A new home energy-saving gas stove based on multi-jet cutting technology

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Abstract. As one of the indispensable living equipment in Chinese family, the energy conversion efficiency of gas stove has been widely concerned. The purpose of this paper is to apply the principle of multi-jet cutting circle and catalytic combustion technology to transform the gas stove, combine with dune-shaped profile combustion technology, improving the combustion efficiency of the gas stove, reducing the proportion of polluted gas in the exhaust gas and the exhaust gas pollution of the gas stove, so as to achieve the purpose of full premix, low emission, high efficiency combustion of the gas stove.

1. Introduction
Nowadays, the vast majority of people's kitchen cookers are gas stoves. It is understood that the number of households using gas in China has reached 200 million, and the gas consumption of residents has reached 33 billion cubic meters. However, according to the energy efficiency rating set by China's "energy efficiency limit and energy efficiency grade of household gas stove" (GB30720-2014) for gas stoves, only about 10% of gas stoves in the market meet the level 1 energy efficiency requirement (combustion efficiency ≥63%). There is still room for improvement. This paper will start from the problems of low thermal efficiency and high exhaust pollution of existing gas stoves in the market, and optimize and improve the equipment by using the existing cutting-edge combustion technology. In this paper, jet cutting technology is used to realize premix of gas and air, dune profile standing vortex technology is used to realize efficient utilization of heat generated by the device, and through catalytic combustion, full premix, low emission and high efficiency combustion of domestic gas stove is realized.

2. Integrated system design:
In this work, aiming at the increasingly strict emission standards of domestic gas stoves by current national standards and the low combustion efficiency of existing gas stoves, we use cutting-edge combustion technology to systematically optimize and improve the existing equipment.

The device mainly includes: the laval nozzle at the bottom which plays the role of air entrainment, the multi-jet cutting round full premix equipment at the lower part, the catalytic combustion equipment in the middle part and the upper heating area, through full premix and catalytic combustion, the
combustion efficiency of gas can be improved, the emission reduction of harmful gas and the maximum utilization of heat.

![Figure 1: The structure of the whole device](image)

**3. Module design**

**3.1. The design of the laval nozzle**

The bottom of the work adopts the laval nozzle design, which is in the form of two end flaring and middle closing. Bernoulli equation is used:

$$ P + \frac{1}{2} \rho v^2 = k $$

It can be obtained that: when methane gas flows into the central inlet part through the flaring inlet, the air flow speeds up and the pressure through the area decreases, so that the external air is sucked into the pipe and then into the multi-jet cutting premix in the next part.
The jet pipeline based on laval nozzle structure is composed of a flaring inlet, a central throat, an outlet and a suction chamber. Natural gas enters the jet pipeline at a speed of 3m/s to form a turbulent jet. During the forward flow of natural gas, the speed is accelerated and a certain negative pressure is formed through the inlet area, which causes the outside air to be continuously sucked into the jet tube and mixed with natural gas into the multi-jet tangential premix in the next part. Designed Laval nozzle size parameters as shown below.

![Figure 2. Laval nozzle](image)

3.2. Multi-jet tangential premixer

In order to achieve full premixed combustion, this work designs an air multi-path ejection and tangential hybrid structure. Borrowing the idea of tangential combustion of pulverized coal in a large coal-fired boiler, different numbers of venturi tubes are set, and the positions of the venturi tubes are reasonably arranged to form a tangential mixed flow field.

![Figure 3. Laval nozzle size design](image)

![Figure 4. Design model of three jet cutting premix](image)
After repeatedly adjusting the Angle of rotation about the Y axis of the venturi tube and the Angle of rotation about the Z axis (tilt up), the project team found that the Angle of rotation gradually increased until between 16° and 18°, the methane to air combustion coefficient was expected to reach $=1.2$. Beyond this Angle, the air coefficient gradually decreased, and the average velocity of ejecting air decreased. When the Angle of tilt is between 6.5° and 7°, the average velocity of ejector air reaches the maximum. Therefore, the work adopts the optimal working condition of $=17°$ and $=7°$ to conduct the combustion simulation of the multi-jet tangential premix.

![Figure 5. Relationship between rotation angle $\beta$ and air coefficient $\alpha$ and relationship between tilt angle $\gamma$ and air coefficient $\alpha$](image)

3.3. Dune-shaped profile standing vortex technology
This module is provided with a multi-layer crescent-shaped dune-shaped protrusion in the second half of the jet pipe. The expanded geometry of the protrusion separates the air flow, and the separated flow returns to the root of the leeward slope under the effect of the pressure gradient to continue to ignite, so that Further mixing of incompletely combusted gas and air and the progress of heat, mass and combustion processes.

![Figure 6. Working principle of sand dune vortex](image)

3.4. Catalytic combustion
The catalyst region is mainly composed of the lower supporting metal network and the upper part of the porous catalyst region, with a thickness of about 8-10mm. The gas flows through this area at a high
speed after passing through the multi-jet cutting full premix, and the harmful gas content of the gas is further reduced by the action of the catalyst. Moreover, due to the blocking effect of the porous catalyst area, the gas jet velocity decreases, reaching the gas flow velocity of daily use.

![Figure 7. Catalytic combustion zone design](image)

The flame temperature of this work is about 912K, which belongs to the temperature range of medium temperature catalytic combustion (600-1000 °C) and belongs to the catalytic combustion controlled by transition diffusion.

At present, the main catalyst types are divided into cordierite honeycomb ceramics of catalysts, noble metal catalyst, load perovskite catalyst, considering factors such as catalytic effect and the equipment cost and life, this work adopts the cordierite honeycomb ceramics surface coating nickel form of low cost and more efficient catalytic in the cost control at the same time, catalytic combustion of fuel gas.

3.5. Acquisition and analysis system design

Natural gas is ejected from the gas supply source, passes through check valves, pressure gauges and flowmeters that prevent backflow, reaches the needle valve, and the gas flow rate can be controlled by adjusting the needle valve switch, and then the gas enters the combustion within the present apparatus works belongs. The combustion temperature is detected by 5 thermal sensors set in the multi-jet tangential premixer, inside the catalytic combustion area, and at different heights outside the device. The detection data is sent to a data acquisition system, and the temperature distribution diagram is obtained after computer analysis.

![Figure 8. Acquisition and analysis system design](image)
4. Parameter verification and result analysis

Through the investigation and visit of the natural gas company, it was found that the flow rate of CH₄ with natural gas line supplying the gas stove was about 2m/s, and the air entrainment speed was about 5m/s. Therefore, the above two conditions were used to set the parameters in this analysis, and the flow trace line and vortex center of methane premix combustion were obtained, as shown in the figure below.

Acquisition and analysis system design.

![Combustion premixed flow trace and vortex center diagram](image)

**Figure 9.** Combustion premixed flow trace and vortex center diagram

The incoming airflow forms a good tangential circulation around the central axis and has a relatively stable vortex center, which is conducive to the rapid and stable mixing of methane and air. Due to the combustion of methane and air, the velocity of the outlet flow can reach 26.7633m/s.

The distribution diagram of temperature and product after combustion is as follows:
When the combustion temperature is high, NO\textsubscript{X} and CO\textsubscript{2} are generated in large quantities, the temperature distribution in the combustion chamber is relatively uniform, and the premixing effect of CH\textsubscript{4} and oxygen is relatively good. The high-temperature combustion zone and NO, CO\textsubscript{2} generation zone appear in the premixer duct, which is conducive to the residence of the later combustion gas in the tangential combustion zone and further mixing and burning, which basically eliminates the rapid NO\textsubscript{X}
due to local rich fuel. In addition, the monitoring of combustion area does not have the area of flame temperature higher than 1800 k, therefore generated when fewer type thermal NO\textsubscript{X}, NO\textsubscript{X} generation greatly reduced.

Methane is almost completely burned up after being mixed with oxygen in the premix pipeline. After the first half of the flow through the pipeline, the gas velocity is obviously stratified with the inlet velocity due to the expansion of combustion. Moreover, after entering the tangential premix region, the velocity field is evenly distributed, and the gas flow is stable, which is conducive to the stable emission of flame after combustion.

Export products: CH\textsubscript{4} is about \(1.86972 \times 10^{-8}\), CO\textsubscript{2} is about 0.044715, NO\textsubscript{X} is about \(2.93689 \times 10^{-14}\), the wall temperature is about 791.924k, the average outlet temperature is 912.793k, and the outlet pressure is floating between 110 and 190Pa.

Design parameters of the open pipeline: the flow rate of CH\textsubscript{4} in the natural gas pipeline is 2m/s; the flow rate of the laval nozzle is 2.5m/s; the methane intake pipeline is a cylindrical pipe with a diameter of 10mm; the air intake pipeline is an annular pipe with an outer diameter of 26mm and an inner diameter of 10mm. According to the flow calculation formula:

\[
Q = \frac{\pi D^2}{4} \cdot v
\]  \hspace{1cm} (2)

It can be known that the flow rates of CH\textsubscript{4} and air are:

\[
Q_{air} = \pi \times [(0.13)^2 - (0.05)^2] \times 2.5 = 0.1m^3/s
\]

\[
Q_{CH_4} = \pi \times (0.05)^2 \cdot 2 = 0.0157m^3/s
\]  \hspace{1cm} (3)

(4)

According to the concentration calculation formula of the mixed gas, it can be known that:

\[
n_{air} = \frac{1L/s}{22.4L} = 0.047mol/s
\]  \hspace{1cm} (5)

\[
n_{CH_4} = \frac{0.0157L/s}{22.4L} = 0.0007mol/s
\]  \hspace{1cm} (6)

\[
M_{CH_4} = 0.0007mol \times 16 = 0.0112g
\]  \hspace{1cm} (7)

Therefore, in the mixture gas, the volume fraction of CH\textsubscript{4} is 15.7\%, which exceeds the upper limit point of methane explosion concentration and can be used for stable combustion. According to the heating calculation formula of natural gas mixture, it can be known that:

\[
X_j = \frac{\frac{Q \cdot M_j}{Z_j(t,p)}}{\sum_{j=1}^{N} \frac{Q_j \cdot M_j}{Z_j(t,p)}}
\]  \hspace{1cm} (8)

Among them: \(X_j\) is the mole fraction of natural gas component \(j\); \(Q\) is the volume fraction of natural gas component \(j\); \(Z\) is the compression factor of natural gas component \(j\).

Take the mixed gas as the ideal state gas:

\[
H_m^0(t_1) = \sum_{j=1}^{N} (X_j \cdot \frac{M_j}{M}) \cdot H_j^0(t_1)
\]  \hspace{1cm} (9)
Among them: $H^0_m(t_1)$ is a mixture of ideal quality calorific value; $H^0_j(t_1)$ is the ideal mass calorific value of natural gas component j; $X_j$ is the mole fraction of natural gas component j; $M_j$ is the molar mass of natural gas component j; M is the molar mass of the mixture;

Finally, it can be calculated as follows:

$$H = 58.87 \times 0.0112 = 0.6593 KJ$$  \hspace{1cm} (10)

The calculation formula of wall heat loss $Q_L$ is as follows:

$$Q_L = h_0 \cdot \sum A(T - T_0) + \varepsilon \sigma \sum A(T - T_0)$$  \hspace{1cm} (11)

Among them: $\sigma$ Stephan - the Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/(m²·K⁴); A is the heat exchange area of the wall outside the combustion chamber, and A=0.019 m²; T is the average external wall temperature of the micro-combustion chamber; $T_0$ is the ambient temperature, $T_0=25^\circ C$; $h_0$ is the heat transfer coefficient of natural convection, $h_0=10$ (W/(m²·K));

According to the finite element analysis results, it can be known that the temperature in the middle of the gas stove is about 994.1k, and finally calculated.

$$Q_L = 10 \times 0.019 \times 694.1 + 5.67 \times 0.7 \times 694.19 \times 10^{-8} = 131.86 J$$  \hspace{1cm} (12)

Converted heat loss $QL=131.86 J$.

Thus, the thermal efficiency of the gas stove can be seen as follows:

$$\eta = \frac{H - Q_L}{H} = 86.7\%$$  \hspace{1cm} (13)

5. Conclusion

The efficiency of the existing advanced burners in the market is generally about 60%, but according to the finite element analysis results, the combustion efficiency of this product reaches 86.7%, which is much higher than the existing products, and the generation of polluting gas is significantly reduced, so as to achieve low emission, high efficiency, stable combustion of household burners, with high energy saving and emission reduction benefits.

6. References

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