Low-Emission Waste-to-Energy Method of Liquid Fuel Combustion

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Waste-to-energy approaches, aimed at using cheap energy carriers (oil production and refining waste, etc.), require the creation of new technologies with high energy efficiency and low emissions. One of the environmentally friendly methods is a superheated steam injection (SIM) into the combustion zone. At the same time, trends in CO_2 reduction and recycling make carbon dioxide more attractive to use together with, or instead of, steam.

low-emission combustion | waste-to-energy | carbon dioxide | superheated steam

1. Background

Energy is the most important factor that determines the efficiency of the economy and technologies. At the same time, the energy industry is one of the main sources of anthropogenic impact and pollutant emissions [1]. Despite the active development of alternative and renewable energy sources [2], the consumption of fossil fuels in absolute terms has not decreased, and its share of the global energy balance exceeds 3/4 [2][3]. One of the urgent problems is that, in addition to carbon dioxide, substances hazardous to human health and the environment, such as nitrogen and sulfur oxides, soot, carbon monoxide, and other compounds, can be formed during fossil fuel combustion. To date, environmental technologies at thermal power plants can account for up to half of the total cost of the plant [4][5]. This implies the need to search for economically justified technologies for reducing emissions, whose application cost would be competitive, and the total cost of suppressing emissions would not exceed the value of the economic equivalent of preventing damage from these emissions. Another significant problem is the accumulation of a large amount of substandard combustible waste, including hydrocarbon waste, generated during the extraction, transportation, and processing of fossil fuels. Annually, over 20 million tons of used lubricating oils alone accumulate all over the world (with fresh oil consumption of over 40 million tons) [6], up to 160 million tons of oil sludge [7], and more than 2 billion tons of municipal solid waste [8]. As a rule, these are combustible substances contaminated with mechanical impurities, often containing a large amount of water, available at a low cost, and emitting a large amount of harmful substances during traditional combustion.

Currently, the waste-to-energy trend [9][10][11], aimed at involving combustible waste in the fuel balance, is being developed. This, on the one hand, allows cost reduction through the use of such a cheap type of fuel, while solving the problem of its disposal; on the other hand, this partly predetermines special concern for environmental protection and the prevention of excessive emissions when using low-grade fuel. Thus, for the successful development of this area and to ensure its sustainable development, it is necessary to create and develop highly efficient and environmentally friendly technologies and equipment [12].

2. Low-Temperature Combustion

One of the possible ways to reduce harmful emissions from the combustion of low-quality fuels is the organization of low-temperature combustion (LTC). The main idea of this approach is to use the systems of exhaust gas recirculation (EGR), flue gas recirculation (FGR), or the addition of diluent gases to reduce oxidizer concentration and, as a result, reduce the flame temperature [13]. Taken together, these allow reductions of emissions of soot, NO_x, CO, and other harmful substances [14][15]. Exhaust gas recirculation is well-established and widely used to reduce NO_x emissions in gas turbines and internal combustion engines [16][17][18]. Flue gas recirculation can also be implemented in high-power pulverized coal boilers [19] and circulating fluidized-bed boilers [20]. The main idea of this method is to decrease NO_x emissions by reducing the flame temperature and oxidizer concentration due to ballasting the mixture with combustion products or other diluent gases. In addition, owing to uniform and highly efficient mixing and the burning out of fuel in the furnace volume, there is a decrease in the number of organic compounds formed: carbon monoxide, benzopyrene, etc. Due to the lower combustion temperature, in the case of using solid fuel, ash sublimation is reduced, and the pollution of the heating surfaces is reduced.

The use of the low-temperature combustion method to reduce harmful emissions, including its use within the waste-to-energy approach, is an attractive option because it can be implemented without the introduction and use of expensive systems. However, in some cases, it may be necessary to increase the size of the furnace to ensure a longer stay of a particle and its complete burnout, for example, as in furnaces with low-temperature swirling combustion and a circulating fluidized bed (CFB) [21].

3. Steam and Carbon Dioxide as Diluent Gases in the Systems of Low-Temperature Combustion

It is known that, in the case of the air burning of fossil fuels, the basis of the recirculating gas mixture, in addition to nitrogen, is carbon dioxide and water vapor. Moreover, the water is in a state of superheated steam, and its molar fraction in the combustion products can be a multiple of that of CO_2. For example, it can be twice as much if methane is used as fuel. Thus, the efficiency of water collision is more than four times higher than that of carbon dioxide, and this implies significant effects on recombination reactions, in particular, in high-pressure conditions [22]. At the same time, the thermal diffusivity of both H_2O and CO_2 is lower than that of air, which can locally affect the flame structure and combustion rate [23]. Therefore, it is essential to take into account the influence of superheated steam, as the most important component in the gas recirculation system, on combustion processes in schemes of low-temperature combustion. In addition, it is possible to use water and steam as independent diluents. Thus, it is noted in the literature that the injection of water or steam has several advantages, e.g., it can be considered an effective way to reduce the heat load and suppress detonation in the combustion chamber [24]. Moreover, the technology of steam injection is more efficient than gas recirculation approach for the reduction of NO_x emissions [25], which is often associated with an increase in the heat capacity of the mixture due to the addition of water during fuel combustion (the physical effect). A similar conclusion was reached by the authors, who studied the combustion of a hydrogen–air mixture [26], a methane–air mixture [27][28], and a propane–butane mixture [29]. In turn, it is noted in [30][31] that the addition of water vapor has not only a physical effect, due to the combustible mixture dilution, but also a chemical one, because of a change in the course of reactions. Thus, dilution with steam reduces not only NO_x emissions but also the formation of CO. The first is believed to be achieved by lowering the flame temperature, and the second is presumably due to elementary reactions in the water–gas shift: $CO + H_2O = CO_2 + H_2$.

Another direction in the development of low-emission combustion is the potential use of pure carbon dioxide as a diluent, which can be obtained in industrial volumes during the operation of promising highly efficient power cycles of the Allam [32], JIHT [33], Graz [34], and other [35][36][37] methods. The carbon dioxide formed during the operation of these power cycles is of high purity and parameters (up to 300 bars) and can be used in various technological processes, including those aimed at improving the quality of fuel combustion. Also, the effects of dilution with superheated steam and carbon dioxide on the turbulent kinetic flame during methane combustion, typical of combustion chambers of gas turbines and internal combustion engines with EGR systems (combustion chambers with high pressure and temperature), were experimentally studied in [23][38]. The dilution effects of superheated steam and carbon dioxide on CO and NO_x emissions were compared. It was found that the effect of dilution with steam on the structure of the turbulent flame region is small compared to the effect of dilution with CO_2. Dilution of the premixed mixture with carbon dioxide has also been effective in suppressing flame oscillations. Other studies have noted that dilution with CO_2 has a stronger effect on flame propagation and extinction than other diluents such as H_2O [39], N_2 [40][41], and He [42]. Dilution with carbon dioxide can also suppress the formation of soot, due to the chemical effect of competition for the H radical with the formation of CO and OH in the reaction $CO_2 + H \rightarrow CO + OH$ [43]. When studying the characteristics of an explosion under closed chamber conditions, it was found that the addition of carbon dioxide reduces the rate of pressure increase and the rate of flame deflagration, which leads to a decrease in explosiveness [44][45].

According to the abovementioned publications, it can be concluded that the use of a system of low-emission combustion based on the addition of diluent gases such as CO_2 and H_2O can potentially be used in the waste-to-energy process. However, despite the rather large number of proposed approaches to the use of diluent gases, the degree and mechanisms of the effect of pure substances (especially CO_2 and steam) on the flame characteristics and the course of chemical reactions still have some gaps; there are no unambiguous conclusions about the advantage of one or other substances in the disposal of combustible waste.

4. The Original Method of Low-Emission Combustion of Liquid Combustible Waste in a High-Velocity Jet of Superheated Steam

Earlier, the method for burning liquid hydrocarbon fuels and combustible wastes in a high-velocity jet of superheated steam (SIM) was proposed at IT SB RAS [46][47][48]. Thus, the presence of water vapor accelerates the breakdown of complex organic compounds. The steam gasification reaction occurs with the participation of products of thermal decomposition and incomplete combustion of fuel containing carbon, with a synthesis gas forming ($H_2O + C = CO + H_2$) [31]. In particular, due to the impact of a high-velocity jet on a drop of fuel, primary atomization and the creation of a homogeneous fuel spray occur [49]. Together, this increases the completeness of combustion and the rate of fuel burnout. In addition, the injection of water vapor into the combustion zone enhances the formation of active OH radicals, which leads to a soot emissions reduction [31]. When a combustible mixture is diluted with steam, the formation of thermal nitrogen oxides is reduced, due to an increase in the total heat capacity of the mixture and a decrease in its temperature [48]. At the same time, the investigated method of combustion allows the use of combustible waste with mechanical impurities, since the atomization is carried out without the use of fuel nozzles, but by atomizing the fuel with a steam jet. This allows one to eliminate the problem of clogging the fuel supply channels and the coking of the fuel injector orifice.

Based on the proposed combustion method, low-emission liquid fuel burners of various designs were developed and tested for the disposal of liquid combustible waste. While using the original atmospheric spray-type burner for burning heptane [50], diesel fuel [48], waste oil [47], fuel oil [51], and crude oil [52], it was shown that this method allows a reduction in soot, CO, and NO_x formation. For burners with a forced air supply to the combustion chamber [53], regimes providing significant reduction in the content of nitrogen oxides in the flue gases of up to 70% with a high completeness of fuel combustion were found. At that, the burners do not undergo significant changes when changing fuel and are distinguished by a simple design.

The proposed method and the developed burners by IT SB RAS are considered highly efficient and environmentally friendly, which potentially allows them to be used when implementing the waste-to-energy approach in practice. However, it is difficult to carry out reliable numerical calculations when designing burners of this type, since the kinetics of combustion of liquid hydrocarbons, especially substandard ones, in a steam jet is still poorly understood; the exact mechanisms have not yet been elucidated. In addition, to date, trends in CO_2 reduction and recycling make carbon dioxide more attractive to use together with or instead of superheated steam (SCIM—steam and carbon dioxide injection method or CIM—carbon dioxide injection method). Those possibilities of mixing or replacing superheated steam with other types of diluents have also not been studied in the burners; there are no estimates of changes in the combustion parameters of fuel with such a replacement.

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