Comparative analysis of characteristics of liquid fuel combustion for various designs of oil-steam burners

I S Anufriev and E P Kopyev
Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia
kopyeve@itp.nsc.ru

Abstract. The paper presents a comparative analysis of experimental data on combustion of liquid hydrocarbon fuels in the presence of superheated steam in two designs of the developed burners. By the example of diesel fuel burnt in a spray burner it is shown that lower values of nitrogen oxide contents in the exhaust gases are achieved in comparison with an evaporative burner. At that, the content of carbon monoxide in some regimes is lower for the evaporative burner. The regimes with the minimum content of toxic combustion products are found for both designs of the burners.

1. Introduction
Currently, the issue of environmentally friendly combustion of heavy hydrocarbons and substandard fuels for cheap energy production is relevant [1,2]. One of the promising approaches to reduce toxic products when burning liquid combustible waste is steam injection into the combustion zone as an effective way to suppress nitrogen oxides and soot formation [3,4].

Water and steam are used in practice to solve a number of problems: from reducing the heat load and suppressing detonation [5] in the combustion chamber to dispersing heavy fuels and burning water-fuel emulsions. The addition of steam both changes the process of some elementary reactions (chemical effect) and leads to dilution of the combustible mixture (physical effect), which ensures a decrease in the flame temperature [6]. The presence of steam in the combustion zone leads to a decrease in NOx emissions due to an increase in the heat capacity of the mixture during combustion of hydrogen-air [7] and methane-air [8–10] mixtures, as well as natural gas [11].

However, the efficiency of using water or steam injection greatly depends on various factors: type of device, method of supply, type of fuel, steam concentration, etc. In gas turbines using natural gas [3], steam injection into the combustion chamber is the most effective for NOx suppression. And when burning kerosene, it is more useful to inject steam into the ignition area [12]. The best effect is achieved when steam is added to the region of the maximum flame temperature, [13] which, in particular, can be located at the end of the combustion zone [14].

Despite the abundance of works dealing with the effect of steam and water on the combustion process, there is very little information in the literature on the combustion of substandard liquid fuels (such as waste oils, refinery waste, crude oil, etc.) with steam injection and the effect of steam parameters and methods of supplying steam and fuel on combustion indicators. Therefore, to solve the problem of environmentally friendly disposal of liquid combustible waste, the authors have previously studied two new designs of burners with fundamentally different methods of supplying superheated
steam and fuel and their mixing, developed at IT SB RAS, using the example of burning diesel fuel. These are laboratory samples of an original vertical evaporative burner with controlled forced supply of superheated steam to the combustion zone [15] and an atmospheric burner with spraying liquid hydrocarbon fuel by a jet of superheated steam [16]. It is shown using the evaporative burner [15] that when fuel is burned in a jet of superheated steam, the content of nitrogen oxides and carbon monoxide in the combustion products is significantly lower than the maximum permissible concentrations established for this type of burner, according to the performance standards [17]. The developed spray burner [16] demonstrates the possibility of efficient combustion of diesel fuel and waste engine oil [18]; a 30% reduction in NOx was ensured with the supply of steam in comparison with air due to the effect of diluting the combustible mixture and lowering the flame temperature.

The purpose of this work is a comparative analysis of the experimental data obtained earlier by the authors during the combustion of liquid hydrocarbon fuels with addition of superheated steam in two different original designs of laboratory burners aimed at determining the most preferable method of steam supply to the combustion zone.

2. Burners

2.1. Evaporative burner with forced supply of superheated steam

An evaporative burner with forced supply of superheated steam was studied by the authors in [15]. A detailed description of the burner, the methods for measuring its characteristics and the results obtained in the presence of a supplied jet of superheated steam are presented in [15]. The experiments were also carried out with the supply of a jet of heated air instead of steam; their results are given in [19]. The principle of burner operation is based on the combustion method proposed by the authors of [20], when the products of thermal decomposition and incomplete combustion of evaporating liquid fuel are gasified at a high concentration of steam in the combustion chamber, and the reaction products are burned out in an external flame (Fig. 1). Since the burner is of an evaporative type, its power is limited by the rate of fuel evaporation, including limitation due to the furnace size. The optimum fuel flow rate was previously defined as 0.8 kg/h for diesel fuel. The burner design provides for a natural flow of atmospheric air into the reaction zone through the openings in the lower part of the combustion chamber. This air flow is required to ignite evaporating liquid fuel in the combustion chamber. Two steam nozzles connected to an external steam generator (opening angle of 17°) are installed coaxially above the combustion chamber at the base of the gas generation chamber and are oriented vertically (outlet diameter of 0.5 mm). The lower nozzle is directed downward into the prechamber (with an inner cavity in the form of a hemisphere and a conical outlet). A steam jet is supplied to the combustion chamber to remove thermal decomposition products, which prevents coking of the inner surfaces. The upper nozzle is directed upwards into the gas generation chamber.

2.2. Spray burner

Characteristics of the spray burner operation both in the case of supply of a high-speed jet of superheated steam and a jet of heated air instead were investigated in [16]. The main feature of the device is organization of an original method for dispersing liquid fuel (Fig. 2): a high-speed jet of superheated water vapor is fed into the gas generation chamber through a steam nozzle (opening angle of 17° and outlet diameter of 0.5 mm) installed at the burner base and directed vertically upward. Liquid fuel flows through the fuel supply pipe into the steam jet base at a predetermined flow rate; as a result, a homogeneous fine-dispersed gas-droplet flow is formed. In addition to spraying the fuel, superheated steam raises the temperature of fuel droplets, which intensifies mass transfer and mixture formation, contributing to stable ignition. The advantage of using this scheme over an evaporative burner is that when spraying fuel, it is possible to vary the power of the burner over the wide ranges.
Figure 1. Flow chart of an evaporative burner operation with superheated steam forced supply.

Figure 2. Flow chart of spray burner operation

3. Comparative analysis of measurement results
To perform comparison, the regimes with the same thermal power (fuel flow rate $F_f = 0.8$ kg/h) were selected. The relative flow rate of steam (or heated air) $\gamma$, equal to the ratio of the mass flow rate of steam $F_v$ (or heated air $F_a$) to the flow rate of the supplied fuel $F_f$, was varied. According to [16], the spray burner had a number of restrictions on the flow rate of the supplied steam (or air) associated with flameout at an oxidizer excess, as well as with underburning at its lack. Therefore, for the evaporative burner, the values of $\gamma$ are given in the range from 0.3 to 1.5 for steam and from 0.7 to 1.5 for air, and for the spray burner, these values are given in the range from 0.3 to 0.8 for steam and from 0.5 to 1.0 for air at a power of 10 kW.

Using the data presented in [15,16], the dependences of contents of toxic components CO and NOx in the exhaust gases on the relative flow rate of superheated steam are constructed (Fig. 3-a, b). The values shown in the diagrams are recalculated from the volumetric values [ppm] (shown in the original works) to the mass content of a substance, referred to 1 kg of burnt fuel [g/kg] according to the method described in [17].

Figure 3. Contents of (a) nitrogen oxides, (b) carbon monoxide in exhaust gases for different relative flow rates of steam (solid symbols) or air (hollow symbols) during fuel combustion in evaporative (triangles) and spray (circles) burners at a power of 10 kW.
Figure 3-a shows that with the supply of superheated steam, a decrease in NOx content of about 30% is observed in comparison with the supply of heated air for both designs. However, in the spray burner, this increases the production of carbon monoxide (Fig. 3-b), probably associated with partial underburning of fuel when approaching the regime with the flameout, while for the evaporative burner the contents of CO remain minimal in a wide range of γ. For an evaporative burner, the optimal is the regime with γ = 0.9, for which the mass content of CO is within the measuring error of the device at [NOx] = 1.27 g/kg, which meets the 3 class of EN: 267 [17].

A high CO content in the spray burner may be due to the selected non-optimal power mode of 10 kW. Therefore, for a spray burner we take the parameters corresponding to the power of 15 kW (Ff = 1.2 kg/h) and compare them with the results obtained for an evaporative burner at the power of 10 kW (Ff = 0.8 kg/h). The obtained dependences of the [CO] and [NOx] content in the exhaust gases at different regimes of burner operation are shown in Fig. 4-a, b.

According to the figures, for all the presented regimes of spray burner operation, the content of carbon monoxide is minimal when either superheated steam or air is supplied at a device power of 15 kW. At that, the spray burner implements the regimes with lower NOx emissions as compared to the evaporative burner, in terms of 1 kg of burnt fuel. To explain this behavior, Fig. 5 shows distributions of the average temperature along the symmetry axis of the flame for the compared regimes of burner operation. It can be seen that when combusting diesel fuel in the evaporative burner, the higher average temperatures along the flame axis of symmetry are achieved. The average difference is about 250 degrees. This explains the different contents of nitrogen oxide for the investigated devices. Due to the higher temperatures more “thermal” nitrogen oxide forms. This behavior of average temperatures can lead to the fact that in the spray burner the jet of superheated steam or heated air, supplied instead, interacts directly with the fuel; due to this, the degree of gasification of fuel droplets can be increased. In addition, a second nozzle in the evaporative burner can reduce the degree of air entrainment from the environment, thereby reducing the “dilution” of the combustible mixture with cold air nitrogen, which also affects the temperature in the external flame of the device. Namely, when calculating the impulse of the supplied jet, which is directly related to the amount of ambient air sucked into the burner, according to the method described in [21], it can be estimated that the impulse of the supplied steam jet for a spray burner at γ = 0.85 and a power of 15 kW is 0.268 N, while for an evaporating burner at γ = 0.8 and a power of 10 kW it is 0.133 N. It can be seen that with a power difference of 1.5 times, the ratio of jet pulses is 2.

Figure 4. Content of (a) nitrogen oxides, (b) carbon monoxide in exhaust gases for different γ in the case of steam (solid symbols) or air (hollow symbols) supply during fuel combustion in evaporative (black triangles) and spray (red circles) burners at power of 10 kW and 15 kW, respectively.
Figure 5. Distribution of the time-averaged temperature in the external flame along the axis of symmetry during fuel combustion with the supply of superheated steam at $\gamma = 0.8$ in evaporative (black triangles) and at $\gamma = 0.85$ spray (red circles) burners at power of 10 kW and 15 kW, respectively.

Thus, in spite of the lower indicators of the harmful substance content in exhaust gases for the spray burner, its operation with natural air entrainment from the environment is likely to require more air, which may be an obstacle to its use in areas with strict restrictions on this parameter. Therefore, it is difficult to draw a conclusion about the unambiguous advantage of one or another method of burning liquid fuel with the supply of superheated steam to the reaction zone. Both schemes under study, implemented in different burner designs, have their own disadvantages and advantages and can be successfully used to solve various problems.

Nevertheless, it is advisable to modify the design of the spray burner to organize controlled air supply, both inside the burner and for the ignition of reaction products in the external flame, and to experimentally determine the effect of the amount of incoming air on characteristics of device operation and optimization of operating parameters.

Conclusion

In this work, we compare and analyze previously obtained experimental data on the combustion of liquid hydrocarbon fuels in the presence of superheated steam in two different original designs of laboratory burners. These burners differ in the way of mixing superheated steam and fuel and feeding them into the zone of combustion.

It is shown that when combusting fuel in the spray burner, there are lower values of nitrogen oxide content in the exhaust gases than in the evaporative burner. However, when the burners operate on the same amount of fuel, at equal heat outputs, in the regime with low NOx emissions, a higher content of carbon monoxide in the exhaust gases is observed on the spray burner. Whereas an evaporative burner is characterized by a wide operating range, in which the CO values do not exceed the error of the measured device. In the operating regime, when the power of the spray burner is changed by 15 kW, a spray burner is shown to provide a lower emission of nitrogen oxides than an evaporative burner with simultaneously low emission of carbon monoxide. The low NOx content in the combustion products of the spray burner is associated with a lower average flame temperature due to the direct interaction of the steam jet with the fuel. The results obtained can be used to verify the mathematical model and numerical simulation of the process, as well as in the design of low-emission burners.
Acknowledgments
The study was financially supported by the Russian Science Foundation (project No. 18-79-10134, https://rscf.ru/project/18-79-10134/).

References
[1] Zhao N, Li B, Chen D, Ahmad R, Zhu Y, Li G, Yu Z, Li J, Wang E, Yun S, Yoon H, Yoon I, Zhou Y, Dong R, Wang H, Cao J, He J and Ju X 2020 Waste Management 104 20
[2] Basler B and Felix P C 1982 in Volume 5: Manufacturing Materials and Metallurgy; Ceramics; Structures and Dynamics; Controls, Diagnostics and Instrumentation; Education; Process Industries; Technology Resources; General
[3] Göke S, Schimek S, Terhaar S, Reichel T, Göckeler K, Krüger O, Fleck J, Griebel P and Paschereit C O 2014 Journal of Engineering for Gas Turbines and Power 136 091508
[4] Alekseenko S V., Pashchenko S É and Salomatov V V. 2010 Journal of Engineering Physics and Thermophysics 83 729
[5] Li A, Zheng Z and Peng T 2020 Fuel 268 117376
[6] Cui G, Dong Z, Wang S, Xing X, Shan T and Li Z 2020 Applied Energy 259 114205
[7] Le Cong T and Dagaut P 2009 Energy & Fuels 23 725
[8] Zou C, Song Y, Li G, Cao S, He Y and Zheng C 2014 International Journal of Heat and Mass Transfer 75 12
[9] Albin E, Nawroth H, Göke S, D’Angelo Y and Paschereit C O 2013 Fuel Processing Technology 107 27
[10] Boushaki T, Dhué Y, Selle L, Ferret B and Poinsot T 2012 International Journal of Hydrogen Energy 37 9412
[11] Honzawa T, Kai R, Seino M, Nishiie T, Suzuki Y, Okada A, Wazaki K and Kurose R 2020 Journal of Natural Gas Science and Engineering 76 103158
[12] Furuhatani T, Kawata T, Mizukoshi N and Arai M 2010 Fuel 89 3119
[13] Lellek S, Barfuß C and Sattelmayer T 2017 Journal of Engineering for Gas Turbines and Power 139 021506
[14] Farokhipour A, Hamidpour E and Amani E 2018 Fuel 212 173
[15] Anufriev I S, Alekseenko S V., Sharypov O V. and Kopyev E P 2019 Fuel 254 115723
[16] Anufriev I S and Kopyev E P 2019 Fuel Processing Technology 192 154
[17] DIN EN 267:2011-11. Automatic forced draught burners for liquid fuels.
[18] Anufriev I S, Alekseenko S V., Kopyev E P and Sharypov O V. 2019 Journal of Engineering Thermophysics 28 324
[19] Kopyev E, Sharypov O, Anufriev I and Vigriyanov M 2020 AIP Conference Proceedings 2304 020010
[20] Vigriyanov M S, Salomatov V V and Alekseenko S.V. 2003
[21] Anufriev I S, Krasinsky D V., Shadrin E Y, Kopyev E P and Sharypov O V 2019 Thermophysics and Aeromechanics 26 657