Fuel Processing Technology 156 (2017) 204–210

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Stability and emission analysis of crude rapeseed oil combustion

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ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form 2 November 2016
Accepted 4 November 2016
Available online 12 November 2016

Keywords:
Rapeseed oil
Swirl burner
Flame stability
Pollutant emission

ABSTRACT

The investigation of renewable liquid fuels has received high attention in the combustion science of the past decades. However, the combustion of crude rapeseed oil has received less attention due to its poor combustion properties. Therefore, the scope of the current paper is to experimentally investigate its utilization in an atmospheric test rig designed for 15 kW combustion power. For the current investigation, a lean premixing and prevaporizing burner equipped with an airblast atomizer was used. During the investigation, the combustion air flow rate and the atomizing pressure were varied. For comparison, the same measurement series were carried out utilizing diesel oil. Stable combustion of rapeseed oil was limited by inadequate atomization, critical swirl number, and blowout. By contrast, diesel oil combustion was only limited by blowout. The emission of *CO* and NO_X were compared to an actual decree from which emphasized that CO governed the overall emissions. The optima are located at similar atomizing pressure and primary equivalence ratio for both fuels. Therefore, crude rapeseed oil might be an appropriate substitute for diesel oil in steady combustion.

1. Introduction

One of the greatest challenges of the 21st century is to solve the problem of sustainable economy. However, liquid fuels seem to dominate the transportation sector in the foreseeable future [1]. Regardless of the most probable step being the increase of the renewable content of the standardized fuels, the current paper investigates the combustion of crude rapeseed oil and compares it with diesel oil in a steady operating burner. Such solutions can be found in gas turbines [2,3], furnaces, and boilers [4,5]. By skipping the nowadays widely applied transesterification process of crude vegetable oil, the fuel production cost may decrease significantly. There are available research papers about the utilization of crude vegetable oils in heat engines (see, e.g., [3,6,7]) but in a smaller number than the investigation of transesterified ones (e.g., soy or rapeseed methyl ester [8]).

To prevent the contaminations [3,9], malfunction [10] or even failure [11] in a heat engine, more data is required in order to understand the design requirements of the combustion of vegetable oils. There is wide agreement among the researchers in that preheating of them is necessary to achieve proper atomization and evaporation [3,6,9,10,12,13]. A modern, lean premixing and prevaporizing (LPP) burner was used for the current investigation. It ensures homogeneous V-shaped flame through the breakdown of the precessing vortex core [14], hence, low nitrogen oxides emission [15].

Since there are significant differences in combustion properties of diesel oil and rapeseed oil (e.g., flash point, volatility, and heating value) [16,17], operation-related problems cannot be necessarily solved in all cases by preheating the fuel further [13]. Therefore, a blowout stability analysis is additionally required in addition to determining the safe operating regimes of the system running on such a fuel [11,18,19]. As a consequence, a flame blowout measurement was performed. To extend these limitations, there are different control techniques discussed in the literature (see, e.g., [11,20,21]). But these methods have to be configured for the particular combustion chamber.

2. Characterization of the spray and the swirling flow

2.1. Spray characteristics

In order to characterize a spray with a single parameter, the Sauter mean diameter (*SMD*) is usually estimated, which is the average volume-to-surface droplet diameter of the spray. While in-situ spray measurement was presently not feasible, the widely recognized semi-empirical formula of Rizk and Lefebvre [22] was used here for its estimation:

$$SMD = d_0\left[0.48\left(\frac{\sigma}{\rho_A w_A^2 d_0}\right)^{0.4}\left(1+\frac{1}{ALR}\right)^{0.4}+0.15\left(\frac{\mu_L^2}{\sigma\rho_L d_0}\right)^{0.5}\left(1+\frac{1}{ALR}\right)\right]. \quad (1)$$

Bolszo [2], Prussi et al. [3], and Nakamura et al. [23] also used Eq. (1) for the same burner. Additionally, the Ohnesorge number (*Oh*), the

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http://dx.doi.org/10.1016/j.fuproc.2016.11.004

Nomenclature

ALR	air-to-liquid mass flow ratio [−]
B	height of the swirler vanes [m]
d_0	diameter of the fuel jet [m]
D_{premix}	diameter of the mixing tube [mm]
E	emission [mg/m^3]
G_x	axial thrust [N]
G_φ	axial flux of angular momentum [Nm]
L_{premix}	length of the mixing tube [mm]
$\dot{m}_\varphi$	mass flow rate through the swirl vanes [kg/s]
$\mathrm{MFR} = \frac{\rho_A w_A^2}{\rho_L w_L^2}$	momentum flux ratio [−]
$\mathrm{Oh} = \frac{\mu_L}{\sqrt{\sigma \rho_L d_0}}$	Ohnesorge number [−]
r	radial coordinate [m]
p_g	atomizing gauge pressure [bar]
R	radius of an orifice [m]
R_1	inner radius of the mixing tube [m]
$\mathrm{Re} = \frac{\rho_A w_A d_0}{\mu_A}$	Reynolds number [−]
s	thickness of swirl vanes [m]
S	swirl number [−]
SMD	Sauter mean diameter [m]
u	axial component of the velocity [m/s]
w	velocity [m/s]
$\mathrm{We} = \frac{\rho_A w_A^2 d_0}{\sigma}$	Weber number [−]
z	number of swirl vanes [−]
α	vane angle [deg]
λ	air-to-fuel equivalence ratio [−]
μ	dynamic viscosity [Pa s]
ψ	blockage factor [−]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscripts

A	atomizing air
L	liquid

Reynolds number (*Re*), the Weber number (*We*), and the momentum flux ratio (*MFR*) were calculated and discussed, due to their significant impact on atomization [24–26].

2.2. Swirl characterization

Being a dimensionless quantity, the swirl number (S) is widely used for describing swirling flows, hence swirling flames (see, e.g., [24,27,28]). It can be calculated as follows:

$$S = \frac{G_\varphi}{G_x R}, \tag{2}$$

proposed by N. A. Chigier and J. M. Beér [29]. However, exact measurement of the flow field is not available for determining S in the most cases. The axial thrust (G_x) and the axial flux of angular momentum (G_φ) can be estimated from the burner inlet conditions. Therefore, Eqs. (3) and (4) were used for our particular case, assuming the conservation of momentum [30]:

$$G_x = 2\pi \int_0^R \rho_A u_A^2 r dr \tag{3}$$

$$G_\varphi = \frac{1}{1-\psi} \frac{tan\alpha}{1 + tan\alpha \, tan(\pi/z)} \frac{\dot{m}_\varphi^2}{\rho_A 2\pi B}, \tag{4}$$

where ψ is the blockage factor of the swirl vanes, calculated by Eq. (5):

$$\psi = \frac{z\,s}{2\pi R_1 \, cos\alpha}. \tag{5}$$

3. Measurement configuration

The used LPP burner, equipped with an airblast atomizer, shown in Fig. 1. It has a central 0.4 mm diameter fuel pipe. Coaxially with this (1.4 mm outer diameter, 0.8 mm inner diameter), the high-velocity atomizing air enters the mixing tube then atomizes the low-velocity fuel jet. The third inlet section is for the combustion air which enters the mixing tube through four radial orifices and fifteen fixed 45° swirl slots. The length and the diameter of the mixing tube were L_{premix} = 75.5 mm, and D_{premix} = 26.8 mm, respectively. Note that this burner was designed originally for a micro gas turbine application.

Fig. 2 shows the atmospheric combustion test rig, incorporating the investigated LPP burner. The atmospheric pressure was 100,149 Pa, and the temperature was 22 °C. Both standard diesel oil (EN 590:2014) and rapeseed oil had a separate fuel line for easy changeover purposes. Its role is detailed in Section 4.1. Rapeseed oil arrives at the fuel mixer through an electric preheater, reaching 150 °C temperature. The fuel properties are listed in Table 1. The distillation curve and the evaporation analysis of the applied fuels were published elsewhere [12,31]. As the desired combustion power was 15 kW in all cases, the mass flow rate of the diesel oil was 0.35 g/s while the mass flow rate of rapeseed oil was 0.4 g/s calculated from their lower heating value.

The atomizing air passes from a high-pressure air system through a pressure regulator valve and a rotameter (3–30 l/min measurement range, 4% accuracy class according to VDI/VDE 3513) to the airblast atomizer. The gauge pressure of atomizing air (p_g) varied between 0.3 and 2.3 bar during the measurements and was measured by a pressure transducer (1 kPa accuracy). In a preliminary analysis, the thrust of the atomizing air correlated well with the adiabatic expansion through a

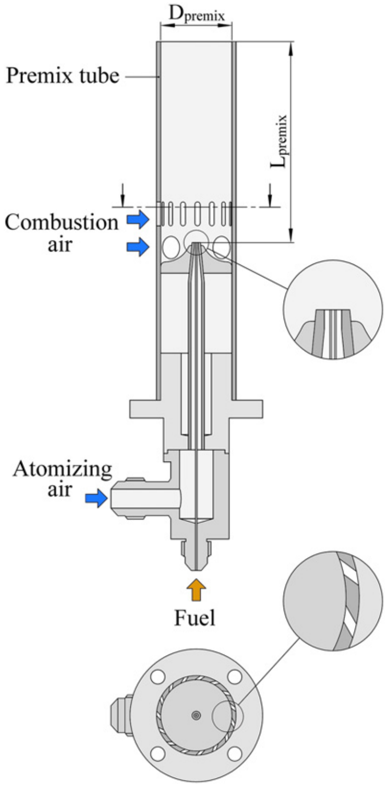

Fig. 1. The investigated LPP burner.