Characteristics of sub-standard liquid hydrocarbons combustion when interacting with superheated steam jet

Kopyev E.P. [1], Anufriev I.S. [1,2], Sharypov O.V. [1], Tsepenok A.I.[3]
[1] Kutateladze Institute of Thermophysics SB RAS,
Novosibirsk, Russia
[2] Novosibirsk State Technical University
Novosibirsk, Russia
[3] OOO «ZiO-COTES»,
Novosibirsk, Russia

1 Introduction

Huge amounts of hazardous wastes of oil production and refining, which are not suitable for recovery, have been accumulated in the territory of Russia, posing a large-scale threat to the ecological well-being of the country [1]. In particular, according to the RF Ministry of Emergency Situations, in 15% of the Arctic zone of Russia a critical level of environmental pollution has been recorded. However, the Arctic has unique climatic conditions, including flora and fauna, which require special attention from the point of view of ecology. In particular, due to the long winter period, these areas are characterized by long periods of decay and decomposition of harmful substances. In this regard, there is an undoubtedly important and urgent problem of environmentally safe disposal of accumulated combustible industrial waste (including waste oil, lubricants, and oil sludge).

A large part of these wastes is not suitable for recovery, but can be incinerated, which would simultaneously solve another urgent problem for the conditions of the Far North – the problem of autonomous heat supply to residential and industrial facilities, located in remote areas. The existing liquid fuel combustion technologies [2-4] are generally focused on high-quality fuels (especially scarce in remote areas of the Arctic), do not meet modern environmental standards and require an additional expensive flue gas treatment system. In addition, they are characterized by operation problems, associated with coking of internal surfaces of burners, etc.

IT SB RAS has recently proposed the method of combustion of liquid hydrocarbon fuel in a superheated steam flow with gasification of carbonaceous particles of incomplete combustion of liquid hydrocarbons. Evaporative burners served to show [5, 6] that the supply of superheated steam to the combustion zone of liquid hydrocarbons sharply intensifies the combustion. This method of burning is characterized by stable ignition, high combustion efficiency, cost-effectiveness, and feasible implementation in the autonomous

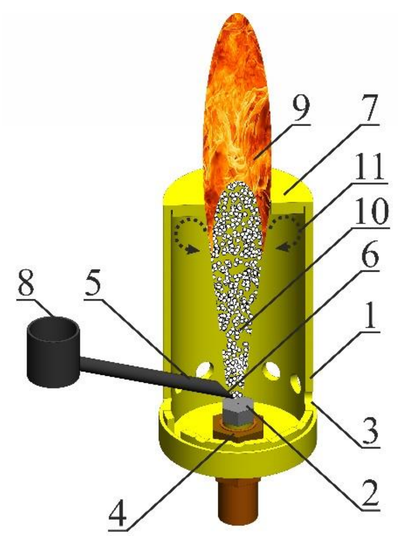
Correspondence to: kopyeve@itp.nsc.ru

burners of various capacities. The results of the performed complex experimental research testify that the method of burning in a superheated steam jet is promising for solving the tasks of efficient and environmentally safe disposal of substandard liquid hydrocarbons and combustible production waste with production of thermal energy. However, the combustion of such fuels in evaporative burners causes a number of problems, associated with the instability of ignition of such fuels, high combustion instability in the combustion chamber, relatively fast coking of burner surfaces, etc. Therefore, for combustion of substandard liquid hydrocarbons in the mode with steam gasification it is necessary to develop and study fundamentally different ways of fuel supply and mixing with water vapor.

One of the promising methods of spraying unconventional liquid hydrocarbons is a technical solution based on the liquid interaction with a high-speed steam flow [7]. A distinctive feature of this method is that the fuel and the spraying medium (carrier phase) – water vapor – are not pre-mixed with each other. The superheated steam leaves the pneumatic nozzle in the form of a jet into which the liquid fuel is fed, resulting in a fine-dispersed gas-droplet flow. In practice, this is an important advantage, since there is no contact of liquid fuel with the nozzle, which prevents coking of its surfaces and subsequent failures in the burner operation.

2 Experimental setup and technique

This work by the example of the waste automobile transmission oil studies the combustion of substandard liquid hydrocarbons in the perspective burner, realizing the described method of dispersion and burning of liquid fuel (Figure 1). The objective of the work is to study the influence of superheated steam parameters (flow and temperature) on the thermal and environmental characteristics of the combustion process.



(a)

(b)

Figure 1. (a) Scheme of the burner: cylindrical housing – 1, steam atomizer – 2, air supply holes – 3, steam line – 4, fuel feed tube – 5, chamfer – 6, nozzle – 7, fuel receiver – 8, torch – 9, steam-oil jet – 10, recirculation zone – 11. (b) characteristic stable combustion mode in the burner unit by the example of used transmission oil

Laboratory sample burner was made of AISI 304 steel. The main components of the burner are: the housing, together with the output nozzle forming the gas generation chamber; the installation surface; a steam atomizer (diameter of 0.5 mm) with a holder and a steam line; and a fuel line with a fuel receiver. The outer diameter of the burner is 60 mm, the height is 140 mm, and the outlet diameter is 25 mm. The fuel supply tube is installed at an acute angle to the horizon, and the end of the tube is located in close proximity to the base of the steam jet and has a chamfer (Figure 1-a). The design of the burner device ensures a stable supply of fuel and further formation of a homogeneous gas-droplet flow. The design provides a natural air inflow from the atmosphere into the reaction zone through the holes in the lower part of the housing. Atmospheric air is necessary to ignite the liquid. Fuel is supplied to the burner through the fuel line. The steam atomizer connected to the external steam generator (opening angle of 17°) is coaxially installed at the base of the gas generation chamber and is oriented vertically upwards.

The burner is equipped with (Figure 2) fuel dosing system, fuel heating system, water dosing system, and electric steam generator. Stable mass fuel flow rate (up to 2 kg/h) is set by the fuel injector and the pump, and the mass is controlled by electronic scales Acom PC-100W-10H (maximum permissible error of 1 g). For high viscosity fuel, heating (up to 110°C) and primary filtration systems are used. The electric steam generator (average power intake of 1.5 kW) allows obtaining superheated steam at the output with the following parameters [8]: temperature up to 550 ° C, pressure up to 1 MPa, and mass flow rate up to 1.6 kg/h. The steam temperature is measured on the walls of the steam generator by means of chromel-alumel thermocouples of K type. The pressure is controlled using a digital pressure sensor OWEN PD-100 (accuracy of 1 kPa). Stable water supply to the steam generator is provided by a plunger dosing pump ND 0.5R 1.6/100 K14A (accuracy class – 0.5) with flow rate up to 1.6 l/h. The water weight is controlled using electronic scales Acom PC-100W-5 (maximum permissible error of 0.5 g).

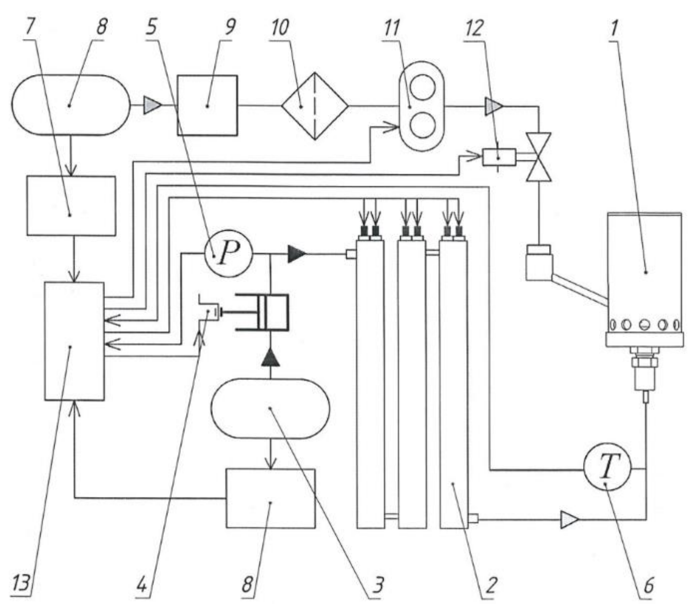


Figure 2. Scheme of experimental setup: 1 – burner, 2 – electric steam generator, 3 – water tank, 4 – plunger dozing water pump, 5 – manometer, 6 – steam temperature sensor, 7 – electronic scales for fuel mass control, 8 – fuel tank, 9 – fuel heating system, 10 – fuel filtration system, 11 – fuel pump, 12 – dozing electromagnetic valve, 13 – automated control unit.

The burner is launched as follows (Figure 2). The pump supplies water at a given flow rate to a pre-heated steam generator, from which steam enters the burner through the nozzle and heats its elements. Automatic power control of the steam generator ensures the achievement of the set temperature of the superheated steam. After that, liquid fuel at a set flow rate is supplied the base of the high-speed steam jet with, resulting in a uniform fine-dispersed gas-droplet flow. The thermal interaction of the phases can significantly reduce the viscosity and surface tension of the liquid fuel. At supersonic steam jet flow rate (about 400 m/s), the interfacial pulse exchange ensures efficient dispersion of the liquid into particles (droplets) with a characteristic size of 10-30 μm [9]. The known methods of oil fuel spraying can achieve a characteristic droplet size from 50 microns. The degree of fuel burn-out, energy and environmental indicators of combustion depend on the size of the sprayed particles. However, in addition to fuel spraying, superheated steam increases the temperature of the fuel drops, which contributes to their faster evaporation and subsequent ignition in the combustion chamber. Ignition of the dispersed fuel at the beginning of the process is realized by an external gas burner through the air holes in the lower part of the housing. As a result of the jet inflow on the inner plane of the nozzle, the recirculation region is formed in the peripheral zone (Figure 1-a), in which ignition is initiated at start-up, and the steam-oil jet ignition is stabilized during operation of the device. At the same time, steam gasification of thermal decomposition products occurs in the combustion zone, which also increases the combustion indicators of liquid hydrocarbons. The resulting combustible mixture of CO and H_2 burns in the torch, mixing with oxygen from the atmosphere (Figure 1-b).

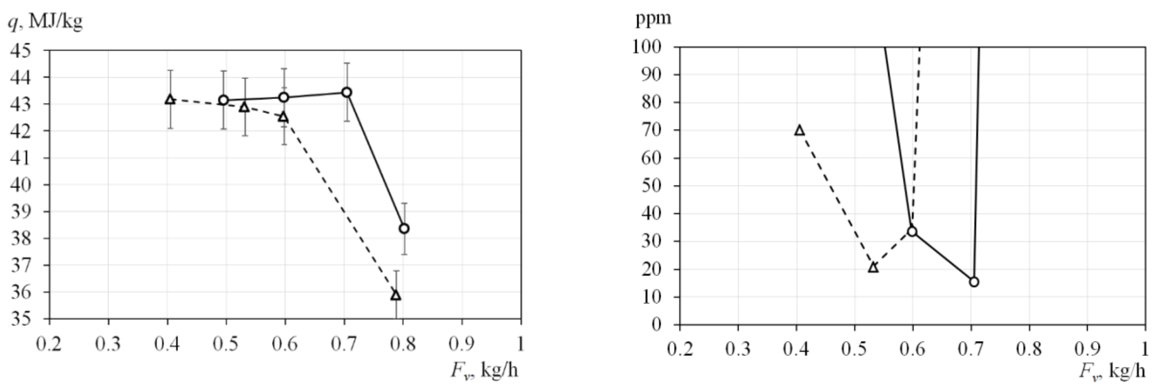
Useful power is an indicator of the energy efficiency of the burner. In the steady-state operation of the device, it is defined as a difference between the thermal energy obtained by the working body from the reaction products, and the energy waste on maintaining the process (per time unit). Energy losses to the environment obviously reduce the useful capacity of the burner. A flow calorimeter was used to measure thermal power at various regime parameters [5]. The torch of the burner device was introduced into the internal channel of the calorimeter after establishing a constant temperature difference of water at the inlet and outlet. The temperature of the coolant (water) was measured at the inlet and outlet of the calorimeter at steady-state thermal conditions, using chromel-alumel thermocouples. The characteristic time of thermal relaxation of the calorimeter was about 6.5 min. Volumetric flow of water was regulated by the valve and was recorded using the flowmeter (limits of relative error of 2 %). In the experiments the volumetric flow rate of the coolant was about 400 l/h, which provided the temperature difference of water at inlet and outlet of no more than 50°C. The volumetric flow rate and the temperature of the gases leaving the calorimeter were measured using the thermoanemometer Testo 4251, (the velocity measurement error was ± (0.03 m/s + 5 % of the measuring value), and temperature was ±0. 5 °C). The gas flow temperature at the calorimeter outlet was close to the ambient temperature.

TESTO 350 gas analyzer (error of 5%) was used to control the composition of gaseous combustion products. Sampling of reaction products was carried out at the calorimeter output.

3 Results

Experiments to measure the composition of combustion products and to determine the heat release were carried out at different operating modes of the burner. For a given fixed $\gamma = F_v/F_f$, the steam flow rate F_v and the fuel flow F_f rate were changed. Earlier, on the evaporative burner, the effect of the superheated steam temperature on the concentration of CO and NO_x in combustion products had not been found, so measurements were carried out at constant (optimal from the point of view of energy consumption) temperature of superheated steam of 270 °C (deviation within ±5%). Absolute pressure of steam depending on F_v was 0.4÷0.9 MPa, and steam superheating reached 130 °C.

Figure 3 presents the results of processing of the received experimental data for two values of the relative steam flow rate γ = 0.5 and γ = 0.6, at which stable burning of the used fuel is ensured.



(a) (b)

Figure 3. The specific amount of heat *q* obtained from combustion products in the calorimeter (a) and CO concentration in the combustion products (b) in different modes at a fixed γ (steam temperature of 270 °C): Δ – γ = 0.5; ○ – γ = 0.6.

The analysis of the results shows that the specific amount of heat *q* (per 1 kg of burnt fuel) and the concentration of CO in the combustion of waste automobile transmission oil with the supply of superheated steam jet significantly depend on the steam consumption (including the flow rate) and the fuel flow rate (the burner power) in the burner design under study. The maximum value of *q* reaches 43.5 MJ per 1 kg of fuel (Figure 3-a). Results of gas analysis (Figure 3-b) show that the lowest content of the toxic CO in the exhaust gases (about 30 ppm) is observed at F_v =0.5÷0.6 kg/h. The increase in steam consumption at a fixed γ leads to fuel underburning: the value *q* decreases (Figure 3-a), and the concentration of CO increases sharply (Figure 3-b), exceeding the upper limits of the device measurements (for CO – 500 ppm). The lower limits of steam consumption in the studied modes are close to the combustion failure, and these modes are also characterized by a sharp increase of CO concentration in combustion products. This CO behavior can be explained that at F_v =0.5÷0.6 kg/h and fixed γ the burner combustion regime approaches to stoichiometric, ensuring a completely process. At the steam flow rate decrease at the fixed γ, the burner regime becomes a regime with a lean fuel mixture, and, in opposite, at the steam flow rate increase, the burner regime becomes a regime with a rich fuel mixture.

The obtained experimental data confirm the prospects and environmental friendliness of the proposed method for disposal of substandard liquid hydrocarbons and allow organizing the optimal operating modes of burner devices based on this principle.

The studies were carried out with the financial support of the RF Ministry of Education and Science, RFMEFI60417X0185.

Measuring of environmental performances were carried out by request of the OOO «ZiO-COTES».

References

[1] SRI FRCEC (2015) Waste management - problems, solutions. Analytical review. Moscow: SRI FRCEC (in Russian)

[2] European Commission (2006) Integrated pollution prevention and control. Reference document on best available techniques for large combustion plants

[3] Aiuchi K, Moriyama R, Takeda S, Kitada S, Onozaki M, Katayama Y (2007) A pre-heating vaporization technology of coal-water slurry for thegasification process. Fuel Processing Technology. 88: 325.

[4] Lishtvan II, Falyushin PL, Smolyachkova EA, Kovrik SI (2009) Fuel suspensions based on fuel oil, peat, waste wood, and charcoal. Solid Fuel Chemistry. 43: 1.

[5] Alekseenko SV, Anufriev IS, Vigriyanov MS, Kopyev EP, Sharypov OV. (2016). Characteristics of diesel fuel combustion in a burner with injection of a superheated steam jet. Combust. Expl. Shock Waves. 52: 286.

[6] Alekseenko SV, Anufriev IS, Vigriyanov MS, Dulin VM, Kopyev EP, Sharypov OV (2014) Steam-enhanced regime for liquid hydrocarbons combustion: velocity distribution in the burner flame. Thermophysics and aeromechanics. 21: 393.

[7] Vigriyanov M.S. (2012) RF Patent 2450207 (in Russian).

[8] Anufriev I, Arsentyev S, Vigriyanov M, Kopyev E, Sharypov O (2017) Burning of substandard liquid hydrocarbons with steam gasification. MATEC Web of Conferences. 115: 03013.

[9] Anufriev IS, Kopyev EP, Shadrin EY (2017) Investigating characteristics of liquid hydrocarbon spraying by a steam jet. MATEC Web of Conferences 115: 05010.