids (see Figure 3).

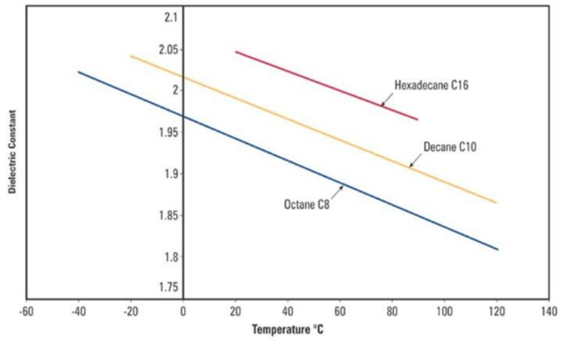


Figure 3. Dielectric constant variation with temperature for octane, decane and hexadecane [23].

Dielectric constant might be unrelated to previous presented fuel properties as it does not define exact parameters of the fuel that can influence injection or combustion. Nonetheless, when talking about fuel quality sensing, in combination with other parameters it is able offer a clear image of fuel type or make.

2.1.2 Fuel contaminants

Sulphur content

Sulphur is a common element of raw fossil oil. During diesel manufacturing, oil needs complex processing in order to reduce the sulphur content. Final result is the so called Ultra Low Sulphur Diesel or ULSD, a fuel with lower energy content and lower lubrication specifications. Removal of sulphur has started in 2006, with new legislations in Canada, Europe and US that had as a primary target PM emissions, but overall emissions as well [1]. Rob Lee [3] and Hochhauser [5] in their literature studies propose the reasons behind these decisions. Their explanations are based on the conclusions of prior multiple studies performed by different teams of researchers.

First conclusion is that sulphur main impact is on particulate matter (PM) emissions. Some of the PM constituents have been found to be derived sulphates, mostly sulphur dioxide based, SO_2. In very small percentages sulphur trioxide, SO_3, or sulphuric acid, H_2SO_4, can also lead and affect PM emissions [5]. Lee et al.[3] in 1999 were claiming that reducing the level of sulphur in the fuel, even to zero, will not have a similar effect on particulate matter emissions, meaning they will not significantly decrease or go to zero. This is because of small percentage of sulphur based particulate matter in the whole PM mass. Pointing out a large number of studies, Hochhauser in 2009 supports the idea that, for HD engines, sulphur content in the fuel affects only the sulphate portion of PM emissions. Anyway, decreasing the sulphur from 350 ppm to 3 ppm in content will decrease PM emissions by almost 30% [5].

Second conclusion concerning the sulphur content is that its derivatives have a great influence on modern after treatment systems (oxidation and NO_x catalysts), exhaust gas recirculation system and regenerative PM trap operation. These systems will be “poisoned” by deposits of sulphate derivates and their efficiency in treating other emissions will drop, which leads to increased levels of such emissions [3]. This is for example supported by the findings of Wiartalla et al. [15] who blamed sulphur content for an increase in HC and PM emissions reading. Hochhauser is yet supporting the idea that sulphur concentrations smaller than 50 ppm will have no effect on modern after treatment systems [5]. Corrosion might also appear as an effect of high level of sulphur content, and thus sulphuric acid condensation [3].

Water content

Water content is not to be considered as a diesel fuel important parameter. But it represents one of the most common contaminants found in all types of fuels, not only diesel. This is mainly due to condensation, either in storage tanks or inside vehicle tanks. Diesel contamination is caused by diesel’s absorbance capability of 100 mg/kg at room temperature as an example [13]. Therefore, all vehicles have filters that are capable to separate water, but their efficiency is not 100%. The main effects of water contamination are to be seen on the injection elements (fuel pipes, fuel pumps, injectors) that are exposed to corrosion and thus on lower combustion quality. Water corrosion will occur only if water is in free form. Fuel properties, like viscosity or density will change when mixed with dissolved water. EN 590 standard allows a concentration of 200 mg/kg water contamination, which has been proven to be maximum possible level on most of the markets [13, 17].

2.1.3 Conclusions on fuel properties

Some of the most important fuel parameters have been presented. As already mentioned, they were presented throughout earlier studies as well and together are considered to have the biggest influence on exhaust emissions or engine operation. Still, when taken and analyzed individually, their impact is not that important. On the other hand, when fuel qualities are easy and quick to detect by on-board analyzing technologies, they could be used to adapt engine operation strategy so that emissions might be reduced. It has to be mentioned that fuels are characterized by many other parameters that were not discussed in the current paper, like: cold filter plugging point (CFPP), corrosivity, lubricity, total contamination, etc, but the existing technologies are not able to detect and analyze them and thus, they were not presented.

2.2 Laboratory technologies for fuel quality analysis

The Periodic Table of Elements and chemistry itself invariably came up with a countless number of ways in which different constituents can react and bond together. Oil and fossil fuel chemistry are part of these processes and have proposed a large amount of different possibilities and combinations. Methods and tests for analyzing and differentiating elements were put in place in order to know and control the mixtures. For controlling emissions level, international legislative organizations had to turn their attention to fuel composition and properties as well. By adopting common legal standards, fuel quality is controlled to have the same composition right from refinery. These standards are different depending on geographical region, but they apply in more than one country and thus all the fuels in that specific region will have a common denominator. To have a clear image of the fuel properties and to give clear restrictions on certain fuel parameters, laboratory test procedures were put in place. They were also legislated and put into standards so that everyone will use same procedure for fuel analysis.

In order to create an image on the diversity of these laboratory tests, which are specific for just one fuel characteristic, some of them will be presented as described in standards. This way, the challenge to create a quickly and easy adaptable on-board technology may be illustrated. The following are the laboratory techniques available for the fuel properties mentioned in subchapter 2.1 ("*Fuel properties*").

Determination of cetane number (CN) and derived cetane number (DCN)

To determine the cetane number of a diesel fuel, ISO standard EN ISO 5165 regulates that a standard single cylinder diesel engine should be used. It is a four stroke engine, with variable compression ratio. It is indirect injected and operated at constant speed during the test. A depiction of the used apparatus is presented next.

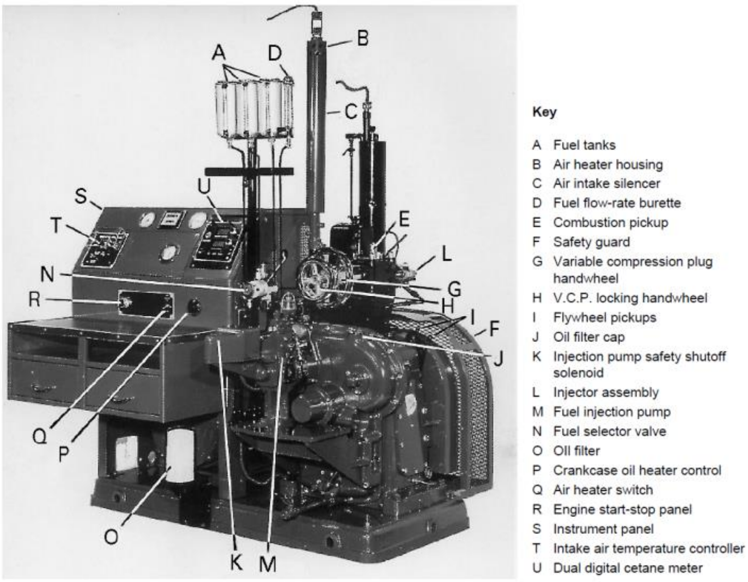


Figure 4. Image of the single cylinder diesel engine used for cetane number determination [24]

The cetane number itself is the result of comparison between combustion characteristics of the analyzed fuel with those of reference fuel with known cetane number (hexadecane and heptamethylnonane). By combustion characteristics, EN ISO 5165 refers to ignition delay, expressed in degrees of crank angle rotation. The standard mentions though that “the relationship of the test engine performance to full scale, variable speed, variable load engines it is not completely understood” [24]. This statement shows again that, taken individually, CN cannot predict in any way normal engine operation or emissions. The laboratory test for defining the derived cetane number (DCN) is described in the EN 15195:2007 standard. According to it, DCN is the “measure of the ignition performance of a fuel in a standardized engine test” [25]. The test principle is to inject a small quantity of sample fuel inside a combustion chamber pre-charged with compressed air. The test rig has sensors that are able to detect injection start and combustion start for each injection. After 15 consecutive injections, that have the purpose of creating stabilized conditions, 32 consequent injections are performed and the ignition delay is measured. The average value is then inserted into Equation 2 , where ID represents the ignition delay in milliseconds.

$$DCN = 4{,}460 + \frac{186{,}6}{ID} \quad (2)$$

The obtained derived cetane number is an estimate of the actual cetane number (CN). The apparatus used for DCN tests is presented in Figure 5.

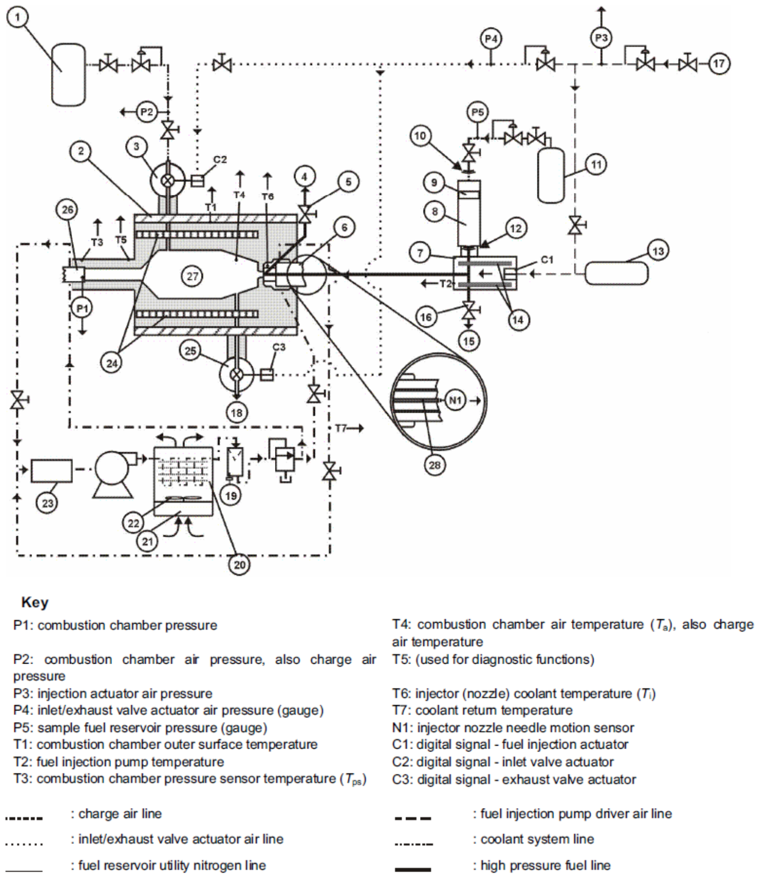


Figure 5. Representation of combustion analyzer for derived cetane number [25]

Determination of fuel density

EN ISO 12185 describes the use of an oscillating U-tube density meter as a method of density measurement for fuels within 600 - 1100 kg/m^3. The resolution is ± 0,1 kg/m^3, but the standard mentions that results might be influenced by changes in fluid's viscosity. The U-tube used in density measurement also needs calibration with two previously measured and calibrated fluids. These two, must be chosen so that their densities should constitute the values interval (minimum and maximum) for the measured fluid. Results are always written function of the measured temperature (usually for most of the fluids 15°C or 20°C). Density is always temperature dependent [26].

Determination of fuel viscosity (dynamic and kinematic)

The measurement of kinematic viscosity is done according to SS - ISO 3104 by determining the time for a volume of liquid to gravitationally flow through a calibrated glass capillary viscometer. This procedure can apply for both types of petroleum product, opaque or transparent. Further on, by multiplying the obtained result (kinematic viscosity) with fluid's density, we can obtain the dynamic viscosity. This last factor is proportionality factor between the applied shear stress and the local shear velocity (liquid velocity gradient). Viscosity is also temperature dependent, that is why, the fixed volume of fluids that is analyzed by means of time flow, has to be at a controlled temperature. The apparatus is comprised of a viscometer, a viscometer holder, a temperature controlled bath, a temperature measuring device and a time measuring device. The formula used for kinematic viscosity is:

$$\upsilon = C * t \; (3)$$

where υ is the kinematic viscosity in mm^2/s, C is the viscosimeter's calibration constant in mm^2/s^2 and t is time in seconds (s). Dynamic viscosity expression:

$$\eta = \upsilon * \rho * 10^{-3} \quad (4)$$

where η is the dynamic viscosity in millipascals (mPa), ρ is the density in kg/m^3 and υ is the kinematic viscosity in mm^2/s [27].

Determination of Aromatics Content

Determination of aromatics is done for all the fuels with boiling range from 150°C to 400°C and with a FAME content of up to 5%. As a detection method, high performance liquid chromatography with refractive index detection is used. Results offer the amount of mono-, di- and tri-aromatic content of the fuel. Using mathematical equations, the polycyclic aromatic content (summation of di- and tri-aromatic hydrocarbons) and the total aromatic content can be determined. The standard also draws attention to the fact that high content of oxygen, nitrogen or sulphur may interfere with the analysis, as well as the di-alkenes and polyalkenes. The apparatus for the analysis is a very complex one and is comprised of: liquid chromatograph, sample injection system, sample filter, column system, temperature control device or room (heating block or air-circulating HPLC column oven), refractive index detector, computer or computing integrator, volumetric flasks and analytical scale [28]. The schematic of the apparatus is presented next.

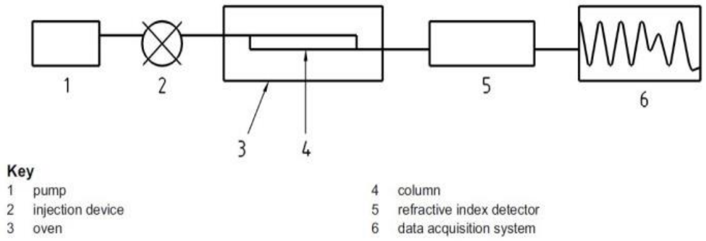


Figure 6. Schematics of liquid chromatograph used for aromatics content analysis [28]

Determination of fatty methyl ester (FAME) content

The method for determining the amount of FAME in diesel fuel is the infrared spectrometry. EN 14078 standard divides the measurements in two types, function of FAME concentration: range A (0,05 - 3 volume fraction % (V/V)) and range B (3 - 20% (V/V)). Diesel fuels with concentrations higher than 20% (V/V) can also be analyzed as long as they are diluted, but the precision data to compare with the results is unavailable. The apparatus is comprised of: infrared spectrometer with capacity to operate in the infrared range of 400 cm^{-1} to approximately 4000 cm^{-1}, with a resolution of 4 cm^{-1}. Test cells made of KBr, NaCl and CaF_2 are also used. After an initial calibration of the apparatus, the test sample is diluted with the appropriate FAME free solvent, the sample placed in the spectrometer and then the mid infrared absorption spectrum is recorded. The typical absorption band for esters is around 1745 ± 5 cm^{-1}. The initial results are considered in grams per litre and a conversion to volume fraction (% (V/V)) is done by adopting a fixed density of 883 kg/m^3 for FAME according to next equation [29]:

$$Y_S = 100 * \frac{X_S}{883} \quad (5)$$

where Y_S is the FAME content in % (V/V) and X_S represents the FAME content in grams per liter (g/l).

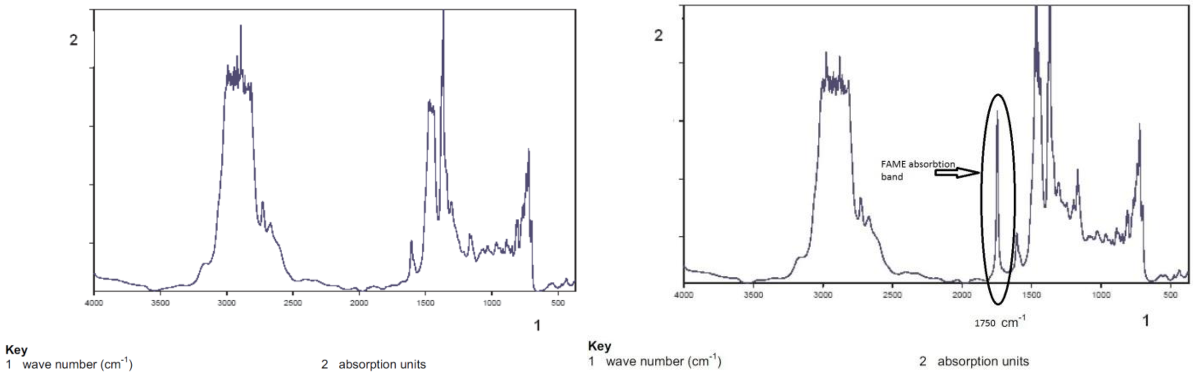


Figure 7. Examples of mid infrared analysis results for diesel without FAME (left) and for diesel mixture with 5% (V/V) FAME (right) [29]

Determination of water content

EN ISO 12937 describes the method to be used in determining the water content of petroleum product with boiling points below 390°C, excluding fuel oils and compounds that contain ketones. The method covers water mass fraction concentrations (%(m/m)) between 0,003 % (m/m) to 0,100 % (m/m). The apparatus used for determining water content is comprised of: automatic coulometric Karl Fischer titrator, non-aerating mixer, syringes, balance with capacity to weigh ± 0,1 mg, 100 ml volumetric flask, sealable bottles, ovens, cooling bath and thermometer. The test method starts by visual inspection of the sample to be tested after it has been shaken for 30 s. If no water or particulate matter is visually detected, with a syringe, three portions from the sample are drawn and injected into the titrator. At the end of titration process, the excess iodine is detected and measured. Based on the stoichiometry of the reaction, one mole of iodine reacts with one mole of water. Thus, by measuring the quantity of titrated iodine, the mass of water can be found. [30]

Determination of sulphur content

In order to detect the sulphur content, EN ISO 20884 suggests a wavelength-dispersive X-ray fluorescence (WDXRF) as a test method. It addresses the homogeneous automotive fuels from 5 mg/kg to 500 mg/kg with a maximum 3,7 % (m/m) oxygen content. The method can also apply to diesel blends with up to 10 % (V/V) fatty acid methyl esters (FAME). The sample to be analyzed is exposed to the primary radiation of an X-ray tube. The wavelength-dispersive X-ray fluorescence spectrometer measures the count rates of the S K-$L_{2,3}$ X-ray fluorescence or of the background radiation. A calibration curve defined for the relevant measuring range shows the sulphur content of the analyzed sample [31].

Conclusions

As it was shown, for every type of fuel characteristic, a certain type of fuel analysis exists. Every analysis of course has to show good reproducibility and validity of their results according to test methods. This is done in order for the results to be accepted. Also, there are a lot of techniques that require reagents, solvents or samples in order to be able to complete the analysis. Not all of these different types of analysis are impossible to install on vehicle. Some techniques are already being used for detecting fluid properties (e.g. infrared spectrometry for detecting Ad-Blue quality). The real challenge comes from making them portable and from finding the space on the vehicle to place all of them. Another important aspect would be to make them communicate with the vehicle’s Engine Control Unit (ECU) so that the engine operation is adapted to various changing fuels. The best way would be to find a technology that would incorporate most of the laboratory techniques, that would be able to read multiple fuel parameters and could easily communicate with the ECU. At the same time, the representative sensor for this technique should be small and its mounting should be easy.

2.3 On-board technologies for fuel quality analysis

With increasing speed and mobility in every day operations, a need for quicker controls of fuel quality is needed. On board or in line technologies that are able to provide the similar qualitative and quantitative answers, as laboratory tests do, were developed. Some of these technologies that can quickly analyze multiple fluid properties and parameters are presented in the following pages.

2.3.1 Tuning fork technology

Short history of tuning fork

The tuning fork itself as an instrument was first presented in 1711 by John Shore [32]. He was the first to observe that by striking a u-shaped elastic metal bar against a hard surface, it will resonate with a specific constant pitch, producing a pure musical tone. The purity of the tone itself is a result of the fact that most of the vibrational energy is concentrated at fundamental frequency, and the little amount of harmonics created at the beginning of the pitch are quickly dissipating [2].

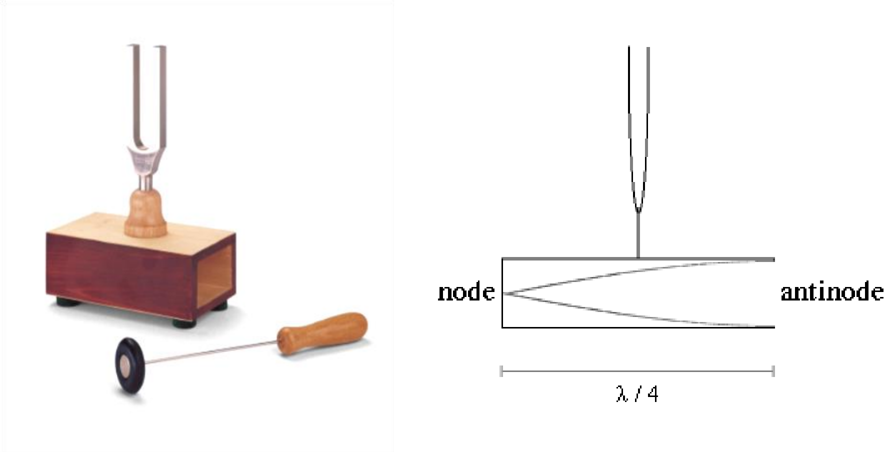


Figure 8. Ttuning fork mounted on a resonant chamber with soft striking hammer (left) [33] and node – antinode of sound wave in the resonant chamber (right) [34]

In 1839 a French instrument maker, Albert Marloye, decided to add a resonance box at the end of handle (Figure 8 (left)).

The decision to add the box came from the fact that Marloye observed that there is a point of no vibration at the end of each prong with little influence on the handle itself. More over the handle was transmitting the vibration. By having an opened and a closed end, the resonance box acts as an amplifier of the fork's sound (Figure 8 (right)).

In 1860, Hermann von Helmholtz designed and manufactured an electromagnetically driven tuning fork (see Figure 9). As a normal tuning fork's sound dissipates in time, the physicist produced this device that has a continuous sound at a specific frequency. The idea was to place a circuit contact just in reach of the tuning fork, which once it started to vibrate, was acting like a switch between a battery and a wire coil. This was producing a magnetic field which was driving the fork continuous vibration.

Fig. 32.

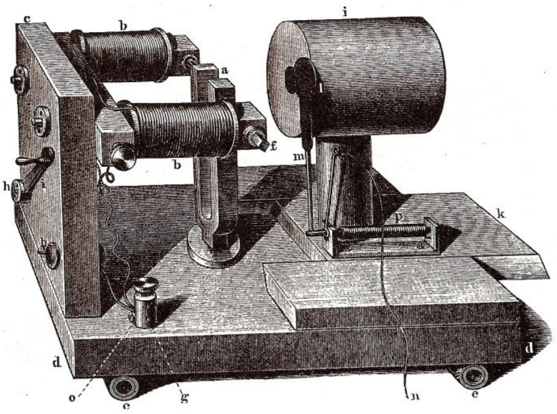


Figure 9. Hermann von Helmholtz’s electromagnetically driven tuning fork [35]

Tuning fork mechanical resonators

Continuing von Helmholtz idea, during recent studies, scientists observed that function of the medium where the tuning fork is placed in, the resonator performs differently [36](see Figure 10). Technology advances allowed the manufacturing of a miniaturized single structure monocrystalline quartz tuning fork (see Figure 11 - Sensing elements). In order to be able to resonate when energized, the two spikes of the fork are metalized. If for example, in air or vacuum, a sinusoidal voltage is applied, the thin metal film on the quartz fork will curve due to mechanical stress. It is to be mentioned that using a piezoelectric substrate allows the mechanical excitation of the tuning fork to be replaced by an electrical excitation. Piezoelectricity defines the ability of a material to convert a voltage to a mechanical displacement, and conversely, to generate electrical charges by the deformation of the crystalline matrix. As a result of the sinusoidal nature of the voltage, the fork itself will start to resonate/oscillate to a certain frequency. This is a consequence of the system’s electrical impedance. If the fork is submerged in a liquid environment (e.g. fuel, oil, water, etc.), due to the medium’s characteristics (e.g. viscosity, density) and the friction of the fork with the medium, a change in oscillation frequency can be observed [36].

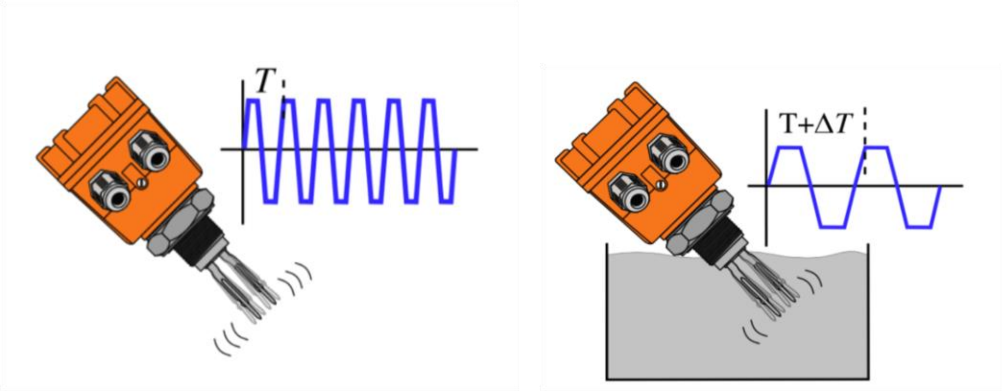


Figure 10. Tuning fork frequency in air (input) (left) and tuning fork frequency in liquid (output) (right) [37]

By using an algorithm for interpreting measured signals, along with a database of well-known fluid characteristics, a sensor equipped with a similar tuning fork (see Figure 11 (right)) is able to measure different fluid viscosities, densities and their dielectric constant and function of these values to differentiate the fluids as well.

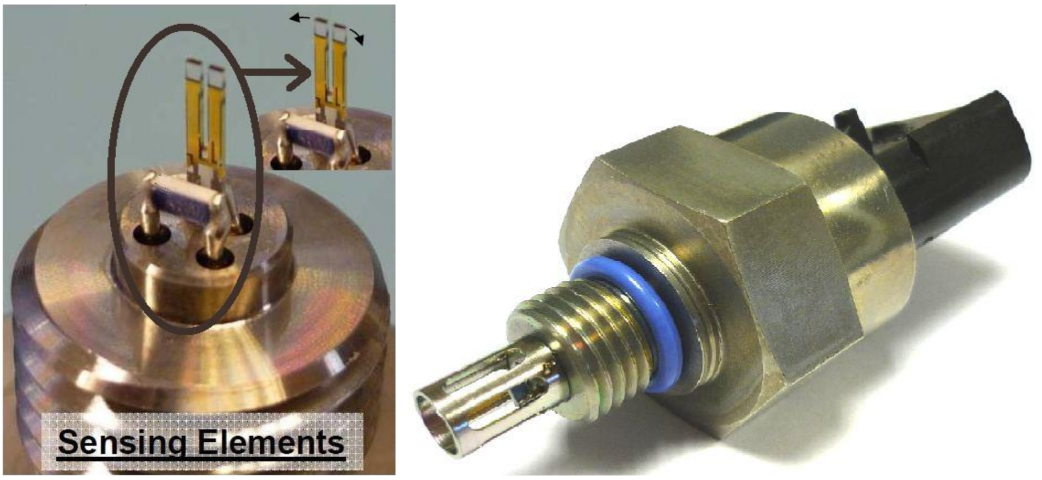


Figure 11. Monocrystalline quartz tuning fork (above) and sensor equipped with metalized tuning fork (below) [38]

The sensor is part of a complex but small electrical system (see Figure 12) which, as already mentioned, has the capacity as a reactive part of the impedance. The whole system, including the sensor, can be represented by equivalent circuit depicted in Figure 12 (right).

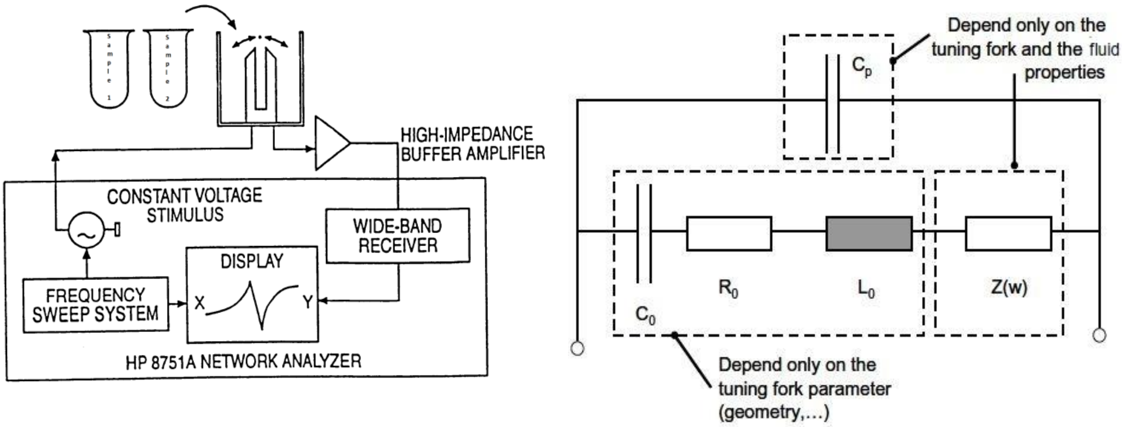


Figure 12. Block diagram showing the sensor's electrical system construction (left) and tuning fork sensor's corresponding electrical system (right) [39]

In order to function correctly, an initial calibration of the sensor is required. This is done by exciting the sensor in the air. $Z(\omega)$ [39], system's impedance, it is considered at this point as being equal to 0, or:

$$Z(\omega) = Ai\omega\rho + B\sqrt{\omega\rho\eta} * (1 + i) = 0 \quad (6)$$

where ρ is the fluids density, η its dynamic viscosity and ω the resonant frequency. A and B are representing constants dependent on the fork's geometry and oscillation mode. Now, C_0 sensor's mechanical compliance, R_0 its mechanical loss and L_0 its mass inertia, all vacuum values, can be identified. Another element can also be identified, C_p [39] or the capacitance between the parallel electrodes, defined by the next equation.

$$C_p(\varepsilon) = C_p(1) + (\varepsilon - 1)\frac{dC_p}{d\varepsilon} \qquad (7)$$

Where ε is the fluid's dielectric constant, $C_p(\varepsilon)$represents electrode's capacitance in vacuum and $\frac{dC_p}{d\varepsilon}$ is the sensitivity to modifications in the electrical properties of the tested fluid. Further on, the sensor is put in contact with the tested fluid. By knowing its physical properties, A, B and $\frac{dC_p}{d\varepsilon}$ can be identified. A varying algorithm is applied in order to calculate real values for all three mentioned parameters. Once A, B and $\frac{dC_p}{d\varepsilon}$ are found for a reference fuel, the sensor is ready to be used and by varying fluids, changes in density, viscosity and dielectric constant occur. Compared to the equivalent circuit, it will give the new fluid's physical properties (ρ, η, ε) and it will recognize and differentiate different types of fluids. [39]

Advantages and disadvantages

Among the stated advantages of this technology, accuracy and repeatability of its measurements stand out [38]. Also, sensors incorporating this technology are small, compact and robust with no moving parts. This allows the sensor to be mounted in almost any position. Temperature and medium are also non important for a tuning fork sensor to start to work [38]. Sensors equipped with this technology can also be mounted either in-line or in-tank. Another advantage is the number of measured parameters. As already mentioned, sensors are able to measure up to four fluid properties: viscosity, density, dielectric constant and fluid's temperature. Using a deciphering algorithm, combinations of dielectric constants and density for example can offer other information like concentration of one type of fluid into another type of fluid (e.g. B10, B30).

One of the disadvantages is that the sensor's fork might be prone to material build-up, which may lead to inaccuracies in the readings. A second disadvantage would come from the fact that other fuel's parameters cannot be read. Important parameters like cetane index or aromatic content are not detected.

2.3.2 NIR (near infrared) spectroscopy technology

Short history of NIR

William Herschel is considered to be the first one to mention near-infrared energy right in the beginning of the 19th century. In 1881, Abney and Festing were the first who measured infrared spectra with the help of photographic plates. And, in 1905, William Coblentz reported exact measurements of IR spectra between 1000 nm and 16000 nm. It was only in 1950 to be firstly adopted in industrial applications. In the beginning it was used as a supplement reading along devices that were using different wavelengths from ultraviolet (UV), mid-infrared (MIR) or visible (VIS) spectrometry. The first chemical apparatus using exclusively NIR technology was presented in 1980s. Once the light-fiber optics and the monochromatic detector were developed, the NIR technology became a powerful tool of scientific research. It was also introduced in other fields of expertise like medicine, physics or even physiology [1][40].

NIR spectroscopy and sensors

From the technique point of view, NIR spectroscopy is considered to be an analytical one. It is based on the absorption of electromagnetic radiations that have wavelengths in the region of about 750 – 2500 nm (see Figure 13) [41].

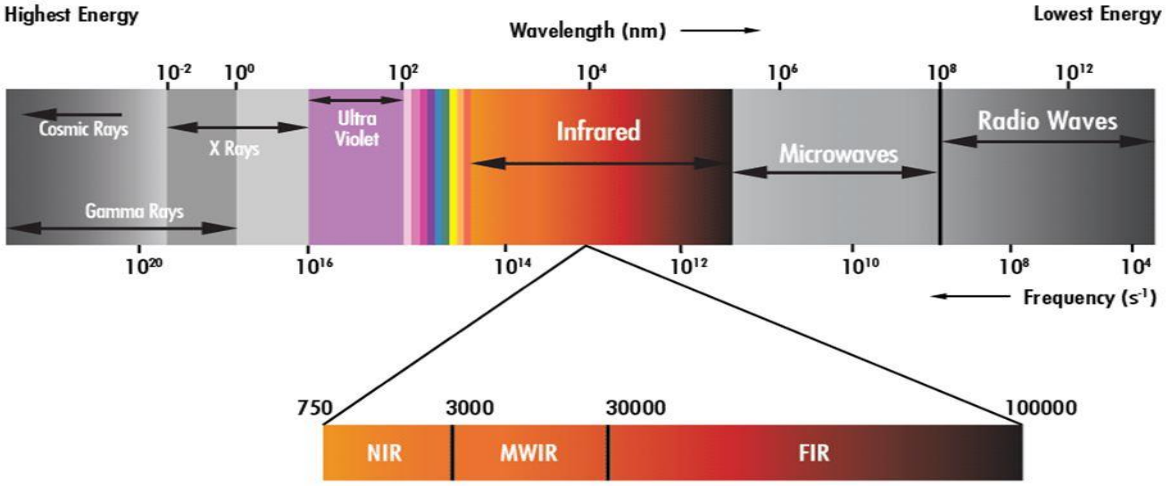


Figure 13**.** The electromagnetic spectrum with NIR ranging from 750 nm to 2500 nm [42]

From the molecular point of view, every constituent is comprised of atoms and atom bonds. These constructions are always vibrating with a certain frequency which is defined by the atom's mass and bond's strength. If a light source is used to send a certain type of photon energy at a certain wavelength, the amplitude of vibrations will change. This is happening as long as the emitted energy of a single photon has the same value as the difference between two vibrational levels in molecule, and thus can be absorbed to make transition to the excited level. The remaining photon flux continues to propagate until a NIR detector detects it. By comparing the emitted energy at a certain wavelength with the detected one, the NIR absorption spectrum can be drawn as the characteristics of media. (see Figure 14). This is considered to be the working principle of NIR spectroscopy. [41]

Unfortunately, automotive fluids are composed most of C-C, C-H, O-H bonds, which have fundamental vibrations wavelengths in the Medium and Long Wave infrared spectra (2500 nm to 25000nm). Still, NIR is able to read results due to overtones and combination bands. As it can be seen in Figure 15, overtones and combination bands are fundamental frequencies of different molecules that are adding together to give a shorter wavelength value. The preferred ones when analyzing fluids would be the first and the second overtone. But the costs to produce this type of light sources and NIR detectors for automotive industry would be too high right now. This is why, the third overtone (with wavelengths between 800 – 1000 nm) is preferred. The big disadvantage of using third overtone is that it has few and not that pronounced absorption peaks. Furthermore, exact interpretation of results can be misleading [41].

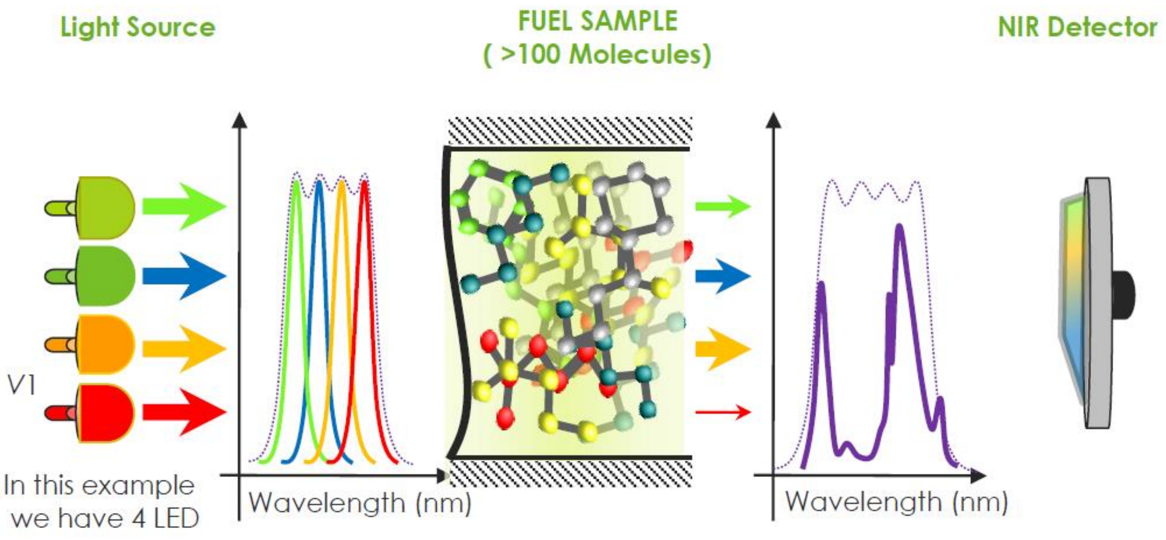


Figure 14. NIR spectroscopy functioning principle [41]

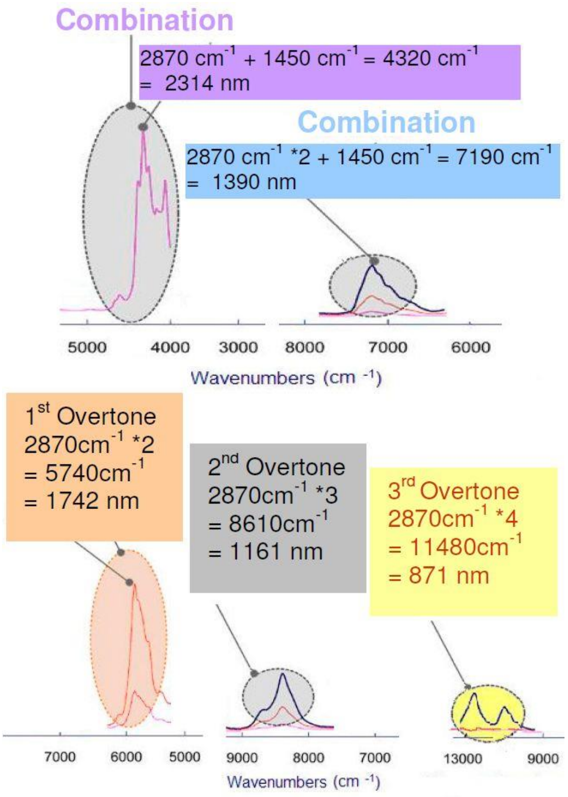


Figure 15. Overtones and combination bands correlated to NIR vibrations (from the absorption mode side) [41]

Advantages and disadvantages of NIR spectroscopy

One of the most important advantage of this technology is that it is a non-invasive / non-destructive technique. This way, disturbances due to flow are avoided. It is a much more complex technique that is able to determine both physical fluid properties (e.g. density, viscosity) and chemical properties (e.g. aromatic content, oxygenates content, etc.). Depending on the company's knowledge and advancement in decoding algorithms, sensors which incorporate this technology, are able to read from six up to fifteen parameters (e.g. density, bio content, aromatics content, fuel type, cetane number, etc.). There is no need for reagents or other materials to prepare the samples while results are comparable in accuracy with those of other analytical techniques [43, 44, 45].

On the other hand, the limited wavelength range might be the most important disadvantage. It may lead to difficulties in interpreting highly absorbing samples and also to increased duration of measurement. Small ppm concentrations changes (e.g. adding cetane number enhancer additive) might not be detected as well. Depending on the company that is using this technology, as already mentioned there are sensors which are not able to detect some other important properties. For example, sulphur content is one of these parameters. It is either undetectable, or if it is detected, then the range and accuracy are not suited to categorize between a legislated ULSD and a non-ULSD fuel. Also there are sensors that are not able yet to detect viscosity, water content or distillation points.

2.3.3 Other technologies

Microelectromechanical systems (MEMS) technology

It is mentioned the first time in 2010 by Sparks et al. [46] in their study on "*Monitoring and Blending Biofuels Using a Microfluidic Sensor*". It consists of a sensor with the size of a finger tip and it comprises of a hollow silicon tube that is sealed to glass (anodic bond) (Figure 16). The glass wafer acts as a printed circuit board (PCB) and contains the metal electrodes used to carry electrical signals.

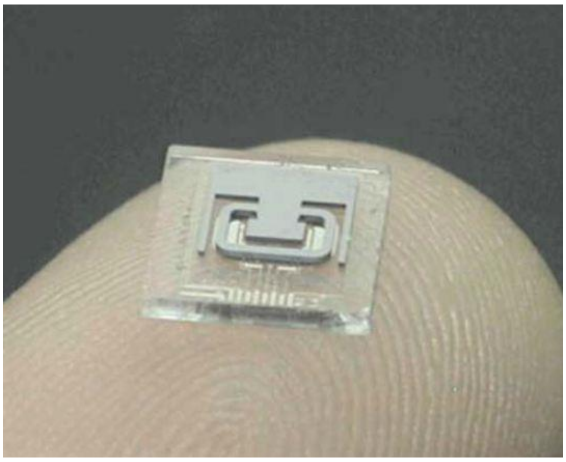


Figure 16. MEMS sensor chip [46]

For temperature measurements, the chip is equipped with a thin-film metal layer. The resonator is also packaged at wafer level to reduce vibrations of the micro tube and two holes are present in the bottom of the glass chip in order to allow fluid through the micro tube. The working principle is based on the "*Coriolis meters*". It is able to measure density, viscosity, temperature and flow. Throughout these values is able to detect concentration level, purity, water content and grade of various petrochemicals based fuels. The technology is mostly used in food and medicine industry. [46]

Resonant cavity dielectric technology

Although not entirely confirmed in Tat and Van Gerpen's 2001 study [47], the working principle of their dielectric fuel composition sensor is believed to be the resonant cavity dielectric technology. Sensor measurements are based on a square wave output that has a frequency specific to fuel composition (e.g. No.1 commercial diesel has 51,84 Hz while FAME has 58,96 Hz).

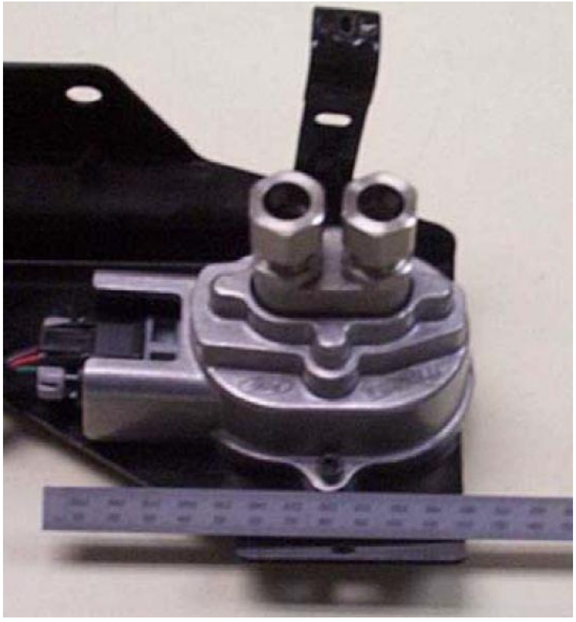


Figure 17. Flexible Fuel Composition Sensor used by Tat and van Gerpen during their studies [47]

The wave's peak length in duration was proportional to the fuel temperature. The sensor had been able to detect differences between 6 distinct diesel fuels and 12 types of biodiesel with a 10% error in the blend level.

UV-VIS spectroscopy

Even if a real sensor does not exist yet, Zawadzki et al. [48] in 2007 and later, in 2010 Chuck et al. [49] mentioned about the UV-VIS detection method in their studies. The method has almost the same working principle as the NIR technology, but the spectrum wavelengths are situated between 400 and 800 nm and from the molecular point of view, the light with most of the wavelengths are primarily absorbed by the n-heptanes bonds.

Both teams of scientists concluded that the method can be applied to diesel fuels and to detect biodiesel blends but high aromatic contents might inhibit the sensor usefulness, especially when using only one wavelength [48, 49]

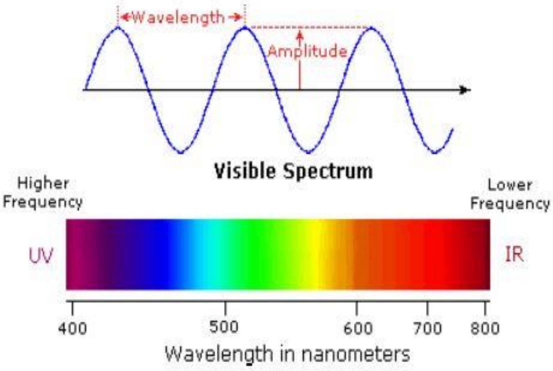


Figure 18. Visible spectrum range[50]

Interdigitated capacitive sensing technology

Although it started as fluid level sensing technology, recent studies showed it is able to offer promising results on fuel property readings as well. In 2008, Mendonça et al. [51] used a sensor based on interdigitated structures that were of use as electrodes for a capacitor. The fluid was acting as a dielectric. The resistivity of the electrode could also detect some chemical reactions.

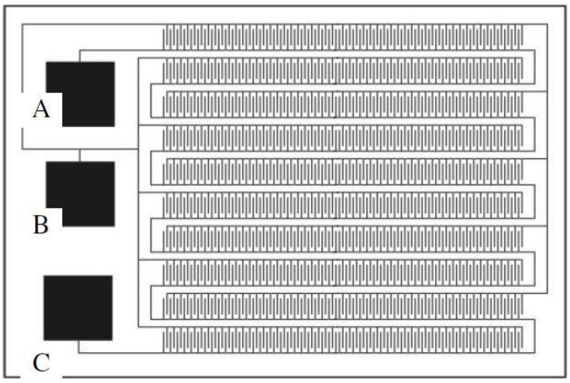


Figure 19. Interdigitated structures sensor for fuel quality measurements. [51]

Pads pairs A-B or B-C were used to measure different dielectric values like: impedance, capacitance, resistance or phase angle, while pads pair A-C was measuring the resistance between the extreme points of the same electrode. Results were encouraging. In 2013, Skwarek et al. [52] also used in their study capacitive sensor elements. They were able to measure dielectric constant between different capacitors and thus to characterize different fuels. It was concluded during the study that the sensors layout still needs optimization.

Ultrasonic technology

This technology is also used mostly for fluid level sensors, but with more advances in transmitters and receiver technology, it is more recently able to interpret fluid properties as well. Ultrasonic technology uses ultrasonic waves that are propagating longitudinally through fluids with frequencies between 18 kHz and 1Ghz. Depending on fluid properties and the interpretation algorithm of a certain sound wave (that has different reflection and transmission factors), two different fluids can be identified. [53]

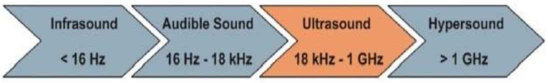


Figure 20**.** Acoustic waves classification [53]

Most of the fluids properties sensors based on this technology are available for oil or Ad-Blue applications [53, 54]. One of the reasons behind this is mainly due to the complex composition of the fuel and large number of possible contaminants that it might have. Ad-Blue has more predetermined composition and any differences are easier to detect and interpret than in fuels case using ultrasonic technology. Regarding the oil, level sensors are already in place and it would be possible to adapt it for reading oil properties as well.

Thermal detection system

By detecting fuel's kinematic viscosity and temperature, the sensor using this technology is able to differentiate diesel from kerosene and also to find different biofuel concentrations. [55]

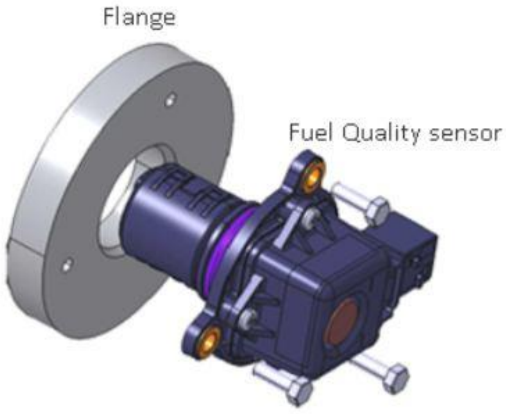


Figure 21**.** Fuel quality sensor with thermal detection system. [55]

2.3.4 Conclusions for on-board technologies

It can be concluded that some of the technologies are very simple, and using a simple reading, like dielectric constant or viscosity. Information on automotive fluid properties in combination with temperature and a decoding algorithm can be found. However by having only two readable parameters, not all of them are able to offer enough details on fluid properties. Lack of good accuracy and repeatability for their readings is another drawback.

More complex technologies like the tuning fork technology or the NIR spectroscopy are able to detect more fluid parameters, and the final algorithms are able to ensure good accuracy and repeatability of measurements. Most of the simpler technologies can be considered in some way to be contained in these two technologies from the working principle point of view or acquired parameters (e.g. interdigitated capacitive sensing and thermal detection are included in tuning fork, while UV-VIS and ultrasonic are "included" in NIR).

Considering the total number of measured parameters, the NIR spectroscopy is the technology that is able to read more fuel parameters than the tuning fork technology. Yet, there are NIR sensors on the market that are not able to read fuel viscosity for example, one characteristic that the tuning fork is measuring. Also, being still under development, there might be that other parameters are not in the required range with the required accuracy. (e.g. sulphur content).

The interest of the current study is to measure as many parameters as possible and to compare these readings to sensor's specifications. One of the sensors that will be used according to planned tests, equipped with NIR technology, is able to measure four of these parameters plus three more: heating value, gasoline and toluene content. Basically, infrared spectrometers are measuring the fuel optical absorption using the NIR spectral range, for different wavelengths. Based on these readings of the raw ingredients composition and on the correlation with known results from lab tests (wet chemistry), results are offered throughout a specific user friendly communication interface. Sulphur content is still under development but needs to be tested for range and accuracy. When talking about tuning fork sensors, all of these sensors are able to measure four properties as well: viscosity, density, dielectric constant and temperature. Using a decoding algorithm as well and with the help of dielectric constant and density/viscosity changes it is able to predict different type of fuels (e.g. kerosene, diesel, jet A, etc.) and FAME concentrations (e.g. B10, B30, etc.).

Also, both Tuning fork and NIR have at least one or two existing and testable sensor prototypes on the market.

These are the reasons why these two technologies are chosen for test in the current study.

2.4 Development of tuning fork and NIR fuel quality sensors

2.4.1 Tuning fork sensors

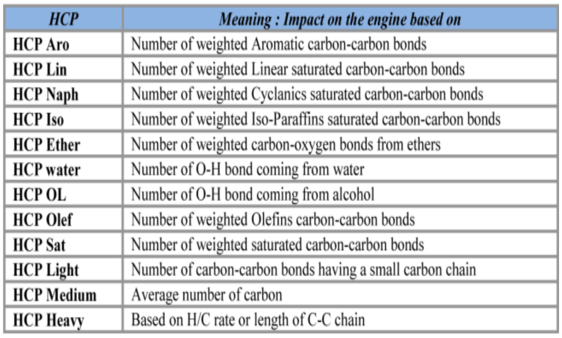
The use of tuning fork sensors goes back to the beginning of the 1980 as mentioned in Kanazawa et al. [56] 1986 study. In their paper they claim that there has been at least three previous studies in which quartz resonator based sensors were used to detect different properties of liquids. Some of them agree on the ability to detect changes in fluid's density, surface absorption or bulk conductivity. Others referred to mass sensitivity. The general idea is nonetheless that quartz crystal based sensor is able to detect changes in resonance frequency when placed in liquids. Kanazawa et al. [56] developed a “simple shear wave model” which proved the dependence of oscillation frequency of the quartz crystal with the liquids changes in density and viscosity [57]. In 1999, Matsiev used a flexural mechanical resonator to test 96 fluid samples. His approach was a model applied to flexural resonator impedance in liquid, which gave a good reading of density, viscosity, dielectric constant and conductivity for the tested liquids [57]. One year later, in 2000, in a new study by Matsiev he states that “practical measurements with flexural resonators are relatively convenient and simple”. He offers in this new study instructions on how to calibrate a tuning fork sensor and considers them to be attractive measurement tools at a reasonable price for almost any type of liquid, even for polymer solutions [58]. It is in 2002 that Matsiev published his patent for a tuning fork based sensor [36]. In the same year, Su et al. [59] used the quartz tuning fork in a study about biosensor applications. For this purpose they coated the fork with specific biomolecules and tried two different types of excitation: mechanical (tuning fork is placed at the end of a piezoelectric plate) and self-excitated (using a tuned circuit). Their conclusion was that the self-excited sensor is much better as the mechanical excitation has a major drawback when it comes to sensitivity due to the mechanical Q-factor (calculated from the resonant frequency and the full width of the resonant frequency at half maximum). Also the solution seems to be much more interesting when miniaturized fork manufacturing techniques are being put in place. However, they also state that temperature and humidity might influence the sensor's operation and needs to be furthermore investigated [59]. Zhang et al. [60] in 2002 also used the same type of sensor for measuring fluid density. The sensor was placed at the end of a lead zirconate titanate (Pb[Zr(x)Ti(1-x)]O3 [61]) (PZT) plate. The PZT plate was used as an actuator for piezoelectric excitation. They used 5 different types of liquids (e.g. acetone, benzene, toluene, etc.) and their conclusions were that results had a maximum standard error of ±8%, with dependency on the Q-factor again. Yet, the low cost of the sensor makes it a good solution for cheap density readings. In 2003, Jakoby et al.[62] performed a study on oil quality using a tuning fork sensor. The sensor measured oil viscosity, temperature and permittivity, and using these analysis characterized oil properties. The oil for analysis was taken at regular intervals from a regular passenger car. Results were compared to laboratory results. One of the conclusions reflected the fact that that contaminants for example will increase oil viscosity. Regarding the readings, their conclusion was that the micro-acoustic sensor was able to give same readings as the laboratory measurements [62]. Zhang et al.[63] in 2003 performed a new test using a crystal tuning fork sensor for bio- or liquid detection, at a certain frequency of 32,768 Hz. They proved in their study that this type of new sensor has comparable results to the quartz crystal microbalance, these results being related to high sensitivity and good stability. Regarding oil viscosity a new study is performed in 2005 by Agoston et al.[64]. Their starting point was that oil's viscosity can be measured by a micro-acoustic sensor. As a first conclusion, the paper states that changes in viscosity produced by oil additives cannot be measured. Secondly, regarding oil aging, the study concluded that the viscosity is increased in oxidized oil, and thus the sensor was able to detect this change. Final conclusion was that the sensor is able to measure oil oxidation due to thermal stress. In 2005 Matsiev et al.[65] uses a quartz tuning fork mounted at one end of a printed circuit board (PCB). This configuration was chosen as it was considered to offer better temperature stability. Using oil as test fluid, five different samples and a specific test procedure, they recorded density and viscosity values for 10 consecutive times. Their conclusion was that the sensor had a repeatability of readings better than the normal analytical methods are offering (approximately 1% lower repeatability error for analytical methods). In 2009 Milpied et al.[39], were the first ones to propose tests using a miniaturized tuning fork flexural resonator, performed with more than one type of fluid. Each type of liquid was also tested by having different types of contaminants or concentrations, most common possibilities for each type of fluid (e.g. water/fuel dilution in oil, soot contamination of oil, fuel type and FAME content, urea concentrations). Their conclusion was that the miniaturized sensor is considered to be very versatile, monitoring a large variety of properties for different fluids. It offers at the same time accurate readings in a very quick manner [39]. This sensor type is also used by Scheider [21] in his Master Thesis experiments. His paper concentrated more on testing different types of biodiesels and blends, with different contaminants in different temperature conditions. He concluded that when it comes to fuel types or blends, the sensor was able to detect changes in density, viscosity and dielectric constant, and based on model algorithms, it was able to define these fuels. From the total number of fuel contaminants (water, glycerol, methanol and sulphur), only sulphur (below several thousand ppm) was not detected. Temperature had been also measured because of its influence on readings, with the biggest impact on the dielectric constant. Comparable in a way with Agoston et al.[64] study, Scheider also states that the aged fuel will have an increased viscosity. Although biodiesel is recognized as being more prone to fuel aging, the normal aged diesel fuel had a larger increase in viscosity. The cause could not have been explained. His final conclusion was that the sensor he used, although unable to detect sulphur, had accurate readings for all the other parameters being a promising on-line sensor to be used for fuel quality sensing [21]. Also in 2011, Waszczuk et al.[66] performed a test using a quartz tuning fork as a sensor device for testing up to 14 different liquids (e.g. acetone, ethanol, toluene, 1-butanol, etc.). Their conclusion was that with the help of resonance frequency and of the equivalent electrical resistance, viscosity and density could be determined. They cannot be measured independently yet. Authors concluded that within an appropriate model, the measurement accuracy is better than 3,5% error. Latest study involving tuning fork sensors was done by Kadu et al.[67]. They used their sensor in a test where they wanted to see if emplacement position for an in-line urea pipe has an influence on readings. Their conclusion was that for in-line positioning, when it comes to urea readings, the horizontal installation of the sensor is offering more consistent results [67].

2.4.2 NIR sensors

As already mentioned, near infrared (NIR) is a well known in-line technology and NIR sensors are used in a wide area of field and industries since 1980s. NIR sensors are used for example in: medical diagnostics [68, 69], food industry [70, 71], food chemistry [72], biotechnology [73], agriculture [74], aeronautical and other industries [75, 76, 77]. Investigations involving miniaturized NIR sensor for automotive industry are not completed. Individual studies performed by developing companies or announcements of launching such types of sensor can be found, but not that many of published studies include concrete results. It was in 2007, that Lunati et al.[43] proposed the first study involving a miniaturized sensor that might be used in-line with a fuel system on a vehicle. The technology was firstly named HydroCarbon Profiler (HCP) and it was including the NIR based sensor as hardware and a software module (called the HCP approach) that was using a complex mathematic algorithm to decode sensor’s readings and transformed them into usable data. Five different types of gasoline fuels on two vehicle types were used for analysis. In spite of the fact that the study cannot fully confirm the correlations between fuel properties or composition and pollutant emissions or fuel consumption, it showed that emissions and fuel consumption can be normalized using HCP technique. They had been also aware that future development of this technology is going to be challenging both technically and economically [43]. One year later, Lunati et al.[44] came again with a new study, using the same HydroCarbon Profiling approach and a NIR sensor to measure water, alcohol and ethers content in biofuels used within a Flexfuel engine. They were able to confirm that the combination between hardware (NIR sensor) and software (HCP) was able to monitor water, ethanol and ether content in the fuel. The HCP took into account the high level of oxygenates of biofuels and their O-H or C-O bond origins. This way, it can separate the water reading from ethanol for example. All the readings, according to the study are done in less than 1 second, and considering that the sensor is also using a CAN BUS communication, connection with vehicle's ECU is simple. Thus, real time adjustment for engine optimal operation is possible for different types of fuels [44]. After 3 years, a new team lead by the same Dr. Alain Lunati (Lunati et al.[41]) performed a new study in which mixtures of Methanol and Ethanol in gasoline fuels were determined using a new miniaturized NIR Flex-fuel sensor. This study was caused by the increased use of Methanol-gasoline mixtures that were used on the world-wide market, especially in China. The method was similar: the combination of hardware (NIR sensor) and software (HCP method) which demonstrated the ability to detect ethanol and binary or ternary methanol mixtures with high accuracy. The fuels used in their study were also analyzed with FT-NIR spectrometer showing that the Standard deviation Error of Prediction (SEP) was rather similar for both techniques. Their results might get even better as they state that future work is to be done in the field of enlarging the MTBE/ETBE (Methyl tertio-butyl ethers / Ethyl tertio-butyl ethers) products database [41]. In 2012, Lunati et al.[45] used his continuously developing sensor for optimizing a diesel engine by detecting and measuring diesel fuel properties. One of the first conclusions was to classify diesel fuel types, which were detected by the sensor, function of their emissions results. Biodiesel and different blends were also detected and its impact on engine operation was "clearly identified" [45]. A coherence between fuel properties and impact on emissions is still being studied on a hydraulic bench. Final conclusion was that reading from a NIR sensor might be able to provide useful information to the ECU in order to adapt engine operation according to fuel properties [45].

In all of Lunati et al.[41, 43, 44, 45] studies, indifferent of fuel type, they claimed that their NIR sensor was able to measure more properties than the tuning fork one. For example, NIR sensor is able to detect: Motor Octane Number (MON), Research Octane Number (RON), Road Octane number (PON=(MON+RON)/2), cetane number (CN), percentage of ethanol, methanol or FAME, viscosity, density, water content, aromatic content and fuel type. This number of parameters is so large due to HCP model which is able to detect and separate different components, and then using a deciphering algorithm and a comparable fuel database, to offer values for these parameters (see Table 3).

Table 3. Meaning of HCP detection method [45]



HCP	*Meaning : Impact on the engine based on*
HCP Aro	Number of weighted Aromatic carbon-carbon bonds
HCP Lin	Number of weighted Linear saturated carbon-carbon bonds
HCP Naph	Number of weighted Cyclanics saturated carbon-carbon bonds
HCP Iso	Number of weighted Iso-Paraffins saturated carbon-carbon bonds
HCP Ether	Number of weighted carbon-oxygen bonds from ethers
HCP water	Number of O-H bond coming from water
HCP OL	Number of O-H bond coming from alcohol
HCP Olef	Number of weighted Olefins carbon-carbon bonds
HCP Sat	Number of weighted saturated carbon-carbon bonds
HCP Light	Number of carbon-carbon bonds having a small carbon chain
HCP Medium	Average number of carbon
HCP Heavy	Based on H/C rate or length of C-C chain

2.4.3 Conclusions for on-board fuel quality sensors

Both types of sensors seem to offer good capabilities of fuel type and quality detection. Although it is not excelling in total number of readings, the tuning fork sensor seems to be more robust and to offer repeatable and more accurate readings, no matter what type of liquid. Either for oil or for fuel, the tuning fork is able to read density, viscosity, dielectric constant and temperature. All of these are done in a reasonable quick time in the order of *milliseconds*. Its intrusion into the fuel line was not proven to have a great influence on readings, unless deposits are formed on the fork. The NIR sensor is attractive as it is not intrusive although it is placed in-line. Yet, reading times are still slower than the tuning fork one. The NIR sensor used by Lunati et al. [45] in their study for diesel fuel sensing has measurement duration of less than 30s after measurement request. This time is still unconfirmed. This is happening due to a need for a good spectral quality and also due to fluids with high absorbance capability. Its greatest advantage is the total number of parameters it can read (e.g. FAME percentage, ethanol, methanol, gasoline and water content, density, cetane number, total aromatic content and viscosity) or possible to read (e.g. sulphur content, oxidation stability and vegetal oil content). The NIR sensor offers results comparable in accuracy to analytical techniques according to Lunati et al. [41] study.

This leads to a final conclusion that a test of performances with each type of sensor, along with a comparison of performances between the two technologies could be useful and interesting.

3 METHODS

This chapter describes the fuel quality sensors and the equipments needed to build the rig, that was used during experiments. In addition, it provides information regarding the tested fuels and the testing procedure.

3.1 Equipment

In order to perform the fuel quality sensing tests, a rig that could simulate a heavy-duty vehicle (e.g. truck, buss) low-pressure circuit was necessary. The test bench is newly built and part of the components are Scania original parts, while others were bought from a Swedish car parts supplies retail store. Along with the rig and its parts, the fluid quality sensors were used for fuel quality measurements. Their technical specifications, a short description of test procedure and fuel blending process are presented in the following subchapter.

3.1.1 Test rig

A new test rig to check the capability of fuel quality measurement for different types of sensors was built. The rig is going to be used only for this type of experiments, since a large number of different fuels were tested. Using fuels contaminated with sulphur and water concentrations higher than normal or special fuels like ethanol was the reason to build a new test bench.

Because large quantities of different combustibles were used, the first safety measure was to consider placing the rig inside a well-closed box padded on the bottom part with absorbent mats. This way, during fuel changes or in case of accidental spilling, the operator of the rig and the environment was protected. It also complies with Scania safety and work protection regulations. The 25-litre canister, as seen in Figure 22, was also placed in a smaller padded tray. The upper part of the canister had a removed portion of 11cm in diameter. The Ad Blue measurement unit (Figure 26) was inserted in this opening and its main use was to heat the fuel inside the canister. In order to do this, the pipe of the unit was connected to a 25l water pot. Heated water was then recirculated with the help of a electrical water pump (Figure 24). The pot was placed on top of an electrical heater and the water temperature inside the pot was read with the help of a T100 K-type thermo couple. The temperature was only read and not precisely controlled. The electrical heater was turned on and off in order to increase or decrease the temperature. For lowering the temperature, the water line was adapted to be connected to a secondary water source and a bucket with normal cold tap water was used. The 25 l fuel canister had two smaller openings (1 cm diameter each) used for fuel intake and fuel return. The fuel was driven from the canister by the fuel pump (Figure 23) through the rest of the rig, until it returned to the canister. A Scania fuel filter was used in order to take out the possible pulses in the fuel flow, inducted by the fuel pump. Immediately after the fuel pump, a valve that can be closed was placed along with a T-connection and another exterior valve. This external valve was adapted to a 4 bar variable intake air pressure. The valve allowed pressurized air to be inserted in the rig in order to empty it and it was used during fuel changes. This valve was only operated when the valve in front of the fuel pump was closed. It was done in order to protect the fuel pump. On the other side, between the filters and the “pressure control valve” (in the fuel flow direction), the three quality sensors were placed, another T100 thermocouple and a pressure sensor just before the mentioned “valve”. The pressure sensor was used to read the pressure in the system, which was manually controlled by closing of the mechanical “pressure control valve”. Another similar pressure sensor was placed between the fuel pump and the filters to read the pressure after the fuel pump. The fuel flow was unknown. When first valve was closed and a secondary one was opened, the “pressure valve” was redirecting the fuel towards the evacuation pipe. The secondary valve was used to empty the system of the previously recycled fuel and it was fully closed during tests. The fuel quality sensors were placed according to the next scheme: FQS1 – Sensor A, FQS2 – Sensor B and FQS3 – Sensor C. There was a third T100 thermocouple inside the 25 litre canister. The level sensor available as a part of the Ad Blue system was used only to check the fuel level informally. The water pump and the three fuel quality sensors were powered through two different power supplies. Both power supplies are able to provide the necessary 12V for these parts but at different amperage (up to 20A for the water pump, and maximum 2.5A for quality sensors). The fuel pump was operated with a 40V power supply unit and 50A, because more current was needed for high pressure operation. The two pressure sensors and the level sensor were connected to a 10V with 2.5A power supply unit. The three T100 thermocouples were directly connected to the National Instruments acquisition module.

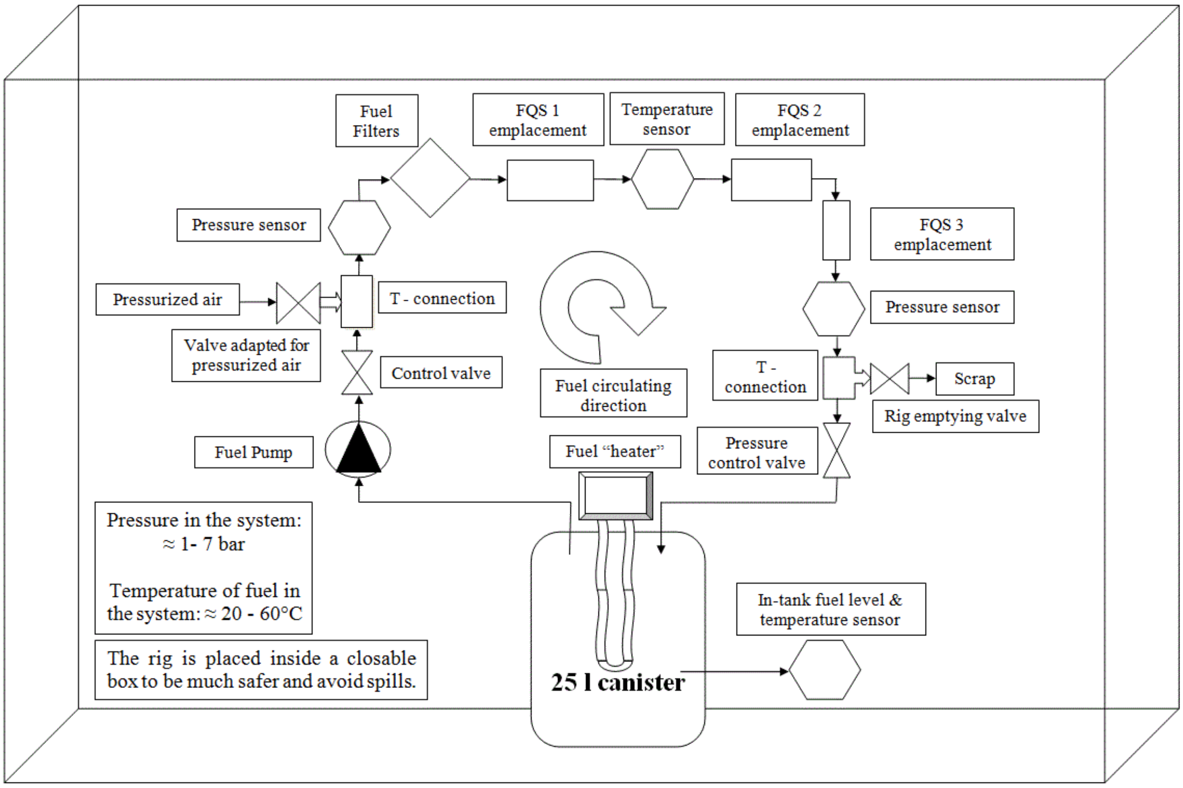


Figure 22. Fuel quality sensor test rig schematics

3.1.2 Sensors

As already mentioned in *Chapter 2*, two technologies were going to be evaluated and compared. For *tuning fork technology*, two different sensors were used. One is a general fluid property sensor (Sensor A), while the other is specific for fuel quality measurement (Sensor B). When considering *near infrared spectroscopy (NIR)*, only one type of sensor (Sensor C) was used for evaluation.

Sensor A

Sensor A is a fluid property sensor. The sensor is able to measure the direct and dynamic relation between different physical properties (e.g. density, viscosity, dielectric constant and fluid temperature) of engine oil, hydraulic and gear oil, transmission and brake fluid, refrigerants, solvents and fuels. This way it can provide information regarding the quality, contamination level and condition of the mentioned fluids. A detailed specifications of the fluid parameters measured and analyzed by this sensor are offered in Table 4.

The measurement intervals along with the accuracy for each property can be seen, as offered by the manufacturer. In Table 5, a summary of other technical specifications can be consulted. The sensor itself can be easily mounted in line or in tank. It is also available for a large range of applications and installations like: flow conduits for different engines types (e.g. heavy-duty engines for vehicles or off-road applications, industrial applications), fluid reservoirs (e.g. refineries or petrol stations), HVAC&R, compressors and turbines. The sensor uses CAN communication. This way, connection with a “Host controller” or vehicle ECU is easy to make. The wetted parts of the sensor are specially treated for corrosion and other contaminants protection, being able to offer long-term stability and reliable readings. Its circuits are protected against Electrostatic Discharges (ESD) and against Electromagnetic (EMC) interferences.

Table 4. Sensor A fuel measured values

Parameter	Symbol	Unit
Viscosity	µ	mPa-s(cP)
Density	ρ	gm/cc
Dielectric Constant	ε	-
Fluid temperature	T	°C

Table 5. Sensor A specifications

Sensor A	
Type	Fluid Property Sensor
Technology	Tuning fork
Mounting position	In-line / In-tank
Communication protocol	CAN
Supply Voltage	12 / 24 V
Supply Current	max. 100 mA
Operating pressure	max. 25 bar
Measured parameters	Density, viscosity, dielectric constant, fluid temperature
Dimensions	M14x1.5, HEX 30, 73.3 (long)

Sensor B

It is the second tuning fork sensor that was used during tests. As Sensor A, Sensor B is also able to measure the direct and dynamic relation between different physical properties (e.g. density, viscosity, dielectric constant and fluid temperature) but this time for different fuels (e.g. diesel and biodiesel, marine heavy diesel, gasoline or kerosene, etc.). The sensor is able to provide information regarding the type of fuel, fuel's quality, contamination level and condition. Regarding the exterior aspect of the sensor it is identical to SENSOR A. The only difference between the two sensors is the ability of the sensor to differentiate and detect different fuel types. Sensor B is also suitable for on and off highway vehicles, fuel tanks, industrial equipment, turbines, compressors or HVAC&R applications. SENSOR B also comes with the possibility of CAN communication. Sensor B has a stainless steel sensor body, and all the wetted parts are also treated against corrosion and other contaminants. It has protected circuits against Electrostatic Discharges (ESD) and against Electromagnetic (EMC) interferences. Other technical specifications can be read in Table 7.

Table 6. Sensor B fuel measured values

Parameter	Symbol	Unit
Viscosity	µ	mPa-s(cP)
Density	ρ	gm/cc
Dielectric Constant	ε	-
Fluid temperature	T	°C
Fuel type	e.g. Gasoline, biodiesel, diesel	

Table 7. Sensor B specifications

Sensor B	
Type	Fuel Monitoring Sensor
Technology	Tuning fork
Mounting position	In-line / In-tank
Communication protocol	CAN
Supply Voltage	12 / 24 V
Supply current	max. 100 mA
Operating pressure	max. 25 bar
Measured parameters	Density, viscosity, dielectric constant, fluid temperature, fuel type
Dimensions	M14x1.5, HEX 30, 73.3 mm (long)

Sensor C – NIR fuel quality sensor

Sensor C is a infrared spectrometer and it is still a prototype, produced accordingly, assembled and tested manually. The sensor is measuring the fuel optical absorption in the near infrared spectral range. Due to its dimensions, *Sensor C* is considered to be a micro-spectrometer that is using a special made integrated voltage controlled tunable interferometer together with a thermopile detector. This is more widely known as Micro-Opto-Electro-Mechanical-System or MOEMS. The sensor is able to read the following fuel parameters: density, cetane number, lower heating value, bio content percentage, aromatic content, diesel, toluene and gasoline content (see also Table 8 for more data). For more technical specifications, please refer to Table 9.

Table 8. Sensor C - fuel measured values

Parameter	Symbol	Unit
Cetane	-	-
Density	ρ	kg/m3
Lower heating value	LHV	MJ/kg
Bio Content	B**	%
Aromatics content	-	%
Diesel content	-	%
Toluene content	-	%
Gasoline content	-	%

Table 9. Sensor C - specifications

Sensor C	
Type	Fuel Quality Sensor
Technology	Near Infrared (NIR) spectroscopy
Mounting position	In-line
Supply Voltage	12 V
Supply current	max. 200 mA
Operating pressure	max. 10 bar
Measured parameters	Density, Cetane number, Lower Heating Value, Bio content, Aromatics, diesel, toluene and gasoline content
Dimensions	126 x 99.8 x 103.3 mm

3.1.3 Rig components

Fuel pump

The electric fuel pump used for fuel recirculation in the rig is a “Type 044” pump, as seen in Figure 23.

Figure 23. Type 044 electrically driven fuel pump

Its specifications are presented in Table 10. It is not a Scania standard fuel pump, being bought in a Swedish car parts supplies retail store. The pump is an enhanced version of a normal Type 044 pump as it is able to provide up to 8 bar. A standard 044-type pump ensures in general a fuel pressure of maximum 5 bar. The pump can be fitted outside the tank and can run on different types of fuels.

Table 10. Type 044 electrically driven fuel pump specifications

Fuel pump: type 044 (ON/OFF; no flow control)	
Maximum pressure	8 bar
Fuel in connection	M18 x 1,5
Fuel out connection	M12 x 1,5
Power supply	12 V
Electrical connections	positive M6 / negative M5
Fuel flow	270 l/h at 3 bar
	200 l/h at 5 bar

Water pump

The water pump used in the rig has the role of recirculating heated water through the spiral pipe of Scania’s Ad-Blue system. This pump is also bought from a Swedish car parts supplies retail store. The part is able to function either with salted water or with tap water.

Figure 24. Electrically driven water fuel pump

It is a on/off electrical pump and the flow can be controlled by increasing/decreasing the voltage. During the current tests the water flow was kept constant. More technical details are specified in the next table.

Table 11. Electrically driven water fuel pump specifications

Electric water pump (model 25-9747) (ON/OFF)	
Power supply	12 V
Water flow	approx. 28 l/min
Propeller	rubber
Hose connection	G 3/8" threaded pipe
Pressure	1 bar
Dimensions	152x95x82

Fuel filter

The fuel filter was used to take out the possible fuel flow pulsations coming from the fuel pump. Only the casing was used, while the actual filters being removed. The Venturi mechanism (seen in Figure 25 on the same side as the red plug, but much closer to the bottom of the filter; dark grey coloured), used to suck up separated water from the pre-filter back to the fuel tank was also removed.

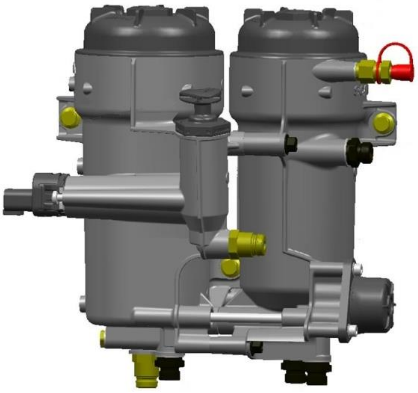


Figure 25. SCANIA fuel filter for LPFC

The removal of the filters and the Venturi system was done to eliminate the influence of contaminated fuels on later tests. Only the left side of the filter casing (the pre-filter) was utilized, to reduce the amount of fuel used to “wash” the system before each test. The pre-filter has a volume capacity of approximately 1,5 litre (no filter) and the maximum flow can be up to 200 l/h (with filter). The 300W fuel heater, normally used on vehicles to heat the fuel and to prevent the diesel fuel from being clogged with wax during cold weather, was not used during the experiments.

Ad-Blue system

The Scania Ad Blue system was used mainly to heat the fuel inside the 25l canister. Being used in the Ad Blue tank with the same purpose by recirculating cooling agent from the engine, it was a safe mode to raise the temperature of the tested fuels up to 50°C (for more volatile fuel blends) or 60°C (for diesel blends). The system itself can be seen in the next figure.

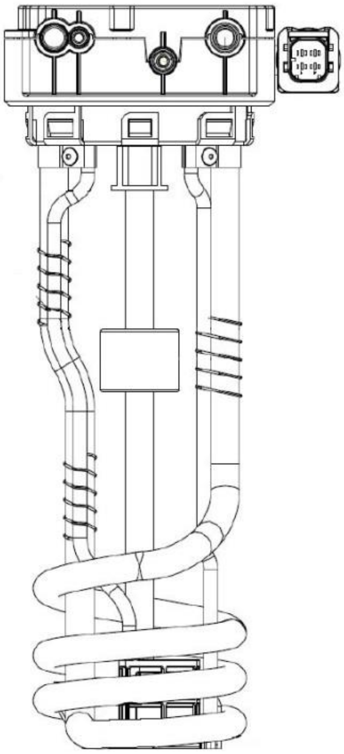


Figure 26. SCANIA Ad Blue system with level, temperature indicator and the spiral piping used for recirculation of heated/cooled water [78]

The Ad Blue assembly has a length of approximately 540 mm (distance from the lowest point of the pick-up unit to the bottom surface of the support plate) and its heating tube has a total length of approximately 2820 mm and a outer diameter of 12,7mm. The tubing is made of stainless steel with equal or better thermal heat transfer coefficient then stainless steel 316 [78]. Maximum flow of water through the system is 12 l/min.

Pressure transducers

The two pressure transducers used to measure the fuel pressure in the rig are Scania original parts. Their input pressure range is 0 to 10 bars and the operating supply voltage is 5V with an excitation current of maximum 10 mA. Communication with the sensor is done through a 4-pole Deutsch connector.

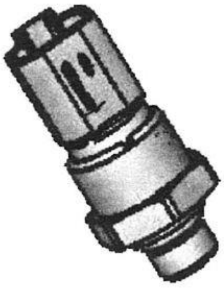


Figure 27. Scania 10 bar pressure transducer

3.2 Tested fuels

The successful fuel quality detection analysis should cover as broad variety of fuels as possible. Thus different types of fuels were chosen to test. All the diesel fuels or diesel blends were obtained from Scania test laboratories. The ED95 blend was also provided by Scania test laboratories. The class 1 fuels (e.g. toluene, iso-octane, n-heptane) were acquired from KTH and the gasoline was taken from a public Statoil petrol station. All the fuels obtained from Scania are provided by a Swedish oil company called Preem. ED95 is supplied by Sekab and the kerosene from Starta AB.

Table 12. Test type and fuel types used for fluid quality sensing

Test type	Fuel type
B0 + FAME tests (density, pressure, temperature, blends)	B100
	B75
	B50
	B25
	B14
	B7
	B0
Aromatics test (toluene)	T5
	T10
	T15
Dielectric constant tests (ethanol)	ED95
	ED75
	ED50
	ED25
Water contamination tests	B0 with 200 ppm water
	B0 with 1000 ppm water
	B0 with 10000 ppm water
Sulphur contamination tests	B0 with 2000 ppm sulphur
	B0 with 1000 ppm sulphur
	B0 with 500 ppm sulphur
Special Fuels (viscosity, cetane number, LHV, density)	Swedish MK1
	Kerosene
	Marine diesel / Heavy diesel
	Gasoline 98
	Iso-octane
	n-heptane

In order to comply with Scania safety regulations and to minimize any possible degradation of stored fuel, a ventilated, dark closet was used to deposit all the fuel. As it can be seen in Table 12, base fuel types were used along with different types of blends. Fuels were divided by types of tests, which are more detailed in the next subchapter.

3.3 Software

Three different acquisition software were used for recording signals. Each of the sensor came with their specific software, while for the pressure and temperature, LabView was used.

LabView interface for pressure and temperature indication

LabView was used to create a new interface where pressure and temperature could be observed and kept under control (see Figure 28). The upper left corner has three "thermometers" which are displaying the temperature measured by thermocouples in three different places: the canister, fuel line and the heated water pot (from left to right). The bottom left corner is showing the data received from the two pressure sensors: after the fuel pump and before the "pressure control valve". Bottom right corner offers an image of the fuel level inside the canister, while on the upper right corner the two buttons used for recording: red is "Start recording" and grey is "STOP" and used for interrupting communication with the sensors.

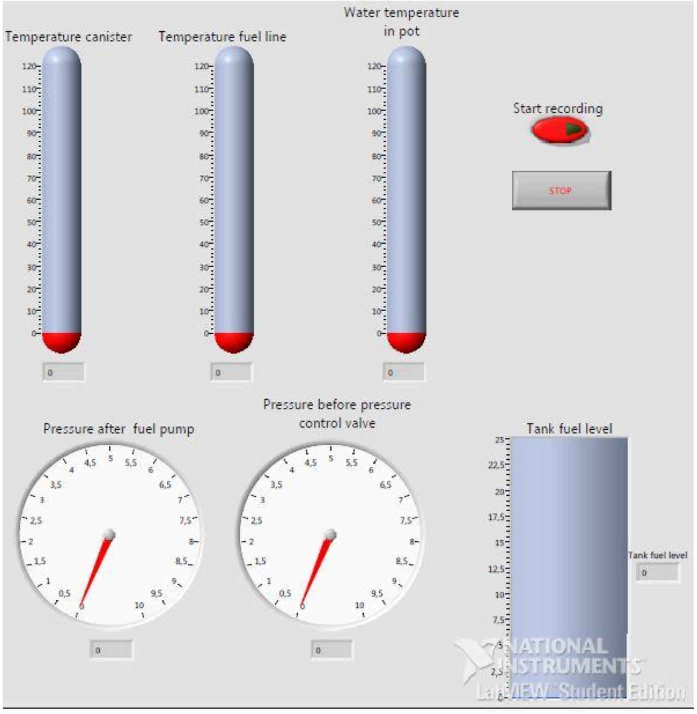


Figure 28. LabView interface window

3.4 Test procedure

3.4.1 Test conditions and measurements

The test for evaluating the fuel quality sensor was divided into different types of tests, each one with specific conditions of pressure and temperature, so that the recordings can show quantitative results for each type of sensor that can be compared with original specifications. *First type of test* was used to verify the ability of each sensor to measure the density for different biodiesel blends. The capability of all three sensors to recognize these blends is also of interest. One can compare then viscosity and dielectric constant with the known values for tuning fork sensors or LHV, viscosity, cetane number and aromatics for the NIR sensor.

According to the general e*quation of thermal expansion for liquids* (see Equation 8), the volume of a liquid changes with changing temperature.

$$\delta V = \beta * V_0 * \delta T \quad [8]$$

where δV is the change in volume, β is the volumetric temperature expansion coefficient for specific liquid, V_0 is the initial volume and δT represents the change in temperature. And as volume is a ratio of mass and density (see Equation 9) and mass was constant, density was dependent on these volumetric changes.

$$V = \frac{m}{\rho} \quad [9]$$

Due to this dependence, the test procedure presented in Table 13 was used during the *first type* of test. Equation 8 was also applied to calculate density's standard value which is used as a comparison with the sensor's density readings.

Table 13. Used procedure for test 1

Test type	Fuel type	Test condition													
B0 + FAME tests (density, pressure, temperature, blends)	B100	7 bar	5 bar	3 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	5 bar	3 bar	1 bar
	B75														
	B50														
	B25														
	B14	20°C	20°C	20°C	20°C	30°C	30°C	40°C	40°C	50°C	50°C	60°C	60°C	60°C	60°C
	B7														
	B0														
	MK1														

Before each test a certain amount of fuel blend was taken out and fresh B0 poured in. This was done so that the specific fuel blend mass concentration can be obtained. The exact quantities are presented in the next subchapter. After the B0 test, MK1 (Dieselolja Miljöklass 1 - Diesel environmental class 1) was used for analysis as a part of the last test. This last assessment involved a wider variety of evaluated fuels. The test was performed at this point, so that no contaminants used in future experiments could temper with the sensor readings.

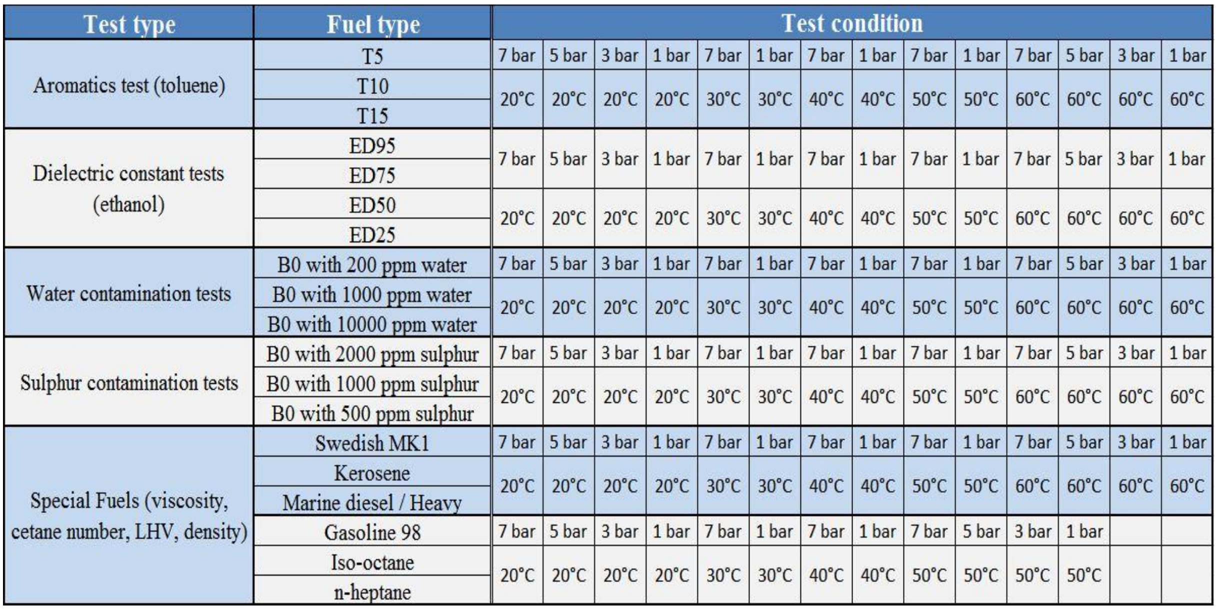
The *first test* started with the use of different blends at 7 bars of pressure and 20°C (first fuel used is B100). This pressure was chosen because it is similar to the average pressure in the low pressure circuit of a standard Scania truck. The average ambient temperature of 20°C was chosen as a starting temperature. In framework of the project we limited us with no lower temperature as it would require a much more complicated rig. The pressure was then decreased gradually with 2 bar until we reach 1 bar. The next measurements were performed every 10°C, while temperature was increasing gradually up to 60°C. Thus the test simulates the real fuel rise in temperature under usage of fuel return. For each temperature point (e.g. 30°C, 40°C, etc.), measurements were taken at 1 and 7 bar. Once it reached 60°C, the temperature was kept constant at this value and four recorded points were made from 7 down to 1 bar for each type of blend. The pressure variance was performed in order to verify if it affects sensor's ability to evaluate fuel properties. For a complete test matrix, consult Table 13. An average of 10 values wwere recorded for every condition point.

Next test involved the analysis of sensors ability to detect aromatics content changes. For this purpose, toluene was mixed in three different mass percentages with B100: 5, 10 and 15%. All three blends were tested at different temperatures and pressures according to Table 14. Before the test, the rig was completely emptied and two cycles of full wash with B100 was performed.

Although none of the tested sensors are built to detect ethanol, *third test* dealt with the sensors capability to detect ethanol blends in different mass percentages with B0 fuel. Four different blends were tested: ED95, ED75, ED50 and ED25. The experiments started with known properties fuel (ED95) which was diluted with B0 to obtain lower ethanol concentrated blends. Before the test, the rig was “washed” once with B0 and once with ED95.

Fourth test involved the use of water as a contaminant to check sensors capability of detecting it. Normal B0 diesel fuel was used and with the help of a pipette, three different levels of water were poured in the fuel: 200 ppm, 1000 ppm and 10000 ppm. The test conditions were similar to the ones of the second test as it can be seen in Table 14.

Table 14. Test conditions for 5 different test



Test type	Fuel type	Test condition													
Aromatics test (toluene)	T5	7 bar	5 bar	3 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	5 bar	3 bar	1 bar
	T10	20°C	20°C	20°C	20°C	30°C	30°C	40°C	40°C	50°C	50°C	60°C	60°C	60°C	60°C
	T15														
Dielectric constant tests (ethanol)	ED95	7 bar	5 bar	3 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	5 bar	3 bar	1 bar
	ED75														
	ED50	20°C	20°C	20°C	20°C	30°C	30°C	40°C	40°C	50°C	50°C	60°C	60°C	60°C	60°C
	ED25														
Water contamination tests	B0 with 200 ppm water	7 bar	5 bar	3 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	5 bar	3 bar	1 bar
	B0 with 1000 ppm water	20°C	20°C	20°C	20°C	30°C	30°C	40°C	40°C	50°C	50°C	60°C	60°C	60°C	60°C
	B0 with 10000 ppm water														
Sulphur contamination tests	B0 with 2000 ppm sulphur	7 bar	5 bar	3 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	5 bar	3 bar	1 bar
	B0 with 1000 ppm sulphur	20°C	20°C	20°C	20°C	30°C	30°C	40°C	40°C	50°C	50°C	60°C	60°C	60°C	60°C
	B0 with 500 ppm sulphur														
Special Fuels (viscosity, cetane number, LHV, density)	Swedish MK1	7 bar	5 bar	3 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	5 bar	3 bar	1 bar
	Kerosene	20°C	20°C	20°C	20°C	30°C	30°C	40°C	40°C	50°C	50°C	60°C	60°C	60°C	60°C
	Marine diesel / Heavy														
	Gasoline 98	7 bar	5 bar	3 bar	1 bar	7 bar	1 bar	7 bar	1 bar	7 bar	5 bar	3 bar	1 bar		
	Iso-octane	20°C	20°C	20°C	20°C	30°C	30°C	40°C	40°C	50°C	50°C	50°C	50°C		
	n-heptane														

Fifth test was largely similar to the water contamination, with the only differences that sulphur was used as contaminant and the contamination process was reversed. The test started with a high sulphur/high aromatic Scania test diesel fuel, and then normal B0 was used to dilute it to 1000 ppm and 500 ppm. Lower ppm concentrations were not tested as none of the sensors specifications claim to detect something below this concentration yet. For both, water and sulphur contamination test, normal B0 was used to wash the rig twice before and after each test.

The last test was performed with marine heavy diesel, kerosene, gasoline, iso-octane and n-heptane as test fuels. In order to use a larger number of fuels for comparison, results from tests with Swedish MK1and High aromatic content/high sulphur diesel were used. Cetane number, density viscosity, dielectric constant, aromatic content and LHV were compared for these different fuels. Each test was preceded by a thorough wash of the system with the fuel that was to be used on the next recording. For Gasoline 98, n-heptane and iso-octane, the tests were done only at up to 50°C, while for the heavy diesel, up to 60°C. The pressure varied from 7 down to 1 bar in steps of 2 bar.

3.4.2 Fuel blending

Because the volume of fluid varies with its density, and the fluid's density is variable with temperature, the only constant in a volumetric mass density relation is the mass (see Equations 8 and 9). Consequently, the decision of weighing the fuels was taken in order to have a better control on fuel blending process. As an example, for obtaining B50, 10 kg of B0 were mixed with 10 kg of B100. For the weighing procedure, a 0 to 15 kg scale with three digits measuring unit was used along with a 5l graded cup. The empty rig takes in approximately 2.2 kg of fuel.

The tests started, as mentioned in Table 13, with B100 biodiesel fuel. The measured quantity is 10 kg B100. For B75, 3.33 kg of B0 were added and for B50, 6.67 kg of B0. Before the B25 test, 10 kg of B50 were taken out of the rig. The remaining 10kg are comprised of 5kg B100 and 5 kg of B0. This quantity was mixed with another 10 kg of B0, resulting in 20 kg of B25. By keeping another 10 kg of B25 in the rig (2.5kg B100 and 7.5kg B0), and by adding 7.857 kg we obtain 17.857 kg of B14. For the B7 test, 5 kg of B7 Euro VI diesel fuel with known properties was used. Another similar quantity was used to wash the rig before the test. Same washing procedure applied to the normal B0 test. This experiment was followed by the MK1 fuel test, a Swedish diesel with no FAME content and very low sulphur content. As already mentioned, along with some other special fuels, this test was used to evaluate sensor's capability to detect various fuel qualities (viscosity, cetane number, LHV, density). For the toluene test, the mixture was comprised of 9.5 kg of B100 and 0.5 kg of toluene. 5 kg were saved separately while the difference was recirculated to scrap in order to wash the rig. For T10 test, 0.263 kg out of 5 kg of T5 was recirculated to scrap and 0.263 kg of more toluene was added. For T15, the same procedure applies.

Third experimentation used ethanol blends in concentrations of 95, 75, 50 and 25% ethanol content. Starting with 9.5 kg ED95 as a base fuel, to obtain ED75, 1.9 kg of B0 was needed. Once this experiment was over, another 4,275 kg of B0 were added to obtain ED50. The obtained 19 kg ED50 was divided in two and the remaining 9.5 kg was mixed with 2.375 kg of B0 and 11,875 kg of ED25 was obtained.

For the water contamination tests, 10 kg of B0 were contaminated with the help of a 5 ml pipette with 2, 10 and 100 g normal tap water.

In the sulphur experiment, 5 kg of high sulphur content diesel fuel was used. The initial concentration of sulphur was between 1950 and 2050 mg/kg. Next step involved blending 5 kg of low sulphur content B0 which lead to 10 kg of diesel fuel with around 1000 mg/kg sulphur concentration. Afterwards, 5 kg of blend are scrapped and 5 fresh kg of unsulfured B0 was again added to get a mixture with 500 mg/kg sulphur content.

Fuels that did not need blending (e.g. kerosene, Swedish MK1, marine diesel,etc) were used for the other tests.

4. RESULTS AND ANALYSIS

Next section presents the results of the performed experimentation. Data are presented for both technologies (NIR and tuning fork) and all three sensors. All results are discussed and analyzed.

4.1 Results interpretation methodology

It has to be mentioned right from start that all of these measurements offer no results when referring to reproducibility for all sensors and fuel types. Only one type of each sensor was tested and for each fuel, only one measurement was performed.

In the figures presented, meta-graphs are built according to the matrix of experiments that were performed (see Figure 29). When presenting variables that are specific, in every image, for the Sensor A and Sensor B, the subplots contain two bars for every fuel type. For Sensor A it is the blue, left bar and for Sensor B it is the dark red, right bar (see Figure 30). For Sensor C there is only one column (blue) for each type of fuel.

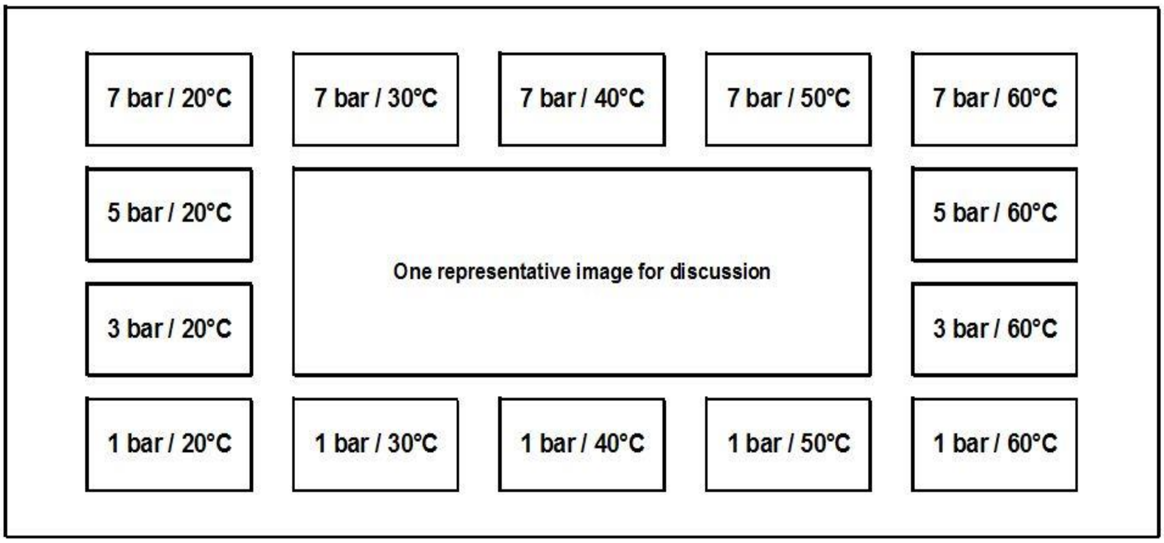


Figure 29. The matrix of recorded points that will be represented and discussed as meta-graphs.

At the top of each bar, which reflects the average value of multiple recorded points (12-18 points for first 2 sensors and 5 for Sensor C), a light green line presents the error of measurement (maximum and minimum measured value) for each sensor and each type of fuel. This interval can be regarded as the standard deviation, and will be referred to from this point forward as the measurements precision (see Figure 30 and Figure 31). The light red line represents the reference interval of the analyzed fuel. Because the fuels analysis data sheets received two months prior to current tests refers to centre of specified tolerance interval, the author believe that measurement true value deviates very little from that reference value. Thus this deviation should be negligible compared to sensor accuracy.

This interval is built starting from the reference value found in the data sheet of each fuel (e.g. the density for B100 fuel is 0.878 at 20°C). For the Scania fuels, the data sheets are laboratory analysis bulletins. From this value, the accuracy of each sensor (stated by the manufacturer) is subtracted for the lower value, respectively added for the higher one (see Figure 30). This will be referred as the manufacturer stated accuracy.

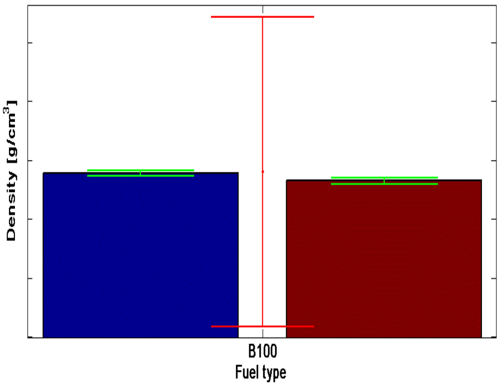


Figure 30. Zoom on B100 measurement and reference intervals (light green line for measurements accuracy and light red line for reference interval) as seen in future plots (Sensor A (blue left bar) and Sensor B (dark red right bar))

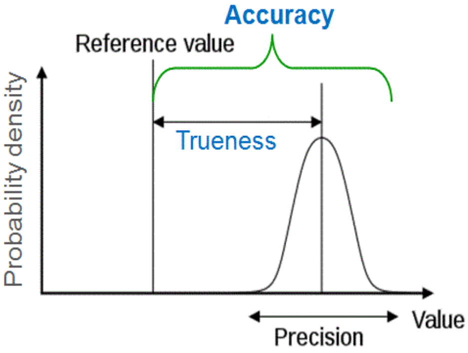


Figure 31. Terminology used to present results

Additionally for each fuel, to some specific temperature dependant parameters (e.g. density, viscosity, etc.) a thermal dependence model is applied for temperatures up to 60°C, starting from the reference value. For each new calculated measure (at different temperatures) reference intervals are also calculated with the same rule as for the 20°C reference value.

The difference between the average measured values and the fuel reference value (calculated or from data sheet), also known as the deviation from true value, is referred to, from this point forward, as the sensor trueness or trueness error (see Figure 31).

The sum of trueness and precision is considered as the measured accuracy and it will be compared with the manufacturer stated accuracy.

4.2 Diesel and Biodiesel blends

Experiments were conducted with different types of diesel and biodiesel blends in order to investigate the ability of the sensors to accurately measure bio content levels or fuel type recognition. A strong interest goes also into their capability to distinguish between different qualities as: dynamic viscosity, density, dielectric constant, lower heating value, aromatics content and cetane number.

Bio content and fuel recognition

Measurements indicate that Sensor C is unable to predict the Bio Content of the fuels it analyses with good precision or accuracy as it can be seen in Figure 33.

The experimental study shows that the sensor is both imprecise and has a high trueness error for 6 out of 7 fuels at 20°C and 1 bar. It is only the biodiesel (B100) that it is precise, within the accuracy stated by the manufacturer. Regrettably, for less than 0,5% it is not “true” to reference value (as it can be seen in Figure 32).

And although the overall precision and measured accuracy is not as specified by the manufacturer, it can be seen that the sensor is able to measure the increasing trend offered by the increased level of FAME in the diesel fuel (B0). One can also notice that on the overall measurements (all temperature and pressure conditions), at this level, for small differences in bio content Sensor C cannot precisely distinguish the blend. For more than minimum 25% FAME content difference, readings from Sensor C can be considered as useful for different applications.

Considering the tuning fork, only Sensor C is able to recognize type of fuels with a certain amount of “confidence index”. The confidence index, as defined by the manufacturer, indicates the distance from the measured fluid properties to the value in the sensor fuel database. In our case, for predominant B0 blends, the sensor recognized the fuel as “Diesel”, while for predominant B100 blends, the fuel was considered to be “Biodiesel”.

B50 is recognized as a diesel blend throughout most of the points. This has no logical support as, it will be seen, the density and viscosity readings showed no pressure influence. Furthermore, the temperature influence should have acted in the opposite way.

In conclusion, Sensor C has a reasonable ability to detect fuel type, as long as the difference in FAME content is larger than 25-30%. Precision and measured accuracy are usually not within the stated accuracy.

When referring to Sensor B, the sensor is able to detect evaluate as diesel fuels, blends from B0 to somewhere between B25 and probably B40. Afterwards, starting with possibly B60 up to B100 all the fuels are recognized as biodiesel. The exact accuracy is hard to be mentioned.

Density

When talking about density readings, first observation is that, as expected, the density is decreasing with temperature and both Sensor A and Sensor B are able to record this fact. The measured values from the sensors show a decreasing density trend with increasing temperature.

For the decreasing density with increasing temperature model, the general *equation of thermal expansion for liquids* ($\delta V = \beta * V_0 * \delta T$) is used. δV is the change in volume, β is the volumetric temperature expansion coefficient for specific liquid, V_0 is the initial volume and δT represents the change in temperature. Both volumes are replaced with the mass over density ratio, where initial and final mass is considered to be the same. The volumetric temperature expansion coefficient for other blend than B0 and B100 are calculated by linear interpolation. Calculations start at 15°C, considered standard condition for reference value.

When comparing the measured densities with the calculated density model it can be observed that there is a slight over-estimation of the model for highly concentrated biofuels (e.g. B50, B75 and B100); this is believed to be due to the fact that the algorithm of calculation used by the author is applicable mainly to diesel fuels with a higher content of hydrocarbons and lower or no content of oxygenates. The overestimation is observable for all sensors by looking at the difference in trend between the 20°C lines (blue) and the 60°C ones (red) (see centre image in Figure 34 and Figure 35). One can observe that with increased concentration of biodiesel in the diesel blend, the error increases (see B50, B75 and B100 in both Figure 34 and Figure 35 at 60°C). It explains why the readings at 20°C and 1 bar (lower left corner in Figure 34) for B100 have a low trueness error, while at 60°C and 1 bar (lower right corner in Figure 34) trueness error increases. For Sensor C the same trend can be observed in Figure 35. It is specified by the manufacturer that Sensor C will not adjust the density readings function of the temperature.

Comparing the two tuning fork sensors it can be noticed that Sensor A is much closer to the reference values than Sensor B (a lower trueness error). It needs to be specified that the B7 fuel used for tests, is not obtained by mixing the existing B14 with B0. It is a Euro VI reference fuel, used by Scania, obtained most probably by mixing B0 directly with B100. These two fuels might have different densities than the ones used in this study and this could explain why the measured density values for B7 and B14 are rather similar.

It is also observable that the density reading is not affected by pressure. The values and the trends are similar for all different pressures for the same temperatures. It is to be said that for Sensor C the readings at 3, 5, 7 bars and 20 °C have a good measured accuracy with no direct influence from the increasing pressure. The 20°C and 1 bar precision error for B25 is considered to be and outlier as there is no logical explanation. The error is not encountered in any other test condition.

A thorough comparison on the accuracy intervals cannot be performed as the tuning fork sensors are having a ±*x* % of the measured value, while the NIR sensor has ±*y* g/cm^{3,} no matter the fuel type. Yet, when comparing values measured by the tested sensors, there is very little difference under standard conditions (1 bar, 20 °C), and both are able to make precise measurements within the mentioned accuracy intervals.

Sensor C is very close in accuracy with the Sensor A and slightly better than Sensor B.

In conclusion, by analyzing the presented figures for measured density, one can draw the conclusion that the sensors have good measured accuracy, within the manufacturers specified working conditions. It also needs to be reminded that the overall decreasing density with increasing temperature model applied by the author to the reference values might be inappropriate for fuels blends with increased bio content. From precision point of view, Sensor A is showing the more precise readings. Sensor C, considering only the 1 bar 20°C condition, has the next best result. Sensor B, while within the specified accuracy, has the highest trueness error of all tested sensors.

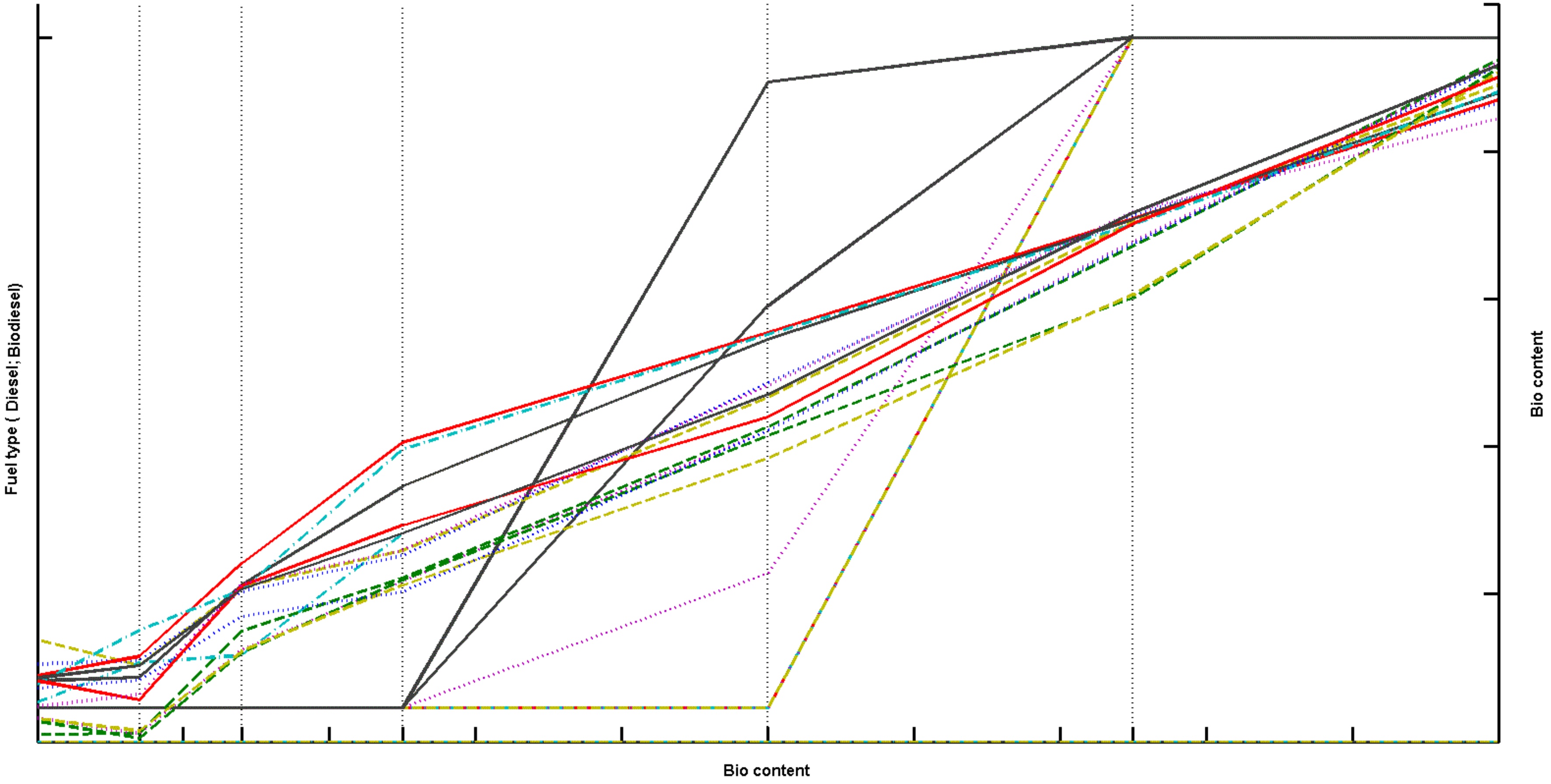


Figure 32. Bio content (right side y-axis)as measured by Sensor C and the “Fuel type” (left y-axis)as measured by Sensor B against the fuel composition (x-axis).

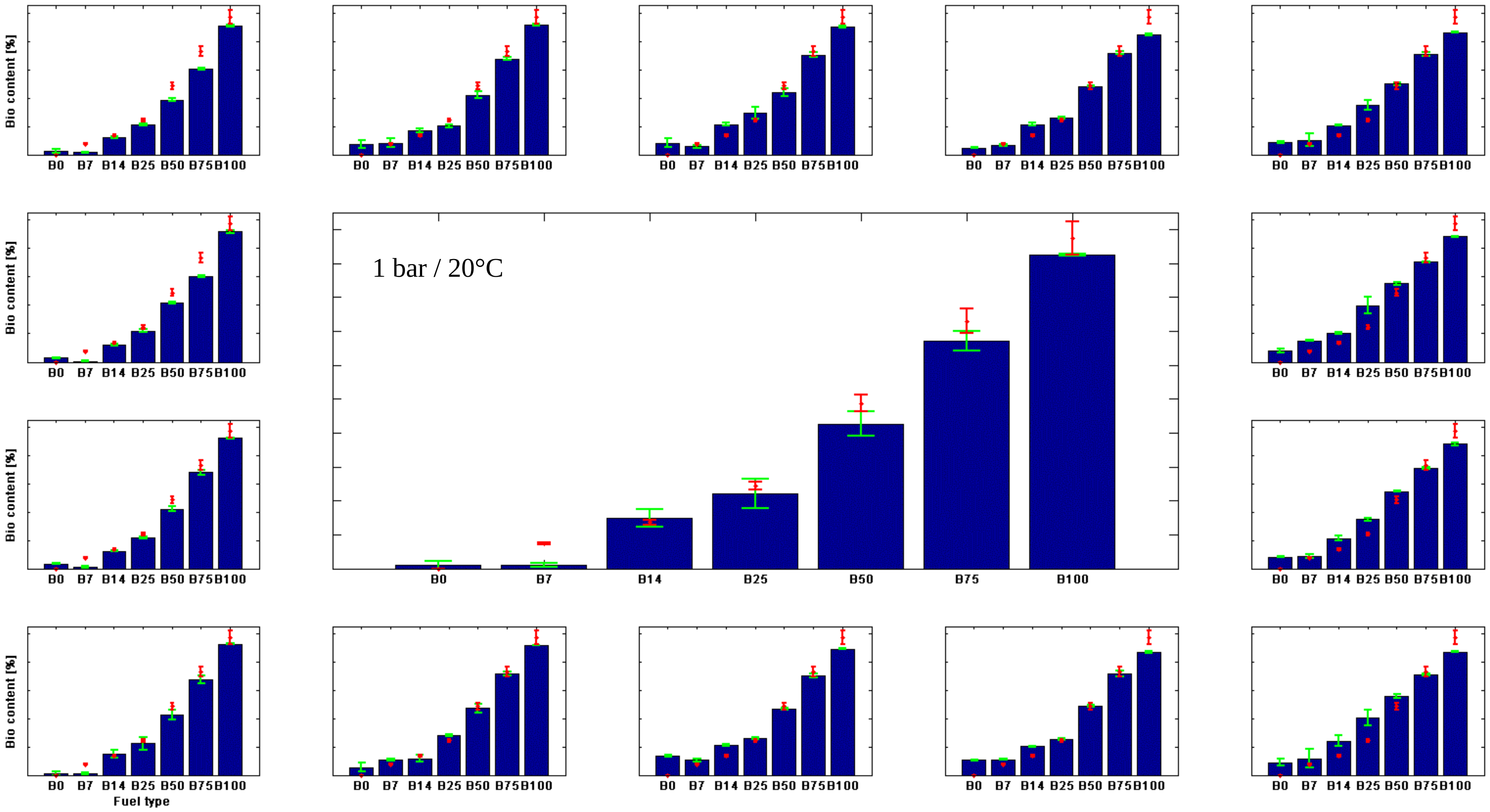


Figure 33. Bio content (y-axis) as measured by Sensor C for different types of fuel blends.

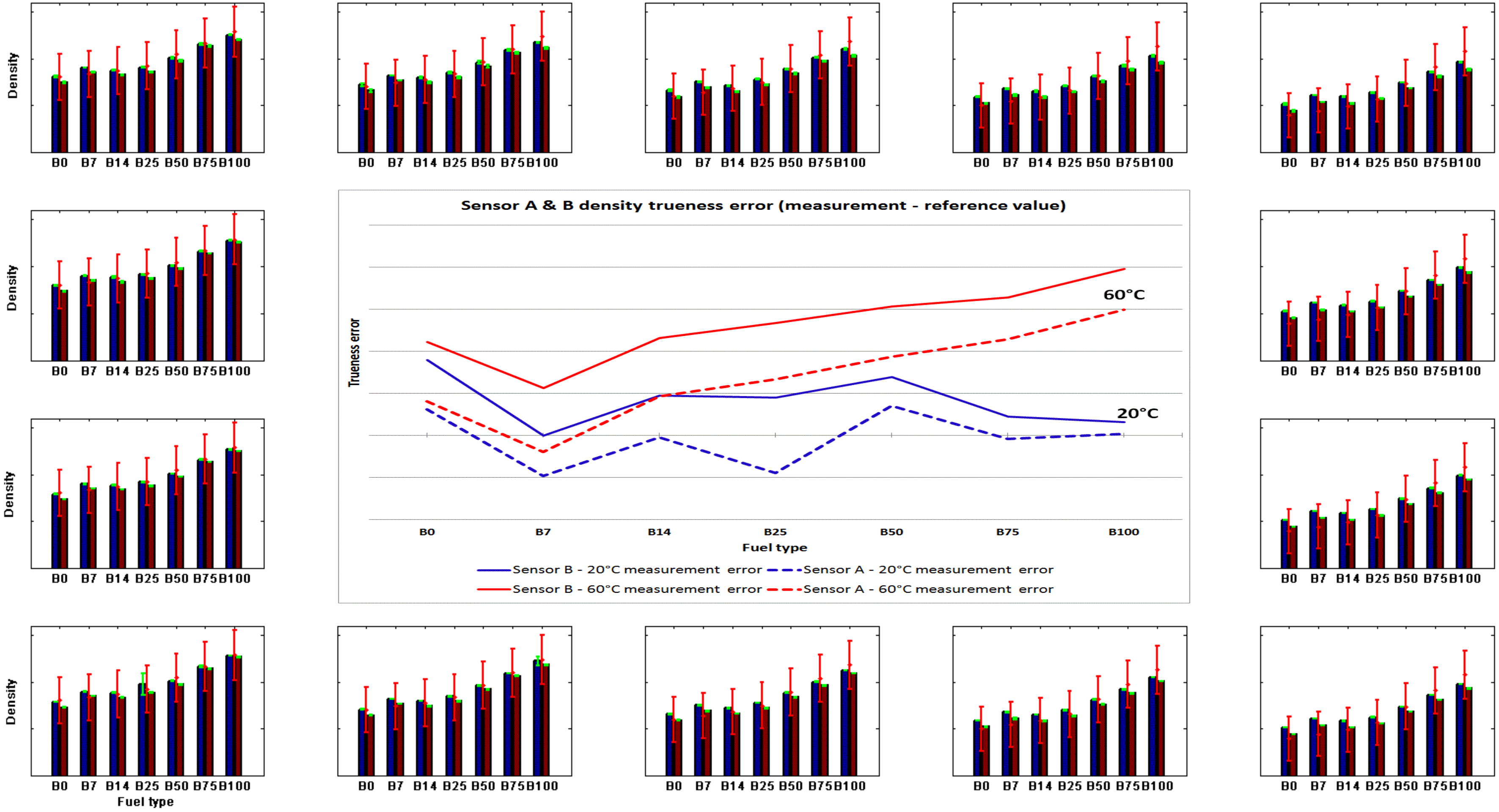


Figure 34. Density measurements for Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of Biodiesel fuel blends (x-axis).

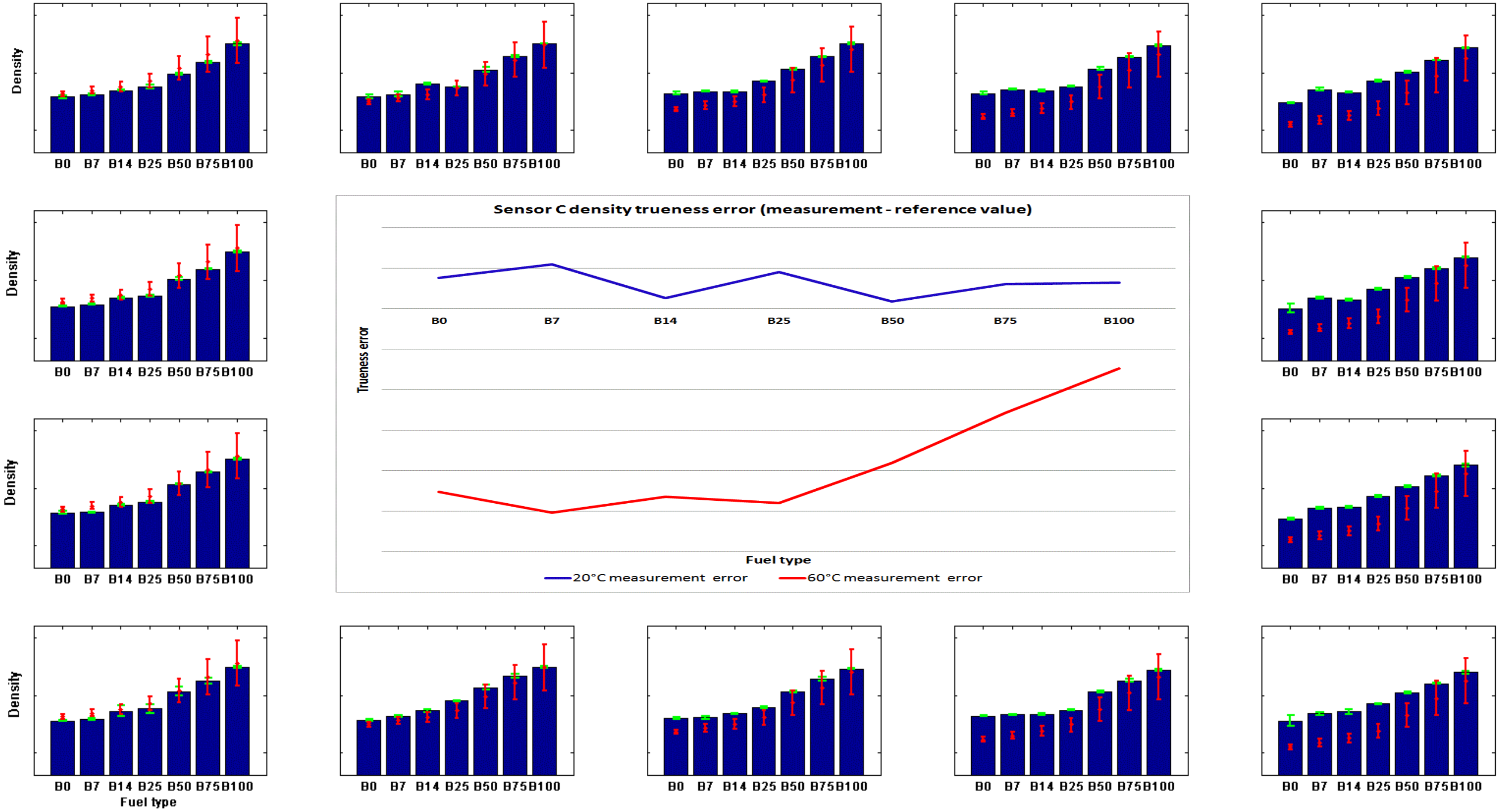


Figure 35. Density measurements for Sensor C for different types of Biodiesel fuel blends (x-axis).

Viscosity

It is to be mentioned that only the two tuning fork sensors are able to measure the viscosity of the analyzed fuels. The standard condition for measuring viscosity reference value is 40°C, and not 20°C. In order to obtain reference viscosity at temperatures other than 40°C, an on-line calculator (for blends) is used [79]. As entry data, values from B0 and B100 fuel data sheets are used. The "model" (according to the center image from Figure 36 is more appropriate for temperatures comprised between 40°C - 60°C than for those in the interval 20°C - 40°C (see comparison in central image of Figure 8 between the orange lines and the red lines (40°C - 60°C) and between the blue and the orange lines (20°C - 40°C)). One can notice that the measurement errors are smaller for 60°C recorded points and closer to 40°C values. Because B7 is a standalone fuel and is obtained by mixing unknown B0 with unknown B100 (unknown fuel parameters to author) the viscosity is very different when compared to the rest of the fuels.

When referring to sensor precision, it can be seen that there is no important difference between diesel or biodiesel blends, with all measurements situated within the accuracy interval stated by the manufacturer. One average value for B25 is very close to its maximum limit, but as already mentioned in the "*Density"* discussion, it is to be considered an outlier as there is no logical explanation for the large precision error. Furthermore, the sensor showed no internal error.

Both sensors are also able to measure the different viscosity values and their increasing trend for all the blends obtained by mixing diesel B0 (low viscosity) with biodiesel B100 (high viscosity).

Comparing the overall measurement of the two sensors, a slight advantage can be seen for Sensor B sensor on the overall measurements, not including the B25 outlier.

From the trueness point of view, both sensors are offering low trueness errors for diesels and biodiesels, without considering the B7 outlier.

When compared to each other, at 40°C, considered the reference condition, no visible advantage or difference is to be observed. When going towards 20°C, Sensor A is more precise, while towards 60°C, the readings are similar again.

As expected, temperature has an influence on viscosity readings and both sensors are able to sense this influence. With higher temperatures, we get lower viscosities. Furthermore, even if for B100 the drop is important, both sensors are offering good precision and accuracy.

From pressure point of view, there is no influence on the readings.

It can be thus concluded that the overall impression is that both sensors offered accurate readings, and the viscosity measured by these sensors can be used for different strategies.

Dielectric constant

Although there are no reference dielectric constant values in any of the tested fuels data sheets, generally known values for B0 and B100 are taken into account [*www.dieselnet.com*]. It can be seen that, no matter the condition (temperature and pressure), there is a constant factor that can be applied to B0 to obtain the B100 reference value (or vice-versa). Thus, linear interpolation was used to calculate the standard dielectric constant values for the remaining blends.

As the dielectric constant is temperature dependent, a model for decreasing dielectric with increasing temperature is needed as well. By evaluating the values for decane and hexadecane from 20°C to 60°C seen in Figure 34 (chapter 2), a small decrease is observed. This is subtracted from the reference values at 20°C to obtain the 60°C reference value for all the fuels.

Later, linear interpolation is used to find values for 30, 40 ,and 50°C.

When it comes to sensor readings, the dielectric constant value is the only parameter that is similar for both sensors (A and B). As already presented, density and viscosity are different in values when comparing the two tuning fork sensors. There is no influence of pressure on the recorded value, however as expected, temperature has an impact on dielectric constant.

The values are showing a decrease in dielectric constant from 20 to 60°C. The precision of the readings is also very good, much less than the sensor accuracy, stated by the manufacturer.

As it can be observed in the central image of Figure 37, both sensors have a lower trueness value with B0 fuels than with B100 (for all temperatures and pressures). Another interesting observation is that B0 trueness at 7 bar has almost the same trace as B100 at 1 bar. At this point, besides the oxygenates content in B100 that might influence the readings, no other logical reason can be offered for this situation.

In conclusion, taking into account that the reference values are generally accepted values, not fuel specified values, no clear decision on sensors ability to read dielectric can be made. Nonetheless, by acknowledging previously measured density and viscosity, and the fact that the dielectric constant ones show comparable values and trends from temperature to temperature, final conclusion might be that the sensor is able to measure dielectric constant correctly.

Aromatics content

Aromatics content is a parameter read only by Sensor C. The reference values for other than B0 and B100 fuels are obtained by linear interpolation between B0 and B100 standard values. No temperature dependence model is applied by the author, as it is not considered physically plausible.

When analyzing measurements, the recorded values are showing a decrease in aromatics when temperature rises from 20 to 60°C at 1 bar. From 1 to 7 bar at 20°C a change can also be seen. One can conclude that the aromatics measured by Sensor C are influenced by temperature in a more important way and by pressure in a smaller one. None of these things are physically plausible.

At 20 °C and 1 bar the readings are also imprecise and untrue when compared with the values given by the fuel data sheet.

In conclusion one can notice that the overall readings are not stable (see central image in Figure 38) and untrustworthy. As a result, the aromatic content measurements are not reliable to be used at this level.

Lower Heating Value (LHV)

Lower Heating Values are read only by Sensor C. As a reference, standard values for B0, B7 and B100 are used. For the other blend rates, linear interpolation between the values of B0 and B100 are adopted. No temperature dependence model is applied to the standard values as it is considered to be unphysical.

LHV recorded values by Sensor C are showing a small decrease from 20 to 60°C. This change is comparable to the sensor accuracy specified by the manufacturer. Considering these values, it cannot be stated that there is an influence of pressure or temperature on the readings. It can be said that the overall accuracy is fluctuating. Sensor C shows a unrealistic value for all B100 measurements, no matter the conditions (pressure or temperature). For B75, 12 out of the 14 recorded values are also unrealistic. B7 and B50 with 3 out of 14, respectively 2 out of 14 unrealistic values are considered outliers. For B100, one possible explanation could be the reference value of B100, very close to the lower limit of Sensor C reading interval.

As heating values for denser fuels are related to its volume, it can be stated that biodiesel with high density will have a lower value for LHV. And the sensor is able to sense this linear decrease in Lower Heating Value as the percentage of oxygenates increases, either on the overall readings (see as an example in Figure 39 the 5bar/20°C point) or even in the trueness of the sensor which decreases with increasing oxygenates (see central image in Figure 39). It also validates the decrease in aromatics content seen in Figure 38.

Considering all these observations it can be concluded that the sensor is capable to measure lower heating values, but only for B0 to somewhere between B25 and B50 diesel-biodiesel blends.

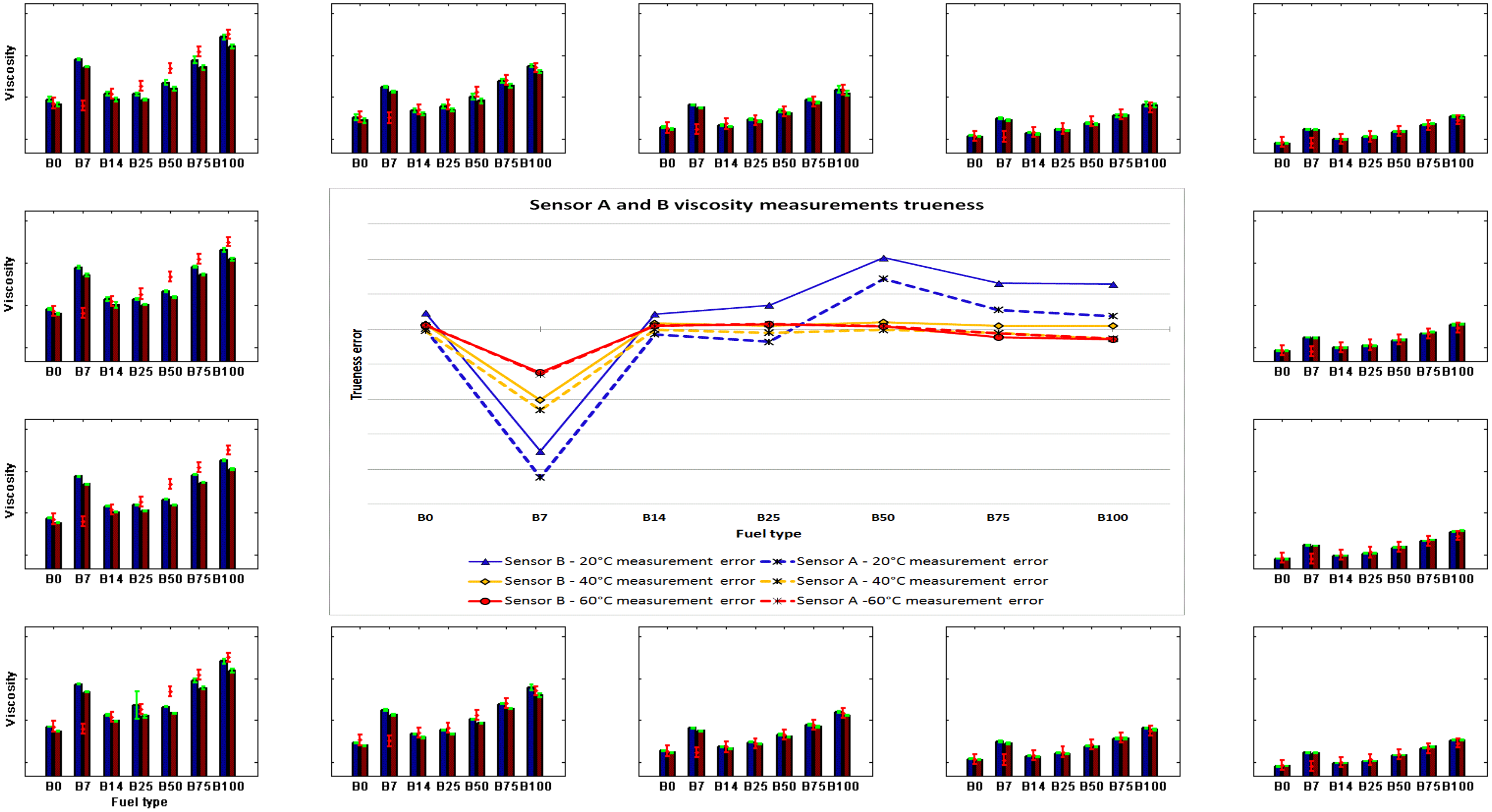


Figure 36. Fuels viscosities as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of Biodiesel fuel blends (x-axis).

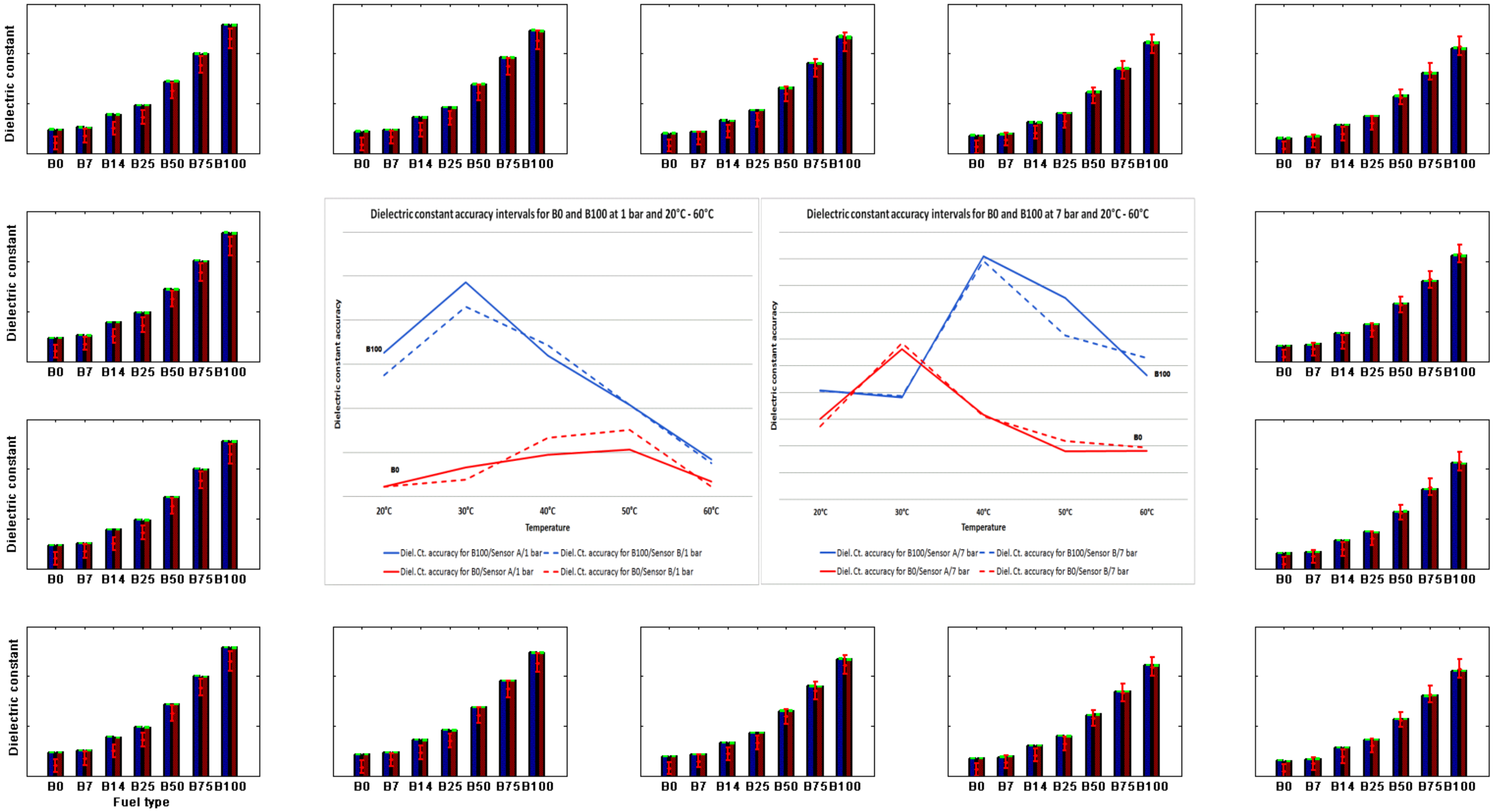


Figure 37. Dielectric constant (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar).

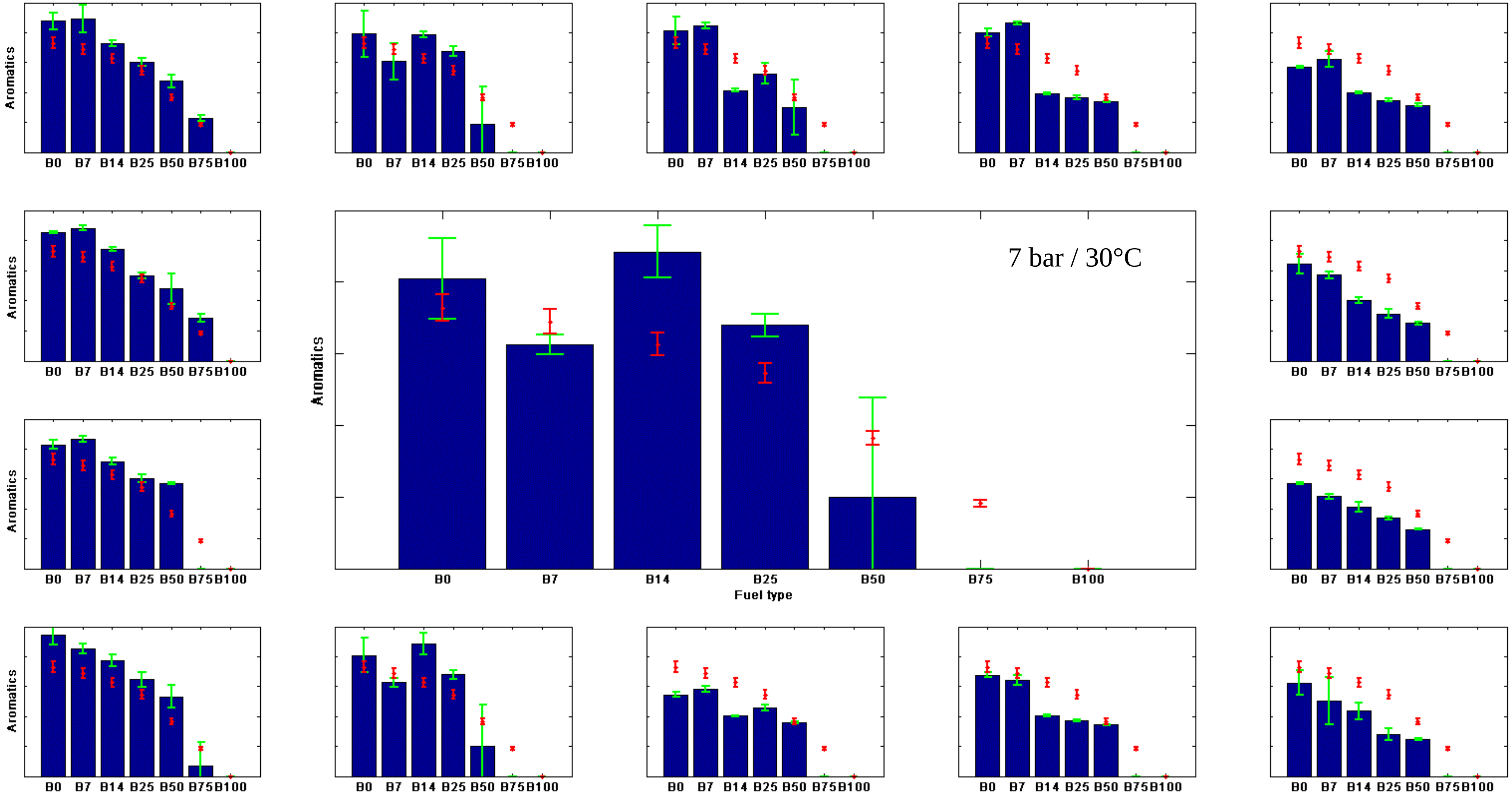


Figure 38. Aromatics content (y-axis) as read by Sensor C.

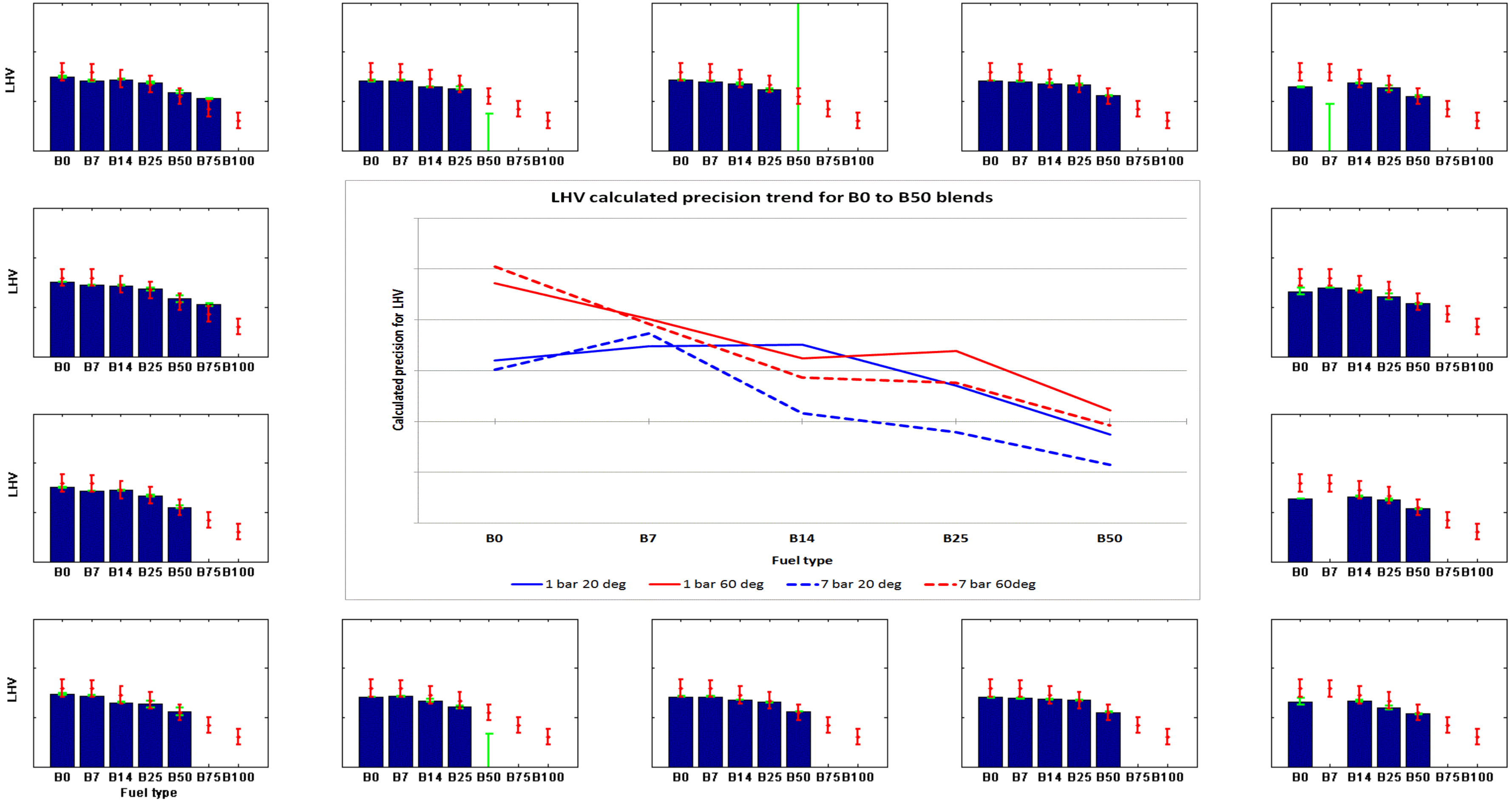


Figure 39. Lower Heating Value (LHV) (y-axis) content level as read by Sensor C.

Cetane Number

Sensor C is able to provide fair cetane number values, inside the standard intervals. These intervals were obtained by linear interpolation for B14, B25, B50 and B75 blends, having the standard values of B0 and B100. B7 was a standalone fuel with its own reference values. It is also visible that the trueness error of the readings seems much lower for higher concentrated B0 blends than for B100 ones (especially B75, B100). The explanation can be offered by analyzing together Figure 38, Figure 39 and Figure 40. It is well known that fuels with higher aromatic content and higher Lower Heating Value will have lower cetane number. Nonetheless, the measured trend is not realistic, as higher concentrations of oxygenates will lead to lower cetane numbers, as seen in the standard interval and its average value (red interval lines on the middle of the blue cetane number bars - Figure 40).

When talking about precision, a short description of the cetane number scale needs to be reminded. As mentioned, cetane number is measured by operating a single cylinder variable compression ratio engine with analyzed fuel. Cetane number is “the percentage by volume of hexadecane (cetane) in a reference blend having the comparable ignition delay” to the fuel that is submitted for analysis [25]. The value represents the average of 32 ignition delay measurements and the accuracy interval is derived from statistical analysis presented in EN ISO 4259 standard [25].

The precision of measurements is fair, within the sensor accuracy interval offered by the manufacturer. A dependency on temperature or pressure is not visible and the sensor is not able to catch any trends in cetane number changes.

It can be concluded that having a high accuracy interval, the cetane values usually measured by Sensor C are true and precise. They can be used in the future for different strategies relating diesel blends.

Temperature readings

It is only the tuning fork sensors that are able to measure fuel temperature. And although it is difficult to have a stable temperature for each recorded point, the sensors show a fair ability to read fluid temperature. The average true error of each sensor is no higher than 1-1.5°C. There is also a small average difference between the two sensors, with Sensor A proving to have a lower trueness error and be more precise at lower temperatures while Sensor B is performing better at higher temperatures.

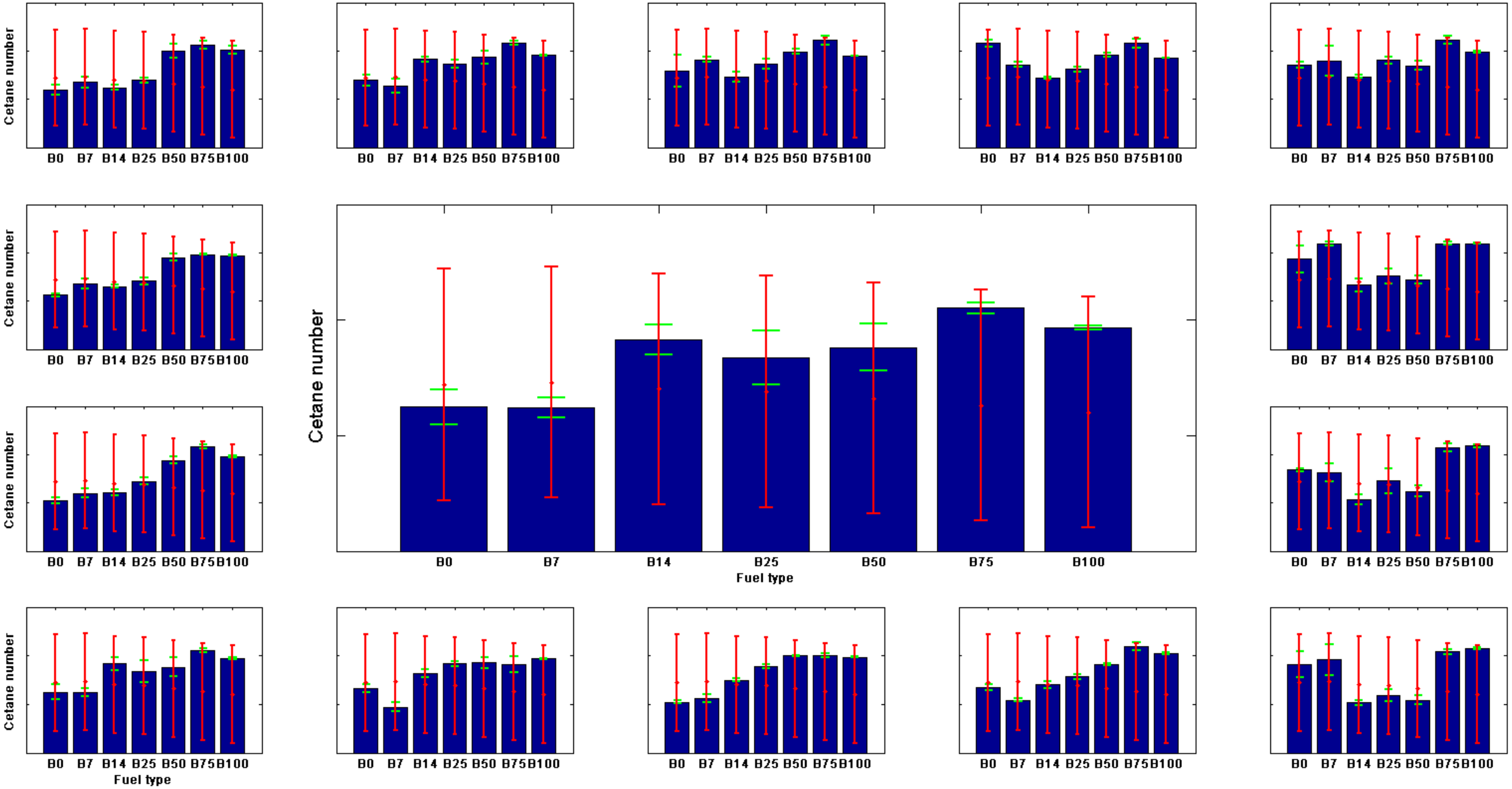


Figure 40.Cetane Number (y-axis) as read by Sensor C.

Figure 41. Temperature (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) sensors for different types of fuel blends

4.3 Aromatics detection

A second type of experiments were performed to test sensors ability to measure different levels of aromatic content in diesel fuel. For this purpose, toluene (a 100% m/m aromatic content fluid) was used as the main source of aromatics, which was mixed with B100. The same mass to mass based mixing procedure was used, so that *X*% toluene would mean *X*% m/m aromatic content. B100 was chosen as the fuel with the minimum or no amount of aromatics.

Matrix from Figure 1 is used to present the results. In this matrix, on x-axis, fuels are renamed as follow: **TAC1** – *B100*, **TAC2** – *low toluene content diesel*, **TAC3** – *medium toluene content diesel*, **TAC4** – *high toluene content diesel*.

As the significant interest is the ability of sensors to measure aromatic content in fuels, it is these results that will be presented first. Nevertheless, if other parameters are found to help in the aromatic content detection or are considered to be abnormal, they are also presented. Sensor C is more interesting as it is stated by the manufacturer that it can directly measure aromatics.

Total Aromatics Content

Nonetheless, the total aromatic content measured data presented in Figure 42 show that, at this level, Sensor C is unable to offer true or precise readings of aromatic content. By analyzing the central image of the mentioned figure, it can be noticed that for the low toluene content, the reading precision at 20°C and 1 bar is a lot more higher than the sensor accuracy stated by the manufacturer. For medium toluene content, the precision is better and within the stated interval, but the trueness error is high. For high toluene content, no values are measured. One of the possible explanations is that the fuel detection algorithm did not work at all for this blend, as other parameters were not recorded either.

Considering the whole matrix seen in Figure 42, it can be noticed that for the *low toluene content diesel*, the sensor is able to measure values in 10 of 14 cases and for the *medium toluene content diesel* in 8 out of 14 cases. Only at 60°C and 1 to 5 bar tests, the values measured for TAC2 have low trueness error. In all other cases the values are low in trueness and precision.

In conclusion, it can be observed that at this level, the dedicated aromatic content application of Sensor C is unable to precisely recognize the right levels of aromatics in a blend and the measurements are considered to be untrustworthy.

Toluene content

Sensor C also presents the capability of measuring the toluene level in a blend. These readings can also indicate on a certain level, the degree of aromatic content. Measured data are presented in Figure 43.

Contradictory to aromatic content measurements, the sensor is able to offer better readings of toluene level for all analyzed fuels.

As it can be observed at 20°C and 1bar, the recorded data and trend are looking realistic. If precision is correct when referring to all measured fuels, the trueness error is higher than expected, especially for TAC3 and TAC4 fuels. For low toluene content, the trueness error is slightly above the specifications. For medium toluene content, the trueness error is again slightly higher, while for high toluene is further away. Although the trend looks realistic, it can be seen that the values are more than untrue. It can be concluded that, although illogical, Senor C appears to be more able to detect with lower trueness error, lower levels of toluene than higher ones. Further testing can help the assessment of this fact.

From precision point of view, at 20°C and 1 bar, it is within specifications.

Final conclusion at this level is that for lower concentrations of toluene Sensor is able to have higher precision and lower trueness error than for higher levels of toluene.

Bio content

The bio content level measurements with Sensor C can be observed in Figure 44. As normal, starting from B100, a 100% bio fuel, the level of TAC1 is the highest one. By adding aromatics to this fuel, the bio content will decrease on a percentage mass per mass (% m/m) base. The descending trend is observable in Figure 44, yet with high trueness error. If for TAC1, at 20°C and 1 bar, the level of bio content is acceptable, but underestimated, for TAC2, TAC3 and moreover TAC4, the bio content level measured by Sensor C is far from real. The values are even more physically implausible as with temperature, the level of bio content is dropping.

Under these circumstances it is to conclude that the bio content readings taken by Sensor C are unable to clarify if the fuel has more aromatic content or just a lower FAME percentage.

Density

As toluene density is 0,87 g/cm^3, a relatively similar in value to B100 density (0,88 g/cm^3) it can be seen in Figure 45 that the tuning fork sensors do not sense, as expected, any major change in density measurements. These readings are not affected by pressure increase. Temperature has an influence, and by using B100, the model applied for thermal dependence it is not very suited for higher temperatures. It can be observed that for 60°C, the trueness error is higher (but within accepted values) than at 20°C.

When analyzing density measurements from Sensor C (see Figure 46), a general decreasing tendency from TAC1 to TAC4 is observable. The trend is unrealistic as the rate of decrease is too important (within accepted limits), especially when compared to the reference value. Moreover, the value for the *medium toluene content diesel* is lower than 100% toluene density.

In conclusion, it can be said that, Sensor A and Sensor B are unable to differentiate through density between B100 or *high toluene content diesel*. It is not to be understood as a fault in the measurements, but by the fact that the densities of the mixtures are relatively the same, one cannot tell the difference. When referring to Sensor C, the conclusion is that it is showing unrealistic density values and it is unreliable to say that the aromatic contamination leads to these results .

Viscosity

In Figure 47, viscosity as measured by Sensor A and Sensor B can be seen. The kinematic viscosity of toluene from literature is around 0,68 cSt, while for biodiesel (B100), the reference value found in the fuel data sheet is 4,3 cSt. It can be thus explained the decreasing viscosity seen in the mentioned figure. With an increased level of toluene, the mixture B100-toluene tends to go towards the lowest viscosity, which is for toluene. In the same way, one has to keep in mind that this decrease in viscosity can also be a consequence of FAME reduction due to B0 presence (e.g. see Figure 36).

It can be concluded that with a higher level of aromatics, the blend viscosity is smaller, but only if the measured density remains at approximately same values (in the B0/B100 blend test, density decreased with lower concentration of FAME, which is not the case as shown earlier).

Dielectric constant

Referring to the measurements of dielectric constant presented in Figure 48, it can be seen that with an increased level of aromatics, the value of dielectric constant is decreasing in the same way that viscosity did. Moreover, as the blend level is gradually increasing, the measured value for dielectric constant is dropping with almost the same value.

The precision of the readings is very good with an overall average much smaller than the accuracy offered by the manufacturer. The high trueness error will not be taken into account as the values are taken from the internet and cannot be fully trusted. The model applied to temperature – dielectric constant dependence is also not convenient as the trueness error at 60°C for dielectric constant compared to the 40°C reference is higher. At 20°C, the values are much higher again but in the opposite way than at 60°C.

Conclusion that can be drawn is that blends with high level of aromatics will have lower dielectric constant values. In addition, a blend that has same density but a smaller viscosity and a smaller dielectric constant, might be considered as a blend with a increased level of aromatics.

Cetane number

It is generally accepted that by mixing a high cetane number fuel with aromatics, the value of CN will go down. By analyzing the values measured by Sensor C in Figure 49 it is easy to see that at this level, considering the accuracy tolerance interval, is hard to state that the cetane number or its variance can be interpreted as the influence of constituents, namely aromatic content.

Lower Heating Value

Sensor C lower heating values measurements are of no use when referring to aromatic content detection, the sensor was not able to provide plausible data for all the analyzed fuels.

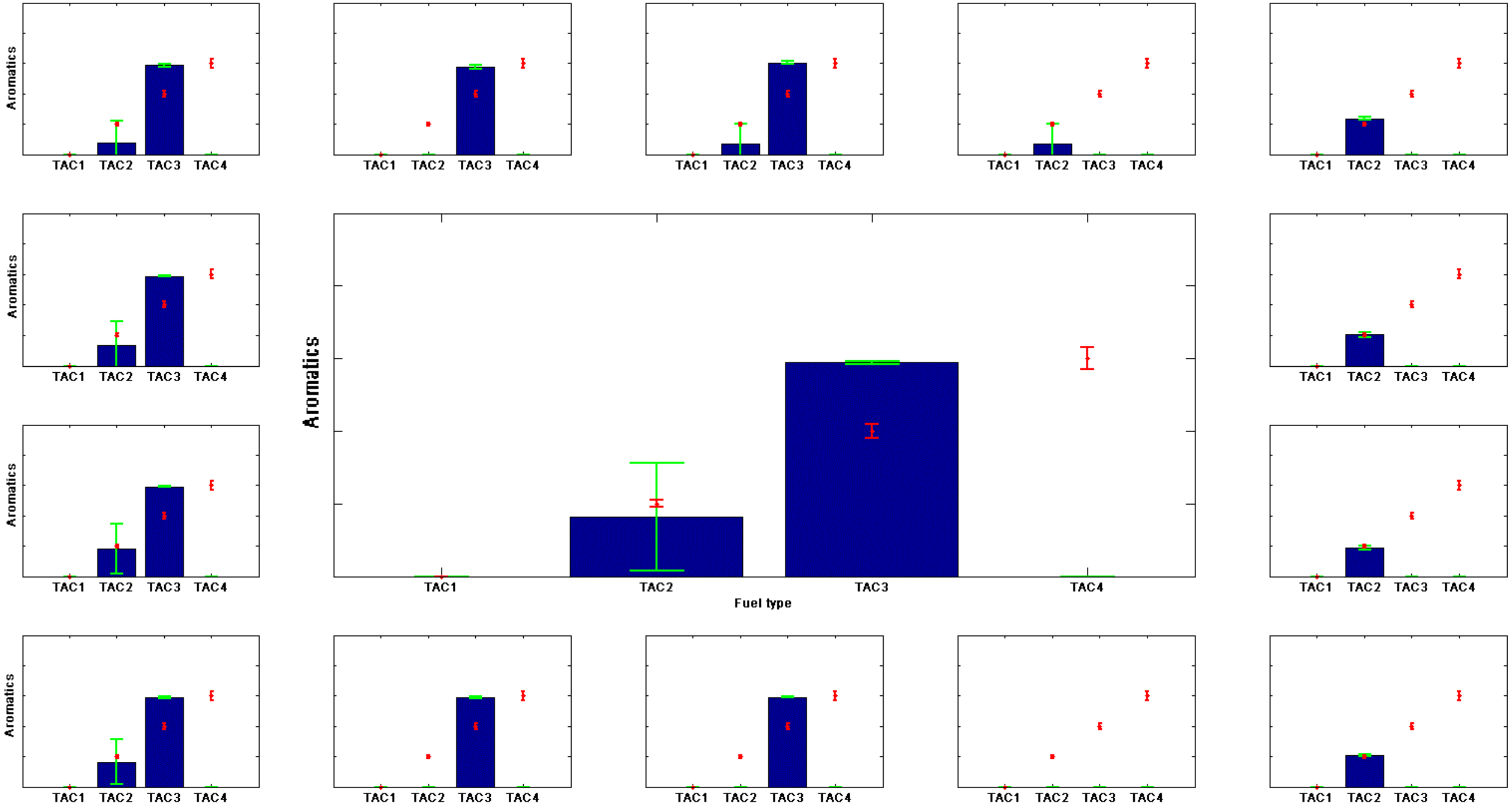


Figure 42. Aromatics content (y-axis) as read by Sensor C for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

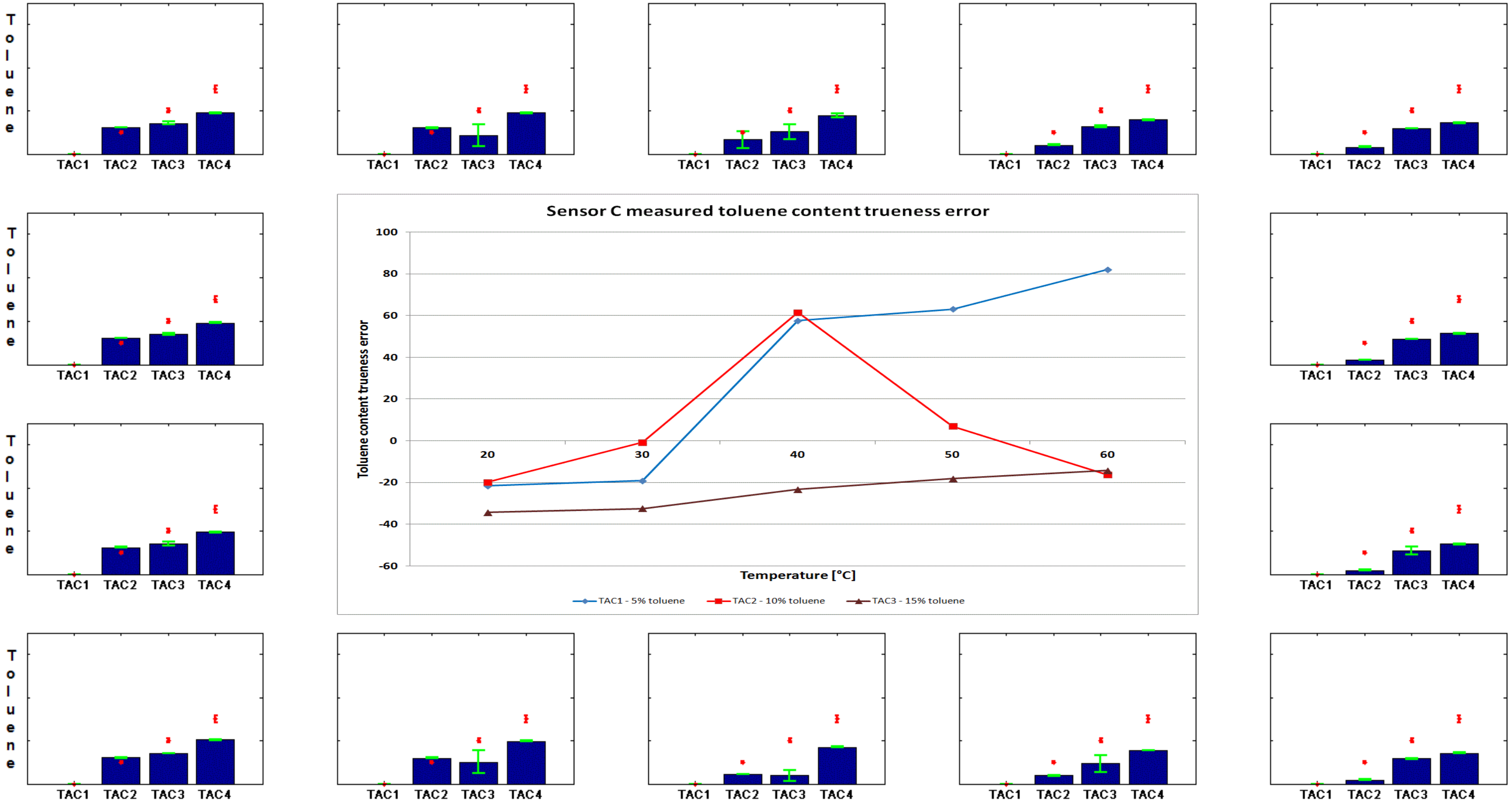


Figure 43. Toluene content (y-axis) as measured by Sensor C for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

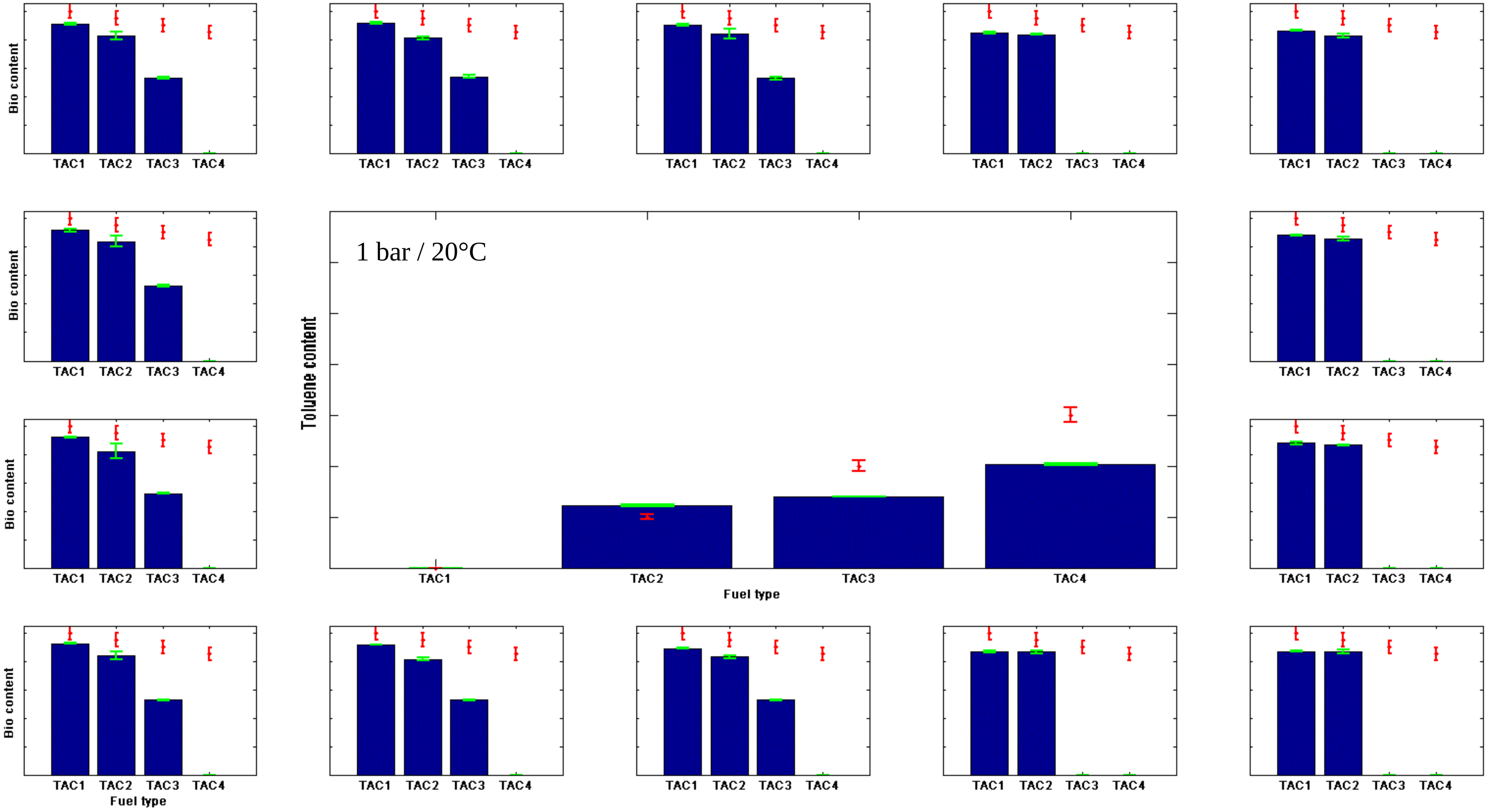


Figure 44. Bio content (y-axis)as measured by Sensor C for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

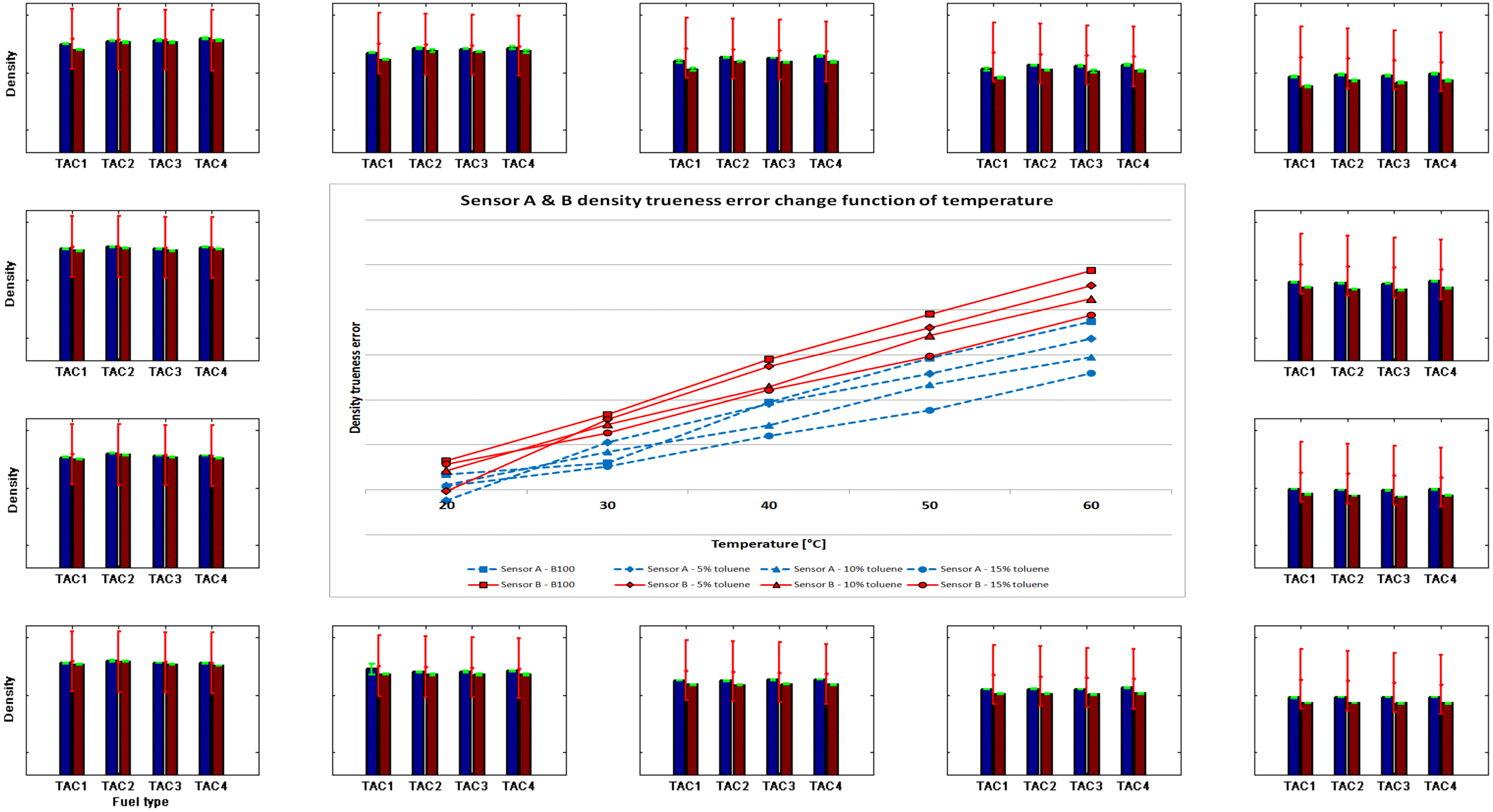


Figure 45. Densities (y-axis) as measured by Sensor A (blue left bar) and Sensor A (dark red right bar) for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

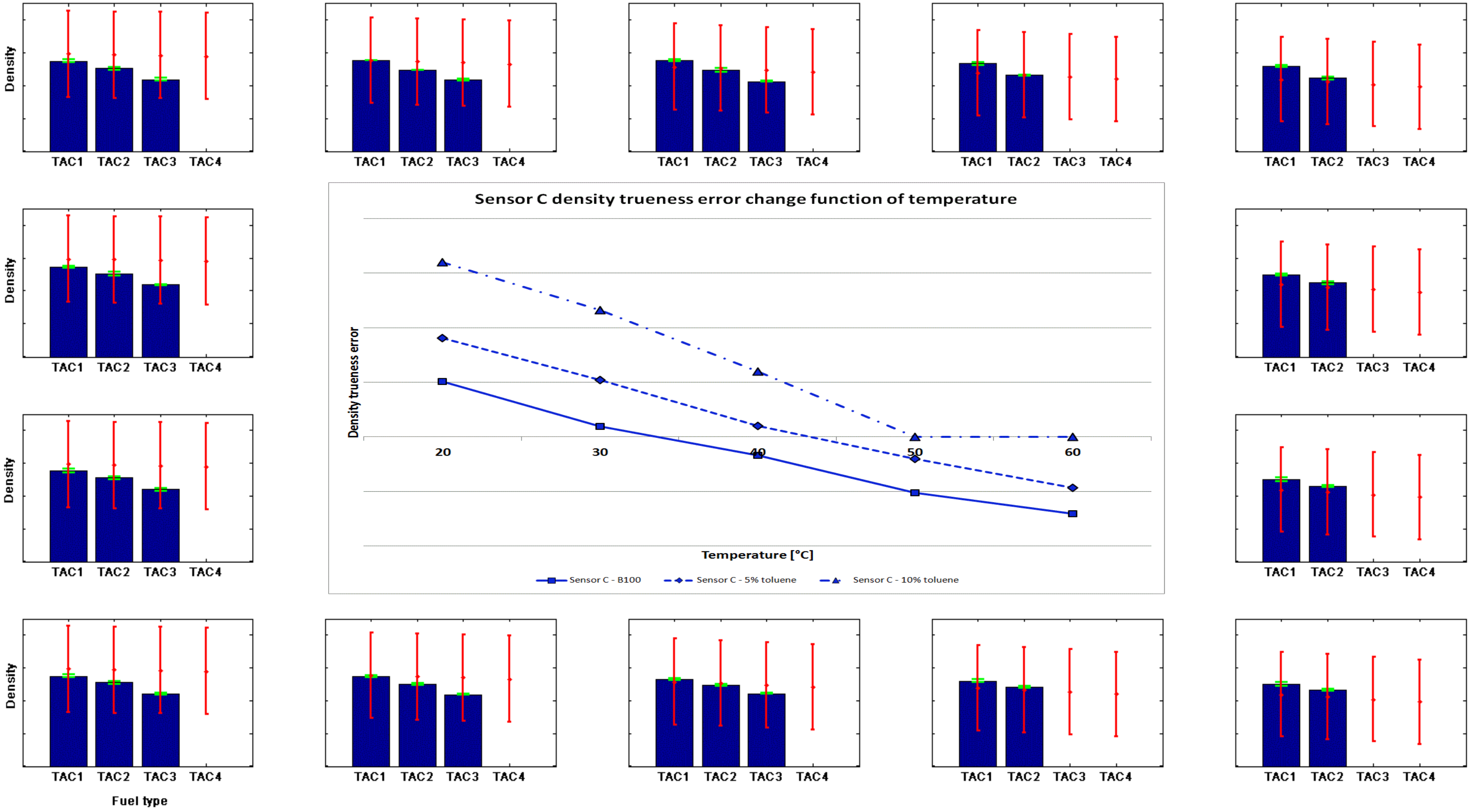


Figure 46. Density measurements (y-axis) for Sensor C for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

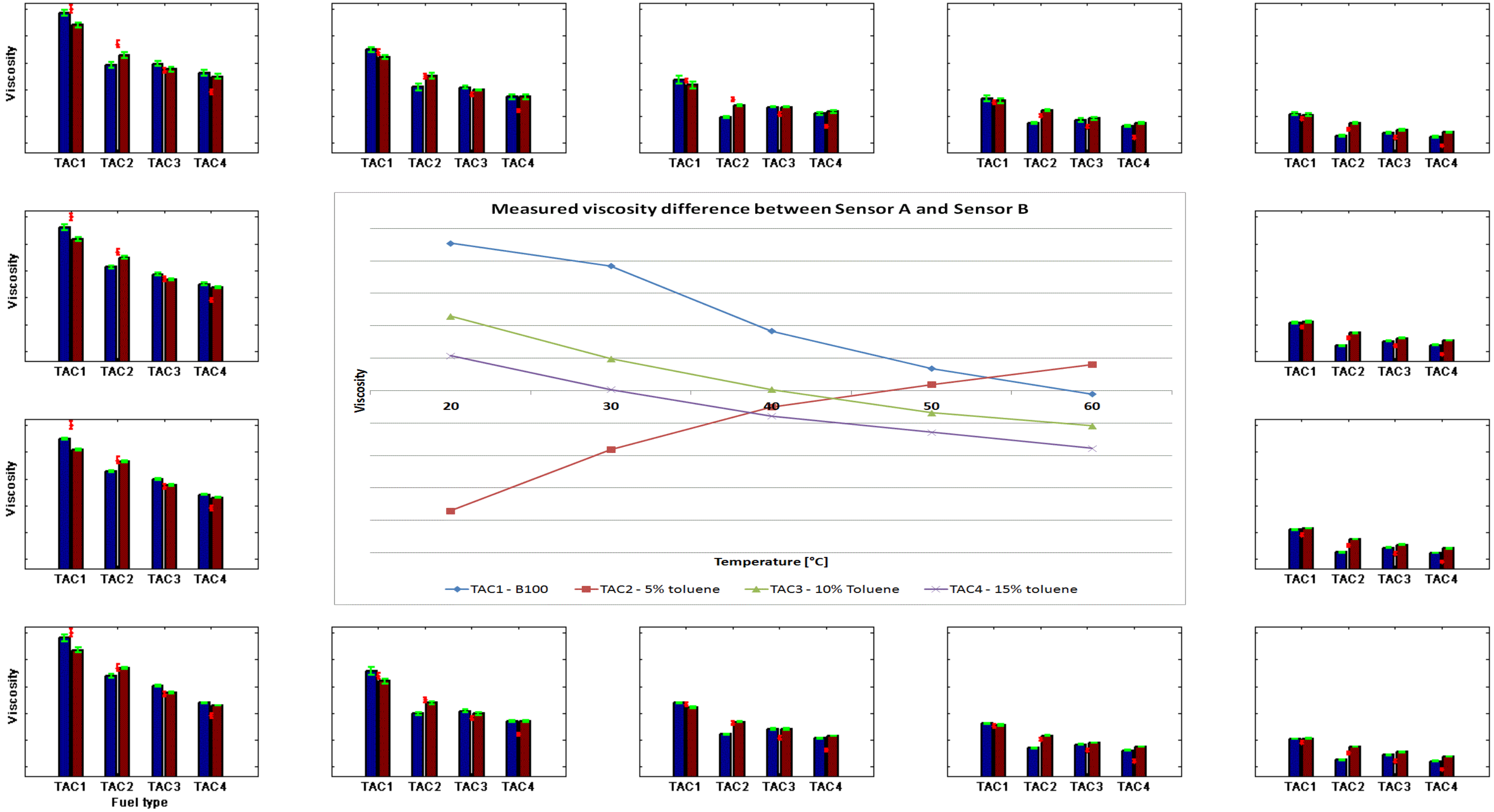


Figure 47. Fuels viscosities (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

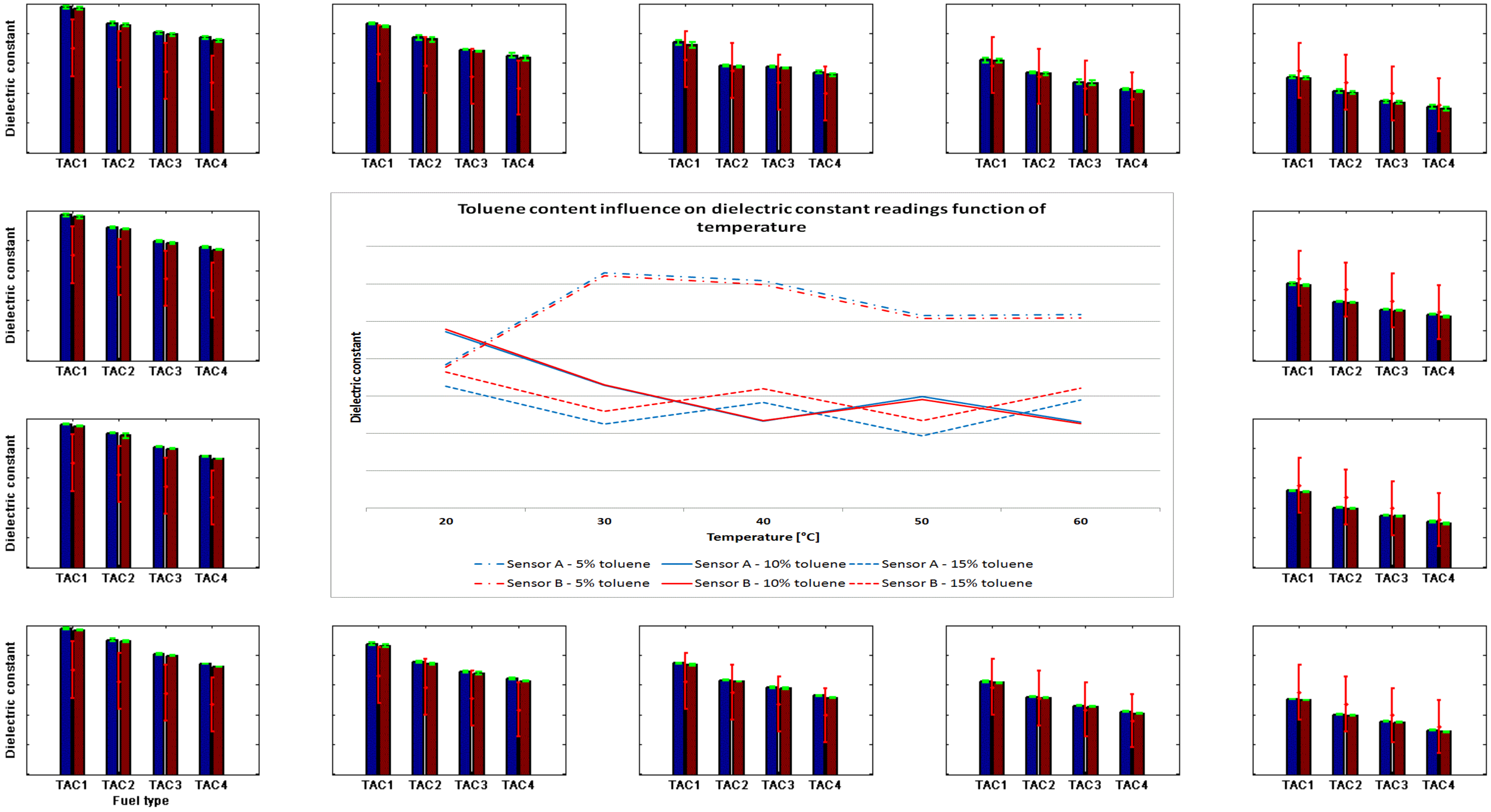


Figure 48. Dielectric constant (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

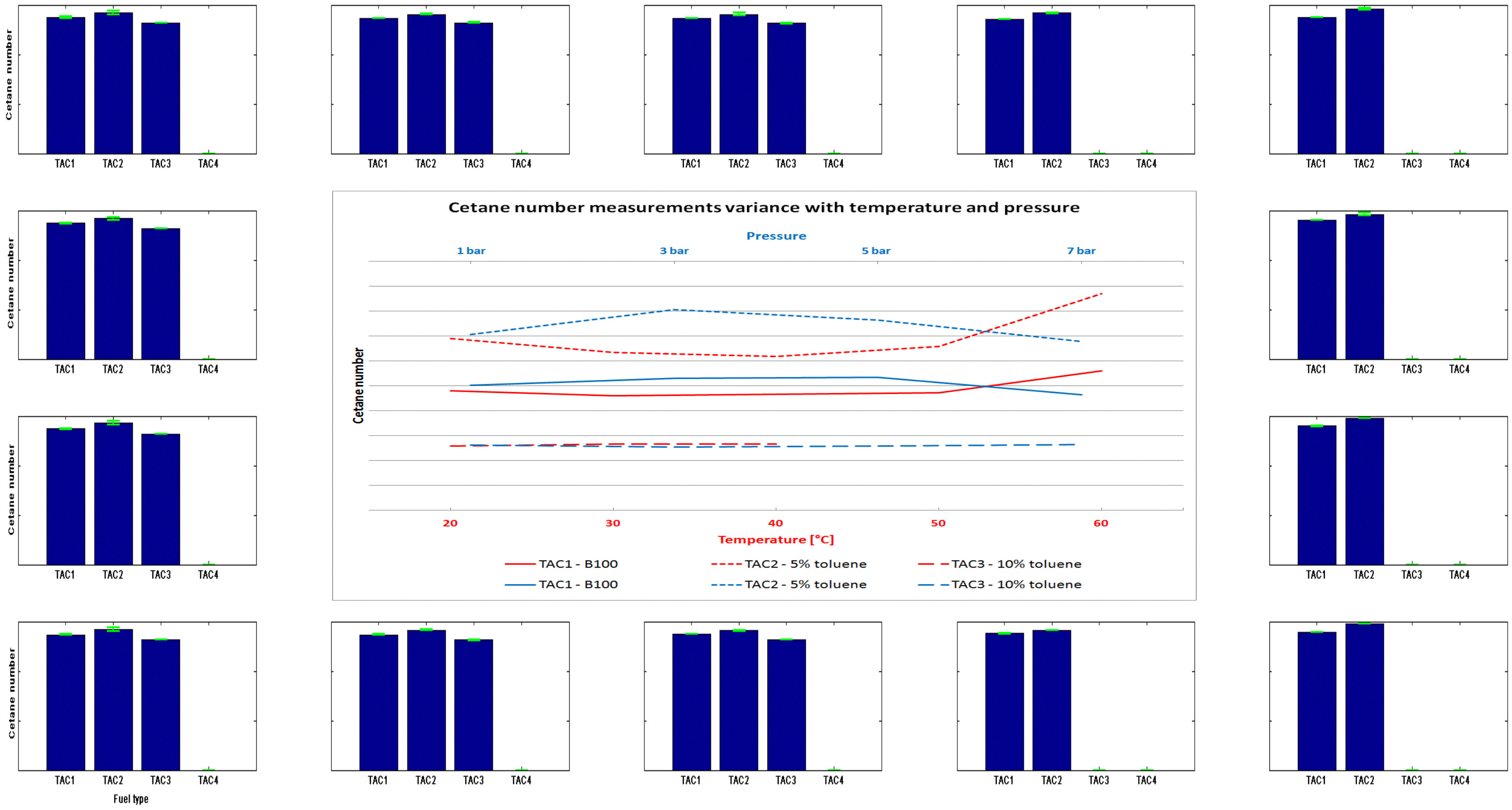


Figure 49. Cetane number (y-axis) as read by Sensor C for different types of diesel/toluene blends (x-axis) (TAC1 – B100, TAC2 – low toluene content diesel, TAC3 – medium toluene content diesel, TAC4 – high toluene content diesel).

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4.4 Special fuels

A third experiment series is conducted with different types of special fuels. These fuels are: high aromatics content diesel fuel, MK1 diesel, marine diesel, kerosene, gasoline, iso-octane and n-heptane. Throughout this type of tests, the ability of the three analyzed sensors to accurately distinguish between different fuel qualities is investigated.

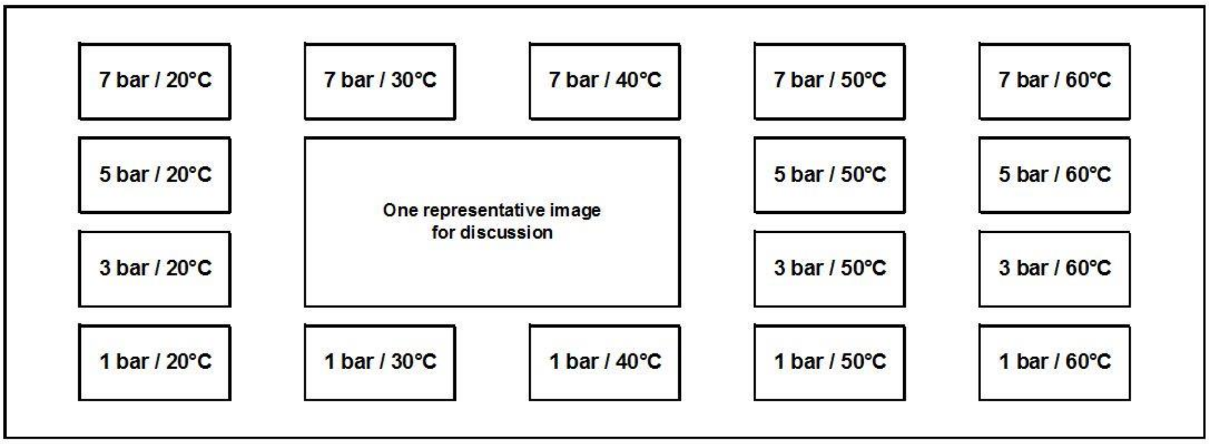

Figure 50. The matrix of recorded points for special fuels that will be represented and discussed as meta-graphs

In the figures presented, meta-graphs are built according to the matrix of experiments that were performed (see Figure 1 and Figure 50). The reason for using the second matrix is that fuels like gasoline, iso-octane and n-heptane were only tested to 50°C with special measurement points at 3 and 5 bars (at 50°C) for these highly flammable fuels. In these matrixes, on the x-axis of the subplots, the special fuels will be presented as follow: SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane and SF7 - n-heptane. In the figures where only Sensor C measurements are presented, subplots at 3 or 5 bar and 50°C will not be presented. For these cases, the matrix from Figure 1 will be used instead. This decision is taken as Sensor C is unable to measure any special fuels at 3 to 5 bars and 50°C, thus no data is available.

Density

Density as a fuel characteristic is the only common parameter that all three sensor are measuring. As can be seen in Figure 52 and Figure 53, Sensor A and B are able to show values for all the analyzed fuels while Sensor C is only able to assess the diesel like fuels.

Not considering the outliers of Sensor A and Sensor B (MK1 diesel at 7 bar/20°C and Gasoline at 1bar/50°C) it can be seen that both of them are able to measure density with low trueness error for all investigated fuels. It has to be kept in mind that the three first evaluated fuels (SF1, SF2 and SF3) have laboratory analysis data sheets. The other fuels only have standard values offered by a general description of the product. As suggested by the fuel providers different batches might vary in properties and present deviation from the data sheet value, as they are mixed in the depot from multiple recipes and constituents. This can partially explain the slight higher trueness error for these 4 fuels: SF4 (kerosene), SF5 (gasoline), SF6 (iso-octane) and SF7 (n-heptane). Sensor A has the lowest trueness error. It is closely followed by Sensor B. Sensor C also proves to be low on trueness error, especially for SF1, SF2 and SF3 at 20°C and 1 bar. Nonetheless, the measurement for kerosene (SF4) shows a higher in trueness error. For decreasing density with increasing temperature, both tuning fork sensors are able to follow the trend and keep their precision. As there is no oxygenate content in any of the diesel fuels, the density temperature dependence model is better suited than in the Bxx fuel blends tests (as described earlier in *Density* for *Diesel and Biodiesel blends* in *Subchapter 4.1)*. Sensor C does not include a temperature dependence algorithm. This results in a higher trueness error with changing temperature.

Regarding precision, all three sensors are in compliance with the manufacturer's tolerance range. Sensor C was unable to measure density for the special fuels SF5 (gasoline), SF6 (iso-octane) and SF7 (n-heptane). One of the reasons, especially for SF6 and SF7 is that the density of the fuels is outside the sensor range.

It can be concluded that all three sensors show good density readings at standard condition (1 bar, 20°C). Moreover, Sensor A and B are offering good results no matter the conditions (temperature or pressure). With a missing temperature dependence algorithm Sensor C looses in trueness with rising temperature. Similar to *Diesel and biodiesel blends* measured density is not influenced by changing pressure.

Viscosity

As density measurements are having a low trueness error for both Sensor A and Sensor B, viscosity measurements are showing same good results. The overall averaged trueness is low for both sensors, excluding the marine diesel (SF3). It needs to be reminded that the reference point for viscosity measurements is 40°C, not 20°C as in density case for example. It can also be seen in Figure 54 that the model used for calculating changing viscosities with increased temperatures is more adapted for higher ones, than for lower. Also the measurements show that both sensors record similar values as the temperature rises. At 20°C Sensor A has a lower trueness error than Sensor B.

A possible explanation for the very low viscosity of SF3 (marine diesel) in comparison with the standard value is that in storage, the fuel might have been contaminated with B100 based fuel. This is confirmed partially by the increased level of bio content as seen in Figure 57 although the fuel data sheet specify for this specific fuel as a reference <0,1 %V/V FAME content. The storage time was also longer than 4 months prior to the experiments.

Another interesting fact to notice is that, although the manufacturer state a minimum viscosity value that can be recorded, for both sensors, most of the points for *n-heptane* (SF7) are lower than this value. Although the percentage is smaller, there are points lower than this value for *gasoline* and *iso-octane* as well. Still, precision and trueness error does not change and show acceptable values.

With a more adapted algorithm for temperature dependence, measured viscosity will be in line with reference values (as it is the case at 40°C). As a conclusion, it can be observed that no matter the fuel type both tuning fork sensors are able to provide accurate viscosity readings.

Dielectric constant

When referring to the dielectric constant readings it has to be mentioned that the standard values considered as reference are not taken from each specific fuel data sheet. All of the values are taken from the internet [*http://www.engineeringtoolbox.com/kinematic-viscosity*] and doubled checked with existing literature. These standard reference values do not seem to fit the actual measured value for *kerosene* and *gasoline*.

Other than this, the tuning fork sensors sensors show acceptable trueness errors and precision, although the temperature dependence model shows room for improvement. Both sensors capture the linear dielectric constant decrease for the first three fuels (SF1 – high aromatic diesel, SF2 – MK1 diesel, SF3 – marine diesel from 20°C to 60°C, 1bar). The sensors are also able to capture the general trend created by the diversity of the fuels.

As a conclusion, Sensor A and B show good results when compared to reference values for most of the fuels. For kerosene and gasoline, fuels with a large precision error readings, the wrong reference value that is used might explain this deviation.

Total Aromatic Content

The *total aromatic content* values measured by Sensor C can only be read for the diesel type fuels SF1 to SF4 (high aromatic diesel, MK1 diesel, marine diesel and kerosene) (see Figure 56). Neither precision nor trueness is good for these readings.

At 1bar and 20°C, only kerosene has precise and true readings. In the SF1 (high aromatic diesel fuel) case, precision is good but the trueness error is high. When referring to SF2 (MK1 diesel), the precision of readings is higher than the one offered by the manufacturer.

The overall readings (other temperature and pressure conditions) are not stable and they oscillate with fuel temperature and pressure change, which is considered to be physically implausible.

In conclusion, the aromatic content measurements are judged to be untrustworthy.

Bio Content

Sensor C has a really high trueness error on all the measurements of *bio content*. Moreover, for gasoline like fuels, it offered no readings at all. When considering the diesel type fuels, although in all the fuel's data sheets, the FAME content was considered to be negligible. It can be seen in Figure 57 that the sensor measured a FAME content from low level in the SF1 (high aromatic diesel) case to an increased level of bio content for SF3 (marine diesel) at 1bar and 20°C. With increasing temperature, the readings became more and more deviated from reference value. None of these readings are supported by other readings of density or viscosity.

In conclusion it can be said that the capability of Sensor C to read bio content is not physically realistic at this level.

Lower Heating Value

In the LHV case, as it can be seen in Figure 51, Sensor C is able to measure values only for two fuels: high aromatics content diesel (SF1) and the marine diesel (SF3). Data from the other fuels are not measured.

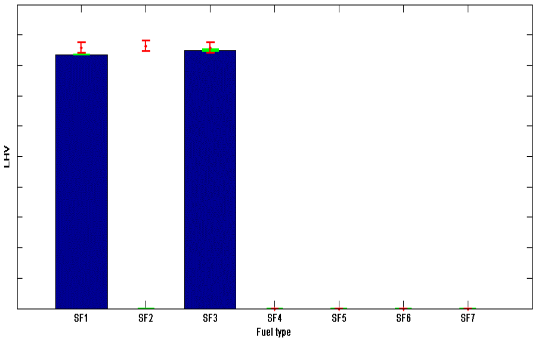

Figure 51. Lower Heating Value (LHV) (y-axis) content level as read by Sensor C for different types of special fuels (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

When referring to these two fuels it can be noticed that the readings are precise and with a low trueness error. Moreover, the rest of measurements for these two fuels are stable in all investigated conditions (see Appendix A Figure 68 for meta-graph). They are very realistic from this point of view as the LHV is not affected by temperature or pressure.

As a conclusion, it can be stated that at this level, the sensor has problems in measuring all diesel type fuel lower heating values. A probable explanation might be the inappropriate fuel data base used by the fuel reconnaissance algorithm. One has to keep in mind that the fuel data base does not contain gasoline type fuels and thus it explains why these fuel type have not been properly evaluated. It is difficult to offer a reasonable explanation for unmeasured diesel fuels (like MK1 and Kerosene) other than an incomplete fuel recognition algorithm. As for the two analyzed fuels and the good results seen in Figure 59, it prove that with future development of the sensor capabilities and better adaptation of the fuel recognition algorithm to all fuel types found on the markets, LHV can become a parameter easy to measure for more types of fuels.

Cetane number

CN is a characteristic specific for diesel fuels and only four types of fuels offered results to interpret. When referring to the measured values, although precise, the readings with Sensor C have a high trueness error (within stated reference interval). From trueness error point of view, the large tolerance interval ensures that all the readings are within this interval for SF2 (MK1 diesel) and SF3 (marine diesel). From the precision point of view, the difference between the minimum and the maximum measured values is below the sensor accuracy stated by the manufacturer.

As seen in Figure 58 (central image), an increasing cetane number can be noticed with increasing temperature. This is considered to be unrealistic. No trend is observable on the pressure increase.

The conclusion relating to the cetane number values is that at 20°C and 1bar, the readings are acceptable. Still, more measurements are needed to fully confirm Sensor C ability to analyze special fuels (marine diesel, kerosene, etc.) from cetane number point of view. Sensor development is also needed, specially for higher temperature measurements.

Fuel recognition

Sensor B is able to recognize SF1 and SF3 as diesel fuels. If for SF1 the reading is considered acceptable, for the marine diesel (SF3) it is not entirely correct. Although it is a diesel fuel, as actually measured by the sensor, light marine diesel or even marine gas oil would have been much close to reality.

MK1 diesel (SF2) is also wrongly detected. SF4 is presented as kerosene which is correct. SF5, the 95 Gasoline is also realistically detected, while for iso-octane it is detected as 95 Gasoline at 20 and 30°C

When talking about Sensor C capacity to detect fuels, it can be seen in Figure 59 that for gasoline it reads a majority Gasoline content, with more than some diesel content. Close values of iso-octane are a proof that the reading is accurate as gasoline is 95% iso-octane. Yet, the higher level of diesel content in the iso-octane it is not correct.

When referring to diesel fuels, all of the measured points are plausible referring to the diesel percentage in fuel. Yet, having a higher aromatic content when compared to MK1 fuel for example, SF1 fuel should have had a higher percentage on the gasoline line due to benzene like components in the aromatics.

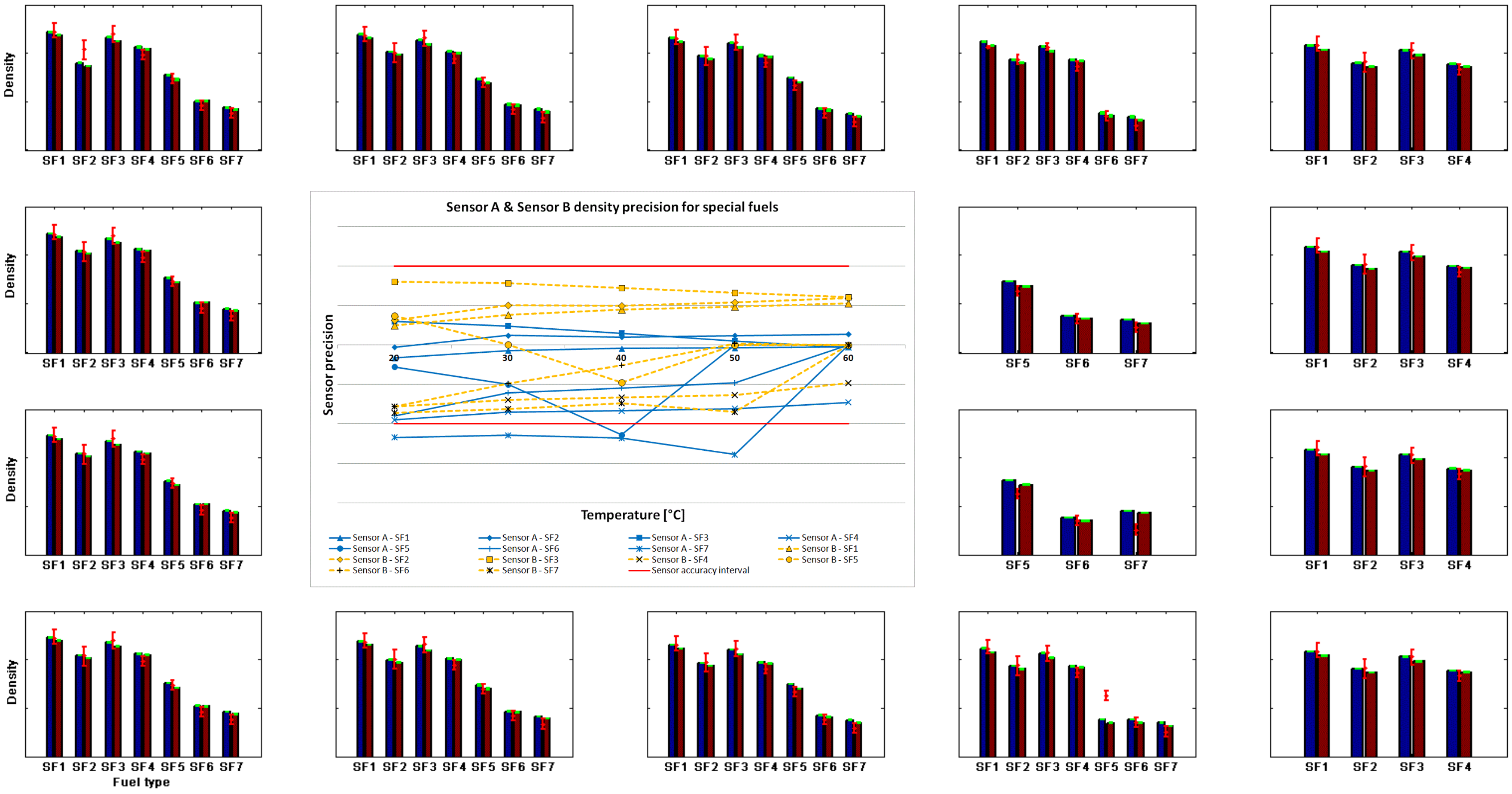

Figure 52. Densities (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

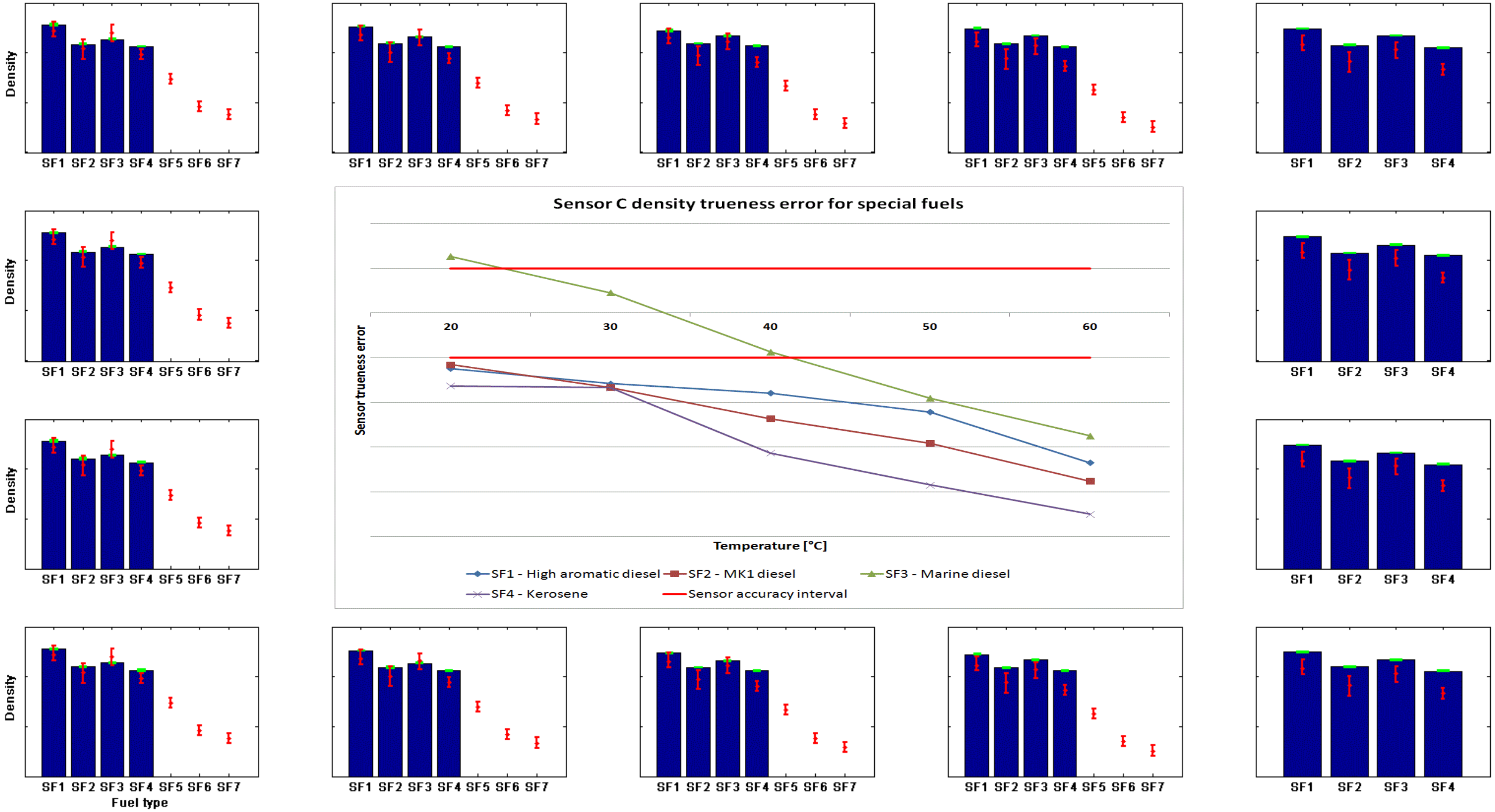

Figure 53. Density measurements (y-axis) for Sensor C for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

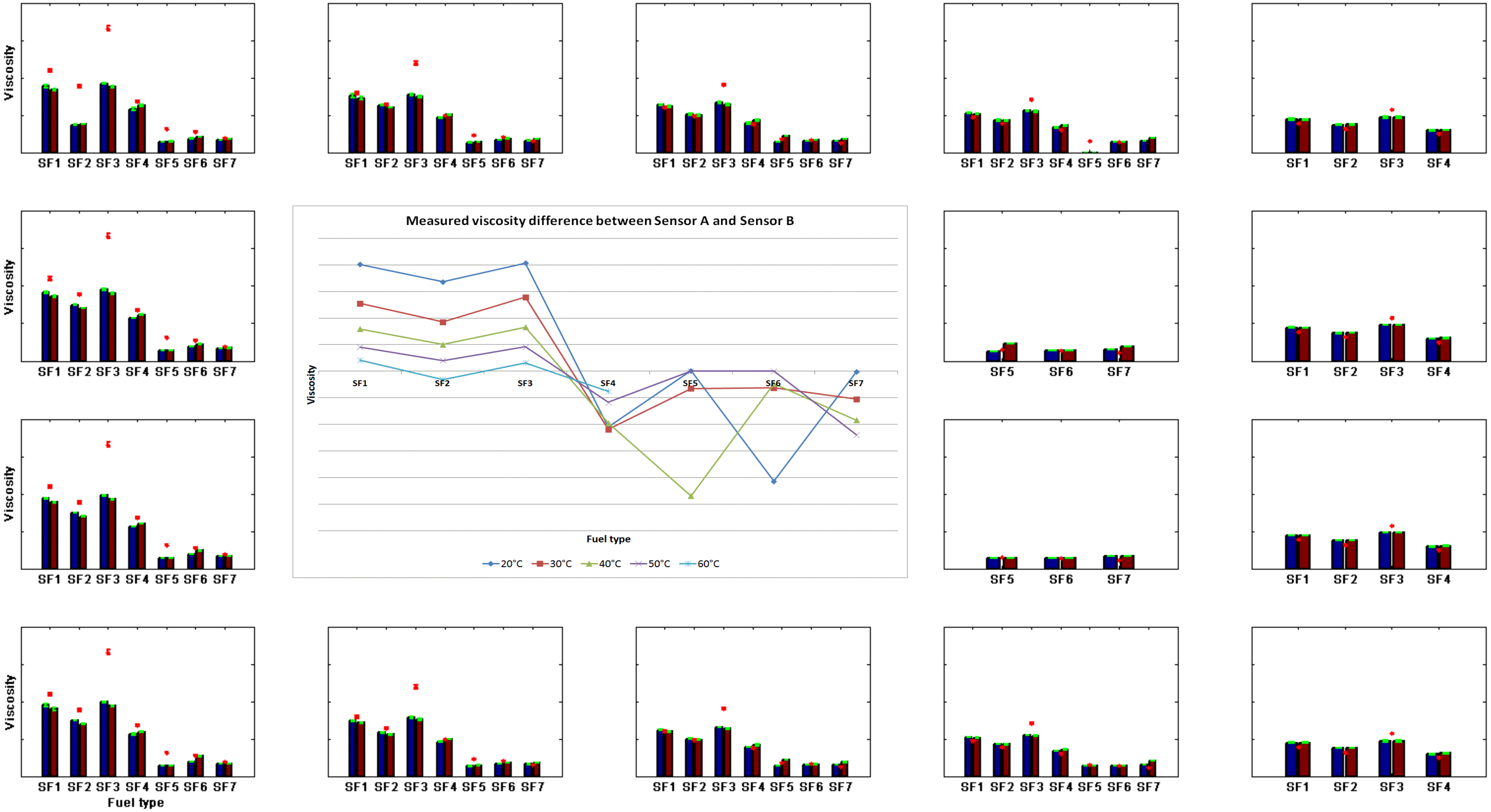

Figure 54. Fuels viscosities (y-axis) as measured by Sensor A (blue left bar) and Sensor A (dark red right bar) for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

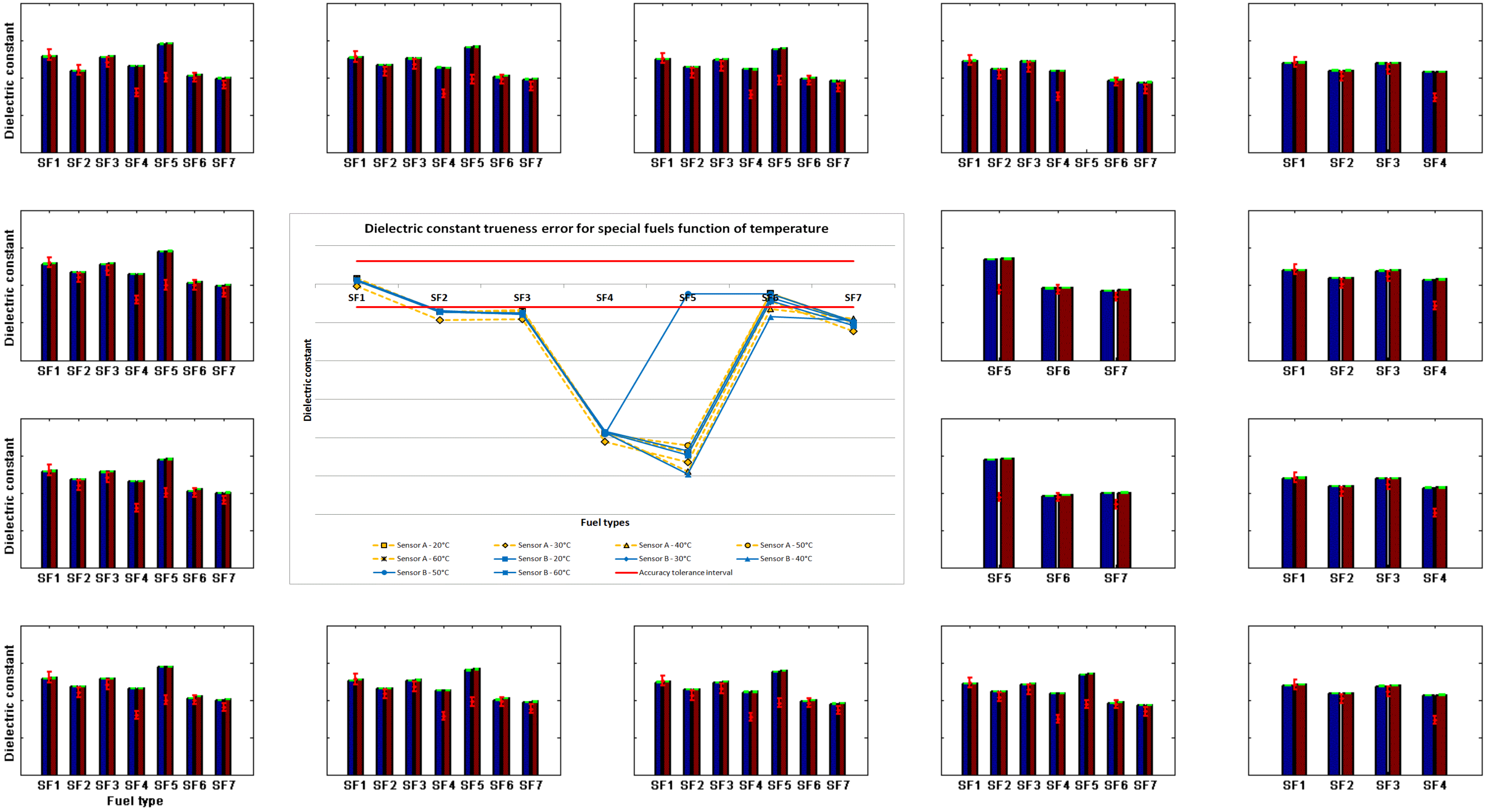

Figure 55. Dielectric constant (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

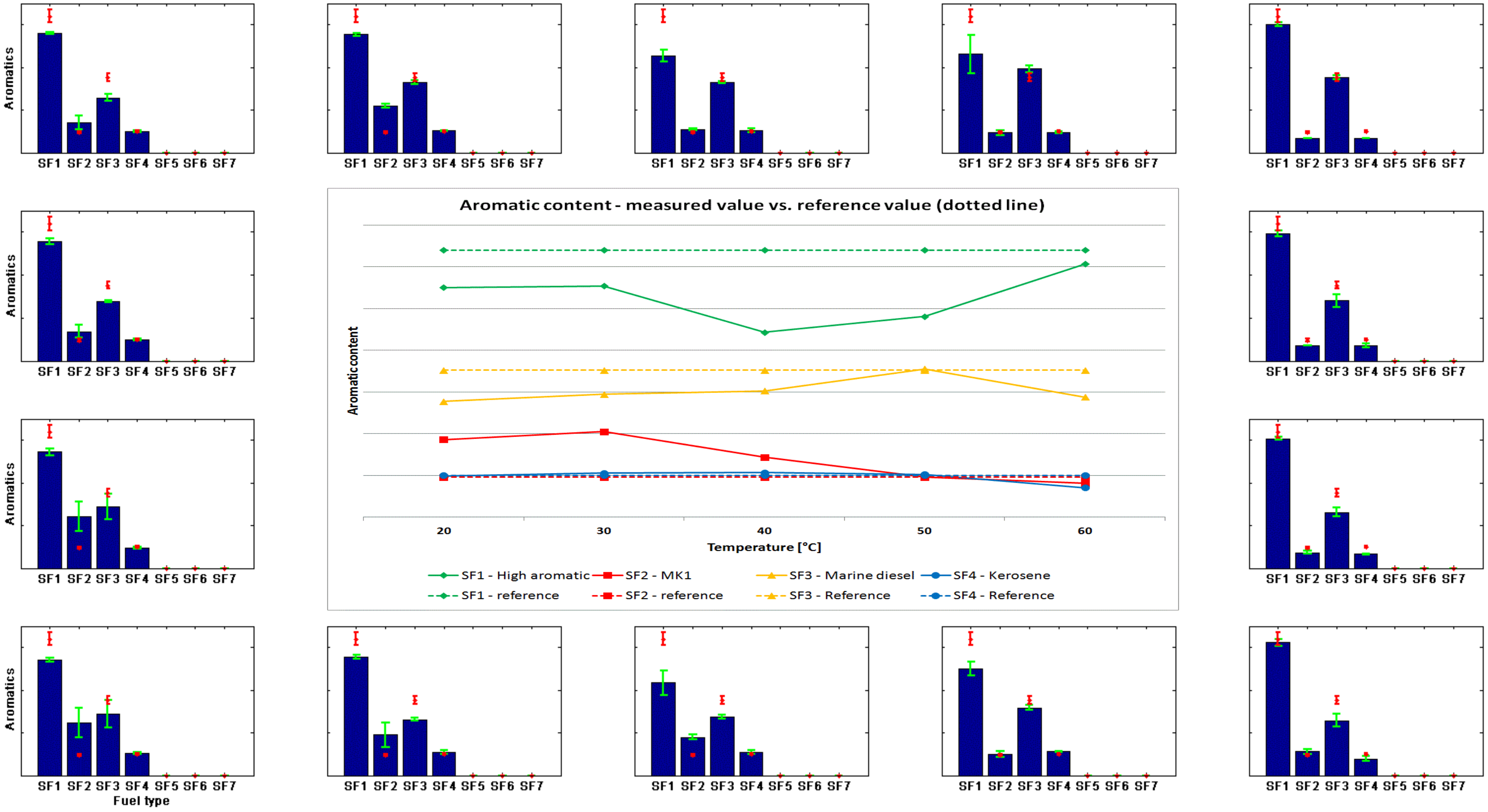

Figure 56. Aromatics content (y-axis) as read by Sensor C for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

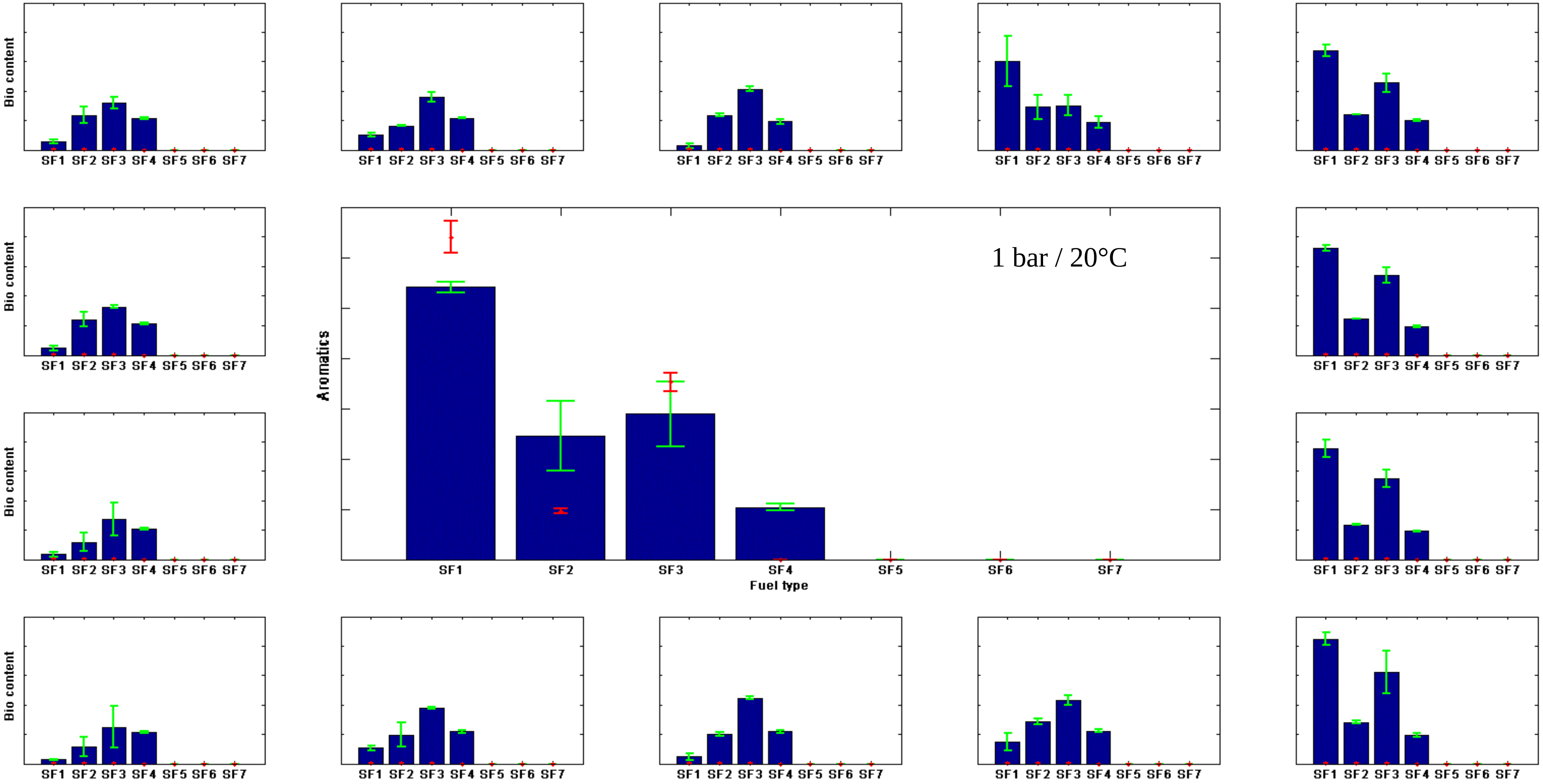

Figure 57. Bio content (y-axis) as measured by Sensor C for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

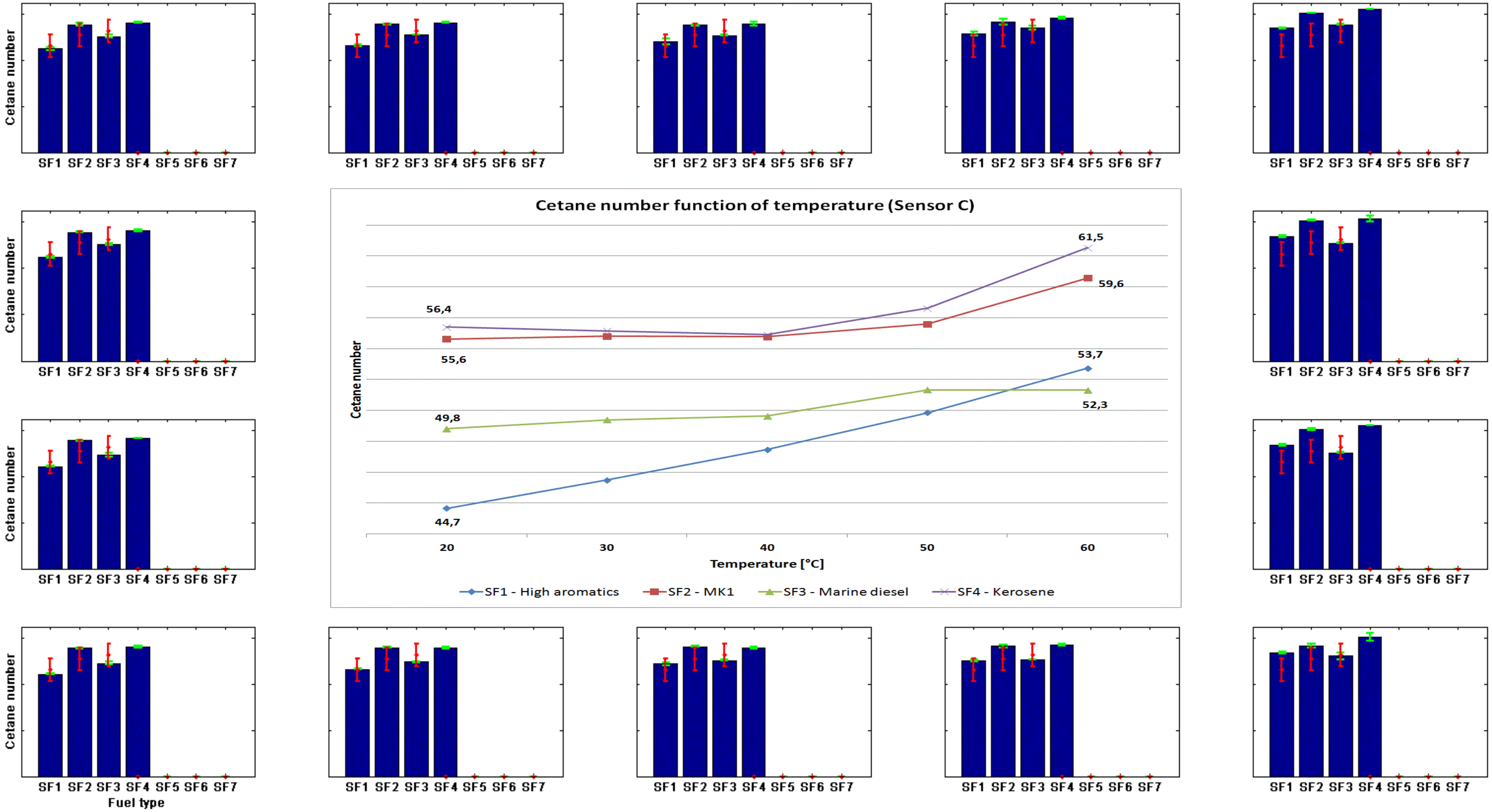

Figure 58. Cetane number (y-axis) as read by Sensor C for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

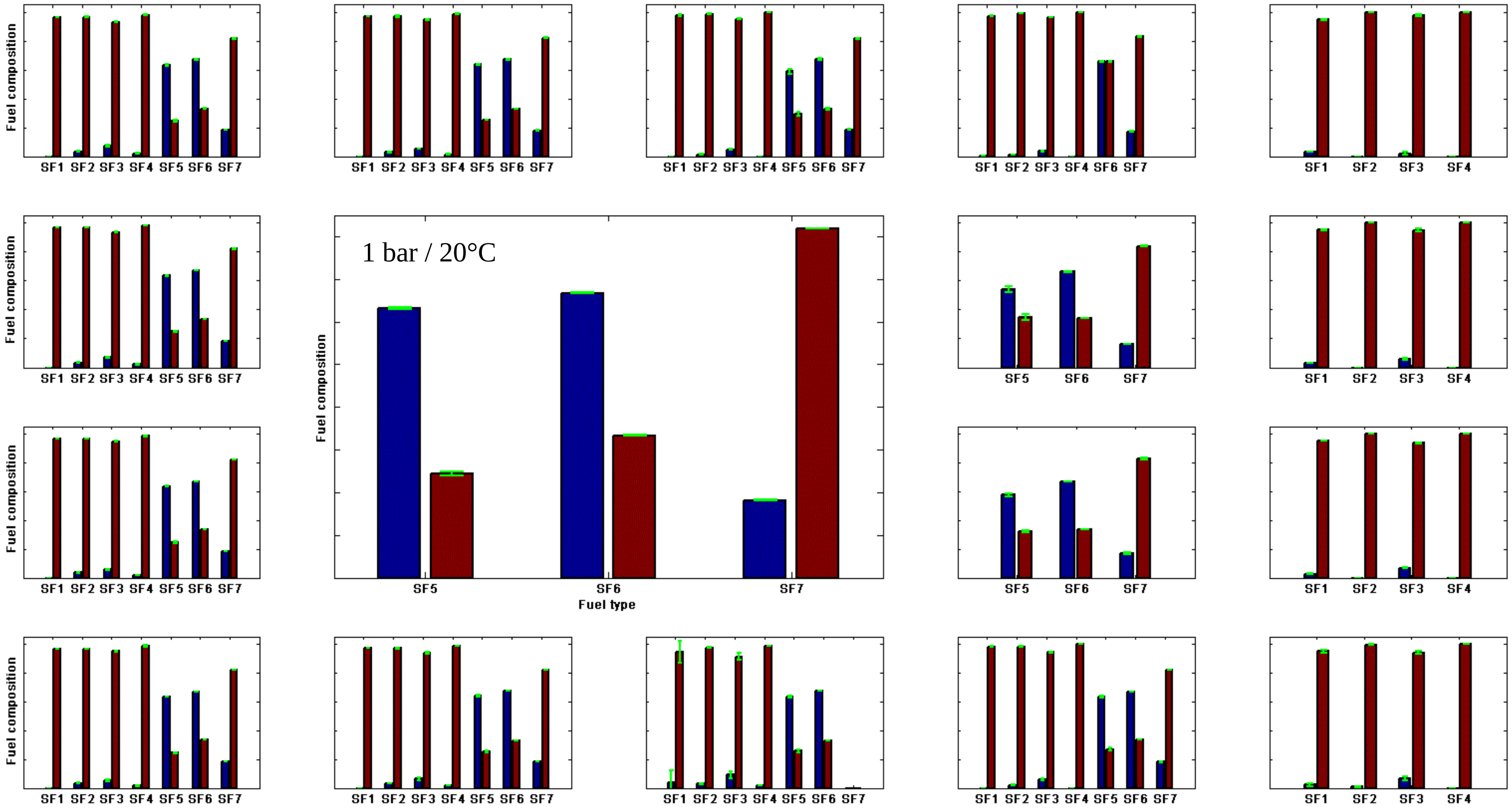

Figure 59. Gasoline content (blue column) and diesel content (red column) as measured by Sensor C for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane).

4.5 Contaminated fuel (water and sulphur)

The fourth series of experiments are conducted with different types of contaminants. These contaminants are sulfur and water. As for testing purposes no solution with high concentrated sulphur is used, the remaining solution to investigate is to start with a high concentrated sulfur content diesel fuel. This fuel has known properties and is considered to be a standalone fuel, with its own mixing recipe and unknown constituents to the author. B0 was added to combine with the high sulfur concentrated diesel in order to obtain two lower concentrations of sulphur. For the water contamination tests, three different concentrations of water are combined with B0 fuel. All contaminated fuels are compared with the original used fuel, B0.

The presentation matrix from Figure 29 was used to show the results. In this matrix the fuels presented on the x-axis are renamed as follow: **CF1** - *high sulfur content diesel* fuel, **CF2** – *medium sulfur content diesel*, **CF3** – *low sulphur content diesel*, **CF4** – *B0 fuel*, **CF5** – *high ppm water content*, **CF6** – *medium ppm water content* and **CF7** – *low ppm water content*.

No reference value is presented as the interest is only to see if contamination either with sulfur or water is measured by the sensors. There is no interest to compare the results with a reference value. If for water contamination test, the dielectric constant is the most important parameter that should offer useful readings, for sulphur it is the combination of fuel characteristics that might help interpret sulphur contamination. One has also to keep in mind that none of the tested sensors is claiming to be able to detect water or sulphur contamination.

Dielectric constant

When referring to dielectric constant measurements of Sensor A and Sensor B, in Figure 60 one can see that this parameter is not measured as it would be expected. Especially for water contamination test.

It is generally accepted that the dielectric constant value for water is very high, therefore an important change in dielectric constant, especially from simple B0 to *high ppm water content* is expected. Although *medium ppm water content* value at 20°C is looking more or less plausible, by analyzing the trend with temperature, it can be concluded that is actually an outlier. It is not likely to say that the dielectric constant is increasing with temperature; on the contrary, it should decrease. Moreover at 7bar and 20°C it is to be observed that the values are approximately equal, which is again implausible.

Sulfur contamination tests shows a slight increase of dielectric constant from B0 to *high sulfur content diesel*. This is less than the sensor accuracy offered by the manufacturer for dielectric constant and one can interpret as precision faulty readings. For B0 to *low sulfur content diesel*, the increase is even smaller. It can be thus concluded that the overall dielectric constant measured values for sulfur contaminated fuel are more realistic than the ones for water. Nevertheless the very small change cannot confirm that it is the presence of sulfur that leads to a increased trend.

As for water contamination, it is clear that neither Sensor A nor Sensor B are able to measure changes in dielectric constant as a result of water contamination. This might be so due to the fact that the fuel and water are separated, with the water laying at the bottom of the tank, not being recycled as a diesel-water emulsion through the piping and thus the sensors.

Density

When referring do density changes, it has to be mentioned that the standard density for B0 at 20°C is around 0,832 g/cm^3, while for the standard high sulfur concentrated diesel, the density is around 0,843 g/cm^3. As the second fuel type is a standalone fuel with possible other “contaminants” as well (e.g. aromatics) it is difficult to state that this difference is coming only from the sulfur content. When analyzing the effect of blending the *high sulphur content diesel* with B0 to obtain *medium sulphur content diesel* it can be seen that density decreases, as B0 has a lower density. This trend is observable when going even lower at *low sulfur content diesel*. Sensor C also captures this descending tendency in density values, as B0 is added in order to lower the level of sulfur in the mixture as can be seen in Figure 62. Thus, by analyzing the measured values in both Figure 61 and Figure 62, it can be concluded that the general trend is that with increased level of sulfur, fuel’s density will go up. Nonetheless, it is unrealistic at this level and with this type of blending procedure to clearly state that it is only the sulfur in the fuel that leads to increased diesel density. Also, for the very low regulated sulphur content [17] it is very improbable that any of the tested sensors will be able to measure the difference.

When investigating the water contamination it can be seen in Figure 61 and Figure 62 that the density measurements are physically implausible and thus cannot be considered as trustworthy.

It is to be concluded that at this level, based only on density reading it is hard to state that sulfur or water can be detected by either of the three sensors, especially for the very low regulated levels.

Viscosity

As it can be seen in Figure 63, most of the Sensor A and B measurements are showing no important difference between viscosities of different contaminated fuels (e.g. between CF1 (*high sulphur*) and CF3 (l*ow sulphur*)). The changes are as for density, improbable and thus one can conclude that it is hard to notice a clear trend in viscosity measurements once contaminants are present in the fuel. Therefore, at this stage of development, it is hard to use viscosity measurements as a way of detecting fuel contaminants, especially for less than the legislated maximum value for water and for sulfur contaminants.

Total Aromatic Content, bio content, lower heating value and cetane number

As it can be seen in Figure 64, Figure 65, Figure 66 and Figure 67 none of these measurements offer neither a valid trend nor good accuracy/precision that could lead to a certain conclusion of contaminant influence (water or sulphur in this case). That is why the overall conclusion for these constants is that without a specific parameter that could measure correctly and individually each contaminant, Sensor C is unable to detect any of these two possible contaminants.

Figure 60. Dielectric constant (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

Figure 61. Densities (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

Figure 62. Density measurements (y-axis) for Sensor C for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

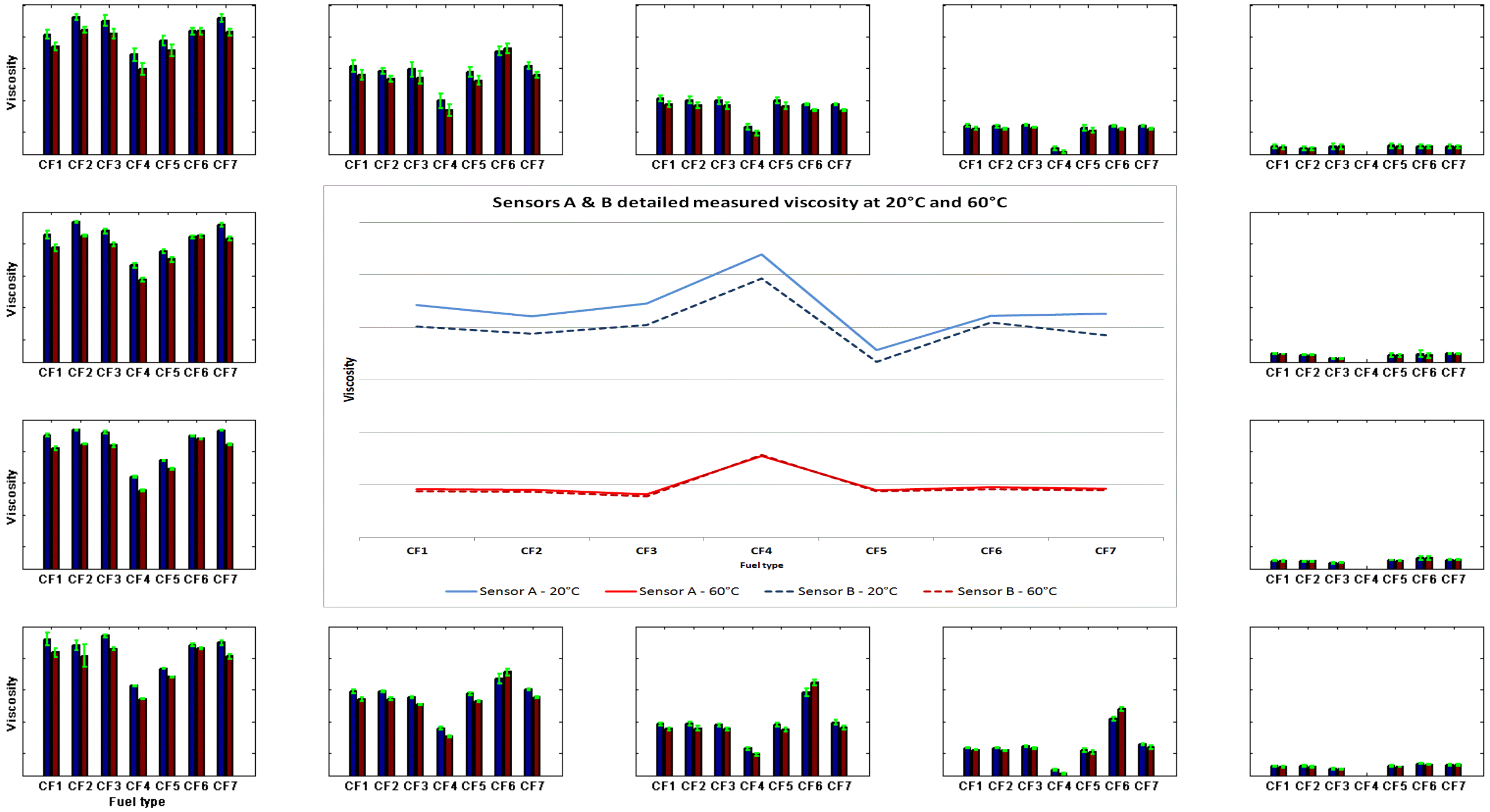

Figure 63. Fuels viscosities (y-axis) as measured by Sensor A (blue left bar) and Sensor B (dark red right bar) for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

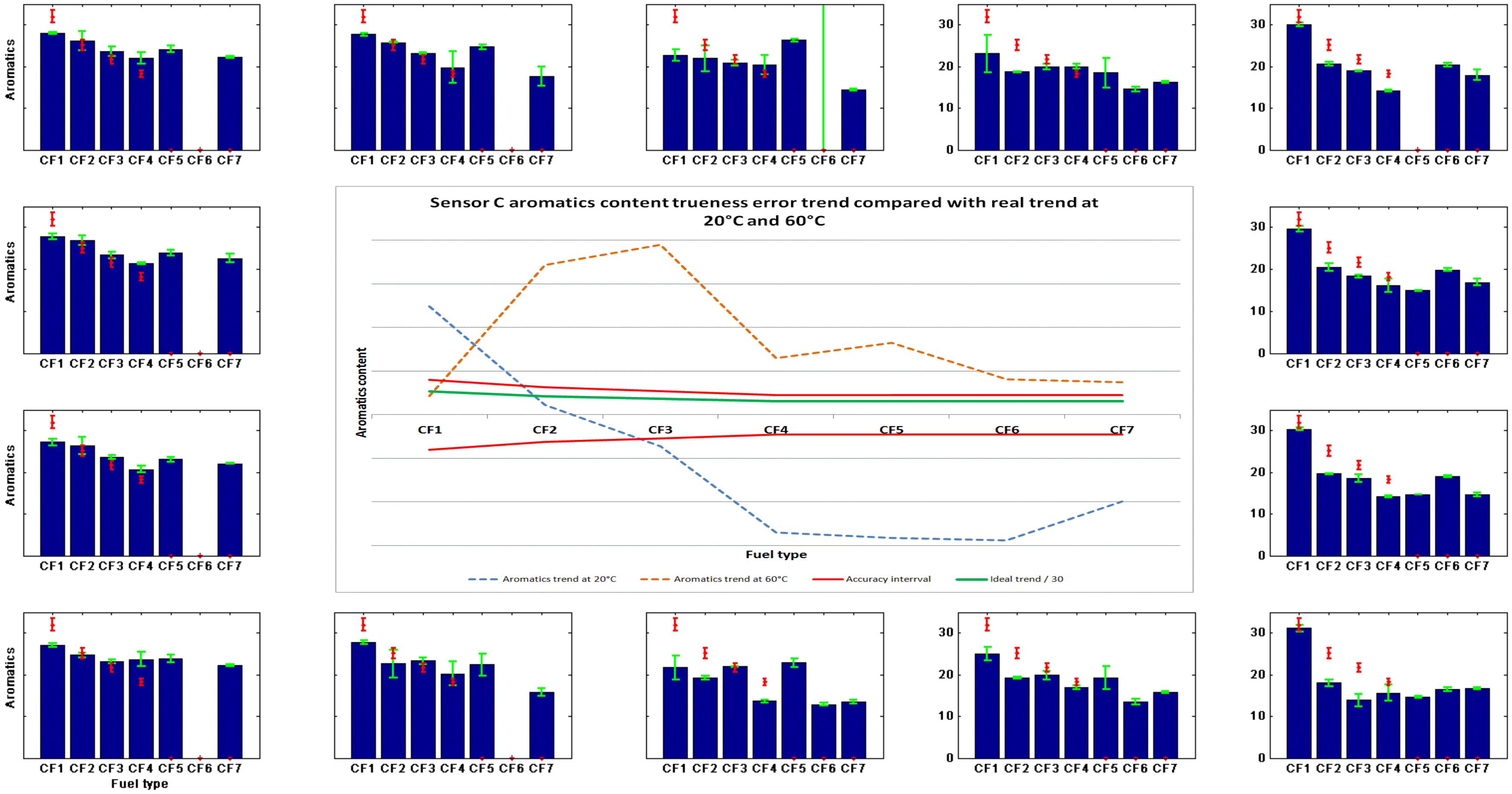

Figure 64. Aromatics content (y-axis) as read by Sensor C for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

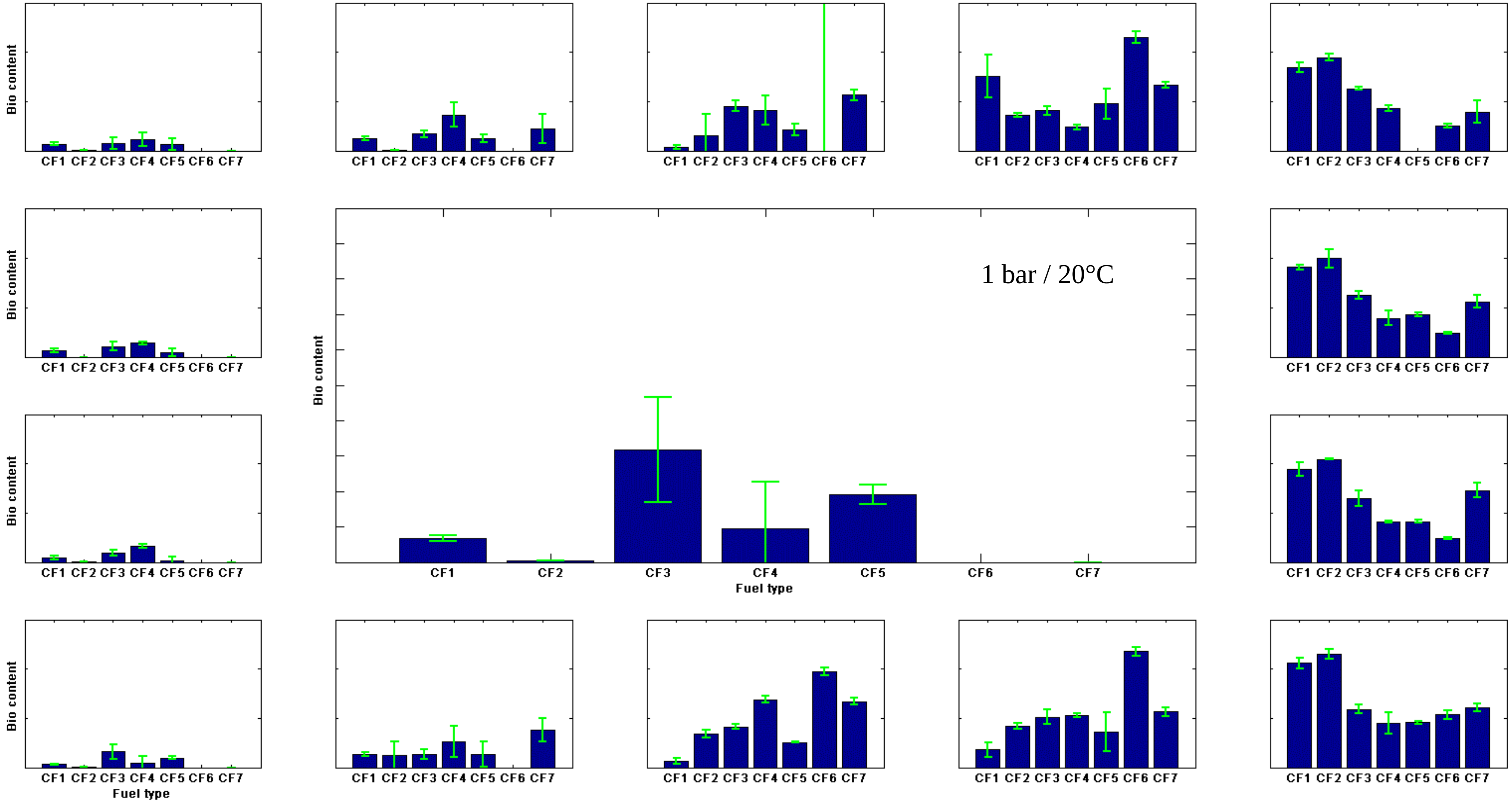

Figure 65. Bio content (y-axis) as measured by Sensor C for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

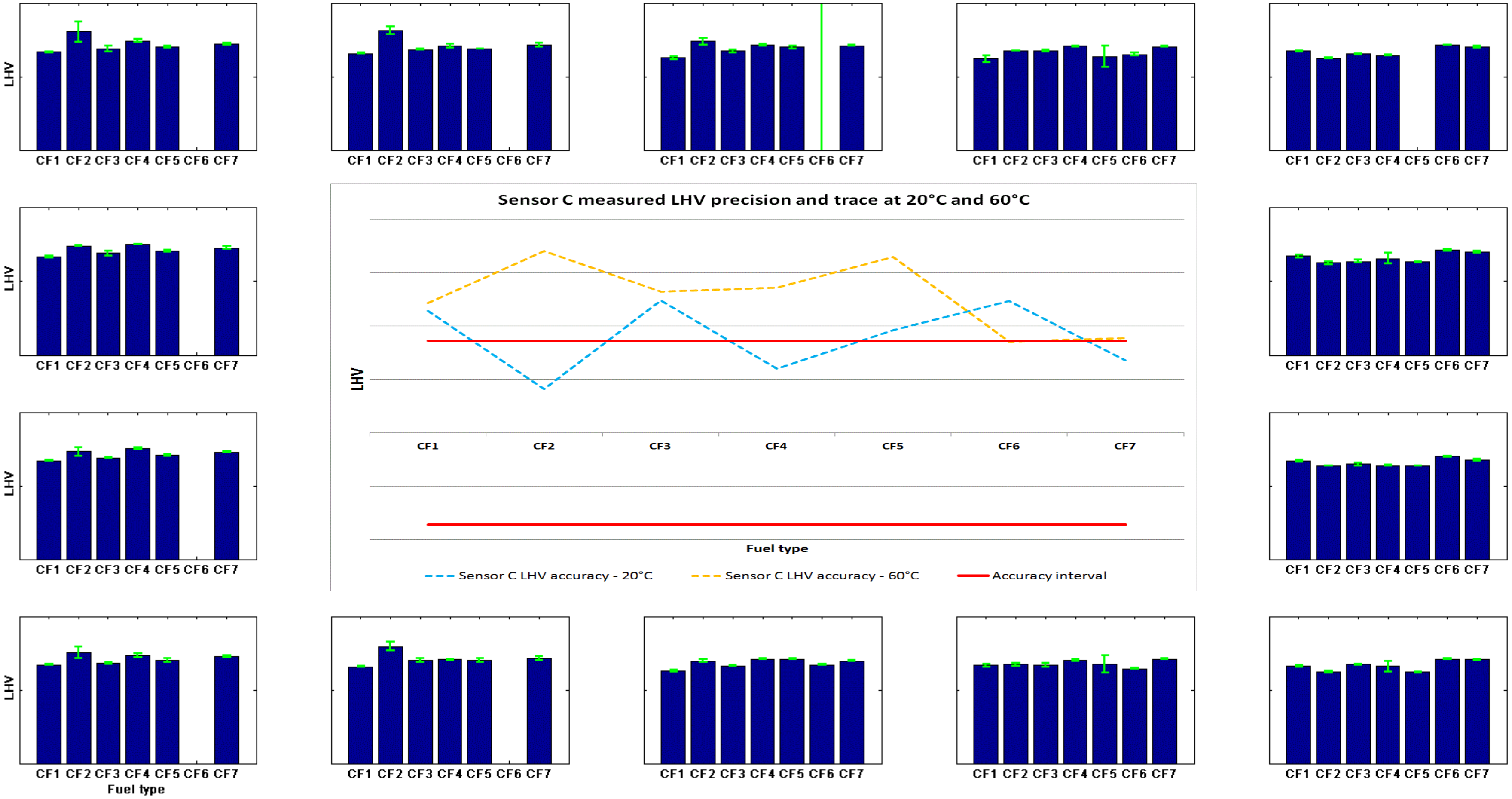

Figure 66. Lower Heating Value (LHV) (y-axis) content level as read by Sensor C for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

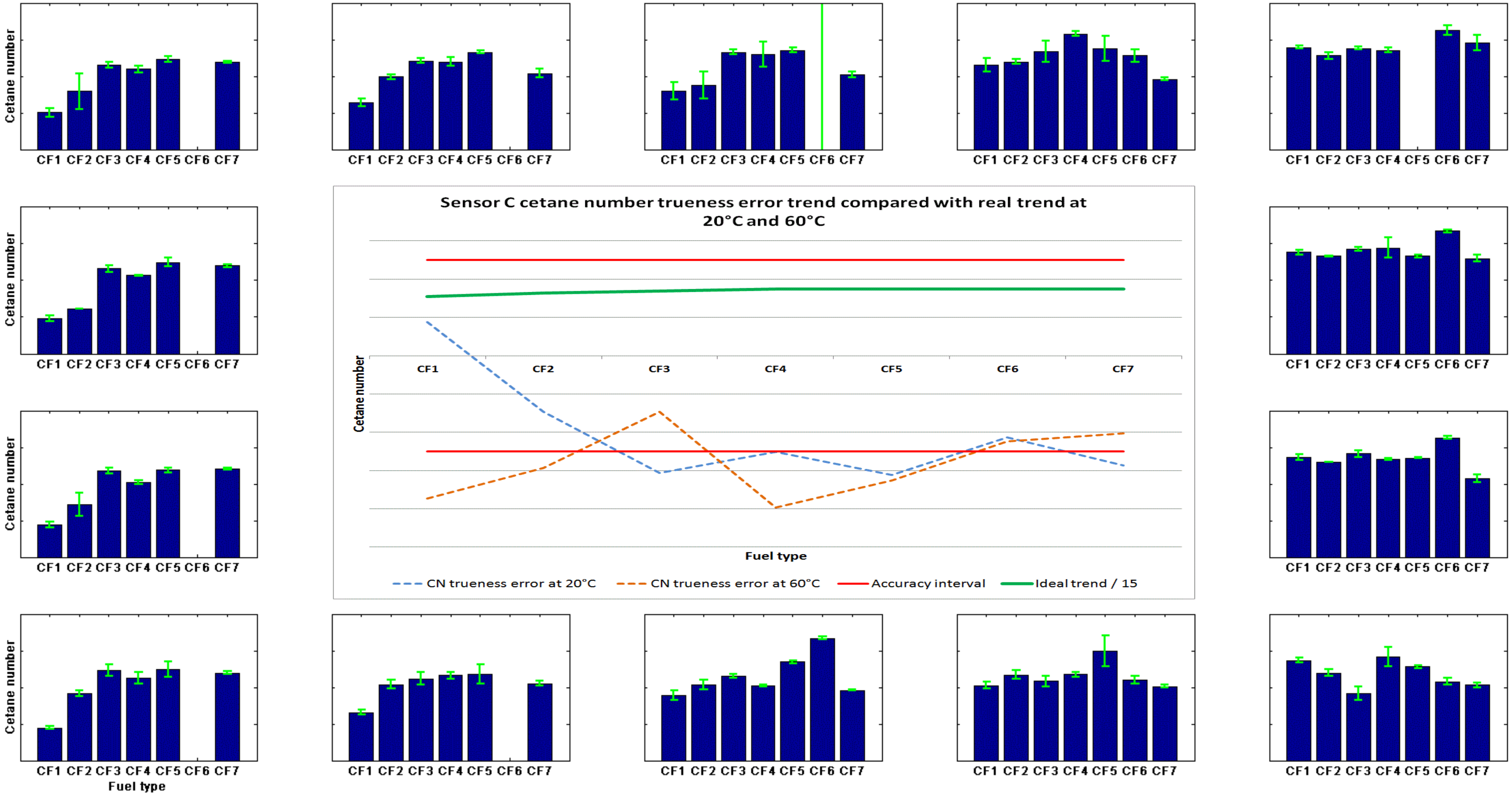

Figure 67. Cetane number (y-axis) as read by Sensor C for different types of contaminated fuels (sulfur and water contaminants) (x-axis) (CF1 - high sulfur content diesel, CF2 – medium sulfur content diesel, CF3 – low sulfur content diesel, CF4 – B0 fuel, CF5 – high ppm water content, CF6 – medium ppm water content, CF7 – low ppm water content).

4.6 Ethanol blends

Ethanol is largely use as a fuel for heavy duty engines, especially by the public transportation vehicles, namely busses. The most common blend is ED95 which is comprised mainly of 95% ethanol and 5% diesel. Also, some ignition improvers for cold starts are part of the blend along with corrosion inhibitors. With this type of fuel, emissions restrictions are more easy to pass for heavy duty engines than with regular diesel fuel, or even biodiesel.

Thus the interest for this type of blend is increasing a sensor that would be able to measure its characteristics would be very useful. Nonetheless, neither for the Sensor A and B nor for the Sensor C, the manufacturers state that the sensors are able to measure ethanol blends.Even so, four different types of ethanol/diesel blends were used for testing. Besides the normal ED95, three other blends were obtained by adding normal B0 to the original ED95. The resulting blends were "*high ethanol diesel*", "*medium ethanol diesel*" and "*low ethanol diesel*".

Out of 728 measurements presented in this table, only 2,6% (19 values) were inside the accuracy interval stated by the manufacturer (cells with green filling and white font). Out of these 48 points, 2 were measured by the Sensor B. The rest of 46 points were all measured by Sensor A. Sensor C was unable to measure any correct values.

ED95 blend was the worse blend to measure as both Sensor A and Sensor B were only showing the default maximum value in most cases. 7 bar and 50°C was the only point where the sensors were able to measure some incorrect values. Sensor C was able to record only one value, equal to 0, at low temperatures (20 and 30°C) and stopped working before recording at least another value for the rest of the situations.

For *medium ethanol diesel,* Sensor C had rather the same behavior, while the other two sensors started to record more values, especially on lower temperatures. Sensor A performed much better in comparison with Sensor B.

When referring to Sensor B sensor's ability to recognize fuel type, as values were recorded only for *medium ethanol diesel,* it has to be mentioned that as no ethanol strategy or fuel type is set, in most of the cases the sensor recognizes the blend as a blend of diesel and kerosene.

For *medium ethanol diesel,* Sensor B, the fuel quality recognition designated sensor has not measured any values as it happened after with *low ethanol diesel*. This sensor actually stopped working, and showed only the maximum default value, even when trying to measure fuels with known characteristics. After approximately 4 hours of continuous "conditioning" and functioning in B100, it started to work again. After this procedure, the values measured by the sensor for the mentioned known two fuels were similar to previously measured ones, and thus it was concluded that the sensor will be used further on.

Sensor A was the only one that worked with both *medium ethanol diesel* and *low ethanol diesel*. If for *medium ethanol diesel* was only able to record points from (30°C to 60°C), for *low ethanol diesel* has measured values no matter the test conditions. Sensor C started to record more than one value once with *medium ethanol diesel*. Still, even in *low ethanol diesel* case was unable to record all 5 points like in all the previous tests that involved Bxx fuels or contaminated ones.

In conclusion, it can be said that only Sensor A was able to perform arbitrarily and was able to read 46 out 168 points that it had to measure. At this level it is the only one that in a very little way might handle small percentages of ethanol in ED (ethanol-diesel) blends. The other two sensors were clearly in impossibility of offering any realistic and usable readings.

5. CONCLUSIONS

In this chapter general conclusions of the previously analyzed results are presented. These conclusions are divided in two: a discussion on each measured parameter and a technology/sensor comparison will be made.

5.1 Fuel properties of qualitative fuel

As already presented in chapter 2.1, either fuel properties or fuel contaminants have an impact on the overall engine operation and emissions. When analyzing them individually, the impact is not that important

5.2 On-board technologies

All the existing on-board technologies are categorized and described as used by other researchers in chapter 2.3.

5.3 Sensors for measuring fuel properties

The chosen sensors to be tested during the current work are described in chapter 2.4. Their performance and results as presented by other researchers are also discussed.

5.4 Fuel parameters

Density

All three sensors show acceptable capabilities of reading density. Unfortunately for Sensor C, this conclusion is valid only for the standard conditions stated by the manufacturer. As it is missing a model for density changes with increased temperature, the sensor lost in precision at higher temperatures. The sensor also has problems with measured density for fuels other than diesel fuels (e.g. gasoline, iso-octane,etc.), when the measured value is 0.

From the precision point of view, the tested sensors offer good results, and not considering some outliers, all three of them have measured values within the manufacturer specified tolerance interval.

When relating to trueness error, at 20°C and 1 bar, where reference values are compared with measured values, all sensors offer acceptable values. The model used for density changes with increased temperature is not always adapted for all fuel types, and thus makes the sensor readings to be high on precision (but within detection interval in most cases). Also, Sensor A proves to have a lower trueness error than Sensor B. Sensor C has also a low trueness error at 20°C and 1 bar, and in some situations (e.g. diesel and biodiesel blends) with better measurements than Sensor B.

The tuning fork sensors show low capability to detect very small changes from low ppm concentrated contaminants. From this point of view, Sensor C shows better abilities although the measurement values are a bit exaggerated.

Viscosity

Viscosity is only measured by Sensor A and Sensor B. At 40°C, both sensors offer realistic readings for well-defined and known fuels. Even for special fuels like gasoline or n-heptane, the measurements show good detection abilities for both sensors.

When referring to contaminated fuels, the large variance and the implausible measurements leads to same conclusion as for density. When low concentrations of contaminants, the sensors are unable to measure correctly the viscosity. One also has to keep in mind that the model used for reference values is possibly built wrong.

When referring to the trueness error, although both sensors show good ability to measure viscosity, it is Sensor A that offer better results than Sensor B. From the precision point of view, both sensors are measuring with respect to the manufacturer's stated interval.

Dielectric constant

Sensor A and B dielectric constant measurement ability is hard to assess at this level as the reference values, especially for well-defined fuels, remained unknown throughout the whole project. As there was no capability to measure this parameter in laboratory conditions, all the reference values are taken from literature and internet.

Nonetheless, both sensors are able to follow trends with temperature increase or contamination (e.g. toluene experiments) with good precision as well. When referring to special fuels, five out of seven fuels were rightfully measured at 20°C with low trueness error and precision.

Unfortunately, the dielectric constant specific tests (e.g. ethanol and water contamination tests) offer measurements that contain errors and values considered to be implausible.

Further tests are needed with well-defined fuels, from dielectric constant point of view, in order to make a final conclusion on tuning fork sensor ability to measure dielectric constant.

Aromatic content

Sensor C is the only sensor that is able to measure total aromatic content. Regrettably most of the measurements are unstable, inaccurate and imprecise. During the aromatic specific test (when toluene contamination was used), the sensor was unable to record realistic values although the toluene levels in the fuel present slight low trueness error.

Nevertheless, measurements taken in the *diesel-bioediesel blending* tests offer a imprecise, but plausible trend at 20°C. Precision is not in respect with the manufacturer stated interval.

Thus, at this level, aromatic content measurements are considered to be untrustworthy as measured by Sensor C.

With no specific strategy for aromatics content detection, for tuning fork sensors it is very hard to conclude that with a relatively constant density (as seen in Figure 42) and with both decreasing viscosity (see Figure 47) and dielectric constant (see Figure 48) it is aromatic content that the sensors detect.

Lower heating value

For lower heating values (LHV) measurement, Sensor C offers good readings only for well-defined fuels. MK1 is one of the well-defined diesel fuels that this sensor is unable to measure, as well as kerosene. One reason could be their Swedish market specificity. Also during the aromatics tests (with toluene contaminant), LHV was not measured in all cases. This has no logical explanation as if the fuel recognition algorithm would not work for these fuel types, other parameters would not be recorded either.

From the precision point of view, the difference between the maximum and the minimum measured value is within the reference interval stated by the manufacturer. The trueness error is also rather good at 1bar and 20°C.

More investigations are needed before making a final conclusion on sensor ability to measure lower heating value.

Cetane number

At 1bar and 20°C Sensor C offers realistic values with good precision and acceptable trueness error. The main reason for plausible values is the large accuracy interval stated by the manufacturer, as not always, the sensor is able to follow a certain trend (e.g. Bxx fuels cetane number).

Sensor C does not offer RON values for gasoline type fuels, and thus, in the special fuels tests no values were measured for gasoline, iso-octane and n-heptane.

However, for all diesels, the cetane number readings can be used as they are offered by Sensor C.

Bio content

Is a characteristic measured only by Sensor C. During the specific tests for measuring bio content (*diesel and biodiesel blend test*) the sensor offers relatively good accuracy and precision readings. If precision is good for most of fuel types, the trueness error is not measured within stated intervals for all analyzed fuels. Yet, the sensor is able to follow the descending trend (from B100 to B0) with all the blends.

For the other tests, with contaminants or special fuels, Sensor C measurements are unreliable and imprecise.

Bio content readings can be used for future tests with the reserve that the fuels should be well defined from the FAME content point of view. Lower concentrations of contaminants might affect measurements precision.

Fuel recognition

Two sensors are able to detect fuel types. The tuning fork Sensor B has a brief number of fuels that can detect, while Sensor C uses NIR technology to detect level of diesel, gasoline and toluene content in each fuel. If Sensor B can specifically state what type of fuel it measures (e.g. gasoline95, diesel or light marine diesel, etc), Sensor C is only reading the mentioned parameters.

Nonetheless, Sensor B is only able to detect well defined fuels (e.g. B0, B100, gasoline, kerosene, etc.), and has difficulties in categorizing more complex fuels (e.g. marine diesel, MK1, iso-octane, etc.). Sensor C is also able to detect diesel, gasoline and toluene content in fuels with good precision. Trueness error is acceptable especially for well-defined diesel fuels.

Final conclusion is that for well-defined fuels, the sensors are able to measure the fuel type.

5.5 Technology and sensor comparison

One needs to keep in mind that all of these measurements offer no results when referring to reproducibility for all sensors and fuel types. Only one type of each sensor was tested and for each fuel, only one measurement was performed.

A first conclusion is that at this level is rather hard to exactly determine which fuel quality sensor is better suited for fuel analysis.

For well-defined fuels, all three sensors offer low trueness error and precise readings of density. From this parameter point of view the lowest trueness error is measured by Sensor A, closely followed in most cases by Sensor C and then by Sensor B.

Having only density as a measure of comparison for all three sensors, it can be said that both technologies are comparable in results.

When comparing the tuning fork sensors between each other, and with viscosity and dielectric constant measurements in mind, it is again Sensor A that has the lowest trueness error. From precision point of view, both sensors are comparable.

Sensor C ability to measure cetane number, lower heating value, aromatic content, diesel, biodiesel, gasoline and toluene content is sensor specific and cannot be compared at this current level with any other used sensor.

Sensor C besides density and cetane number is not able to measure with good precision all the other parameters. From trueness error point of view, only density, cetane number and lower heating value offered acceptable readings, though only for well-defined fuels; all other measured properties are either unstable or imprecise at this point. It need to be kept in mind also that Sensor C has better results only at 20°C and 1 bar.For all three sensors, small concentrations of contaminants or “additives” (e.g. sulphur, water or toluene) are not detected.

It has to be mentioned also that the tuning fork sensors offer good readings for all measured parameters even with temperature variance. Furthermore, Sensor A and Sensor B have the capability to correctly measure fuel temperature.

Final conclusion is that at this level, and strictly applicable to the tested sensors, the overall measurements by Sensor A and Sensor B are more stable and reliable than most of the Sensor C readings.

6. RECOMANDATIONS AND FUTURE WORK

This chapter contains some recommendations the author has for future work .

Considering thesis conclusions, one of the first recommendations that can be examined in the future is the possibility of developing a Scania specific fuel data base for Sensor A. Offering the more precise measurements for density, viscosity and dielectric constant, with an adapted fuel data base, the senor might prove to be the best solution at this point.

From the equipment point of view, a better built rig is a second recommendation. A more adapted and tighter fuel tank, able to safely accommodate different types of fuel (in particular special and highly flammable fuels like ethanol, n-heptane or toluene) is needed. Appropriate piping and joints would also increase the level of safety and tightness. Combined with a more effective fuel temperature control, a wider and constant range of temperatures can be tested in the future.

When referring to fuel types, a finer control of fuel or contaminant mixing might offer better measurements. Also, fuel and contaminants with known reference values would ease the comparison between the measured values and the sample values. Another good idea would be to make several measurements for same conditions and the same fuels or blends, as accuracy and precision result would be better defined this way.

As pressure did not influence the measurements as expected, an *in-tank* testing solution for Sensor A and B would be interesting to assess. Of course that if future developments of *in-tank* versions for the NIR sensors are available, this test could be attractive.

As for long term ideas for future work, next objectives could be considered for the selected sensors (considered viable for use on vehicle):

- physical and ambient tests (e.g. hot and cold conditions, vibrations, humid environment, etc.);

- tests with sensors mounted on vehicles in various locations;

- engine combustion control via an ECU (Electronic Control Unit) that receive information from fuel quality sensors (FQS). Resulting emissions measurement would be another interesting aspect to follow during these tests. During these tests (at constant loads), fuel quality is varied.

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APPENDIX A: LHV Special fuels

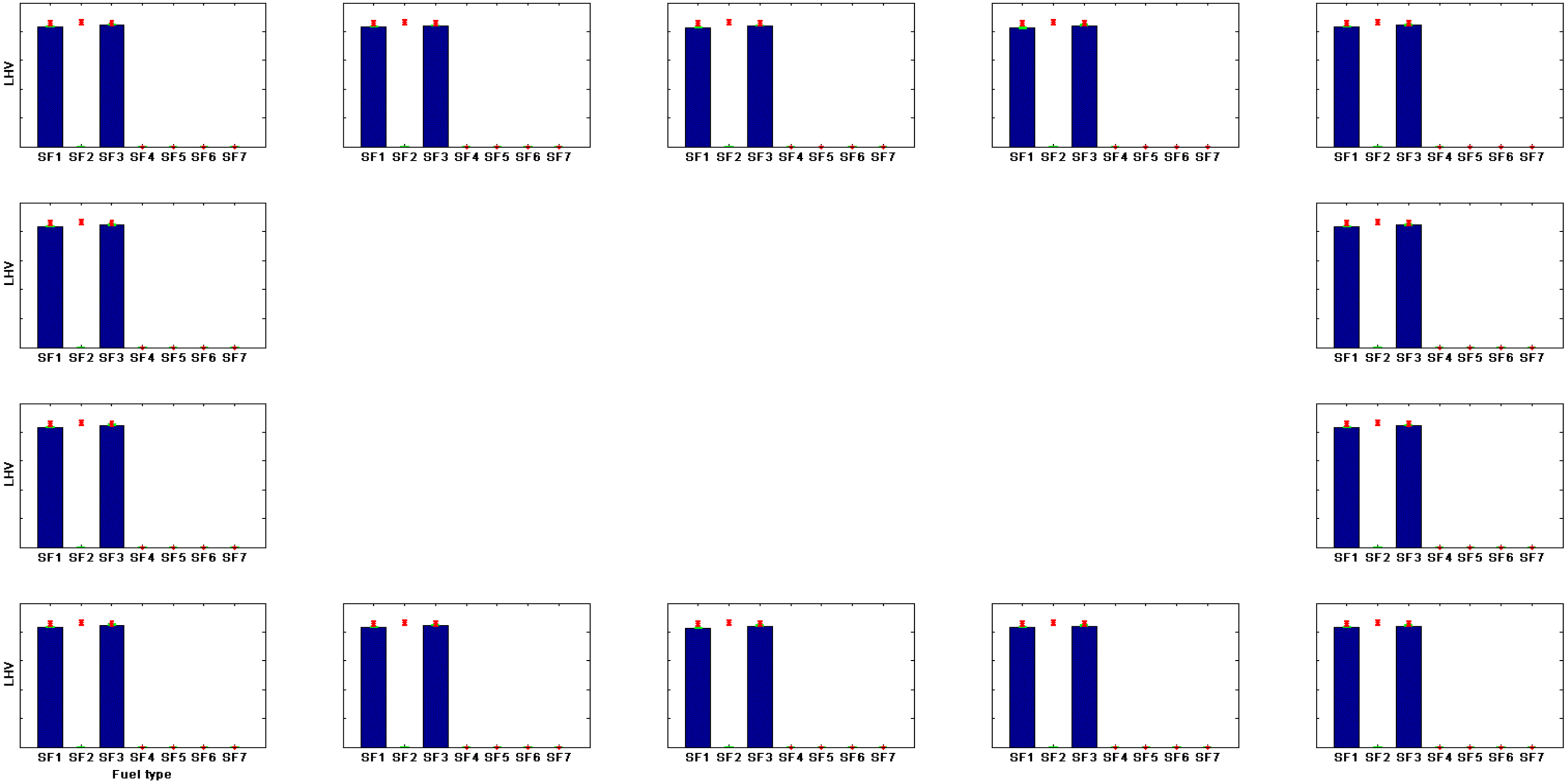

Figure 68. Lower Heating Value (LHV) (y-axis) content level as read by Sensor C for different types of special fuels (x-axis) (SF1 - high aromatics content diesel fuel, SF2 - MK1 diesel, SF3 - marine diesel, SF4 - kerosene, SF5 - gasoline, SF6 - iso-octane, SF7 - n-heptane)

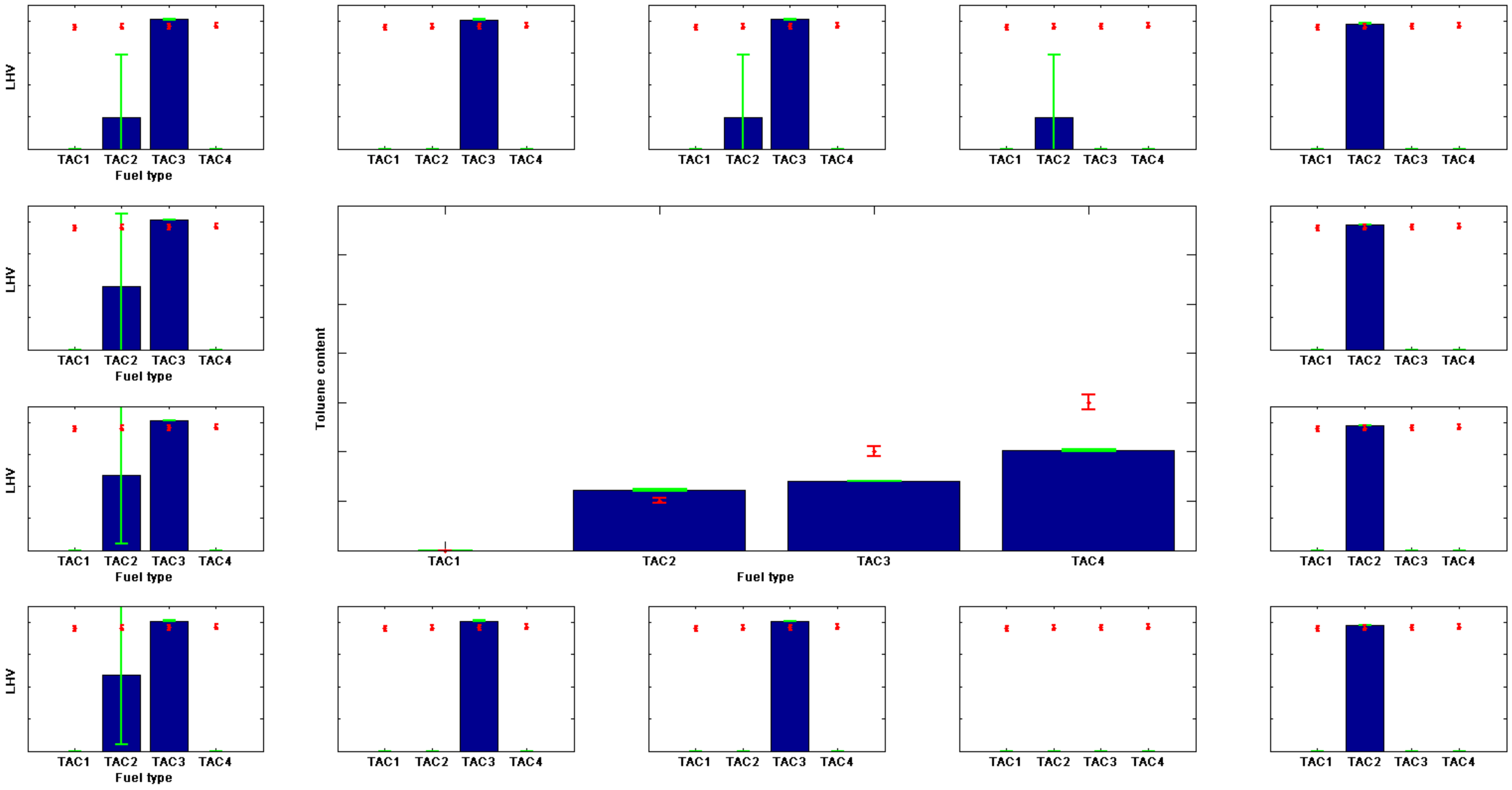

Figure 69. Lower heating value (LHV) (y-axis) content level as read by Sensor C for different types of toluene/diesel blends (x-axis) (TAC1 – b100, TAC2 – low toluene content, TAC3 – medium toluene content, TAC4 – high toluene content)