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The Influence of Atomizing Media on the Quality of the Combustion of Liquid Fuels

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The aim of the work was to experimentally investigate the influence of atomizing medium on combustion properties of methyl-ester of rapeseed oil. Reserves of the fossil fuels are decreasing every day. This is the reason why the huge effort is devoted to finding out an alternative fuel to fulfil the energy demand of the world. Methyl-ester of rapeseed oil is one of the best available sources. The experiments were carried out in a water-cooled horizontal combustion chamber. The pneumatic atomization using the effervescent atomizer was used for tests. Compressed air and superheated steam were chosen as the atomizing media. The tests were performed at three levels of the gas-to-liquid (mass flow rate) ratio (GLR), namely 15, 20 and 25 %.
The experiments were focused on the investigation of flame characteristics, quality of combustion, NO_x and CO emissions, temperature of flue gas, heat transfer and stability of combustion. Results revealed that the heat transfer was higher for about 6 % when the compressed air was used for the oil atomization. This is most likely caused by the exothermic reaction between the fuel and compressed air (air is the reactant, steam is the inert). On the other hand, the atomization by compressed air led to higher NO_x emissions due to higher in-flame temperatures. The distribution of heat fluxes along the flame was very similar for both atomizing media. Combustion was observed stable without pulsation and fuel deposition at the bottom of the combustion chamber for all settings. The flue gas temperature was higher for about 20 °C during the atomization by the compressed air (compressed air – 653 °C, superheated steam – 635 °C). As for the flame characteristics, increasing GLR caused the reduction of the flame length and "sharper" flame.

1. Introduction

Economical aspects and environmental impact of liquid fuels from renewable sources substitution for fossils fuels are considered at many levels. The real environmental impact is debatable and discussed by several authors (Johnson, 2009). For proper liquid combustion, proper fine atomization is needed. Small droplets need a short time to evaporation and subsequent combustion. In this point of view the better atomization the better combustion is achieved. In this paper, the influence of atomization media on the quality of combustion is investigated. The literature search of the current level of knowledge revealed that none of the experiments was focused on the study of the influence of atomization media on the quality of atomization/combustion or emission production. For instance, one of the experiment was focused on substitution of the C-diesel fuel with different vegetable oil (sunflower, rape and soya) mixture used for heating domestic purposes in Spain (Alonso San José et al., 2008). Most of the experiments were focused on the study of the influence of fuel viscosity/fuel preheating (Kermes and Bělohradský, 2013), Gas to Liquid Ratio (Ochowjak, 2012), inlet pressure (Yokoi et al., 2016), high temperature combustion air (Wu, 2007), burner construction (Jedelský and Jícha, 2006), or fuel from renewable sources mixture with extra light heating oil (Alonso San José et al., 2006). The important part of liquid fuel combustion is CFD modelling (Gentile et al., 2016). Importance of this paper consists in a new idea that the atomizing media influences combustion properties. Different industry requirements (heat output increase, jet fouling prevention, emission production decrease etc.) can be solved by the different properties of the atomizing media.

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2. Experimental facility description

2.1 Combustion chamber

All experiments were carried out in a horizontal water-cooled combustion chamber. The inner diameter and the length of the chamber are 1 m and 4 m. The maximum heat output of tested burners is limited by the temperature of flue gas to 1,800 kW. The water cooling system is divided into seven individual sections which allow to evaluate heat fluxes along the flame. Each section has own flow rate and in/out temperature measurement. The combustion chamber has eight inspection windows along the horizontal part and 2 inspection windows located on the rear front of the chamber (opposite the burner). The windows allow to observe the flame and to evaluate its length and diameter. There is an ejector situated in the lower part of a stack. The ejector ensures the negative pressure in the combustion chamber. When the pneumatic atomization is used, the non-preheated air, the preheated compressed air or the steam can be utilized.

2.2 Fuel transport

Fuel was transported to the atomizer from the pressure vessel. The vessel was placed on the industrial scale. The fuel consumption was measured based on the weight decrease of fuel in the vessel per minute. The overpressure in the vessel was kept at 0.5 MPa.

2.3 Combustion air

The combustion chamber is equipped with a high-pressure ventilator. Its maximal capacity is 2,500 m_N^3/h at the overpressure of 4,000 Pa behind the ventilator. All experiments were carried out with the combustion air at the ambient temperature. The temperature of combustion air during all tests was approximately 8 °C.

2.4 Burner

A dual-fuel (liquid/gas) power burner was used for tests. Its maximal heat output is 1,400 kW. A schematic layout of the burner is in Figure 1. The flame ignition is performed by the gas premixed burner with the heat output of 18 kW. This burner also has a role of the flame stabilizer. The burner was in the operation during the tests except the test when the burning (flame) stability without the stabilization burner was tested.

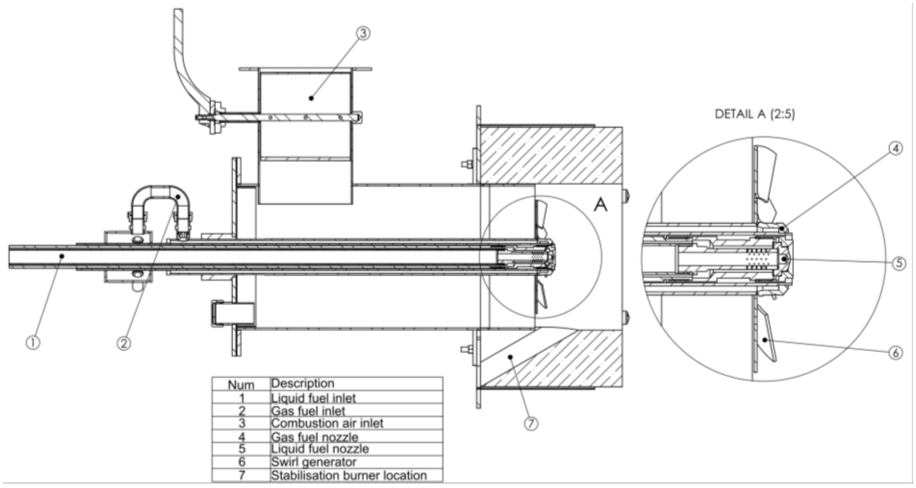

Figure 1: Schematic layout of the burner

2.5 Fuel

As an experimental fuel Methyl-ester of rapeseed oil was chosen. This fuel was certified for the usage in diesel engines according to the standard EN 14214:2008. The fuel analysis was carried out before the experiments. The fuel physical-chemical properties are summarized in Table 1. The analysis included the measurements of the higher heating value (HHV), the viscosity (at the temperature of 20 °C), the RME density, the flash point according to Pensky-Martens method (standard ISO 2719:2002) and the chemical element analysis (hydrogen, carbon, nitrogen, sulphur and oxygen). Subsequently, the lower heating value (LHV) was calculated. In Table 2, the results from the atmospheric distillation of RME are recorded. The intensive evaporation of RME started at 320 °C. Only about 1 % of RME was evaporated till 300 °C, which was probably caused by the impurities in the fuel (such as water, methanol etc.).

2.6 Emission measurement

The measurement of flue gas concentration (CO, NO_x, SO_x, and O_2) and flue gas temperature was located in the flue gas stack. Emissions were measured using the analyzers ABB EL 3020 and SIEMENS ULTRAMAT 23 when the compressed air and superheated steam were used for the atomization.

Table 1: Physical properties of RME

Kinematic viscosity at 20°C	mm^2/s	1.5
Flame point (PM)	°C	148
Density at 15°C	kg/m^3	883
Carbon	wt%	74.24
Hydrogen	wt%	12.61
Nitrogen	wt%	0.00
Sulfur	wt%	0.00
Oxygen	wt%	13.15
Stoichiometric air	m_N^3/kg	9.61
Stoichiometric air	m_N^3/MWh	905.6
HHV	MJ/kg	40.969
LHV	MJ/kg	38.203

Table 2: RME atmospheric distillation

Fraction	Temperature	Mass fraction [%]
1	85 - 320	5.3
2	320 - 330	79.4
3	> 330	15
loss		0.3
Control sum•		100

2.7 Atomizer

Because of the high boiling temperature of RME (see Table 2) very high quality of atomization was required. This can be achieved with the pneumatic type of atomization, namely the effervescent atomization. The Gas to Liquid ratio (GLR) was ranged between 15 % and 25 %. The atomizer used in tests was designed to the maximal mass flow rate of 120 kg/h at the fuel pressure of 1.0 MPa. Compressed air and superheated steam were used as the atomizing media. The maximal pressure of compressed air is limited to 1 MPa. The temperature of compressed air during all tests was 16 °C. Maximal pressure and temperature of the steam are 1.3 MPa and 180 °C.

3. Plan of experiment

All experiments were carried out at the burner's heat output of about 600 kW. The oxygen content in the dry flue gas was kept at 6 %. Variable parameters included the GLR and the type of atomizing medium. The experimental plan is shown in Table 3. In the experiment A, the NO_x and CO emissions were measured, and the combustion stability and the quality of atomization were investigated. In the experiment B, the heat flux into each section of the combustion chamber was evaluated. The influence of GLR on the investigated parameters was investigated only in the experiment A. On the other hand, the GLR was kept constant at 20 % in the experiment B (see Table 3).

Table 3: Plan of experiment

		GLR [%]		
Experiment	Atomizing media	15	20	25
A	Compressed air	•	•	•
	Superheated steam	•	•	•
B	Compressed air		•	
	Superheated steam		•	
•	Measured			

4. Results and discussion

Main operating parameters are shown in Table 4 and Table 5. It is evident that the main difference is in the flow rate of the combustion air. The combustion of fuel atomized by the compressed air is characterized with significantly lower combustion air flow rate compared to the atomization with the superheated steam. This can be explained by the fact that the combustion air needed for the complete combustion is partially substituted by the compressed air. On the other hand, steam is an inert and it does not react with the fuel.

Table 4: Main operating parameters – atomization with compressed air

GLR	Natural gas	RME				Combustion air	Compressed air
	Output	Flow rate	Output	Pres. before burner	Pres. in system	Flow rate	Pres. before burner
%	kW	kg/h	kW	kPa	kPa	m_N^3/h	kPa
15	37.3	52.0	551.8	180	500	685.8	220
20	44.3	52.0	551.8	220	500	708.3	260
25	39.5	52.0	551.8	300	500	733.3	350

Table 5: Main operating parameters – atomization with superheated steam

GLR	Natural gas	RME				Combustion air	Superheated steam
	Output	Flow rate	Output	Pres. before burner	Pres. in system	Flow rate	Pres. before burner
%	kW	kg/h	kW	kPa	kPa	m_N^3/h	kPa
15	81.0	52.0	551.8	220	500	794.5	260
20	61.0	52.0	551.8	280	500	880.0	300
25	82.3	52.0	551.8	300	500	847.0	360

4.1 Emissions

The influence of GLR and atomizing medium on the NO_x formation is shown in Figure 2. The results show that NO_x emission is decreasing with increasing GLR. This trend can be observed for both atomizing media. This was probably caused by higher flow rates of atomization media, which decreased in-flame temperatures in the flame core. Lower NO_x emission was measured when the fuel was atomized by the superheated steam. The atomization with steam, which is the inert, led to lower in-flame temperatures and to lower NO_x formation. As for the compressed air atomization, NO_x emission limit effective in the Czech Republic, which is 130 mg/m_N^3, was exceeded at GLR = 15 % and 20 %. The NO_x concentration was measured below the emission limit for GLR = 25 %. On the other hand, NO_x concentrations met the emission limit at all GLRs during the steam atomization. CO concentration exceeded the emission limit effective in the Czech Republic, which is 80 mg/m_N^3, during the steam atomization at GLR = 20 % and 25 %. High CO concentrations indicate the incomplete combustion due to the higher mass flow rate of steam. The steam as the inert cools down the flame and makes the mixing of evaporated fuel with the combustion air more difficult. All these aspects decrease the combustion quality. The CO concentrations measured during the atomization by the compressed air were negligible, which indicate good quality of both atomization and combustion. The influence of GLR on CO formation is shown in Figure 2.

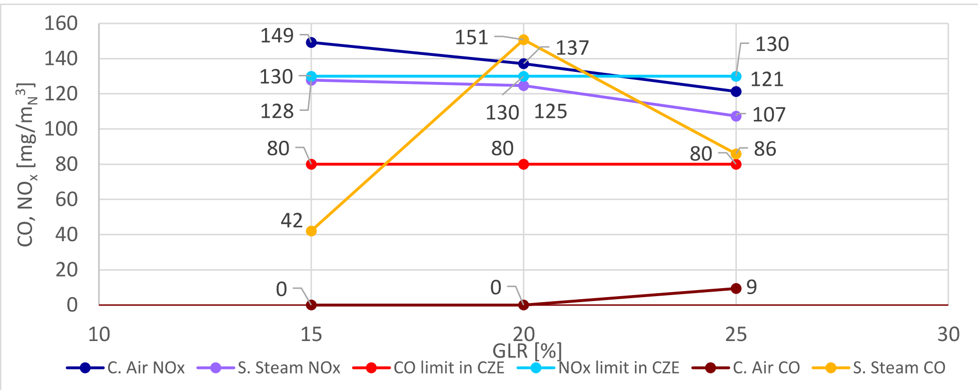

Figure 2: The influence of GLR on CO and NOx formation

4.2 Color and shape of flame, stability of combustion

In all tests, the length and the diameter of flame were approximately 2.0 m and 0.9 m. The flame was yellow and sharp in the case of the atomization with compressed air and soft in case of atomization with superheated steam. The test of burning stability was carried out without the support from the stabilization burner. The flame was stable in all tests. It did not tend to extinguish, flashback, or blow-off.

4.3 Temperature of flue gas and distribution of heat fluxes

In accordance with previous results, higher flue gas temperature was reached during the atomization with the compressed air. This was caused by the oxidation reaction between the atomizing medium (= air) and evaporated fuel. The average temperature difference between atomizing media was 18 °C. The influence of GLR on the flue gas temperature is shown in Figure 3.

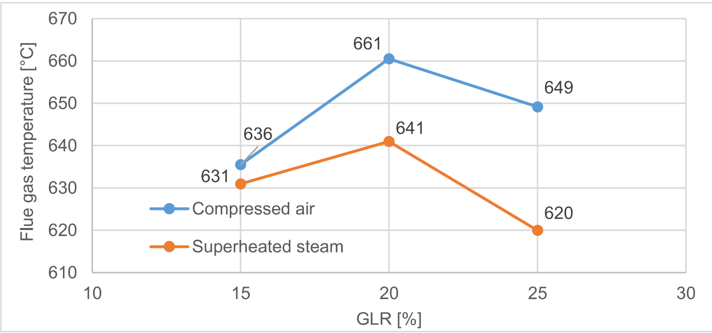

Figure 3: The influence of GLR on the flue gas temperature

Before the measurement of heat fluxes started, it had been necessary to set the combustion chamber to the steady thermodynamic state. This state was defined with both stable flue gas temperature (permissible temperature change is 10 °C within 30 min) and stabilized heat fluxes which were continuously evaluated. After the thermodynamic state had been achieved, the measurement of heat fluxes started. The gas burner was in the operation during this measurement. heat output of the burner was variable during the tests (see Table 6) and had to be considered in the calculation of the combustion efficiency. The efficiency was calculated as the ratio of absorbed heat (calculated based on the calorimetric equation for the cooling water) to heat input (the sum of heat inputs of RME and natural gas). The flow rate of RME was same during tests with both atomizing media. The difference between the efficiencies was approximately 6 % on behalf of atomization with compressed air which is in accordance with previous results. This fact is caused by the oxidation reaction between the atomizing medium (compressed air) and evaporated fuel. It was revealed that the heat flux distribution along the flame was very similar for both atomizing media. The average difference between heat fluxes achieved during atomization with compressed air and superheated steam was 4.5 %. The highest heat flux was achieved in the third section. In this axial distance from the burner, most of the fuel was evaporated and the combustion was the most intensive. The heat fluxes distribution is recorded in Figure 4

Table 6: Heat fluxes and efficiency of combustion according to atomizing media

			Compressed air	Superheated steam
Heat flux	section 1	kW/m^2	18.0	19.1
	section 2	kW/m^2	33.7	34.6
	section 3	kW/m^2	53.0	53.8
	section 4	kW/m^2	49.7	46.8
	section 5	kW/m^2	37.4	35.0
	section 6	kW/m^2	27.1	25.3
	section 7	kW/m^2	16.8	16.6
Heat flux sum of all section		kW	383.9	367.1
LHV RME		MJ/kg	38.2	38.2
Flow rate RME		kg/h	52.0	52.0
Heat output RME		kW	551.8	551.8
Heat output natural gas		kW	44.4	78.6
Efficiency		%	64.4	58.2

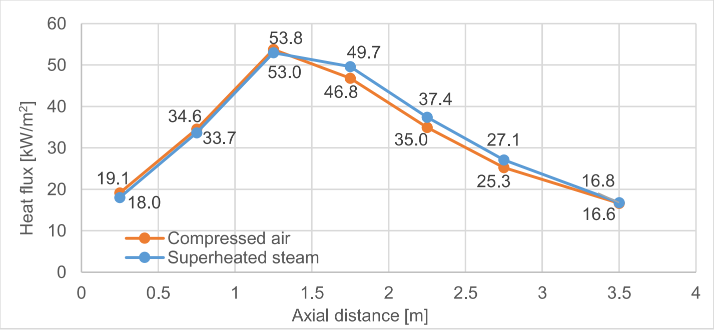

Figure 4: Heat fluxes according to section of combustion chamber

5. Conclusions

The influence of the atomizing medium on the quality of the combustion of liquid fuels has been investigated very little so far. In our tests, we revealed that higher efficiency can be achieved with the atomization with compressed air. The efficiency difference was 6.2 %. More intensive heat transfer was probably caused by the exothermic reaction between compressed air and evaporated fuel that consequently increased in-flame temperatures and heat fluxes. On the other hand, steam as the inert absorbed part of generated heat which resulted in lower in-flame temperatures). As a consequence of higher in-flame temperatures during the air atomization, higher NO_x formation by 13 % was observed.

The emission limit for CO effective in the Czech Republic was exceeded during the atomization with the superheated steam at GLR = 20 % and 25 % (CO emission limit was met at GLR = 15 %). The emission limit for NO_x was exceeded during the atomization with the compressed air at GLR = 15 % and 20 % (NO_x emission limit was met at GLR = 25 %). The emission limits for NO_x and CO were met in all other tests.

The heat flux distribution curves had the similar trend. The results did not reveal any significant influence of the atomizing medium on the heat transfer. The flame was stable during all tests.

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