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AN EXPERIMENTAL STUDY ON LIQUID FUEL ATOMIZATION

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In the analysis of fuel spray macrostructure, nozzle flow characteristics, their spray angles, liquid distribution in the droplet stream and the stream extent were determined. The investigations were performed with the use of an isothermal measurement station, designed for the study purposes, which enables fuel atomization at a mass flow rate of 1,5 to 15 kg h^{-1} and the temperature of up to 120 °C. For the measurements, waste oil was selected as the medium spray due to its significant viscosity fluctuations with temperature. The atomization overpressure and temperature ranges were within 0,5 to 1,0 MPa and 20 °C to 115 °C, respectively. The liquid stream radial intensity distribution for the 50 mm and 100 mm distances from the fuel nozzle and the overpressure of 0,8 MPa, 1,0 MPa at a stable temperature of 60 °C were measured.

Key words: liquid fuel, fuel atomization, temperature, pressure

INTRODUCTION

Combustion of liquid fuels, which are sources of many environmental hazards, such as nitrogen oxides, carbon oxide, polycyclic aromatic hydrocarbons, soot and sulphur oxides, is a subject of intense investigations aimed at reduction in their emission. Through improvement of the process of fuel atomization and a changed method of blending fuel and oxidiser, an attempt to reduce the environmental effects by limiting the amounts of carbon oxide and soot in flue gases was made.

A remarkable progress regarding techniques of liquid fuel applications was observed as a result of improvements of the aircraft jet engine, marine gas turbine and a rocket engine.

Liquid fuel combustion is a complex set of the following inseparable processes: fuel atomization, formation of droplet-oxidiser mix, droplet evaporation, ignition of fuel vapours in the oxidiser (combustion onset), combustion with intense droplet evaporation and their thermal decomposition, afterburning of soot, coke residue and carbon oxide. The first two processes determine the others and show the most significant effects on the phenomena observed during combustion. The primary research on these phenomena began with investigations of processes that occurred during combustion of a single, stationary fuel droplet [1-3]. Then, they were described using mathematical models: to the initial, most simple forms, supplementary formulas were successively added [4,5]. The next stage aimed at understanding of droplet interactions and describing combustion of the droplet plume [6,7]. Important factors were also thermodynamic parameters and droplet environment.

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Selection of the atomization method depends on the physicochemical properties of applied fuel. A main criterion for the selection of atomization method is viscosity at the atomizer operating temperature. The maximum permissible viscosity values depending of the atomization method are presented in the paper by Orzechowski and Prywer [8,9]. Atomization methods are classified according to the type of energy used for initiation of liquid stream breakup into droplets.

Kinetic energy of the gas is utilised in gasodynamic atomizers. A stream of water steam or air and the liquid are delivered to the atomizer, which ensures proper outflow velocity and breakup of liquid into droplets. These atomizers are classified according to the gas-liquid interaction and its direction.

Mechanic energy uses the external power to generate atomizer rotation. There are disc and centrifugal rotary atomizers.

Proper selection of the atomization method and its parameters, i.e. pressure and temperature, ensure formation of droplet stream that shows assumed properties. The stream is usually characterized by three groups of parameters: fuel volume or mass flow rate, macrostructure of the fuel spray and microstructure of the fuel spray. The analysis of fuel spray macrostructure includes the atomizer flow characteristics, spray angle, liquid distribution in the droplet stream and the stream extent.

Based on the above considerations, the aim of the study was to determine flow characteristics of the nozzles, their spray angles, liquid distribution in the droplet stream and the stream extent during the experimental research on fuel atomization.

MEASUREMENT STATION

The atomizer investigations were conducted using the measurement station presented in Figure 1. The sta-

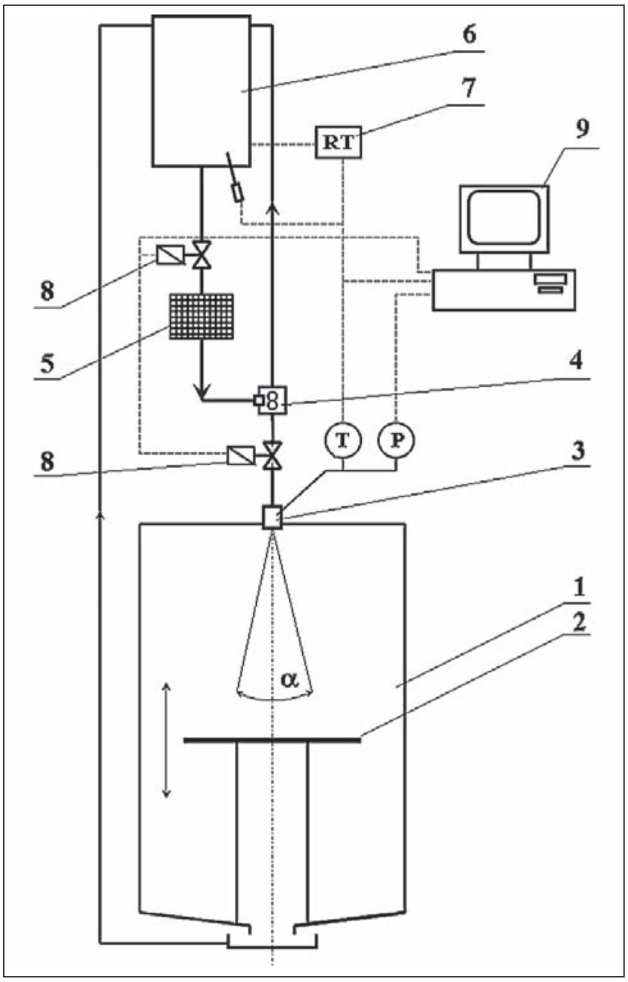

Figure 1 The measurement station for liquid atomization experiments (1 – atomization chamber, 2 – mobile baseplate, 3 – atomizer mounting head, 4 – fuel pump, 5 – initial and primary filters, 6 – fuel tank, 7 – fuel temperature control unit, 8 – solenoid valves, 9 – basic atomization parameter recording unit

tion consists of a vertically positioned transparent chamber, sized 0,7/0,7/1,2 m, intended for experiment observation. In the upper wall, there is a head for atomizer mounting connected with a system of medium spray supply. The fuel system is composed of an isolated tank with a temperature control system as well as a system of filters and a fuel pump. The liquid tank (20 dm^3) is fitted with the primary and secondary heating elements (total power of 1,6 kW, connected to the 230 V mains power line) and a circulating pump to ensure a uniform temperature field within the entire tank volume. The fuel is sucked in through the filter system by the gear pump with bleeding pressure control. The nominal capacity of the pump is 29 dm^3 h^{-1} and the maximum pressure: 2,5 MPa. The pump is driven by a three-phase engine: n_{rev} = 2 780 rpm, N = 150 W, $cos\ \phi$ = 0,78. The liquid is transferred to the head through the pressure measurement system which consists of a pressure gauge (0 MPa to 4 MPa). In front of the atomizer, there is a liquid temperature measurement element consisting of a type K sheathed thermocouple and a digital gauge (Ultrakust 402B). The station is operated by means of a control panel system. During modernisation resulting from experiment-related experience, the station was fitted with the extraction system to remove the finest droplet fraction (in the form of mist) which markedly impeded observation of the experiments but did not affect the results of liquid spray macrostructure investigations.

Technical parameters of the atomizers used in the capacity investigations are presented in Table 1. The outlet diameter was measured using a reflected light microscope with a graduated ocular. As the medium spray, waste oil was selected due to its significant viscosity fluctuations with temperature.

Table 1 **Technical parameters of centrifugal rotary atomizers**

No. of atomiser	Outlet Diameter /mm	Spray angle / degrees	Capacity / kg h-1
R1	0,52	30	4,5
R2	0,54	45	4,0
R3	0,52	60	4,0
R4	0,45	60	2,5
R5	0,42	45	2,5
R6	0,46	30	2,5

RESULTS AND DISCUSSION

As mentioned above, one of the important parameters that affects fuel atomization is its viscosity. For liquid fuels, viscosity is determined experimentally due to different properties resulting from non-homogeneity of raw materials. In Figure 2, the dynamic viscosity coefficients versus temperature for four selected fuels are presented.

The capacity measurements were performed for moderate pressures of 0,5 to 1,0 MPa in three independent measurement series. Then, the results were subjected to a statistical analysis. The liquid stream was measured volumetrically and the result was converted into the mass flow rate. During the investigations, temperature and pressure were controlled and maintained at stable levels. The results are presented in Figure 3. Measurements of the liquid flow rate, $\dot{m}$, and the atom-

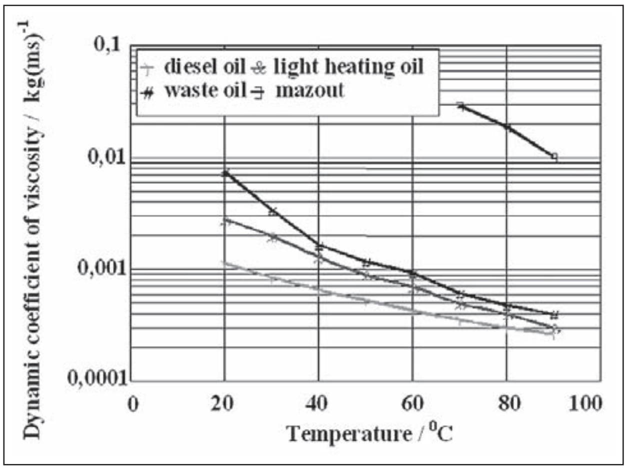

Figure 2 Viscosity versus temperature for the investigated liquid fuels

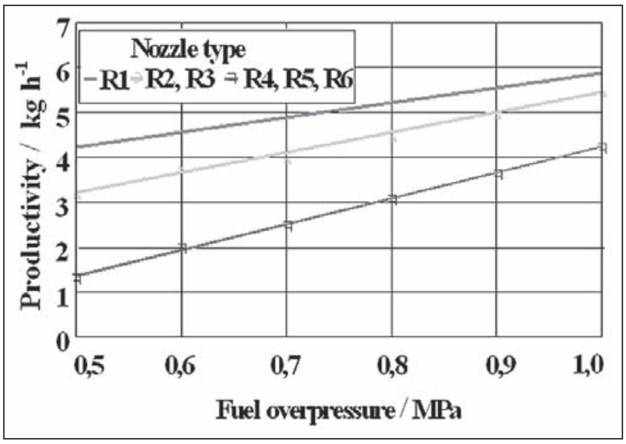

Figure 3 Atomizer capacities versus overpressure for waste oil at 65 °C

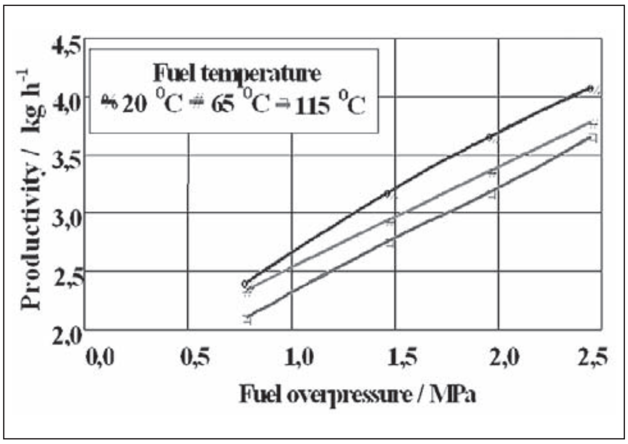

Figure 4 Capacity versus light fuel oil overpressure for a nozzle of the 2,5 kg h^{-1} nominal capacity and the 45° spray angle (R5)

izer outlet diameters enabled determination of experimental flow number, μ, using the equation:

$$\mu = \frac{\dot{m}}{A\sqrt{2 \cdot \rho \cdot \Delta p}} \quad (1)$$

where: A – surface area of the atomizer outlet, m^2; ρ - fuel density, kg m^{-3}; Δp – fuel overpressure, Pa. The values of experimentally determined flow number for R1 to R6 atomizers and the pressure range of 0,5 to 1,0 MPa are presented in Table 2.

During the investigations on liquid fuel combustion, a beneficial effect of the fuel temperature on reduction of hazardous substance emissions was observed. However, the temperature rise results in lower atomizer capacity. To determine the range of changes, three series of atomizer capacity measurements were performed for three different fuel temperatures: 20 ºC, 65 ºC and 115 ºC.

Table 2 **Values of the flow number for centrifugal atomizers powered by waste oil**

Δp / MPa	Flow number / μ					
	R1	R2	R3	R4	R5	R6
0,5	0,182	0,143	0,131	0,080	0,078	0,083
0,6	0,177	0,149	0,139	0,109	0,100	0,105
0,7	0,176	0,154	0,149	0,127	0,128	0,124
0,8	0,173	0,161	0,154	0,147	0,143	0,150
0,9	0,174	0,167	0,157	0,163	0,157	0,166
1,0	0,175	0,173	0,160	0,180	0,179	0,181

The experiments were performed for light fuel oil within the overpressure range of 0,7 to 2,4 MPa. The results for an atomizer nozzle of the 2,5 kg h^{-1} nominal capacity and the 45º spray angle (R5) are presented in Figure 4.

Reduction of of the fuel nozzle capcity with the temperature rise results from changed viscosity of the liquid spray. Using the equation (1) and a near-linear viscosity change with temperature as well as the experimentally determined flow number, a high calculation consistency level in relation to the experiment of capacity versus temperature is obtained. Increased temperature of the fuel spray leads to approximately linear downward shift of the flow characteristics to lower capacities for the same pressures.

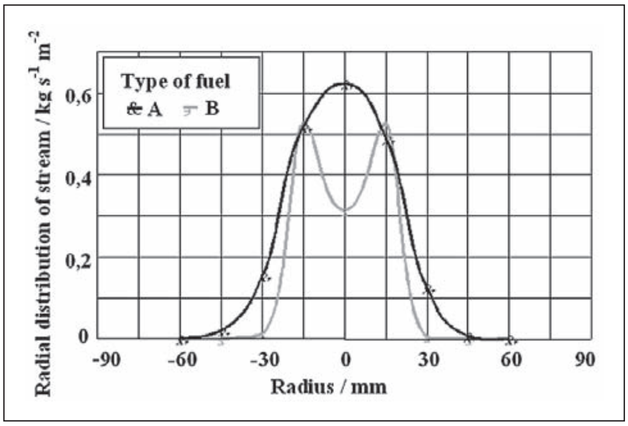

Figure 5 Effects of the fuel type on the liquid stream radial intensity distribution for the R3 nozzle at 50 mm from the nozzle outlet for waste oil (A) and light fuel oil (B) at the overpressure of 1 MPa and the temperature of 60 °C

A remarkable viscosity difference for the waste oil and light fuel oil caused diverse courses of the stream radial intensity distribution curves. For comparison, the R3 nozzle curves were chosen and presented in Figure 5. Waste oil of a higher dynamic viscosity coefficient shows a maximum value of the stream radial intensity distribution of 0,623 kg s^{-1} m^{-2} at the atomizer axis. Light fuel oil of a smaller dynamic viscosity coefficient has a lower value of the stream radial intensity distribution at the atomizer axis: 0,315 kg s^{-1} m^{-2}. The maximum value of the intensity distribution, 0,525 kg s^{-1} m^{-2}, is symmetric for the 15 mm and -15 mm radii.

The effects of the length (distance) on the fuel stream radial intensity distribution, based on the R2 nozzle, are presented in Figure 6. Increased lengths cause a change in droplet arrangement in the stream. For short lengths, the liquid stream intensity values are small at the stream axis and high in its periphery. With the length increase, the stream intensity for its axis is higher while for the

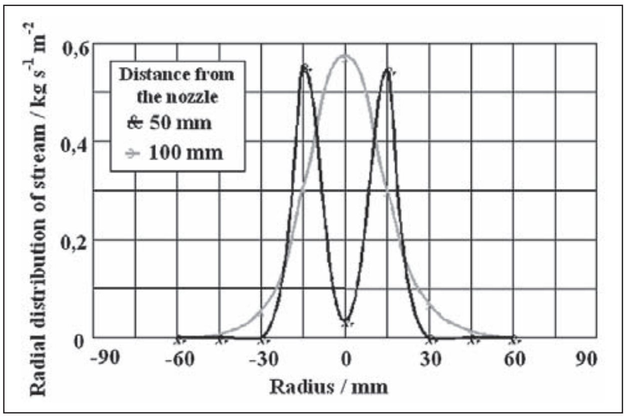

Figure 6 Effects of the distance from the fuel nozzle on the liquid stream radial intensity distribution for the R2 nozzle powered by fuel oil at the overpressure of 1 MPa and 60 °C

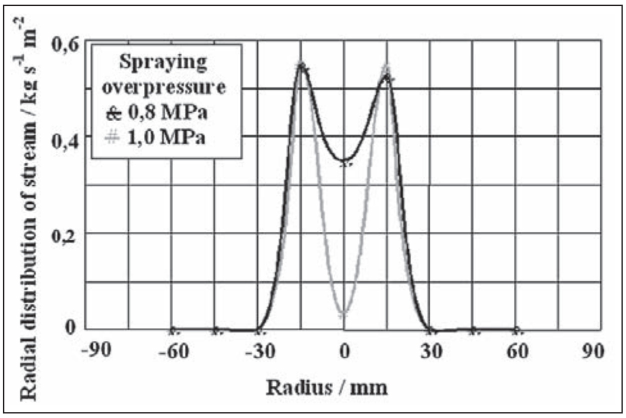

Figure 7 Effects of the fuel overpressure on the liquid stream radial intensity distribution for the R2 nozzle at 50 mm from the nozzle outlet for light fuel oil at 60 °C

periphery, it decreases. The course of liquid stream intensity values versus length, presented in Figure 7, is consistent with the literature data [8,9].

The atomization overpressure change affects the shape of liquid stream radial intensity distribution curve. In Figure 7, a comparison of the radial distribution for the R2 nozzle, powered by light fuel oil at a stable temperature of 60 °C for two overpressures (0,8 and 1,0 MPa) is presented. Each curve has two maxima (for the -15 mm and 15 mm radii) and a minimum at the stream axis. For the fuel overpressure of 0,8 MPa, the fuel stream intensity at the maxima is asymmetric. The difference is 0,021 kg s^{-1} m^{-2}, which corresponds to 3,8 % of the fuel stream intensity at the -15 mm radius: 0,546 kg s^{-1} m^{-2}. The minimum value is 0,35 kg s^{-1} m^{-2}.

The R2 nozzle curve for the overpressure of 1,0 MPa has a shape that is typical of centrifugal atomizers with small values of fuel stream intensity at the axis and two symmetrical (in location and value) maxima: 0,553 kg s^{-1} m^{-2} and 0,546 kg s^{-1} m^{-2} for the -15 mm and 15 mm radii, respectively. The difference in symmetry is 0,007 kg s^{-1} m^{-2}: 1,26 % of the fuel stream intensity at the -15 mm radius. The minimum at the stream axis is 0,035 kg s^{-1} m^{-2}. A difference in the minima for the 0,8 and 1,0 MPa curves is 0,315 kg s^{-1} m^{-2}.

CONCLUSIONS

– Temperature and overpressure of the fuel spray strongly determine the macrostructure and microstructure of the obtained stream. A beneficial effect of increased fuel temperature on the atomization process was observed.
– The spray angle increases with increased fuel overpressure up to the limit value. Further overpressure rise shows no effect on the spray angle.
– The spray angle values, calculated based on the fuel stream radial intensity distribution values, are comparable to the values determined based on direct measurements.
– The radial distribution of fuel stream intensity strongly depends on the atomization overpressure and dynamic viscosity coefficient.

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Note: The responsible translator: Olga Rochowska-Siwiec, Katowice, Poland