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Research on influence of gas quality on domestic gas appliances in China

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Table of Contents

Background

In China, there are a lot of different natural gas sources, such as pipeline natural gas (PNG), liquefied natural gas (LNG), synthetic natural gas (SNG) and so on. The large differences in gas component and property between different gas sources do exist, such as PNG coming from different regions will result in great changes in gas heat value, relative density, Wobbe Index and some other parameters [1]. But unfortunately, until now there are still no useful standards or government laws to manage the gas quality, in China, except the national standard GB/T 13611-2006 (identical to EN437) which prescribes the allowable Wobbe Index of natural gas admitting to pipelines. No systematic research has been carried out to evaluate the potential dangers resulting from the introduction of LNG, which makes the gas interchangeability problems more serious. If the various natural gas sources are supplied into the same gas pipeline, it will absolutely affect the normal use of gas appliances [2]. In the other hand, the major domestic gas appliances mainly include partial premixed combustion burner and fully-premixed type in China. The former is represented as domestic gas cooking appliances and gas instantaneous water heaters, while the latter is mainly condensing wall hanging gas boilers [3]. Usually, the gas heat load range is among 1 kW~70 kW, which is a very large span. So it is important to emphasize the influences of combustion condition, energy efficiency index and flue gas emission index on domestic gas end-users when gas is interchanged.

Aim

This paper carried out the experimental research on combustion characteristics of gas cooking appliances during different gas components and properties. By reviewing the recent progresses on technical research in the field of gas appliance adaptability to gas quality in China, the gas combustion characteristic indexes related to gas interchangeability were summarized. The key combustion characteristic index taking methane as a benchmark relating with CO emission was proposed and defined as "Combustion Index (CI)". The establishment of relevant formulas and characterization methods of CI were also explored. The research group determined and characterized the gas appliance adaptability by limit combustion curves in limit combustion working conditions such as lift out, flashback, CO content exceeding standard value and yellow tip flames. Gas indexes combination characterizing the limit curves above were proposed, which is based on Wobbe Index (WI) and Combustion Potential (CP), meanwhile concerning other parameters such as gas relative density (d) and gas heat value (HV). The combustion characteristics testing system of gas appliances (GCTS) was established to experimental determination and research on the adaptability of major domestic gas appliances, forming the adaptability range of gas appliances in-use in China. The common adaptability range of Chinese major domestic gas appliances was determined by experiment, and the current gas classification standard and natural gas interchangeability in China were also evaluated based on conclusion above.

Methods

1. Experiment methods of combustion index about CO emission

By the earlier works on CO emission of domestic gas appliances burning natural gas and analysing a large number of experiment results of the relationship between CO emission and gas components, it found that the specific value of CO_{mix} and CO_{CH4} exists some kind of mathematical relationship with gas components and relative density [4-6], and it can be defined as such a formula:

$$CI = \frac{CO_{mix}}{CO_{CH_4}} = \frac{k_1C_1 + k_2C_2 + k_3C_3 + k_4C_4 + k_5H_2 + k_6N_2}{\sqrt{d_{mix}}} \quad (1)$$

Based on this formula, this paper carried out the experimental research on the combustion characteristic of CO emission of domestic gas appliance to define a new "Combustion Index" named as "CI". The experiment included two phases. The first phase experiment was designed to test CO emission of gas mixtures which were mixed by CH_4 with each one of pure gas component, such as CH_4 & C_2H_6, CH_4 & C_3H_8, CH_4 & C_4H_{10}, CH_4 & H_2 and CH_4 & N_2. Then combining with the test results of CO_{mix}/CO_{CH4} and the test gas compositions, it could use the formula (1) to calculate influence coefficient (k_i) of each gas component. After that, the second phase experiment was carried out by testing the random mixture of four kinds of gas components, but the main gas composition is CH_4 which makes the gas mixture still belong to natural gas. The left value of the formula (1) is tested by experiment, and the right value of the formula (1) can be calculated by the results of first phase (k_i) combined with the gas composition analysis results by gas chromatography. Then comparing with the two values, it corrected the influence coefficient (k_i) of each gas component to make the CI value calculated by formula CI_{equ} equal to the CI value tested by experiment CI_{exp}. Finally based on large experiment results and mathematical statistical analysis, it defined the experimental empirical formula of CI. The experiment system is illustrated on Fig.2 named as "gas combustion characteristic experiment system", and the gas blending method is mixed by each pure gas components which are 99.9% methane, 99.5% ethane, 99.9% propane, 99.2% iso-butane, 99.9% hydrogen and 99.9% nitrogen.

2. Adaptability experiment of gas appliance

With feed gas compositions widely used, gas blending test can be conducted according to the main control index such as Wobbe Index (WI) and Combustion Potential (CP) [7], and the whole distribution range of blending-test-gas can be established. The figure of common distribution range of blending-gas in the formation of three feed gas components, such as one of CH_4, C_3H_8, n-C_4H_{10} and i-C_4H_{10} mixed with H_2 and N_2 can be established respectively, in a planar coordinate system with Wobbe Index (WI) as the y-axis and Combustion Potential (CP) as x-axis. The common gas-blending distribution range of the three feed gas components generally used is shown in Fig.1.

Fig.1 shows the blending-gas distribution range and the common blending-gas distribution range formed by three gas components of $CH_4/H_2/N_2$, $C_3H_8/H_2/N_2$, n-$C_4H_{10}/H_2/N_2$, and i-$C_4H_{10}/H_2/N_2$, etc. as their test gas. It is easily to find that the boundary line is not always linear form. The boundary line of any two groups of combustible gas forms the boundary line for the exponential curve; while the boundary line formation of N_2 and H_2, or N_2 and other combustible gas is straight.

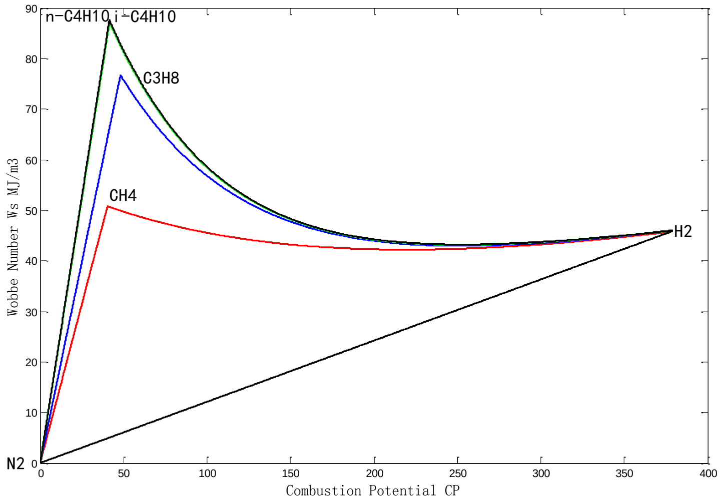


Figure.1 The common blending-gas distribution range with the three feed gases generally used.

In order to test adaptability range of gas appliances, it randomly selected the common type of domestic gas cooking appliances burning natural gas. The reference gas is natural gas of 12T-0, with a rated pressure of 2 kPa. The experiment chosen five domestic gas cooking appliances, numbered as sample 1, 2, 3, 4 and 5. And the design heat loads are 3.8 kW, 3.8 kW, 4.0 kW, 4.0 kW and 4.2 kW individually. The test sample 1, 2, 3 and 5 are two-eyed type, while the sample 4 is single-eyed. The test system is shown in Fig.2, named as "gas appliance adaptability experiment system". By changing the gas mixture components, it determined the scope of the curve parameters of lift out, flashback and incomplete combustion of domestic gas cooking samples. And based on the experimental results, it discussed about the applicability of gas combustion parameters, named as Wobbe Index (WI) and Combustion Potential (CP) [8-10]. Finally it formed the common adaptive range of different domestic gas appliances. Feed gases for gas-blending are selected from methane, hydrogen, nitrogen, and iso-butane, with purities of 99.9%, 99.9%, 99.9%, 99.2%, respectively.

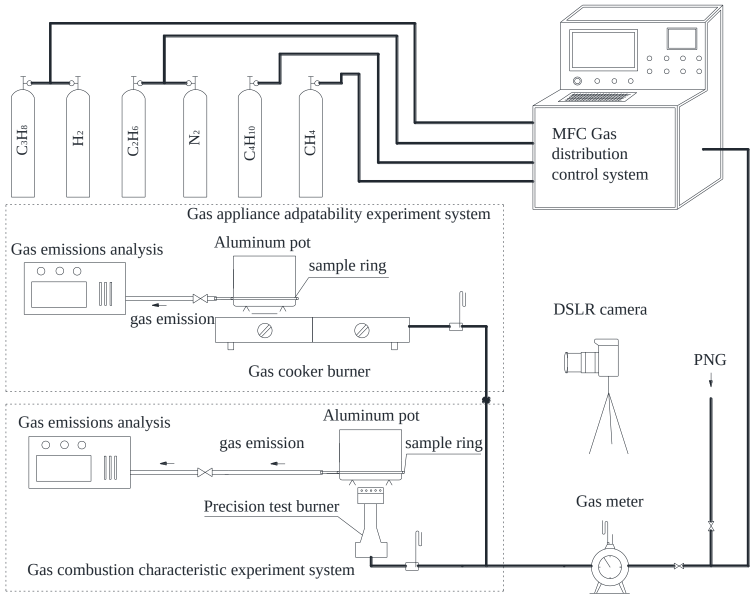


Figure.2 Schematic diagram of gas combustion characteristic and gas appliance adaptability experiment system

Results

1. Combustion Index about CO emission - CI

1.1 CH_4 mixing with one pure gas component

The first phase experiment was designed to test CO emission of gas mixtures which were mixed by CH_4 with each one of pure gas component. Combining with the test results of CO_{mix}/CO_{CH4} and the test gas compositions, it can use the formula (1) to calculate influence coefficient k_i of each gas component. The experiment results of CO emission influence coefficient k_i of each gas component are shown in Tab.1 and Tab.2. By making mathematical statistical analysis of influence coefficient k_i of each gas component, it took the mean value of k_i as the CO emission influence coefficient of each gas component. Such as the CO emission influence coefficient of ethane k_2 is 6.16, propane's k_3 is 9.31, butane's k_4 is 19.51, hydrogen's k_5 is -1.96 and nitrogen's k_6 is -8.16. When the gas mixture is just 100%

CH_4, then the formula (1) can be written as $k_1 = \sqrt{d_{CH_4}} \approx \sqrt{0.555} \approx 0.74$. So the formula of Combustion Index (CI) about CO emission is:

$$CI = \frac{CO_{mix}}{CO_{CH_4}} = \frac{0.74C_1 + 6.16C_2 + 9.31C_3 + 19.51C_4 - 1.96H_2 - 8.16N_2}{\sqrt{d_{mix}}} \qquad (2)$$

Table.1 Experiment results of CO emission influence coefficient of ethane, propane and butane

CO_{mix}/CO_{CH4}	CH_4	C_2H_6	*d*	k_2	CO_{mix}/CO_{CH4}	CH_4	C_3H_8	*d*	k_3	CO_{mix}/CO_{CH4}	CH_4	C_4H_{10}	*d*	k_4
1.690	0.960	0.040	0.575	6.50	1.738	0.969	0.031	0.586	9.68	2.047	0.972	0.028	0.600	17.01
1.750	0.940	0.060	0.585	5.45	1.751	0.957	0.043	0.598	7.94	2.456	0.958	0.042	0.620	20.31
1.828	0.921	0.079	0.594	5.11	1.955	0.950	0.050	0.605	9.58	2.653	0.951	0.049	0.630	19.37
2.031	0.902	0.098	0.604	5.68	2.058	0.942	0.058	0.613	9.76	2.853	0.943	0.057	0.650	19.31
2.184	0.882	0.118	0.613	5.82	2.151	0.933	0.067	0.622	9.68	3.049	0.926	0.074	0.660	18.92
2.475	0.866	0.134	0.621	6.69	2.204	0.921	0.079	0.634	9.07	3.376	0.922	0.078	0.680	20.19
2.885	0.847	0.153	0.630	7.80	2.406	0.911	0.089	0.644	9.86	3.773	0.913	0.087	0.690	21.44
2.946	0.828	0.173	0.640	7.38	2.589	0.890	0.110	0.665	9.65					
2.951	0.808	0.192	0.650	6.87	2.607	0.883	0.117	0.672	9.37					
2.947	0.786	0.214	0.661	6.37	2.601	0.874	0.127	0.682	8.90					
2.273	0.766	0.234	0.671	4.09	2.682	0.863	0.137	0.692	8.89					
Mean				6.16	Mean				9.31	Mean				19.51
Variance				1.137	Variance				0.325	Variance				1.917
Standard Deviation				1.066	Standard Deviation				0.570	Standard Deviation				1.385

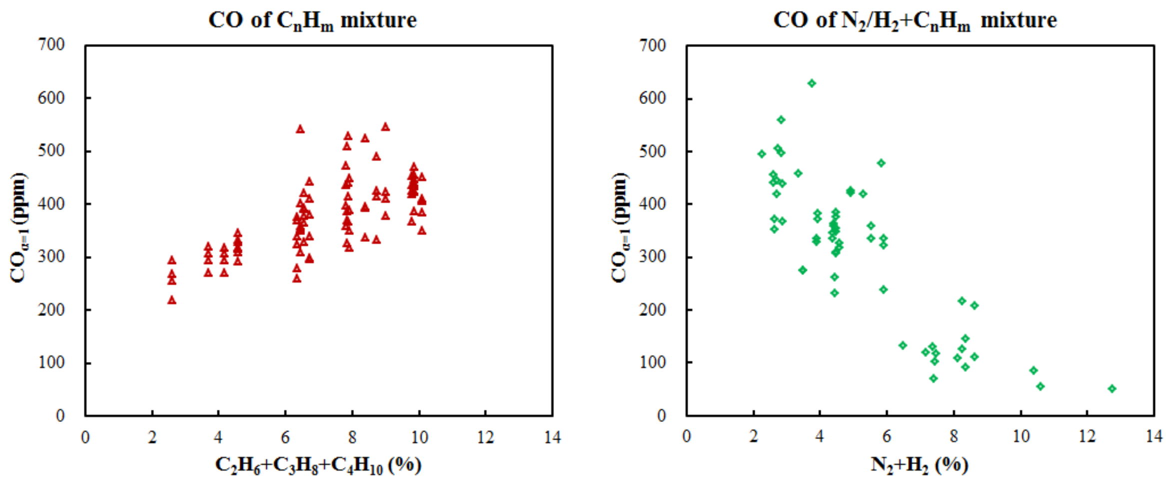
Table.2 Experiment results of CO emission influence coefficient of hydrogen and nitrogen

CO_{mix}/CO_{CH4}	CH_4	H_2	*d*	k_5	CO_{mix}/CO_{CH4}	CH_4	N_2	*d*	k_6
1.163	0.952	0.048	0.532	-1.81	0.463	0.951	0.049	0.575	-8.88
0.553	0.873	0.128	0.493	-2.93	0.447	0.949	0.051	0.576	-8.70
0.613	0.865	0.135	0.489	-2.53	0.348	0.943	0.057	0.578	-8.66
0.508	0.830	0.170	0.472	-2.20	0.344	0.942	0.058	0.579	-8.54
0.455	0.794	0.206	0.455	-1.84	0.346	0.941	0.059	0.579	-8.52
0.317	0.789	0.212	0.452	-2.08	0.262	0.933	0.067	0.582	-8.05
0.250	0.748	0.252	0.433	-1.77	0.273	0.932	0.068	0.582	-7.96
0.400	0.745	0.255	0.431	-1.48	0.284	0.931	0.069	0.583	-7.59
0.309	0.710	0.290	0.414	-1.37	0.222	0.925	0.075	0.586	-7.35
0.137	0.707	0.293	0.413	-1.59	0.223	0.924	0.076	0.586	-7.34
Mean				-1.96	Mean				-8.16
Variance				0.235	Variance				0.337
Standard Deviation				0.485	Standard Deviation				0.581

1.2 CH_4 mixing with other three pure gas components

The second phase experiment was carried out by testing the random mixtures of four kinds of gas components, but the main gas composition is CH_4 which makes the gas mixture is still belong to natural gas. With the experiment results it corrected the influence coefficient (k_i) of each gas component to make the equation value CI_{equ} equal to the experiment value CI_{exp}.

As shown in Fig.3, CO emission increases with the raise of C_nH_m composition and decreases with the raise of N_2+H_2 composition, which matched with the formerly research results [11-13]. That means the results tested by this experiment are believable.



Firgue.3 CO emission changing with gas components

By comparing the experiment tested value of CO_{mix}/CO_{CH4} named as CI_{exp} with equation value of CO_{mix}/CO_{CH4} calculated by formula (2) named as CI_{equ}, the mathematical statistical analysis of the specific value of CI_{exp}/CI_{equ} was made, and the results were illustrated in Fig.4. The mean of CI_{exp}/CI_{equ} is 0.970, and the standard deviation is 0.341, as well as the distribution of CI_{exp}/CI_{equ} results conforms to normal distribution. But actually from the mean value of CI_{exp}/CI_{equ}, it seems like the experiment value CI_{exp} is little smaller than equation value CI_{equ}. And the expression of deviation from average value of CI_{exp}/CI_{equ} is not symmetrical, while the absolute value of positive and negative value is deviated a lot. Although the sum of squares of deviation from mean equal 0, the maximum value of square of deviation from mean is 1.443, which is a big value meaning the equation value CI_{equ} largely deviated with the experiment value CI_{exp}. So it must correct each of influence coefficients k_i to make the equation value CI_{equ} equal to the experiment value CI_{exp}.

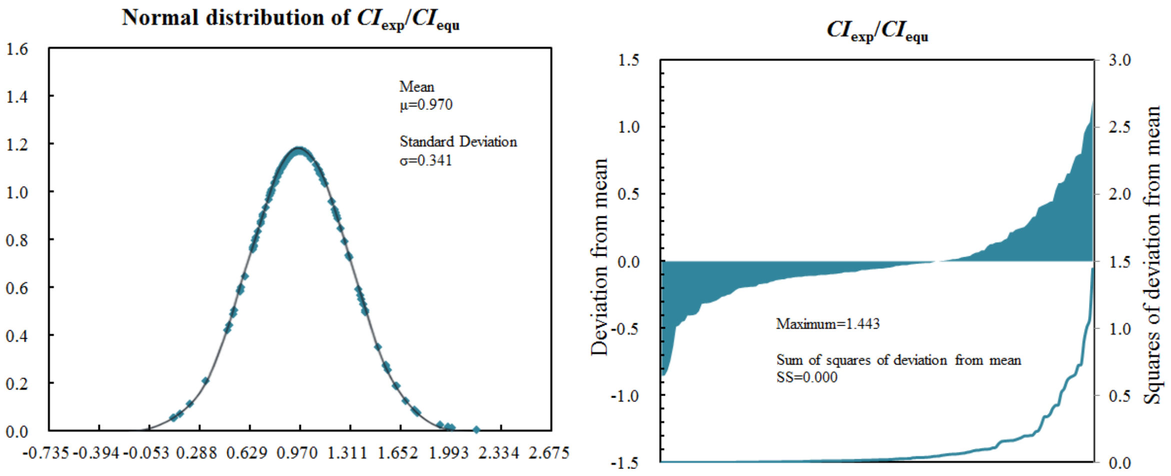


Figure.4 Mathematical statistical analysis of the specific value of CI_{exp}/CI_{equ}

The correction results of CO emission influence coefficient k_i of each gas component are listed in Tab.3. So the formula of Combustion Index (CI) about CO emission property can be written as:

$$CI = \frac{0.74C_1 + 5.1C_2 + 7.8C_3 + 16.3C_4 - 1.9H_2 - 7.6N_2}{\sqrt{d_{mix}}} \quad (3)$$

Table.3 The correction of CO emission influence coefficient k_i of each gas component

CO emission influence coefficient		The first phase experiment	The second phase experiment
CH_4	k_1	0.74	0.74
C_2H_6	k_2	6.16	*5.1*
C_3H_8	k_3	9.31	*7.8*
C_4H_{10}	k_4	19.51	*16.3*
H_2	k_5	-1.96	*-1.9*
N_2	k_6	-8.16	*-7.6*

It compared the experiment value CI_{exp} with the corrected equation value $CI_{equ\text{-}co}$ calculated by formula (3), and made the mathematical statistical analysis of the specific value of $CI_{exp}/CI_{equ\text{-}co}$, as illustrated in Fig.5. The mean of $CI_{exp}/CI_{equ\text{-}co}$ is 1.000, and the standard deviation is 0.280, as well as the distribution of $CI_{exp}/CI_{equ\text{-}co}$ results perfectly conforms to normal distribution, which means the corrected equation value $CI_{equ\text{-}co}$ entirely equals to the experiment value CI_{exp}. Meanwhile the expression of deviation from average value of $CI_{exp}/CI_{equ\text{-}co}$ is symmetrical and the absolute value of positive and negative value is deviated a little. The sum of squares of deviation from mean equal 0, as well as the maximum value of square of deviation from mean is only 0.780, which means the corrected equation value $CI_{equ\text{-}co}$ deviated from the experiment value CI_{exp} in a small range. So it can be concluded that the results calculated by formula (3) are accordance with the experiment tested results.

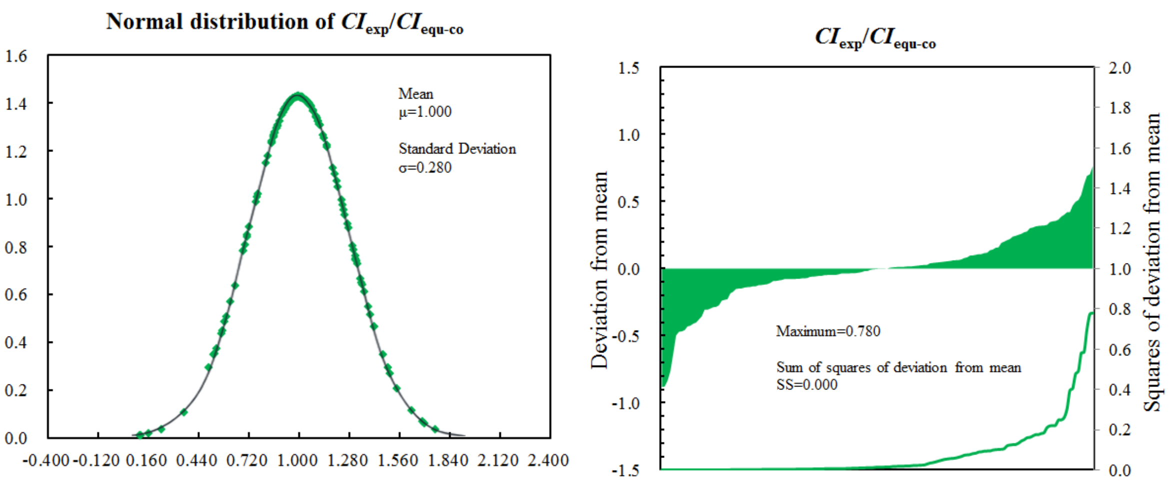


Figure.5 Mathematical statistical analysis of the specific value of $CI_{exp}/CI_{equ\text{-}corrected}$

As normalizing the methane influence coefficient k_1 to 1 in formula (3), it defines a new formula vision of Combustion Index (CI) about CO emission property, as:

$$CI = \frac{C_1 + 6.9C_2 + 10.4C_3 + 21.8C_4 - 2.6H_2 - 10.2N_2}{\sqrt{d_{mix}} / \sqrt{d_{CH_4}}} \quad (4)$$

Where CI is combustion characteristic about CO emission property; C_1, C_2, C_3, C_4, H_2 and N_2 are the volume percentage values of gas mixture, and $C_1+C_2+C_3+C_4+H_2+N_2=1$; d_{mix} is the relative density of gas mixture; d_{CH_4} is the relative density of methane.

2. Gas adaptability experiment results

To test the combustion characteristics of gas cooking appliances by the experiment, a testing system has been established. According to different combination of feed gases by controlling the flow of mixed gas, when the limit conditions of lift out, flashback and CO content in flue gas exceed the standard occur, respectively, the experiment system will automatically collect and store the data of feed gas flows component in mass or volume, and then analyse the flue gas composition and content relevantly. Real-time record of the feed gas flow rate in each branch calculates the ratio of each component in gas mixture in volume. Thus the combustion parameters in gas mixtures will be calculated. Calculated parameters include heat value (HV), relative density (d), flame speed (Sn), Wobbe Index (WI) and Combustion Potential (CP) etc. Combination of mathematical statistics and the limited experimental data processing method, the experimental test results are processed and analysed.

Based on the calculation of other combustion parameters, such as high heat value, relative density, gas flame burning velocity, Wobbe Index, Combustion Potential and yellow tip index, the conclusion are as follows: the two-dimensional graphics established with Wobbe Index (WI) versus gas flame burning velocities can form a similar smooth curve and similar closed surrounded area, but not as good as those formed by the parameter of WI versus CP. While the two-dimensional graphic established by heat value (HV) versus Combustion Potential (CP) parameters, of which curves and forms tend to irregular and it can't express the combustion characteristics of test gases. So the coordinates graphics established with the two parameters of Wobbe Index (WI) versus Combustion Potential (CP) can get the smoothed combustion characteristic limit curve of lift out, flashback, and CO exceeding, and a stable closed adjustability range of gas appliance can be formed, as shown in Fig.6.

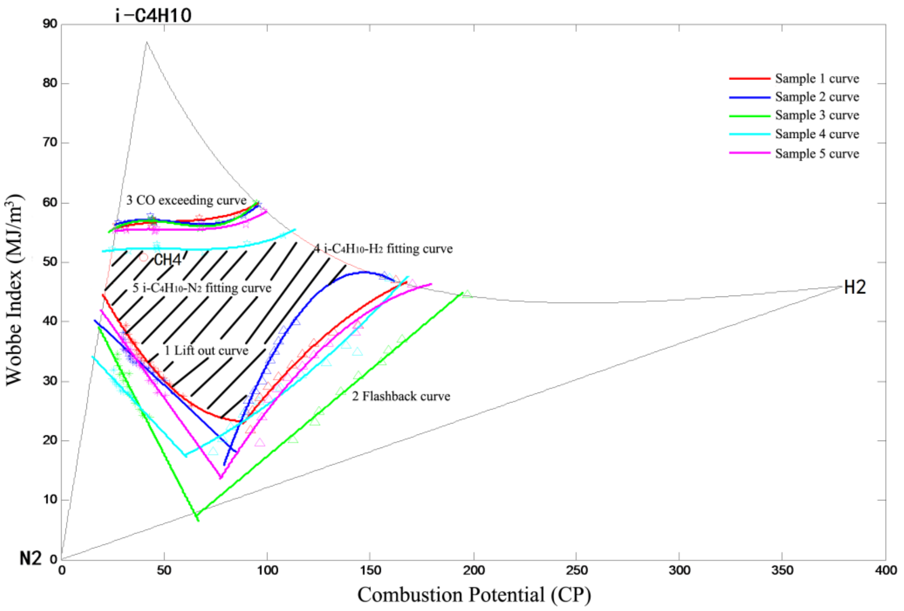


Figure.6 The common combustion adaptability range of different gas cooking samples

The reference gas is located in the closed region of limit curve of lift out, flashback, CO exceeding the limit, i-C_4H_{10}-N_2-H_2 boundary line and i-C_4H_{10}-N_2 boundary line. The combustion requirements of gas cooking appliance can meet that of the reference gas. Based on the combustion adaptability tests with 5 kinds of test gas cooking samples, the ultimate combustion parameters range of gases can be derived as shown in Fig.6. From which we can see that the common adjustability range for the three feed gases of i-C_4H_{10}, H_2 and N_2 is as the shadow area.

According to the combustion characteristics curve shown in Fig.6, the regression analysis and curve fitting can be conducted, and the fitting curve equations are shown in Tab.4. At the same time, with the test results of 5 gas cooking samples illustrated in Fig.6, the coordinates of its reference point is the point where the pure CH_4 gas sites. Compared with the curves of lift out, flashback, and CO content exceeds limit, we can find that the nearest points to the reference point is the CO curve point. So the maximum allowable change of Wobbe Index is calculated and shown in Tab.4. Actually the gas cooking sample 2 has the largest capacity adapt to changes in test gas compositions, whose value of the maximum allowable change of Wobbe Index is 11.2%. While the sample 4 has the weakest capacity of change in test gas compositions, whose value of the maximum allowed change of Wobbe Index is only 1.9%, which means when small changes occur in gas composition, it can make CO gas level increase excessively.

In other experiments, we also tested the combustion characteristic of domestic gas instantaneous water heater samples common used in China, and the preliminary experiment results indicated the similar trend of combustion adjustability range as domestic gas cooking appliance. The specific research results of combustion characteristic of domestic gas instantaneous water heaters will be drawn in the later works.

Table.4 The fitting curves of samples and the maximum allowable change of Wobbe Index

Number of appliances	The fitting curves		The maximum allowable change of Wobbe Index , % $= \frac{W_{\mathrm{lim,min}} - W_{\mathrm{ref}}}{W_{\mathrm{ref}}} \times 100\%$
The common boundary line	$i\text{-}C_4H_{10}\text{-}H_2$	$y=97.5e^{-0.0144x}+32.27e^{0.00091x}$	--
	$i\text{-}C_4H_{10}\text{-}N_2$	y=2.094x	--
Sample 1	Lift out curve	$y=0.0045x^2-0.8011x+58.99$	--
	Flashback curve	$y=-0.0018x^2+0.7513x-29.6891$	--
	CO exceeding curve	$y=-0.0056x^2+0.3198x+50.5121$	9.5%
Sample 2	Lift out curve	y=-0.3237x+45.6219	--
	Flashback curve	$y=-0.0069x^2+2.0473x-102.5272$	--
	CO exceeding curve	$Y=-0.0001x^3-0.0108x^2+0.5588x+47.8411$	11.2%
Sample 3	Lift out curve	y=-0.6731x+51.4152	--
	Flashback curve	y=0.2902x-11.7086	--
	CO exceeding curve	$y=0.0001x^3-0.0151x^2+0.7875x+43.7402$	10.4%
Sample 4	Lift out curve	y=-0.3694x+39.7986	--
	Flashback curve	$y=0.0010x^2+0.0542x+10.7211$	--
	CO exceeding curve	$y=-0.0029x^2+0.1504x+49.7921$	1.9%
Sample 5	Lift out curve	y=-0.4816x+51.2580	--
	Flashback curve	$y=-0.0023x^2+0.9134x-43.1938$	--
	CO exceeding curve	$y=-0.0047x^2+0.2332x+51.7297$	8.6%

Conclusions

This paper carried out the experimental research on combustion characteristics of gas appliances during different gas components and properties. The key combustion characteristics index taking methane as a benchmark relating with CO emission was proposed and defined as "Combustion Index (CI)". The establishment of relevant formulas and characterization methods of CI were also explored. The research group determined and characterized the gas appliance adaptability by limit combustion curves in limit conditions such as lift out, flashback, CO content exceeding standard value and yellow tip flames. The combustion characteristics testing system of gas appliances (GCTS) was established to experimental determination and research on the adaptability of major domestic gas appliances, forming the adaptability range of gas appliances in-use in China. The common adaptability range of major domestic gas appliances was determined by experiments, and the current gas classification standard and natural gas interchangeability in China were also evaluated.

According to the experiment research on combustion characteristic about CO emission property, it defines a new Combustion Index (CI) and the formula is:

$$CI = \frac{C_1 + 6.9C_2 + 10.4C_3 + 21.8C_4 - 2.6H_2 - 10.2N_2}{\sqrt{d_{mix}} \Big/ \sqrt{d_{CH_4}}}$$

Where CI is combustion characteristic about CO emission property; C_1, C_2, C_3, C_4, H_2 and N_2 are the volume percentage values of gas mixture, and $C_1+C_2+C_3+C_4+H_2+N_2=1$; d_{mix} is the relative density of gas mixture; d_{CH_4} is the relative density of methane.

By study on the adaptability of domestic gas appliances, the following conclusions can be drawn:

(1) The combustion performance of gas appliances can be defined and evaluated by the two combustion parameters of Wobbe Index (WI) and Combustion Potential (CP) of test gases, and the bounded closed region was established by limit combustion conditions such as lift out, flashback and CO content in flue gas exceeded the standard limit, as well as the location site of reference gas is also in the region.

(2) The whole gas-blending distribution boundary of i-C_4H_{10}, H_2, N_2 as feed gas is irregularly closed triangle, when Wobbe Index (WI) and Combustion Potential (CP) as gas-blending control parameters. And the combustion adjustability range of gas appliances is a closed area surrounded by 5 smooth curves or straight lines.

(3) The combustion characteristics adaptation index of natural gas composition applied to the test gas appliances must fall within the common adjustability range, and only by which can the gas appliance burning properly.

(4) The experimental system and method introduced above can provide scientific, quantitative evaluation methods and technical measures for combustion adjustability judgment, design quality level evaluation of gas appliances and city gas interchangeability.

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