Design and Uniformity Analysis of Fully Premixed Natural Gas Burner Venturi Mixer

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Abstract. The venturi mixer is one of the key structures of the fully premixed surface natural gas burner. It has the function of uniformly mixing gas and air in a specific fluid space. In order to improve the burn-up rate of the combustion, and make the combustion temperature lowered to reduce the emission of NOx pollutants, a two-channel venturi mixer was designed, according to the venturi mixer performance of pressure loss and uniform. The mixer structure was analyzed by numerical simulation with the evaluation of the uniform performance parameters from the downstream following isometric characteristic cross-sectional. The results show that the venturi shrinkage angle and diffusion angle have little effect on the uniformity of mixer. The number or area of the gas injection holes is related to the uniform performance of the mixer and the pressure loss of the gas. The gas injection holes on the venturi mixer can be adjusted to balance two key parameters and it is an important factor in the design of venturi mixer structure of the fully premixed surface natural gas burner.

1. Introduction
As the country's requirements for energy conservation and emission reduction increase, and the urgent need for energy structure reform. It can be foreseen that the domestic demand for natural gas will continue to grow in the next ten years[1]. The fully premixed surface natural gas burner is a kind of high-efficiency combustion and ultra-low emission natural gas burner, which has gradually become the focus of enterprises, research institutions and developers. Premixing degree and pressure loss are key design parameters for the development and design of fully premixed surface natural gas burners. Therefore, designing a gas/air mixer with high efficiency, compactness, good uniform performance and stability determines premixed surface burner development level.

2. Theory of premixed mixers

2.1 Low emission theory of fully premixed surface natural gas burner
As a sulfur-free fuel, methane (CH₄) is widely considered to be a highly efficient clean fuel[2]. Non-premixed atmospheric burners usually have concentrated concentration areas during combustion. Not only will there be insufficient combustion of the area, so carbon monoxide will be produced, but the inner flame will have less contact with oxygen, which will form a rapid NOₓ[3], simultaneously, the combustion temperature is too high, the outer flame is in sufficient contact with oxygen. According to the Zeldovich mechanism, it also causes the oxidation of N₂ in the air to form thermal NOₓ[4]. In general, the thermal NOₓ dominates pollutant emissions of natural gas burner[5].
\[
\frac{dc_{NO}}{dt} = 3 \times 10^{14} \times c_{N_2}c_{O_2}^{-0.5}c_{NO}^{0.5}\left(-542000/RT\right)
\]  

\[N + OH \Leftrightarrow NO + H\]  

Where \(c_{N_2}, c_{O_2}, c_{NO}\) is the concentration of \(N_2, O_2, NO\). \(R\) is the gas constant (8.314 J/mol·K) and \(T\) is the temperature. It can be seen from the equal mechanism that the thermal \(NO_x\) will be produced in a large amount under high temperature conditions, and the upward trend has grown substantially. Another factor for the formation of the thermal \(NO_x\) is the oxygen contact concentration during combustion, and the amount of thermal \(NO_x\) produced is proportional to the square root of the oxygen contact concentration. As a ultra-low \(NO_x\) emission burner, the fully premixed surface natural gas burner is from the above principles to reduce pollutants. There are two means, one is the surface combustion method. Surface burning uses mesh metal fiber as a porous medium and is laid on the surface of the burner's head. The burning on the surface of the metal fiber mesh belongs to the micro-flame combustion, the overall heat release is uniform, which leads to the reduction of the overall combustion temperature. The other is full premixing. The premixing method belongs to lean fuel premixing, and the excess air coefficient is >1. Although the excess air increases the oxygen contact concentration during combustion, the low temperature air will also carry a large amount of heat during combustion. The reduction of thermal \(NO_x\) caused by flame cooling is far greater than the increase of thermal \(NO_x\) caused by the increase of oxygen concentration.

2.2 Mixers

Normally, when the gas is freely diffused in the air, it takes a long time to mix evenly. Therefore, the gas and air need a sufficiently long mixing distance in the state of absolute flow. But the long mixing distance cannot exist in a burner. For cost reduction and efficiency, a compact mixer is required to design for deep mixing of gas and air. At present, the mixing technology mainly has the structure of dispersing tube type, venturi type, swirling type, and pore network type. The structure of venturi type has the characteristics of high efficiency, compactness and uniform performance.

3. Design of gas/air mixing structure

3.1 Premix chamber and venturi mixer

The mixer is a mechanical device for enhancing lean fuel and rich air mixing, while the premix chamber provides gas and air closed compact mixing space and achieves gas and air a relatively uniform. The premixing chamber and the venturi mixer installed in the premixing chamber are shown in Fig.1. The gas enters from the gas inlet pipe and the air enters from the upstream of premixing chamber. After passing through the venturi structure, the gas and air are evenly mixed in a 365mm×250mm mixing section. The narrowest air flow cross-section area of venturi structure is 61575.8mm².

![Fig.1 Premix chamber and venturi mixer](image-url)
The gas injection hole is a key factor in the design of venturi mixer. According to Kittiwichettapong[6], the gas diffusion velocity in the air through the venturi structure is in relation to gas pressure. Based on this point, six kinds of open-hole venturi structures are designed, which are 40, 56, 72, 88, 104, and 120, φ3mm gas injection hole models.

In order to compare the effect of verification standard and non-standard shrinkage and diffusion angle on the uniform performance of venturi structure, three shrinkage and diffusion angle models are built: standard venturi shrinkage and diffusion angle (21.5°), and non-standard shrinkage and diffusion angle (38.0°, 50.0°). According to the research of Readerharris M.J.[7] and the design requirements of venturi, the non-standard shrinkage and diffusion angle will lead to the decrease of the flow coefficient and the increase of the flow resistance. The structure requires less tolerance to air flow resistance loss and higher requirements for uniform performance under actual conditions.

3.2 Entrance condition
The simulated burner uses 1.4MW as the rated load power of the burner. The volume ratio of fuel and air was 1:14.15, that is, the excess air ratio is about 1.4. The entry condition parameters are shown in Tab.1.

| Table 1. Entry condition parameters |
|-----------------------------------|
|                                  | Gas     | Air     |
| Volume flow rate (m3/s)          | 0.0459375 | 0.65   |
| Temperature/K                    | 298     | 298     |
| Density (kg/m3)                  | 0.7831  | 1.1850  |
| Mass flow rate (kg/s)            | 0.03597 | 0.77025 |
| Pressure (Pa)                    | 4000    | 4000    |
| Diameter of Inlet (mm)           | 60      | 365     |

4. Numerical simulation analysis of mixer models

4.1 Mixer models
To verify the effect of the designed venturi mixer, the following models are established, a total of 8 mixer models, as shown in Tab.2.

| Table 2. Mixer models for CFD simulation |
|-----------------------------------------|
| Name          | Angle | Number of Holes |
|---------------|-------|-----------------|
| Mixer I       | 21.5° | 120             |
| Mixer II      | 38°   | 120             |
| Mixer III     | 50°   | 120             |
| Mixer IV      | 50°   | 104             |
| Mixer V       | 50°   | 88              |
| Mixer VI      | 50°   | 72              |
| Mixer VII     | 50°   | 56              |
| Mixer VIII    | 50°   | 40              |

4.2 Numerical simulation analysis method
In the performance verification of the mixer, the pressure loss and non-uniformity analysis method are used. The undisturbed smooth mixing section at the end of the venturi structure and the downstream
250mm space, and 6 characteristic cross-sectionals are equally divided. The characteristic cross-sectional is used as a mixer performance evaluation section, each section being 50 mm apart.

Numerical evaluation of the uniformity of each characteristic cross-sectional as an evaluation index for the uniform performance of the mixer.

\[
SMD = \int \int \frac{|f - \bar{f}|}{A} dA
\]

Where SMD is the Spatial Mixing Deficiency, \( f \) is the equivalent concentration of fuel, \( \bar{f} \) is the average concentration of fuel on the characteristic cross-sectional, and \( A \) is the area of the characteristic cross-sectional.

4.3 Calculation results
Fig.2 shows the comparison of the standard venturi shrinkage and diffusion angle (MixerI), and the non-standard shrinkage and diffusion angle (MixerII, MixerIII) on the SMD non-uniformity of the mixer. It can be seen from the figure that the standard shrinkage and diffusion angle is the contribution of venturi structure mixing uniformity is slightly higher than the non-standard shrinkage and diffusion angle. Observing the data trend, from the first characteristic cross-sectional to the exit characteristic cross-sectional, the downward trend of each structure is basically the same as the amplitude. Explain that the mixing stroke has a good contribution to gas/air mixing uniformity (SMD decreases by about 0.3 in a 250mm mixing stroke, and still has a downward trend). The shrinkage and diffusion angle do not fundamentally change the uniformity of the mixer within a certain range(21.5°~50°), and the non-uniformity is slightly increased only when the shrinkage and diffusion angle is increased. Considering the axial structure size of the mixer, the smaller the shrinkage and diffusion angle and the larger the axial structure size, the axial structure size of MixerI, MixerII, MixerIII are 304mm, 150mm, 100mm. It can be seen that the increase of the axial size and the increase of the mixing distance will reduce the mixing non-uniformity of the mixer.

The change of the shrinkage and diffusion angle leads to the change of the axial size, and the mixing stroke determines the non-uniformity of the mixer to a certain extent. Both weaken the non-uniformity due to the decrease of the shrinkage and diffusion angle.

![Fig.2 SMD of non-standard angle](image)

Fig.3 shows the CH4 concentration profile over the 250mm equidistant 6 characteristic cross-sectionals downstream of the mixer. From MixerVIII to MixerIII, the CH4 concentration distribution on the characteristic cross-sectionals show that the center and the edge have a concentration concentration zone to a ring concentration concentration zone, and gradually the edge concentration dead zone. It is because the reduction of the opening area leads to a decrease in the gas flow velocity, which causes the gas to be injected at the small hole without sufficient initial kinetic energy, and during the injecting process, the air at a certain velocity is sucked. It causes the radial flow velocity too low, and the
concentration dead zone formed, before the edge of the mixing fluid domain has not been touched by gasflow.

![Fig. 3 Mass fraction of CH$_4$ on the characteristic cross-sectional](image)

According to the calculation, the SMD evaluation values of six characteristic cross-sectionals downstream of the six venturi mixers are obtained, as shown in Fig. 4. The number of openings has a great influence on the uniform performance of the venturi mixer. Within a certain range (40–120 holes),
the smaller the number of openings (or the smaller the area), the smaller the non-uniformity of the cross-sectional area of the mixer outlet. The number of openings has little effect on the air pressure characteristics, but has an exponential effect on the gas pressure characteristics. The smaller the number of openings (or the smaller the area), the greater the pressure loss on the gas side of the overall structure, and the greater the gas pressure required to stably maintain the gas inlet. According to the continuity theorem and the local resistance formula (e.g., equation 4), small opening number (or area) has high injection velocity and high local resistance loss.

\[ \Delta P_f = \frac{\zeta \rho u^2}{2} \]  

Uniformity improvement and high gas pressure loss are caused by the velocity of the injection. In the model VIII, most of the gas injected through the outer holes hits the boundary of the fluid domain, that is, the wall of the mixing space, and the gas injected through the inner holes is collected at the center of the inner fluid channel. The flows form a collision, and the collision leads to uniform diffusion. Simultaneously the larger the average injection velocity at the gas injection holes, the greater the partial pressure loss (e.g., equation 4). According to the calculation results, the static pressure loss of gas is 21524.773Pa, and the dynamic pressure loss is 236Pa. At full load, the inlet pressure of the main gas pipe must be maintained at 23044.773Pa.

![Fig.4 The uniformity and pressure characteristics of the six kinds of gas injection hole structure](image)

According to the actual operation of the fully premixed surface natural gas burner in the experiment and investigated, the gas inlet pressure before the gas valve group is generally less than 20000Pa, and the boiler back pressure is between 500Pa~2000Pa. The gas inlet pressure is generally guaranteed to be between 3000Pa and 5000Pa under full load state. In this pressure range, it can not only ensure the continuity of the gas input, but also filter the back-propagation fluctuation of the gas flow and combustion. Therefore, if the pressure loss is too large, the target effect of the actual operation of the mixer cannot be satisfied.

5. Conclusion

According to the theoretical analysis and numerical simulation results, the guiding conclusions of the design of the full premixed surface burner mixer are obtained:

a. The opening number (or area) of the gas injection holes of the mixer is the key factor for the uniform mixing design of the venturi mixer. The small opening number or area can increase the injection velocity, and increases the gasflow collision dispersion, which is favorable for the gas/air mixing uniformity.
b. The pressure loss of the mixer is a joint factor in the design of the characteristic parameters of the venturi mixer, which is mainly determined by the opening number (or area) of the gas injection holes of the mixer, the smaller the opening area, the greater the local pressure loss, and the greater the overall gas pressure loss of the mixer, vice versa. Mixer gas pressure loss is also a key design factor that determines burner reliability and versatility. High gas pressure loss will require a stable input at the burner gas inlet, reducing combustor versatility and increasing unstable combustion risk.

c. The mixer uniformity design and pressure characteristic design need to be balanced with each other, usually with the stability target as the precondition. Therefore, the gas pressure loss should be taken as the first design target. The uniformity of sacrifice can be compensated for by a structure with enhanced mixing that increases the small pressure loss, such as a large pressure angle swirling vane, a spoiler bluff body etc.

d. The shrinkage and diffusion angle of the venturi mixer has little effect on the uniformity of the mixer in the range of 21.5° to 50°, and the angle can be appropriately increased to reduce the axial dimension of the mixed structure, thereby improving the compactness of the overall structure.

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