CO emission of domestic gas cooker on Dutton diagram

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Abstract. The gas distribution system tends to be connected with multiple gas sources to meet the increasing demand for natural gas. However, different sources may cause a fluctuation of the constituents and lead to an increase of CO emission on domestic gas cookers. The purpose of this paper is to study CO emission characteristics of domestic gas cookers under variable three-component mixtures based on Dutton approach. In this paper, two typical gas cookers with round-port burner and strip-port burner were tested under different three-component mixtures. With reference to Dutton’s approach, CO emissions for three-component mixtures were experimentally measured. A universal formula is derived from fitting the experiment data to predict the CO emission of the cooker. The influence of initial primary air coefficient to this formula is discussed. A series of CO iso-lines are revealed on the Dutton diagram. A method to determine the limit gas was discussed based on CO iso-lines on the Dutton diagram.

1. Introduction

Natural gas industry in China has been developing at a rapid pace since 2000. It was predicted that the annual natural gas consumption would increase to 589–642 BCM by 2025 [1]. In China, more and more cities and provinces began to introduce gases from different sources in order to improve supply security and reliability [2]. There is an increasingly concern as to the response of gas appliances at end-users to variable gas constituents [3]. Gas cooker is the most popular gas appliance in China. It is clearly prescribed in relevant national standards that CO emission (corrected to air-free) should not be higher than 500 ppm [4]. Therefore it is essential to investigate CO emission characteristics of gas cooker under variable gas constituents to ascertain the allowable range of gas constituents [5].

The response of CO emission from a specific burner to changing gas constituents was a part of “gas interchangeability” research. Such research has never been systematically carried out in China [6]. Due to the fact that the management system and gas specification adopted in China is almost the same as those in Europe, namely reference gas together with a set of limits gases, and it would be highly useful if Dutton diagram could be used to predict allowable gas constituents.

The CO emission curves in Dutton diagram were achieved by testing on water heaters at their times [7, 8]. For a water heater with enough volume of the combustion chamber, flame seldom tends to directly contact with the heat exchanger, leading to quite low CO emission. Chinese gas cookers belong to open-flame gas appliances in which primary-air is provided by effective injection, and the secondary-air is supplemented by natural convection around the flame. In addition, the flame is always in direct contact with the surface being heated. The apparent difference between water heaters and Chinese gas cookers suggested that their prediction methods have to be experimentally validated prior to being adopted.
In this paper, two gas cookers of round-port burner and strip-port burner were tested. The heat input of the burners are 3.8kW and 4.0kW respectively. A set of three-component mixtures according to Dutton’s approach were input to the burner. The resulting flue CO emission was measured. The primary air was analyzed through the gas chromatograph. Several sets of CO emission iso-lines were derived and experimentally validated for both types of the cookers. The conclusion can be used to predict CO emission of gas stoves under different gas constituents. In addition, the method of gas quality management in China based upon Dutton diagram was discussed.

2. Experimental facilities and test procedure

2.1 Experimental facilities

The experimental rig was designed according to Chinese national standard GB 16410-2007, including gas blending system, gas cooker, and flue gas analysis systems, as illustrated in Figure 1.

Figure 1. Test system configuration

Gas blending system consisted of 3 high-pressure cylinders and Mass Flow Controllers. The test gas was a mixture of pure methane, propane, and nitrogen. The gas constituents for measurement can be pre-set on controlling computer and maintained constant during measurement. A wet-type gas meter was added to accurately measure gas flow rates of the gas cooker. The tested cookers, with round-port burner and strip-port burner respectively, represent the typical structures of cookers in the Chinese market, Figure 2. The concentrations of the combustion product components are measured by the flue gas analyzer. The tested data are recorded by the computer including O2, CO2, CO.

Figure 2. Tested cookers with round-port burner and strip-port burner

2.2 Test procedure

First, 12T-0 was input to the burner to make the initial adjustment of primary air coefficient. If the primary air is quite small, usually called “soft” flame, it would lead to excessive CO emission. If primary-air coefficient is large, namely a “hard” flame, it tends to lift when substituted by other gas rather than adjustment gas. If the primary air coefficient is properly moderate, it will result in quite acceptable flexibility for changing gas constituents. Unstable combustion phenomena, such as lift and excessive CO emission, will not occur when gas constituents fluctuate. To maintain gas pressure at cooker inlet 2kPa so that burner operated under nominal heat input. To adjust air-shutter so that suitable flame shape can be achieved. Then to record flue gas components. Afterward, different three-component mixtures were successively input to the burner, and flue gas was analyzed. In order to
systematically investigate the influence of Wobbe number and PN number (sum of C3H8 and N2, %) upon CO emission, the input mixture was deliberately designed to remain constant W or constant PN.

3. Results and discussion

3.1 CO emission of the round-port burner on Dutton diagram

The distribution of common natural gas sources in China was investigated. Their three-component mixtures were marked on the Dutton’s diagram to set a range for the CO emission study. The range of Wobbe number is 45-55MJ/Nm³ and PN number is 0-15. Therefore the test gases were selected according to this range. The burner was first fuelled with pure methane. After primary air shutter is fixed, let the burner which injected primary-air operate at nominal heat input 3.8kW. The gas-air mixture from injector was extracted by syringe and was analyzed by gas phase chromatography. It was found that the initial primary air coefficient was 0.3334. Then the burner remained unchanged anymore, and different three-component mixtures were input into the burner to record CO emissions. The test gases and their CO emission are shown in Figure 3.

![Figure 3](image)

**Figure 3.** Experimental data of CO emission of the testing three-component gases

After the investigation, it can be concluded that CO emission increases with increasing PN when the Wobbe number is fixed, and this trend can be described in terms of a first order function. Moreover, the CO emission goes up with the increase of Wobbe number. An exponential function can describe the CO emission with the change of Wobbe number under a constant PN number. Both propane and nitrogen can lead to an increase of CO emission. Therefore CO emission under various gas sources can be calculated by Eq.(1).

$$CO = (w_1 * P + w_2) e^{w_1*W} = (3.797 * 10^{-4} * PN + 0.02)e^{0.0454W}$$  \(1\)

Suppose CO to be a fixed value, e.g., 500, an equation depicting CO=500 can be derived, as Eq.(2). In similar manner, a set of CO iso-lines of tested cooker corresponding to initial primary air of 0.3334 can be derived, as shown in Figure 4.

$$W = -4.890*\ln(3.797*10^{-4} * PN + 0.02) + 30.39$$  \(2\)
To verify the accuracy of the function above, a number of points on the CO emission iso-lines were selected and the three-component mixtures were artificially set up to test CO emissions, as listed in Table 1. According to the verified CO emission and the iso-line, the function derived by several times fitting is accurate enough.

Table 1. Verified three-component mixtures and measured CO emission

| Verified gas code | Volumetric components (%) | Wobbe index (MJ/Nm³) | PN | CO emission (ppm) |
|-------------------|---------------------------|----------------------|----|-------------------|
| 1                 | 95 1.74 3.26             | 49.076 5             | 5  | 513               |
| 2                 | 95 4.04 0.96             | 51.374 5             | 5  | 814               |
| 3                 | 91 2.93 6.07             | 47.657 9             | 9  | 415               |
| 4                 | 91 4.94 4.06             | 49.639 9             | 9  | 626               |
| 5                 | 91 7.51 1.49             | 52.137 9             | 9  | 1013              |
| 6                 | 87 6.31 6.69             | 48.440 13            | 13 | 513               |
| 7                 | 87 8.69 4.31             | 50.739 13            | 13 | 785               |
| 8                 | 87 9.84 3.16             | 51.830 13            | 13 | 1012              |
| 9                 | 87 11.59 1.41            | 53.475 13            | 13 | 1379              |

The initial working condition is not unique. The injector can work well under a range of primary air coefficient and lead to a suitable flame. Fuel the burner with methane again and re-adjust the air shutter to another suitable point. It was found that the initial primary air coefficient was 0.4276 through gas phase chromatography. Then different three-component mixtures were input to the burner again, Figure 5. An Eq.(3) can describe the CO emission changing with Wobbe number and PN number.
Figure 5. CO iso-lines of tested cooker under the initial primary air coefficient of 0.4276

\[ CO = \left( 1.52 \times 10^{-4} \times PN + 0.01095 \right) e^{0.202^W_W} \]  

(3)

3.2 CO emission of the strip-port burner and initial primary air coefficient

The case of the CO emission of the strip-port burner on Dutton diagram is quite similar with round-port burner. The same form of the equation can be derived from fitting the test data. Eq.(4) and Eq.(5) shows the CO emission changing with the Wobbe number and PN number at the initial primary air coefficient of 0.3838 and 0.4239 respectively.

\[ CO_{\alpha'=0.3838} = \left( 6.138 \times 10^{-5} \times PN + 0.01841 \right) e^{0.2098^W_W} \]  

(4)

\[ CO_{\alpha'=0.4239} = \left( 3.686 \times 10^{-5} \times PN + 0.007636 \right) e^{0.2108^W_W} \]  

(5)

Therefore, it can be concluded that for a gas cooker which is initially adjusted under pure methane, its CO emission can be predicted by the formula

\[ CO = \left( w_1 \times PN + w_2 \right) \exp \left( w_3 \times W \right) \].

The different structure and shape of the port result in a different set of coefficients \( w_1, w_2, w_3 \). However, if the coefficients of one burner under different initial primary air coefficient are inter-compared, some interesting regularity can be derived.

The adjustment of the primary air shutter results in different primary air coefficient. But it does not change the structure of the top burner. Comparing the two groups of the CO emission equation, it can be found that for a certain test cooker, the coefficient of \( w_3 \) remains nearly the same when the initial primary air coefficient is different. In addition, although two groups of coefficients \( w_j \) and \( w_j' \) are different correspondingly, yet there is a kind of multiple rations, namely \( CO \approx 0.3838 \approx X \times CO \approx 0.3838 \). And the coefficient of \( X \) can be regarded as the influence of primary air coefficient.

3.3 Limit gas

It is stipulated in Chinese National Standard GB16410-2007 that CO emission from cooker should not exceed 500ppm. If the three-component mixture of a certain gas locates below 500ppm CO iso-line, the CO emission of the tested cooker will satisfy requirements from the national standard. As to a cooker with different geometry, its CO emission can be predicted by the approach proposed above. From the formula, it can be concluded that the worst CO emission appears when both Wobbe number and PN number reach the maximal value in the 12T natural gas range on Dutton diagram, as shown in Figure 6. However, this M point consists of CH\(_4\), C\(_3\)H\(_8\), and N\(_2\) and it is difficult in the process of gas blending. A CO iso-line can be drawn through this M point and will intersect with the CH\(_4\)-C\(_3\)H\(_8\) line. This intersection point represents a gas, consisting of methane and propane only, has the same CO emission with point M. Therefore this gas can be used as limit gas. A cooker, tested with this limit gas, will be judged qualified if its CO emission does not exceed 500ppm.
4. Conclusion

(1) CO emission of two gas cookers with round-port and strip-port were systematically measured when fuelling different three-component mixtures. As to a specific initial adjustment, CO emission was found to increase linearly with increasing $PN$ and to increase exponentially with increasing $W$. A function of $CO = (w_1*PN + w_2)e^{w_3*W}$ can be used to predict CO emission of tested cooker universally.

(2) For a specific test cooker, the coefficient of $w_3$ remains the same when the initial primary air coefficient is different. There is a kind of multiple rations of the two groups of coefficients $w_1$ and $w_2$. The ratio of the two groups reflects the influence of initial primary air coefficient.

(3) On Dutton diagram, there exist a set of CO emission iso-lines for the tested cookers. The worst CO emission appears when both Wobbe number and PN number reach the maximal value. The intersection of the CO iso-line through this point with CH$_4$-C$_3$H$_8$ line can be used as limit gas. If CO emission of the cooker is qualified when tested with this limit gas, the CO emission of the cooker will be qualified when tested with all 12T natural gases.

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