Application of Technology for Combustion of Depleted Ionized Gas Fuel in an Electric Field

N A Ermoshin¹, S A Romanchikov², V O Bayrak² and Yu Yu Kashtanov²

¹St. Petersburg Polytechnic University of Peter the Great
²Military academy of logistics, St. Petersburg

E-mail: ermonata@mail.ru, romanchkovspb@mail.ru

Abstract. A technology is proposed to improve the efficiency of heat devices operating on gas fuel. The technology is based on the use of a method of burning depleted ionized gas fuel in an electric field. Application of the method allows to reduce the formation of soot deposits and provides a more complete combustion of the gas. Increasing the efficiency of heating devices is achieved due to the formation of an electric field by including an ionizing radiation device in the structure of the gas stove. The energy of the ionizing radiation of the gas fuel provides the formation of Coulomb forces. Combustion intensifies, and convective heat exchange increases due to electroconvection. The design of the ionizing radiation device includes electrodes located at a distance from each other. Power is supplied from a voltage source. The electrodes are fixed using porcelain ring insulators. The proposed design solutions provide not only a decrease in gas fuel consumption, but also an increase in the flame temperature and the power of thermal radiation not only in the visible, infrared and ultraviolet ranges. Additional electrolysis of the fuel mixture, and the acceleration of its combustion rate is achieved due to ionization. The results of experimental studies to determine the parameters of the combustion processes of gas fuel (isobutane (CH₃-CH(CH₃)-CH₃) – 72 %, butane (CH₃-CH₂- CH₂-CH₃) – 22 %, propane (C₃H₈) – 6 %) are presented. It was found that with a variable electric field strength for gas ionization, an increase in the temperature of the frying bed by 39%, heat transfer by 2 times, a decrease in carbon oxides by 31–36%, and a decrease in gas fuel consumption by 26% are achieved.

1. Introduction
The most important condition for ensuring the safety and health of the population is proper and high-quality nutrition. It is no coincidence that food supply issues occupy one of the main directions of state policy. This is evidenced by the program documents developed and implemented by the government. First of all, these include the Strategy for improving the quality of food products until 2030 (approved by the order of the Government of the Russian Federation of June 29, 2016 No. 1364-r). The strategy aims to address the issues of ensuring adequate nutrition, preventing diseases, increasing the duration and improving the quality of life of the population, stimulating the development of production and circulation of food products of appropriate quality on the market.

To solve these problems, it is necessary to improve and develop new technical means and technological equipment for food production. The study of the main directions of increasing the efficiency of heat devices operating on gas fuel revealed that a promising way of modifying such heat-generating devices is the use of the technology of combustion of depleted ionized gas fuel in an
electric field. Theoretical and experimental studies [1, 2] on the development of technical solutions aimed at increasing the efficiency of gas combustion allowed us to propose technical devices that ensure an increase in the reliability and environmental friendliness of technological equipment. At the same time, the theoretical and practical problems of energy saving of thermal apparatuses of the food industry remain unresolved. Moreover, the issues of using gaseous fuel when using heat devices at low temperatures have not been fully developed. It is known that gaseous fuel - a mixture of combustible (hydrocarbons, carbon monoxide, hydrogen) and non-combustible (nitrogen, oxygen) gases with a certain amount of impurities, has a low ignition temperature. At low temperatures (minus 10 °C), this mixture liquefies and, as a result, decreases the effects of its use. In this regard, theoretical developments are required to modernize existing samples of technical means and technological equipment. In particular, this concerns the provision of the possibility of using gas-fueled heat devices in low-temperature conditions and, in particular, in the Arctic zone of the Russian Federation [2, 3, 4].

2. Relevance and scientific importance
As a result of the analysis of studies to improve the characteristics of gas equipment, it was found that a promising direction is the improvement of heat devices operating on gas fuel through the implementation of fuel ionization devices. [5, 6]. Studies [7, 8] on the development of technical solutions aimed at increasing the efficiency of gas combustion allowed to achieve certain results, but did not provide a solution to the problem in full. It should be noted that gaseous fuel is a mixture of combustible (hydrocarbons, carbon monoxide, hydrogen) and non-combustible (nitrogen, carbon monoxide (P) oxide and oxygen) gases with a certain amount of impurities, has a low ignition temperature, and at a low (-10°C) it liquefies, which reduces the efficiency of its use [9]. Thus, the purpose of the work is to develop constructive solutions aimed at increasing the efficiency of combustion of gas fuel, in particular, in technological equipment for cooking food remains unresolved.

In order to ensure the efficiency of using gas fuel by increasing the temperature of the torch and heating the frying floor by controlling the ascending heat flows of hot air with intense infrared and other types of radiation, a technical solution "Gas stove PG-PIT" (gas stove with forced ionization of gas fuel) was proposed. The principle of operation of the stove is based on the use of the method of combustion of depleted ionized gas fuel in an electric field.

To create an electric field, electrodes connected to a voltage source are included in the design of the frying floor heating system. Schematic diagram of the PG-PIT gas stove in Figure 1.

Figure 1. Schematic diagram of a gas stove PG-PIT:
1 – burner; 2 – case wall; 3 – perforation for air supply; 4 – electric field; 5 – gas fuel mixture flows; 6 – stovepipe; 7 – flue gases; 8 – ceramic sleeve for gas fuel supply; 9 – voltage source; 10 – grill floor grounding point; 11 – frying floor; 12 – grounding; 13 – insulated electrode for gas mixer with air; 14 – ring insulator of the burner from ground; 15 – insulating pad.
Figure 1 shows a grounded electrode (10) embedded in the surface of the frying deck (11). The second electrode is located in an insulating ceramic sleeve through which gas fuel and ionized air are supplied. Ionization provides additional electrolysis of the fuel mixture and accelerates its combustion rate. The electrodes are powered from a voltage source (high-voltage transformer, through a rectifier). The design provides for the placement of electrodes at a distance of 50 mm from each other. The electrodes are fastened using circular porcelain insulators.

An electric current with an adjustable voltage $U = 7 \, \text{kV}$, a force $I = 2.3 \, \text{mA}$, and a frequency $f = 50 \, \text{Hz}$ is supplied to the electrodes, an electric field is formed between the electrodes. The lean gas mixture is fed into the burner (1) and ignites. The effect of an electric field (4) on the gas fuel (5) provides the formation of Coulomb forces, which intensifies its combustion and ensures the completeness of gas combustion, and also accelerates the release of burning flue gases to a positively charged frying plate. As a result, convective heat exchange increases due to electroconvection and a more uniform heating of the frying surface is provided. Следует It should be noted that a constant electric field leads to intensive mixing of electrified gas fuel molecules with an electrified oxidizer ($\text{O}_2$ или $\text{O}_3$) and their more intense combustion. [10, 11, 12].

An increase in the voltage on the electrodes provides an increase in temperature and heat output, and also increases the luminosity of the torch, Figure 2 [13, 14].

3. Problem statement
An additional effect is provided due to the formation of ozone ($\text{O}_3$) in the high-voltage field, which is a catalyst for the combustion of gaseous fuel. A catalytic electric field introduced into the combustion zone, formed by bipolar high-voltage potentials, accelerates the movement of electrically charged particles of fuel and oxidizer to the opposite electrode (frying floor), i.e. performs the function of an electrostatic pump [15, 16, 17].

The impact of ozone increases the economic efficiency and environmental safety of gas heating devices [18, 19].

In this case, the released thermal power of the frying floor surface is determined by the formula:

$$Q_{PN} = Q_K + Q_L = \left[ \alpha_K \cdot F_{PN} \left( T_{PNep} - T_{Bep} \right) \right] + \varepsilon \cdot 5.67 \, F_{PN} \left[ \frac{T_{PNep}}{100} \right]^4 - \left[ \frac{T_{Bep}}{100} \right]^4 \, \text{Вт},$$  \hspace{1cm} (1)
Providing an increase in the temperature of the frying floor by 39 %, heat transfer by 2 times, efficiency by 22 %, reduction of carbon oxides by 31 %, gas fuel consumption by 26 % when cooking.

The novelty is the creation of a catalyzing electric field in the combustion zone of gas fuel, created by including an ionizing device with an output voltage $U=7$ kV and a current strength $I=2–3$ mA into the gas stove structure. Additional electrification of the gas fuel provides the formation of Coulomb forces, intensifies combustion, and due to electroconvection, convective heat transfer increases.

The value of the technical solution for practice is to obtain additional effects during the combustion of gas fuel, providing an increase in the temperature of the frying floor by 39 %, heat transfer by 2 times, efficiency by 22 %, reduction of carbon oxides by 31–36 %, gas fuel consumption by 26 % when cooking.

4. Practical importance

The carried out experimental studies to determine the characteristics of the combustion processes of gaseous fuel (isobutane (CH$_3$-CH(CH$_3$)-CH$_3$) – 72 %, butane (CH$_3$-CH$_2$–CH$_2$-CH$_3$) – 22 %, propane (C$_3$H$_6$) – 6 %) in an electric field of variable intensity allowed us to obtain the following results [12]:

1). The most effective parameters of the voltage ($U = 7$ kV) on the electrodes for creating an electric field and burning ionized gas fuel in it have been determined (Table 1, Figures 3, 4).
Table 1. Results of surface heating temperature changes frying floor of a gas stove ($t_{hs}$, °C) with increasing voltage.

| Experiment | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------|---|---|---|---|---|---|---|---|---|
|            | Frying floor temperature, $t_{hs}$, °C | 310 | 314 | 320 | 338 | 352 | 374 | 397 | 418 | 419 |
| 1          | 314 | 318 | 325 | 337 | 350 | 375 | 397 | 418 | 419 |
| 2          | 312 | 316 | 323 | 338 | 354 | 376 | 400 | 419 | 420 |
| 3          | 314 | 318 | 325 | 337 | 351 | 375 | 397 | 418 | 419 |
| 4          | 312 | 317 | 323 | 338 | 351 | 377 | 402 | 417 | 418 |
| 5          | 313 | 317 | 324 | 338 | 351 | 375 | 395 | 418 | 418 |
| 6          | 312 | 316 | 323 | 338 | 356 | 376 | 401 | 418 | 422 |
| 7          | 308 | 319 | 328 | 335 | 350 | 374 | 396 | 416 | 420 |
| 8          | 311 | 315 | 321 | 335 | 353 | 376 | 400 | 419 | 422 |
| 9          | 315 | 318 | 326 | 337 | 351 | 376 | 397 | 419 | 419 |
| 10         | 312 | 316 | 323 | 338 | 352 | 375 | 398 | 418 | 420 |

Average value: 312, 316, 323, 338, 352, 375, 398, 418, 420

Figure 3. The influence of the electric field voltage on the luminosity of the flame during the combustion of ionized gas fuel:

a – no voltage; b – at a voltage of 3.5 kV; c – at a voltage of 7 kV.

Due to the intensification of the combustion of gases, the radiation in the infrared and ultraviolet spectrum increases, the heating temperature of the frying floor surface by 39 %.

2). The use of a constant catalyzing electric field with a voltage ($U = 7$ kV) on the electrodes provided the occurrence of an electrothermal effect, which made it possible to reduce the content of carbon monoxide (carbon monoxide (CO) by 36 % and carbon dioxide (CO$_2$) by 31 %) in the exhaust flue gases when burning gas fuel. (Table 2, Figure 4).

Table 2. The results of measuring the concentration of carbon oxides in flue gases.

| Experiment | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------|---|---|---|---|---|---|---|---|---|
|            | Concentration of CO, mg/m$^3$ | 69 | 64 | 63 | 59 | 58 | 55 | 49 | 45 | 43 |
| 1          | 70 | 65 | 62 | 60 | 57 | 54 | 47 | 45 | 44 |
| 2          | 67 | 63 | 62 | 61 | 59 | 53 | 49 | 46 | 43 |
| 3          | 79 | 65 | 62 | 60 | 57 | 54 | 49 | 45 | 44 |
| 4          | 67 | 63 | 62 | 60 | 57 | 54 | 47 | 46 | 43 |
| 5          | 69 | 66 | 60 | 59 | 57 | 54 | 46 | 44 | 43 |
| 6          | 67 | 63 | 62 | 61 | 59 | 55 | 47 | 46 | 43 |
| 7          | 67 | 63 | 62 | 61 | 59 | 55 | 47 | 46 | 43 |
3). An increase in the flame temperature abruptly increases the component of heat transfer by radiation. With an increase of 6% in electricity costs, the technical solution provides a 22% increase in the efficiency of the heating apparatus (Figure 4), and reduces the toxicity of flue gases (CO) by 31–36% (Figure 5).

Figure 4. Dependences of the influence of the electric field catalization on the combustion of gas fuel.
Figure 5. Dependencies of the influence of the electric field catalization on the reduction of exhaust gas toxicity.

5. Conclusions
During experimental studies it was found that the proposed technology of combustion of depleted ionized gas fuel in an electric field and a technical solution for its implementation provide an increase in the flame temperature by 49% during the combustion of gas ionized in an electric field; more complete combustion of the lean air-gas mixture; an increase in the surface temperature of the frying floor by 39%; reduction of gas fuel consumption by 26%; reduction of flue gas toxicity (CO) by 31–36%.

The developed technology has wide practical application not only for the food industry, but also for other industries. It can be used in road construction in the production of asphalt concrete mixtures, in the maintenance of asphalt concrete pavements, for waterproofing technologies for bridge structures and elements. It is expected that significant effects will be obtained from the application of the proposed solutions in heat-generating devices of boiler equipment and other heating systems operating on gas fuel.

6. References
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