Energy for Sustainable Development 33 (2016) 149–154

Contents lists available at ScienceDirect

Energy for Sustainable Development

Experiments regarding the combustion of camelina oil/kerosene mixtures on a burner

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ARTICLE INFO

Article history:
Received 11 March 2016
Revised 27 May 2016
Accepted 28 May 2016
Available online 30 June 2016

Keywords:
Combustion
Camelina oil/kerosene mixtures
Burner
Exhaust gas analysis

ABSTRACT

Camelina is well-suited to be a sustainable biofuel crop, as its seeds naturally have high oil content. The process of obtaining bio-kerosene from camelina oil by hydrotreatment is time-consuming and expensive, thus the possibility of using straight camelina oil/kerosene mixtures as fuel in terrestrial applications is considered. For this purpose, combustion tests were conducted on a burner. Three camelina oil/kerosene mixtures were tested. The influence of the variation of the fuel preheating temperature was also studied and presented. During the tests, the composition of the exhaust gas and its temperature were monitored and registered using two gas analysers. The results were compared with those obtained when the burner was fuelled with pure kerosene.

Introduction

Camelina is an oilseed flowering plant that grows optimally in temperate climates, thus it can be cultivated in Romania. Camelina has several beneficial agronomic attributes: short growing season (85–100 days), compatibility with existing farm practises and tolerance of cold weather, drought, semi-arid conditions and low-fertility or saline soils. Camelina has lower water, pesticide and fertilizer requirements than traditional oilseed crops (Shonnard et al., 2010; Moser, 2012; Dobre and Jurcoane, 2011; Johnson, 2006).

Camelina is a second-generation biofuel feedstock (Anon., 2009). The biodiesel obtained from camelina oil meets the requirements of European and American standards for biodiesel, with the exception of two parameters: the iodine number and the oxidation stability (Frohlich and Rice, 2005; Moser and Vaughn, 2010; Ciubota-Rosie et al., 2013). This is due to the high levels of polyunsaturated fatty acids present in the composition of camelina oil.

On the other hand, the bio-kerosene obtained from camelina oil, by hydrotreatment or Fischer–Tropsch synthesis (Bauen et al., 2009), meets all the requirements regarding performance and safety (Frohlich and Rice, 2005) in order to be used in aviation applications. Starting from 2009, the U.S. Air Force successfully tested blends of classic aviation fuel/bio-kerosene obtained from camelina oil on fighting planes (http://en.wikipedia.org/wiki/Aviation_biofuel; Eynck et al., 2013). Passenger air companies such as KLM and Japan Airlines have successfully conducted flights using fuel mixtures of classic jet fuel and bio-kerosene obtained from camelina oil (http://en.wikipedia.org/wiki/Aviation_biofuel; Eynck et al., 2013).

Up to the present day. many researchers have investigated the possibility of using vegetable oils or biofuels obtained from these oils as fuels for internal combustion engines (Altin et al., 2001; Hartmann et al., 2012; Hazar and Aydin, 2010; Chalatlon et al., 2011; Drenth et al., 2014), for micro gas turbines (Cavarzere et al., 2012a; Chiaramonti et al., 2011; Schmellekamp and Dielmann, 2004; Rosa do Nascimento and Cruz dos Santos, 2011) or for furnaces and boilers (Hosseini et al., 2010; Oprea et al., 2008; Thuneke and Widmann, 2001).

The first results regarding the use of straight camelina oil as fuel were reported by Bernardo et al. (2003). They used camelina oil in diesel engines. The results of the study revealed that camelina oil showed an increased maximum power output, from 38.50 kW, in the case of the classic fuel, to 43.25 kW. A decrease of 50% of the carbon monoxide production was observed. Nitric oxide emissions were higher (6%) for camelina oil at high speed, but similar for the two fuels at speeds under 3500 rpm. CO_2 and O_2 levels were similar for both fuels (Bernardo et al., 2003). Paulsen et al. (2011) have also presented results regarding the use of camelina oil as fuel for diesel engines. Burning behaviour and exhaust emission data revealed that straight camelina oil can be used as fuel on diesel engines, but not for long periods of time due to its high Conradson carbon residue (CCR) values and low oxidation resistance (Paulsen et al., 2011). High CCR values may result in the formation of carbonaceous deposits and low oxidation resistance limits storage time (Paulsen et al., 2011). The remedy is relatively simple. Injection nozzles can be cooled to prevent carbon deposition and the oil can be supplemented with antioxidant additives.

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http://dx.doi.org/10.1016/j.esd.2016.05.004
0973-0826/

Table 1
Thermo-physical properties of tested fuels.

	Density ρ[kg/m^3] (at 15 °C)	Viscosity υ [mm^2/s]				Specific heat c_p [J/(kg K)]			
		40 °C	60 °C	80 °C	100 °C	20 °C	25 °C	30 °C	35 °C
100% camelina oil	926	31.1	17.5	10.9	8.1	2049	2068	2087	2107
75% camelina oil/25% kerosene	890	11.8	7.5	5.2	3.9	2024	2046	2067	2088
50% camelina oil/50% kerosene	869	5.1	3.6	2.7	2.1	2007	2025	2044	2062
25% camelina oil/75% kerosene	820	2.3	1.7	1.4	1.2	1982	2003	2024	2044
100% kerosene	786	0.79	0.45	0.25	0.14	1959	1978	1997	2015

Tests regarding the combustion of straight camelina oil in a furnace have not yet been reported. Thus, this is an area that needs more research to be conducted.

In this paper, results concerning the combustion process of camelina oil/kerosene mixture on a burner will be presented. The purpose of these tests is to observe flame stability, find the optimum fuel preheating temperature and study the combustion efficiency. Usually, burners function using diesel fuel, or other light fuels, not kerosene. However, camelina oil/kerosene has been taken into consideration because the ultimate objective is to test these unconventional fuels on a micro turbo engine, which, in general, functions on kerosene. Based on the conclusions drawn from the tests presented in this paper, it will be possible to define a suitable functioning regime for the micro turbo engine when fuelled with camelina oil/kerosene mixtures as well as an optimum fuel preheating temperature.

Experimental setup

The laboratory testing rig which was used during the experiments includes a multi-fuel burner, which can function fuelled by classic fuel as well as vegetable oil, waste oil or blends (Anon., 2012), a furnace made of heat-resistant bricks and an air compressor which delivers the air flow necessary for fuel entrainment and atomization to the burner (see Fig. 1).

The burner's fuel tank has an electric resistance inside, thus making the preheating of the fuel possible (Anon., 2012). The pressure of the air used for fuel entrainment and atomization and the air flow necessary for the combustion, delivered by the burner's fan, are adjustable (see Fig. 2).

The air flow delivered by the burner's fan was determined by measuring the air velocity using a Pitot tube connected to a KIMO MP200 anemometer (Anon., 2011). The air flow provided by the burner's fan was varied with the help of a fan position controller; this varied from 0 divisions (closed) to 30 divisions (opened at maximum).

The proportions of the camelina oil/kerosene mixtures used in the experiments are: 25% camelina oil/75% kerosene, 50% camelina oil/50% kerosene and 75% camelina oil/25% kerosene. In Table 1, the experimentally determined thermo-physical properties of the mixtures used in the combustion tests are presented. The measurement principle and the equipment used in the experiments are presented in detail in Petcu et al. (2014).

During the combustion experiments, all the measurements were made after the stabilization of the furnace temperature. The fuel temperature was monitored and maintained.

The concentrations of CO, CO_2, NO_x and O_2 in the exhaust gas and the exhaust gas temperature were monitored and registered for 5 min for each test, using two gas analysers, a MRU Vario Plus gas analyser (Anon., 2007) and a Horiba PG-250 gas analyser (Anon., 2004). The MRU Vario Plus gas analyser can record, with a frequency of 1 reading/second, the concentrations of CO, CO_2 and O_2 in the exhaust gas and their temperature. The Horiba PG-250 gas analyser can record, with a frequency of 1 reading/15 s, the concentrations of CO, CO_2, O_2 and NO_x in the exhaust gas. The measuring principles used by the analysers are the following: in the case of NO_x—the chemiluminescence method (Anon., 2004), in the case of CO and CO_2—the non-dispersive infrared method (Anon., 2007; 2004) and in the case of O_2—the zirconia cell method (Anon., 2007; 2004).

The measurements regarding the composition and temperature of the exhaust gas were performed on a single point of the furnace, as it can be seen from the gas analysers positioning represented in Fig. 3a and b. The point in which the measurements were performed was chosen on the furnace's symmetry axis and at a distance close enough to the flame front in order to ensure, at the same time, a proper characterization of the combustion process and temperature values that would not damage the gas analyser temperature probe.

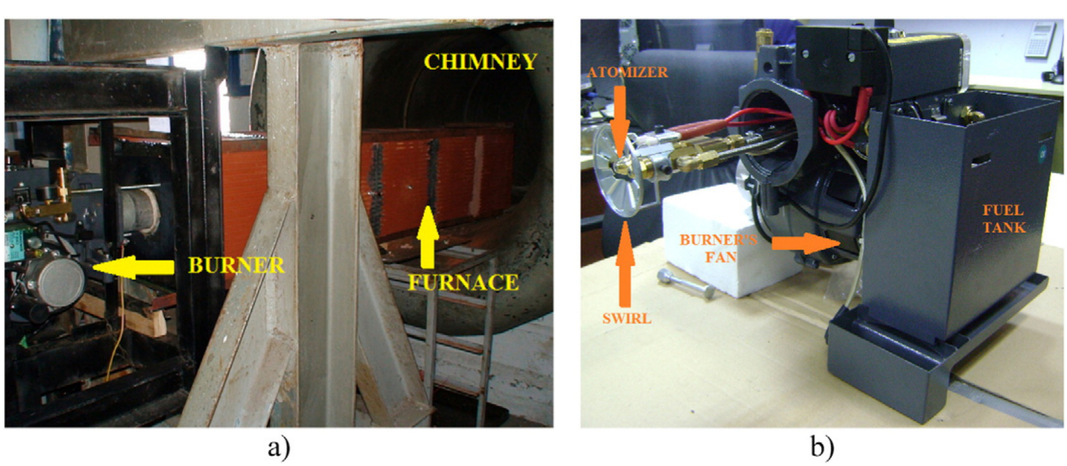

Fig. 1. (a) The testing rig, (b) Kroll KG/UB 100 burner.

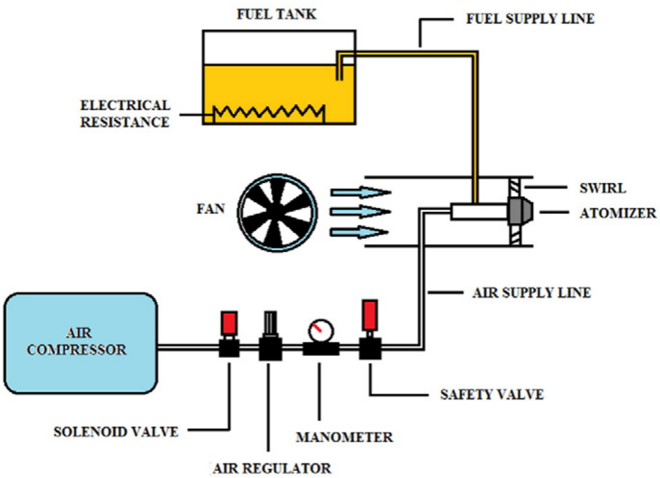

Fig. 2. Burner functioning scheme.

Results and discussion

Functioning regime

The burner was first started using 100% kerosene, at 25 °C. In this case, for the given furnace, the optimum pressure of the air used for fuel atomization was set to 1.5 bars and the air flow delivered by the burner's fan was at 228.5 kg/h. This functioning regime was used in all the tests conducted.

In Table 2, a list of tests performed on the test rig is presented.

During the combustion tests, the atomization air pressure and the air flow delivered by the burner's fan were kept constant at 1.5 bars and 228.5 kg/h, respectively. Two parameters were varied: the camelina oil percentage in the fuel mixture and the fuel preheat temperature. The fuel flow was determined by measuring the time in which 300 ml of fuel mixture was consumed. From the data presented in Table 2, it can be observed that the fuel flow decreases with the increase of camelina oil percentage in the fuel mixture for a given fuel preheat temperature. This can be an effect of the higher fuel mixture viscosity in comparison with pure kerosene's, as it can be seen from the values presented in Table 1. Camelina oil is more viscous than kerosene, its viscosity decreasing with the increase of the fuel temperature. This higher viscosity leads to an increase of the injection pressure. But during the combustion tests, the injection pressure was held constant, thus resulting in a decrease in the fuel flow when camelina oil/kerosene mixtures were used. The increase of the fuel mixture's temperature, resulting in a decrease of its viscosity, lead to an increase of the fuel flow. Even so, the fuel flow was lower when using camelina oil/kerosene mixtures than when using pure kerosene.

The figures below present the interior of the furnace during the combustion tests.

From the pictures above, it can be seen that the flame diminished with the increase of camelina oil in the mixture. The poor atomization of the fuel caused by the higher viscosity of the camelina oil/kerosene mixture can be observed in Fig. 4d. This is an effect of the greater percentage of the camelina oil in the blend (Petcu et al., 2014). For the given functioning regime, the burner could not be started when it was fuelled with 100% camelina oil at 25 °C. The burner could only be started when the camelina oil was preheated at 75 °C. The flame when the burner was fuelled with 100% camelina oil at 75 °C was small and

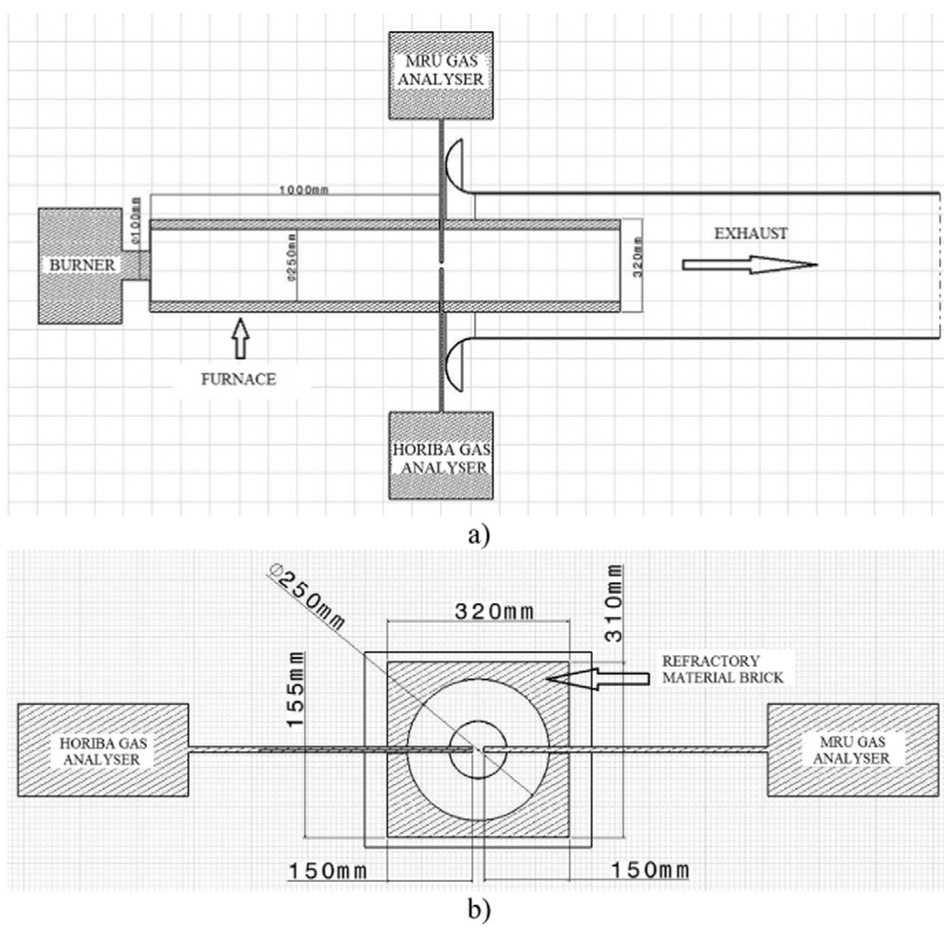

Fig. 3. The gas analysers positioning.

Table 2
Tested functioning regimes

Fuel	Fuel temperature [°C]	Atomization air pressure [bar]	Air flow [kg/h]	Fuel flow [l/h]
100% kerosene	25	1.5	228.5	11.7
25% camelina oil/75% kerosene	25	1.5	228.5	9.4
25% camelina oil/75% kerosene	50	1.5	228.5	10.3
25% camelina oil/75% kerosene	75	1.5	228.5	11.4
50% camelina oil/50% kerosene	25	1.5	228.5	8.0
50% camelina oil/50% kerosene	50	1.5	228.5	8.8
50% camelina oil/50% kerosene	75	1.5	228.5	9.3
75% camelina oil/25% kerosene	25	1.5	228.5	6.9
75% camelina oil/25% kerosene	50	1.5	228.5	7.4
75% camelina oil/25% kerosene	75	1.5	228.5	8.0
100% camelina oil	75	1.5	228.5	6.8

unstable; hence, it was not possible to take a clear photo of it. It has been concluded that, for this functioning regime, it is not safe for the burner to be fuelled with 100% camelina oil at 75 °C because the flame is unstable and may be extinguished. Thus, for future research, other functioning regimes will be tested when the burner is fuelled with straight camelina oil, preheated to at least 75 °C.

Exhaust gas analysis

From Fig. 5, it can be observed that the exhaust gas temperature decreases with the increase of the camelina oil percentage in the fuel mixture. This may be explained by the lower heating values of these mixtures in comparison with pure kerosene. A heating value for camelina oil was not found in the specialized literature nor was dedicated equipment for measuring this characteristic available. However, heating values for similar vegetable oils have been found, these varied around 37 kJ/kg (rapeseed, 37.2 kJ/kg; sunflower, 37.1 kJ/kg; soybean, 36.9 kJ/kg) (Cavarzere et al., 2012b). These values are lower than the heating value of kerosene: 42.8 kJ/kg (Anon., 2005). On the other hand, the exhaust gas temperature increases with the increase of the fuel's preheating temperature. This can be explained by the fact that the fuel's viscosity decreases with the increase of the temperature (Petcu et al., 2014), thus leading to a better atomization and a more efficient combustion process.

From Fig. 6a, it can be observed that the CO concentration decreases significantly with the decrease of the camelina oil percentage in the mixtures. This indicates the lower oxidation rates of the carbon monoxide with the increasing amounts of camelina oil present in the mixture. This is due to the decrease of the residence time of the CO molecules in the oxidation zone, caused by the increase of the time necessary for the atomization and vaporization of the more viscous camelina oil droplets. This reconfirms the fact that the combustion efficiency is strongly influenced in a negative way by the presence of the camelina oil, for the given functioning regime.

Analysing Figs. 5 and 6a, it can be observed that the CO concentration decreases with the increase of the exhaust gas temperature. In a

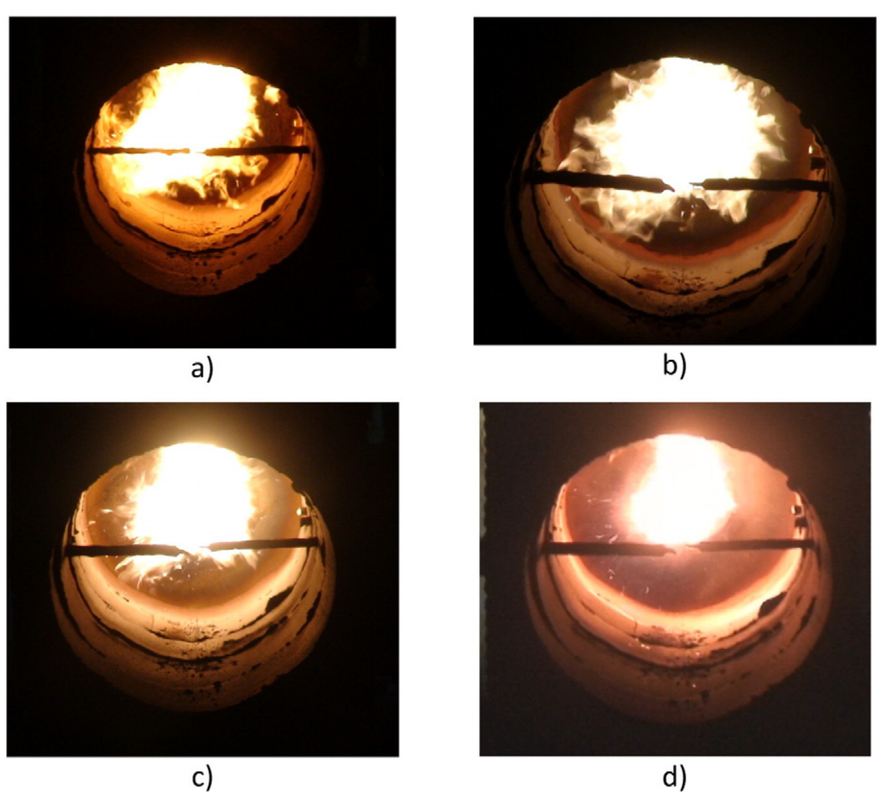

Fig. 4. The interior of the furnace while the burner was fuelled with: (a) 100% kerosene at 25 °C; (b) 25% camelina/75% kerosene at 25 °C; (c) 50% camelina/50 %kerosene at 25 °C; (d) 75% camelina/25% kerosene at 25 °C.

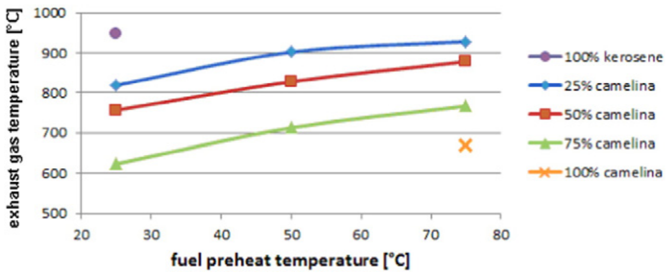

Fig. 5. Exhaust gas temperature function of fuel preheat temperature and of the fuel composition.

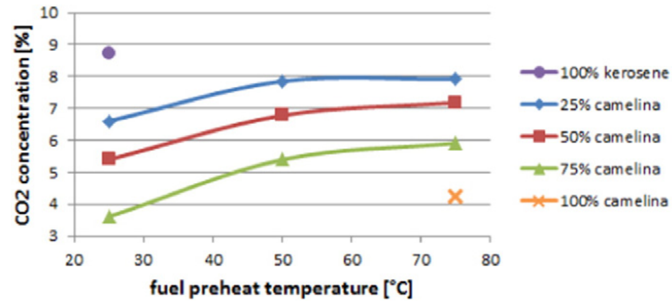

Fig. 7. CO_2 concentration in the exhaust gas function of fuel preheat temperature and of the fuel composition.

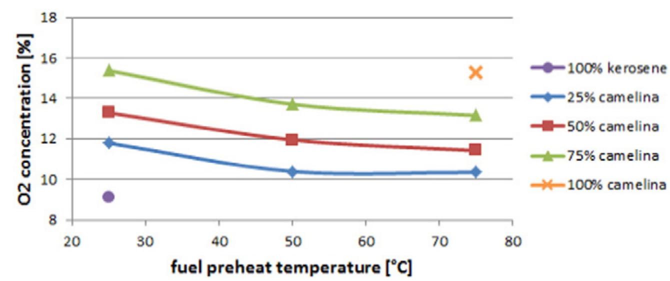

Fig. 8. O_2 concentration in the exhaust gas function of fuel preheat temperature and of the fuel composition.

combustion process, the most important amount of heat is released during the oxidation of carbon monoxide into carbon dioxide (Turns, 2000; Lefebvre and Ballal, 2010). Therefore, exhaust gas with a high CO concentration will have lower temperatures.

Reducing the scale in Fig. 6a from 3500 ppm to 500 ppm, it can be observed in Fig. 6b that the fuel mixture of 25% camelina oil/75% kerosene preheated at a temperature higher than 50 °C provides similarly low CO emissions as in the case of 100% kerosene. Similarly low CO emissions were also obtained when a fuel mixture of 50% camelina oil/50% kerosene preheated at 75 °C was used.

The CO_2 concentration increases with the increase of the fuel preheat temperature, this being an effect of the combustion process improvement. Also, it can be observed from Fig. 7 that the CO_2 concentration decreases with the increase of camelina oil percentage in the mixture. The CO_2 concentration decrease is not totally justified by the increase of the CO concentration. The presence of CO in the exhaust gas is a sign of incomplete combustion (Turns, 2000; Lefebvre and Ballal, 2010). During an incomplete combustion process, in addition to CO, there are also unburned hydrocarbons (C_xH_y), the presence of which also leads to the decrease of the CO_2 concentration. Results regarding the concentrations of unburned hydrocarbons in the exhaust gas are not presented because the gas analysers used were not able to measure these. The trend followed by the CO_2 concentration is also in good correlation with the behaviour of the exhaust gas temperature, the concentration increasing with the increase of the temperature.

From Fig. 8, it can be seen that the O_2 concentration behaviour is in accordance with the trend followed by the CO concentration, the O_2 concentration decreasing with the decrease of the CO concentration. This is caused by the larger quantities of O_2 and CO consumed to create the CO_2 concentration shown in Fig. 7. The O_2 concentration increases with the increase of camelina oil percentage in the mixture, suggesting a less efficient combustion process of the camelina oil/kerosene mixture in comparison with the pure kerosene, for this functioning regime. The growth of the fuel preheating temperature leads to an improvement of the combustion process efficiency, this being confirmed by the decrease of the O_2 concentration in the exhaust gas.

The trend followed by the NO_x concentration is in accordance with the behaviour of the exhaust gas temperature, the NO_x concentration increasing with the growth of the temperature. The growth of the exhaust gas temperature favours the dissociation of the nitrogen molecules which leads to the formation of the nitrogen oxides (Turns, 2000; Lefebvre and Ballal, 2010). From Fig. 9, it can be seen that the NO_x concentration decreased with the increase of the camelina oil

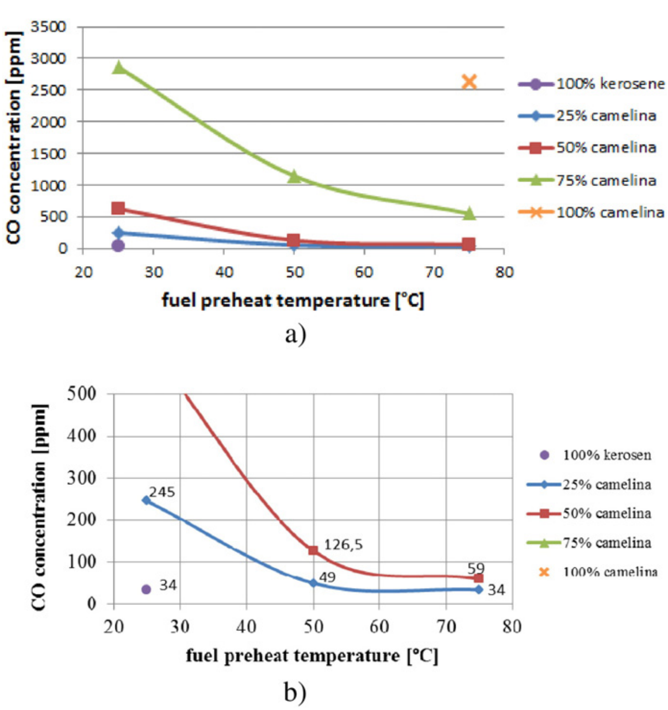

Fig. 6. CO concentration in the exhaust gas function of fuel preheat temperature and of the fuel composition.

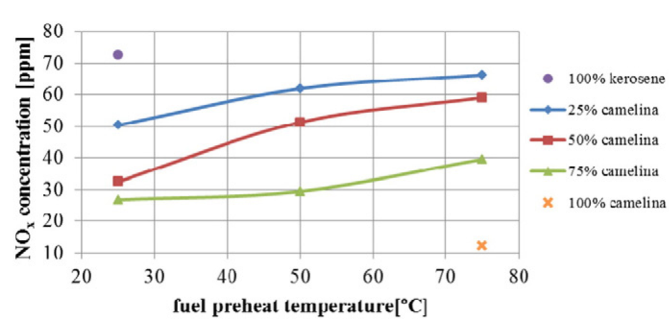

Fig. 9. NO_x concentration in the exhaust gas function of fuel preheat temperature and of the fuel composition.

quantity in the mixture, as well as its growth with the increase of the fuel preheating temperature.

Conclusions

Experiments concerning the combustion of camelina oil/kerosene mixture have been conducted for the same functioning regime of the burner; three fuel preheating temperatures were considered: 25 °C, 50 °C and 75 °C.

The results show that the increase of the camelina oil percentage in the fuel mixtures leads to a lower heating value, thus resulting in a decrease of the exhaust gas temperature. The CO_2 concentration is in accordance with the temperature behaviour, the CO_2 concentration decreasing with the decrease of the temperature. On the other hand, the CO and O_2 concentrations in the exhaust gas increase with the decrease of the temperature. The CO concentration increases significantly when the camelina oil percentage in the mixture is above 50%. This reconfirms the fact that a high percentage of camelina oil in the fuel mixture negatively influences the combustion process efficiency. This is caused by camelina oil's higher viscosity than that of kerosene's, which leads to a worse atomization of the fuel. The NO_x concentration in the exhaust gas decreases due to the decrease of the exhaust gas temperature.

The increase of the fuel preheating temperature, resulting in an improvement of the combustion process by lowering the mixture's viscosity, leads to an exhaust gas temperature growth. The trend followed by the CO_2 concentration in the exhaust gas is in good correlation with the temperature behaviour, the CO_2 concentration increasing with the growth of the temperature. On the other hand, the CO and O_2 concentrations in the exhaust gas decrease with the increase of the temperature. The NO_x concentration in the exhaust gas increases due to the increase of the exhaust gas temperature, the growth of temperature favouring the nitrogen molecules' dissociation, which leads to the formation of nitrogen oxides.

In conclusion, camelina oil/kerosene mixtures can be used as fuels for this kind of burner which can be used in heating systems. It has been shown that a relatively modest addition of kerosene in the fuel mixture leads to a substantial reduction of CO emissions, contributing significantly to an increase in the combustion efficiency.

The results obtained so far have led to the conclusion that an increase of camelina oil in the fuel mixture negatively influences the atomization process. The atomization process improves with the increase of the fuel preheating temperature, as a consequence of the decrease in the camelina oil's viscosity.

We have also reached the conclusion that an increase of the pressure of the air used for the atomization of the fuel will improve the performance of the combustion process.

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