Research Progress on Gas Interchangeability in China

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Keywords: city gas; gas interchangeability; adaptability region; interchangeability region; gas blending.

Summary: The paper reviews technical progress on research and engineering practice in gas interchangeability of recent China cities, from both aspects of urban gas interchangeability and gas appliance adaptability. Aimed at current situation of multiple fuel gases supplied to the city, the technology of interchangeability and conversion of multi-gas resources in one city is developed, the technical methods for determining interchangeability range of city gas and adaptability range of gas appliance has been originally proposed,. The technique of urban gas source allocation and multi-gas interchangeability is firstly advanced and engineering practice fulfilled. The research established technology and equipment of experimental gas blending and adaptability range testing of gas appliance; verified and characterized the key indexes to determine the combustion characteristics of partial-premixed gas appliances; put forward a technical route balancing technicality with economy in multi-gas interchangeability research. It also pointed out that with the diversification of gas burning devices and difference of burning utilization type, a reasonable choice of technical parameters and control indexes of urban gas interchangeability is needed, and a lot of experimental research and technical feasibility studies, to build a comprehensive and scientific technology system of urban gas interchangeability in China, should be progressed.

1 Background

By the end of 2010, in China's total urban gas consumption, the man-made coal gas supply totaled 27.99 billion cubic meters, the length of supply pipeline was 38,877 kilometers; the natural gas supply totaled 48.76 billion cubic meters, and the length of supply pipeline was 256,429 kilometers; and the LPG supply totaled 12.38 million tons, and the length of supply pipeline was 13,374 kilometers [1].served a population of 363 million, an increase of 5.5% from 2009; the total pipe length was 308,680 kilometers, an increase of 12.9%; and with a coverage rate of 92.04%, raised 0.63 percentage points [1]. Currently, urban gas industry is in a period of great development, the situation of man-made coal gas and liquefied petroleum gas as the main sources of urban gas has been greatly changed with rapid growth of natural gas in cities.

China is now gradually speeding up the construction of natural gas transmission pipeline

network. The planned gas pipeline network will take the current West-East natural gas transmission line, Shanxi-Beijing- lines of the 1st ,2 nd and 3rd, Zhongxian-Wuhan-line, Sebei-Xining-Lanzhou-line as the main pipeline, to build a number of trunk and connecting pipelines, extending south to Zhuhai, Beihai, extends to Heilongjiang, Xinjiang and other transnational pipelines connected with Russia in the north and west. By the end of 2020, there will form a big interconnected pipeline network of natural gas with domestic gas sources, imported gas and coastal LNG pipelines, all the lines linking up between the gas sources, and urban gas resource allocation harmonized, to achieve the integrated national gas supply network in China. Now with the national long-distance transmission of natural gas in different gas fields, the formation of multiple interconnected transmission and distribution pipeline network model, the city has formed or are facing a situation of multi-source of gases supplying the same distribution network system.

Accordance with the prediction from relevant authorities, by 2015, China's natural gas consumption in China will reach 240 billion cubic meters; a shortage gap will be 50 billion to 60 billion cubic meters by 2015, and 90 billion cubic meters in 2020 [2]. The situation of large-scale use of clean energy and the objective requirements of energy savings and emission reducing, increased the consumption of natural gas. "Gas Shortage" in cites has appeared several times throughout the country,. For the purpose of guaranteeing gas supply security, standby and peak shaving gas sources are urgently needed to introduce to the cities.

There are many fields of gas utilization, in China. The main field of gas combustion utilization is urban gas, industrial fuel, gas-fired air conditioning, gas-fired cars, gas-fired power generation, etc. The gas burning devices used mainly in domestic combustion equipment, industrial burners, gas boiler burners, internal combustion engines, gas turbines[3], etc. The NGC+ Work Group in U.S. divided the gas end use devices as follows: (1) general gas burning facilities; (2) industrial boilers, furnaces and process heaters; (3) reciprocating engines (including natural gas vehicles); (4) gas combustion turbine; (5) non-combustion uses including LNG peak shaving liquefaction and chemical and consumer product manufacturing [4]. With the increasingly diversification in gas burning appliances and equipment, the capability of which differs to adapt to changes in reference gas components. A series of problems emerged such as the adaptability and matching problems between gas appliances "in use" and new gas sources supplied to cities, the components fluctuation in reference gas or alternate gas with combustion working conditions of gas appliances. When different types or families of gases distributed or used for peak shaving in the same pipeline of one city, there will bring about different effects to gas end use terminals, even deteriorate combustion environment, sometimes which may cause accidents due to large changes in gas compositions.

With the rapid development of natural gas in China, the pattern of independent gas supply in cities changed, and the urban gas supply and management system has undergone great changes. There are still many technical and supervisory problems to adapt to the current

natural gas-based pattern. Specifying and regulating conversion and interchangeability technology of urban gas is the main method, which can the action of exchange and conversion between the former gas and natural gas, the natural gas and alternate or peak shaving gas be carried out safely, efficiently, economically and quickly. The more serious problems existed currently are the interchangeability of multiple gas sources, adaptability of gas appliances, security of gas energy supply, combustion utilization efficiency and gas saving. How to progress the work of urban gas allocation and conversion, and to maximize the utilization efficiency of all end users smoothly and safely under the circumstances of multiple gas sources supply, are technical problems existing till today in gas industry. It is important to carry out theory and practice researches in city gas interchangeability for the work of conversion and interchangeability of urban gas and energy saving in China cities.

Figure 1 shows the total gas supply data (by caloric) in China from 1997 to 2010 [5], Table 1 gives the main combustion parameters and types of natural gas supplied in China [6, 7].

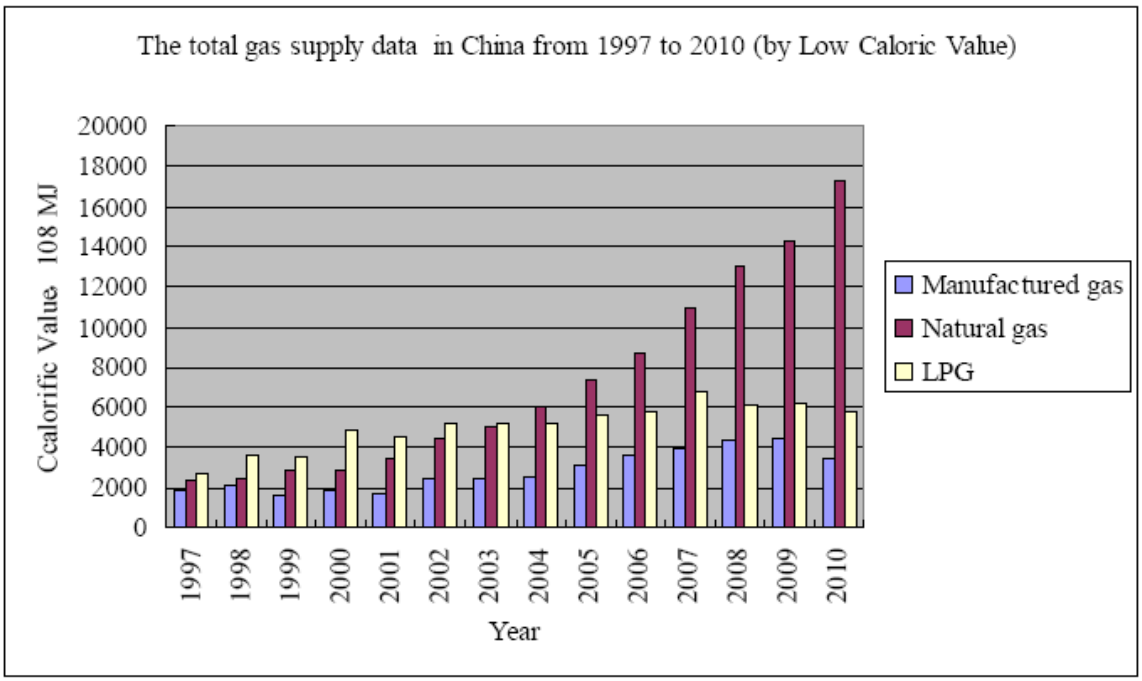

Fig. 1 The total gas supply data in China from 1997 to 2010 (by low caloric value)

Table 1. The main combustion parameters and types of natural gas supplied in China

Name of natural gas	Combustion Characteristics Parameter				Type of natural gas
	High Heating Values, MJ/m^3	Low Heating Values, J/m^3	High Wobbe Index, MJ/m^3	Low Wobbe Index, MJ/m^3	
Shan-Gan-Ning NG	37.49	33.79	48.86	44.04	12T
Talimi NG	38.22	34.45	50.32	45.34	12T
Beihai Guangxi NG	40.74	36.84	50.18	45.38	12T

Chengdu NG	36.50	32.87	48.31	43.50	12T
Zhong-Wu pipeline NG	38.13	34.35	50.44	45.45	12T
East China Sea NG	38.22	34.48	48.94	44.16	12T
Tsingdao NG	37.92	34.16	50.04	45.09	12T
Changyi NG	37.47	33.75	49.85	44.89	12T
Bohai sea NG	37.03	33.42	45.85	41.37	12T
Dongfang South China Sea NG	30.69	27.65	38.02	34.26	10T
The 1st West-East Pineline NG	38.31	34.53	50.40	45.42	12T
Dapeng Guangdong LNG	42.97	38.86	53.55	48.42	12T
Fujian LNG	38.34	34.55	50.61	45.60	12T
Xinjiang LNG	42.90	38.81	52.70	47.68	12T
Central Plains LNG	38.95	35.11	51.23	46.18	12T
Hainan LNG	43.35	39.22	53.26	48.20	12T
NG imported from Burma	37.68	33.93	50.21	45.22	12T
NG from Turkmenistan	38.53	34.75	49.45	44.59	12T
NG from Kazakstan	37.94	34.19	49.58	44.68	12T

2 Overview of gas interchangeability method in China

The NGC+ Interchangeability Work Group from the U.S. gives the definition of "Interchangeability" as follows: the ability to substitute one gaseous fuel for another in a combustion application without changing operational safety, efficiency, performance or materially increasing air pollutant emissions. The new definition is different from the traditional ones, the traditional definition focuses on whether the combustion performance is affected; while the new definition evaluates comprehensively the effect of gas interchangeability from the burning safety, efficiency and energy saving, emission control target of gas appliance.

Among all the determination methods of gas interchangeability advanced, there are four of them widely used for a long time. They are the A.G.A. Bulletin 36 method of the U.S. (1946), the Weaver index method developed from Bulletin 36 (1951), the Delbourge gas interchangeability method from France (1953), the UK Dutton graphics interchangeability method (1978). The general characteristics of them are: the methods are all shaped and proposed before the 1980s based on commonly used domestic gas appliances, mainly applicable to the Bunsen-type flame-based atmospheric burners. The development of gas interchangeability technology represented by the methods in the U.S., France and Britain, has experienced the stages of theory exploration, formula determination, revision, supplementation, and then re-perfection, before they formed a relatively perfect gas interchangeability theory.

The European Association for the Streamlining of Energy Exchange – gas (i.e., EASEE-Gas), was set up in 2002. In its drafting document of the Common Business Practice 2005-001/01 "harmonization of natural gas quality", defines the interchangeability box of high heating value gas (H-Gas), based on any two of the three parameters gross calorific value (HHV), Wobbe Index (WI) and relative density (Rd), plotted the upper and lower limits of the box[8]. In February 2005, NGC+ work group issued the report of "White paper on natural gas interchangeability and non-combustion end use" [4], pointed out the shortage of traditional method for gas interchangeability, and discussed the gas interchangeability research methods after "the expanded application field", and proposed a more practical "operating regime" concept.

2.1 Characteristic parameters of gas interchangeability

Learning from the Delbourge gas interchangeability method, in 1982, China officially introduced the two main parameters Wobbe number (W), combustion potential (CP) of gas to analyze and determine gas interchangeability. After that, gas interchangeability research of atmospheric appliances used Wobbe number, Combustion Potential, Yellow Tip, coking and other indexes of gas to define combustion performance of gas interchangeability. For a long period of time in the past, the relevant experimental study focused on the affect of adaptability of gas appliance using typical man-made coal gas and natural gas.

2.2 Research process of gas interchangeability

Since the beginning of 1970s, man-made coal gas, natural gas and LPG have coexisted in cities of China. According to needs of urban gas interchangeability research, City Gas Designing specification Management Group researched the interchangeability of household gas stoves generally used in cities of Shanghai and Shenyang in Tongji University in December 1980, in order to investigate the stove adaptability and gas interchangeability, and to find out the allowable range of combustion characteristics parameters of Wobbe index (W) and Combustion Potential (CP) of city gases. In February 1982, Household Gas Stove Standards Development Group completed the report of "Burning stability of typical domestic gas stove". The report described the limit ranges of Yellow tip, Flashback and Lifting out of the stoves tested by the method of gas blending in 0.5 times or 1.5 times the rated pressure of reference gases, viz. combustion stability triangle figures. According to that, the permitted fluctuation range of W and CP of city gas within this limits, provide the basis for gas quality standards development, city gas classification and experimental gas blending. And in 1992 the national standard "City gas classification" issued, which regulated the classification principles of city gas, calculation method of indexes and the requirement of index. Current national standards relevant to classification and characteristics of city gas are mainly "classification and essential property of city gas" (GB 13611), "Natural gas" (GB 17820), and so on.

In the books published recently, such as "Handbook of gas inspection and test technology", "Handbook of natural gas combustion process and utilization", "gas combustion and utilization", "Gas Design Handbook", we can find the description of gas interchangeability research.

"The 1st gas transmission pipeline from Shanxi to Beijing", a long-distance transmission pipeline of natural gas in China, completed in September 1997, opened the door to large-scale use of natural gas in cities, and began the practice and application of substituting natural gas for man-made coal gas or LPG mixed with air in China. At the same time there were papers discussing the feasibility of gas conversion by means of natural gas reform, natural gas mixed with low calorific value gas, natural gas mixed with air, or LPG mixed with air, etc. Some literatures described the applicability of natural gas-air mixture conversion with man-made coal gas through calculation and gas appliance testing, discussed the process of technical flow of gas blending, control of heating values of mixed gas, odorant adding and humidity control etc. there were examples in cities succeeded in carrying out the practice of conversion from man-made coal gas or LPG to natural gas, also, there were reviews on the practice of partial area gas conversion or methods of gas interchangeability in a number of cities.

Although a series of achievements, such as reports or articles or patent literature ,has been made in recent years,, the gas conversion practice achieved all around is basically theoretical exploration and primary research, there is no ready-made theoretical system for gas conversion and interchangeability. The researches in the process of gas interchangeability and pipeline network transformation have not been carried out or ongoing, such as the changing disciplines of testing data, combustion performance of gas appliance along with age limit, adaptability properties of gas appliances, relevant technique for gas interchangeability and the research on gas quality reform. There have not been formed satisfactory technical standards or methods for gas interchangeability or gas blending and can not give technical instructions in the process of gas interchangeability in hundreds of cities in China, the overall effect of theory and research is un-ideal and lack of systemic research and practical experimental study on urban gas interchangeability.

Therefore a number of research institutes have carried out the research of these issues in China. In 2006, the “11th Five-Year Plan Period” National Key Technologies R&D Program of China, advanced the project of "key Technologies for City Gas Sources Storage, Distribution and Utilization", combined with a subject "Conversion theory and reform technology of city gas sources".

2.3 Summary of gas interchangeability research recently

With the diversification of gas combustion utilization equipment, more combustion devices

with a high efficiency and low carbon emissions come into families and businesses in cities. The pattern of different combustion types coexisted in the same city thus formed. There are different types of gas burners such as diffused-type burners, atmospheric burners and fully premixed burner in the city's pipeline end. Conversion of different families of gases has different technical requirements, engineering standards and quality control systems. It's also practical technical problems of using different types of gases smoothly, adapting to conversion of multiple gas sources, and achieving the equivalent experimental blending gas.

Since 2005, China Quality Supervision and test Center for gas appliances (CGAC), based on experimental tests with gas appliances, has carried out a series of researches on conversion of natural gas with LPG, and interchangeability of different type of natural gases, according to the difference of combustion types, investigated gas users in specific city separately. The researches have gained a number of achievements. North China Municipal Engineering Design & Research Institute (NCME), supported by the National Key Technologies R&D Program of China during the 11th Five-Year Plan Period, "key Technologies for City Gas Sources Storage, Distribution and Utilization", based on results of "Conversion theory and reform technology of city gas sources" subject, has explored the comprehensive investigation of urban gas interchangeability supplied with multiple gas sources, with a series of results outcome. The researches established initially a set of technical system of multi-gas sources interchangeability. And on March 14, 2011, the whole technology achievements passed the acceptance inspection organized by the Ministry of Housing and Urban-Rural Development of China (MOHURD).

The main research contents include: the establishment of interchangeable test simulation system of various gas sources in China, the study of combustion characteristics of various types of gases and boundary conditions of gas appliances, the development of technology system and implementation measures of engineering conversion, adaptability strategy and assessment of gas quality fluctuation in case of gas emergency supply to natural gas pipeline system.

The main research results are as follows: the interchangeability and conversion technology of cities supplying multi-gas sources has been developed, the technical methods for determining interchangeability range of city gas and adaptability range of gas appliance are originally proposed, which offered an stable support for utilization and optimization of multi-gas sources. The technique of urban gas source allocation and multi-gas interchangeability is firstly advanced and engineering practice fulfilled. The research established technology and equipment of experimental gas blending and gas appliance adaptability range testing, which provided technical foundation for scientific and reasonable engineering practice under the circumstances of multiple gases. And thus carried out experiments with gas blending, a series of manual and automated gas blending devices is invented, which guaranteed the interchangeable gas sources needed during combustion tests of gas appliances.

By experimental determination of gas appliance adaptability range, the adaptable capability and limit range of typical gas appliance to gas quality fluctuation were understood and determined, which can provide the basic, essential technical data for gas appliance production and design, and form the adaptability range of gas appliances most extensive used and the common adaptability range of series of appliances in cities; furthermore ,the determinate, quantifiable urban gas interchangeability range formed and normal and limit working range of gas composition parameters gained, which is useful for guiding the whole regional market "access" of gas appliance products and the interchangeability and conversion practice of urban gas.

3 Research and practice of city gas interchangeability in China

3.1 Combustion characteristics-related parameters of gas appliances

3.1.1 Interchangeability index of atmospheric (partial-premixed type) burners

(1) The main indexes used in gas interchangeability

In general, the principal combustion characteristics indexes related to gas interchangeability usually include: calorific value or heating value (high heating value HHV or low heating value LHV, generally refers to HHV), relative density (Rd), theoretical air required during complete combustion (V_{air}), flame burning velocity (S_n), Wobbe number (W), combustion potential (CP), yellow tip index, and so on.

Conventional indexes used in gas interchangeable blending, mainly are Wobbe number, combustion potential, yellow tip index [7, 9, 10]. The material gases used for gas blending usually are CH_4, H_2, and N_2, or C_3H_8 (C_4H_{10}), H_2 and N_2, or LPG and air, etc.

Scientist Wobbe proposed $H_s / \sqrt{r_g / r_a}$ as a characteristic number, and

$$W = \frac{H_s}{\sqrt{r_g / r_a}} = \frac{H_s}{\sqrt{d_g}} \qquad (1)$$

Where: W—Wobbe number，MJ/m^3;

H_s—High heating value of gas，MJ/m^3;

r_g, r_a —density of gas and air respectively，kg/m^3;

d_g—relative density of gas（take the relative density of air as 1）.

In the standard "Classification and essential property of city gas" (GB/T 13611-2006)，the parameter of combustion potential can be calculated as follows

$$CP = K \times \frac{1.0 H_2 + 1.1 CO + 2.3 (\sum m C_m H_n) + 0.6 CH_4}{\sqrt{d_g}} \qquad (2)$$

$$K = 1.0 + 0.7 O_2 \qquad (3)$$

Where: CP—combustion potential of gas;

H_2、C_nH_m、CO、CH_4、O_2—the percentage by volume of hydrogen, hydrocarbon

(methane precluded), carbon monoxide, methane and oxygen in the gas, %;

K—correction coefficient of oxygen content in gas.

(2) Combustion characteristics index related to adaptability of gas appliance

In order to determine the combustion characteristics indexes related to gas appliance adaptability, the research group established an experimental device, and tested the combustion working conditions of domestic gas appliances, the composition contents of mixed gas in limit conditions of Lift out, Flashback and CO content exceeding limit point of gas appliances are measured. Then all the limit combustion parameters needed can be calculated. According to the key parameters such as Wobbe number, calorific value, relative density, flame burning velocity, combustion potential, Cartesian coordinate system can be plotted. The combustion characteristics indexes representing gas appliance adaptability along with gas quality fluctuation then can be obtained from graphical plot based on experimental data.

The followings are experimental data figures of limit combustion working conditions of three atmospheric gas cooking appliances tested. In accordance with the combustion characteristic parameters of the limit gases in limit conditions of Lift out, Flashback and CO contents exceeding the standard with sample cooker 1 , different combinations of the combustion characteristics parameters of the limit gases were chosen to establish a Cartesian coordinate system. The three limit curves of Wobbe number (Ws) versus high heating value (Hs) are shown in Fig. 2. The limit curves of Wobbe number (Ws) versus relative density (d) are shown in Figure 3. The curves of Wobbe number (Ws) versus flame burning velocity (Sn) are shown in Figure 4. The three curves of Wobbe number (Ws) versus combustion potential (CP) are shown in Figure 5. The curves of Wobbe number (Ws) versus combustion potential (CP) in the range of i-C_4H_{10}, N_2, H_2 gas blending distribution are shown in Figure 6.

Similarly, according to the limit combustion characteristics parameter data of sample cooker 2 and sample cooker 3 , respectively, under the conditions of Lift out, Flashback and CO contents exceeding the standard, we can establish the corresponding Cartesian graphs, as seen in Figure 7-14.

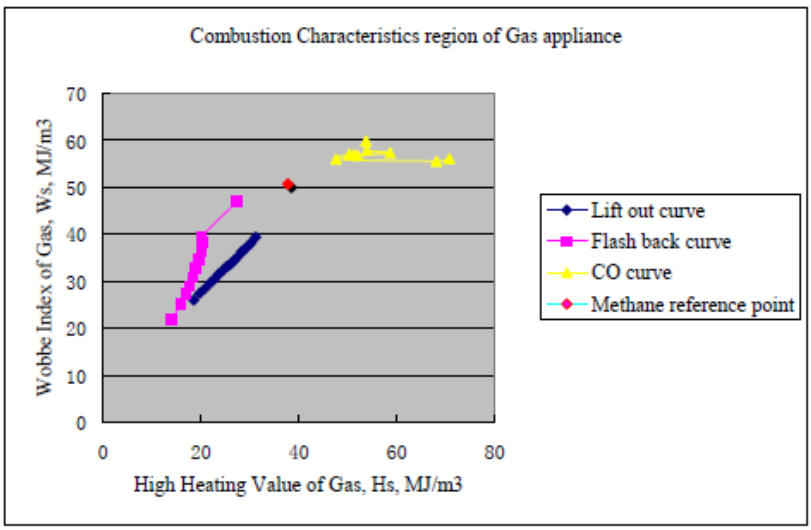

Fig. 2 Limit curves of Wobbe Indexes versus High Heating Values of limit gases of the 1st cooking appliance

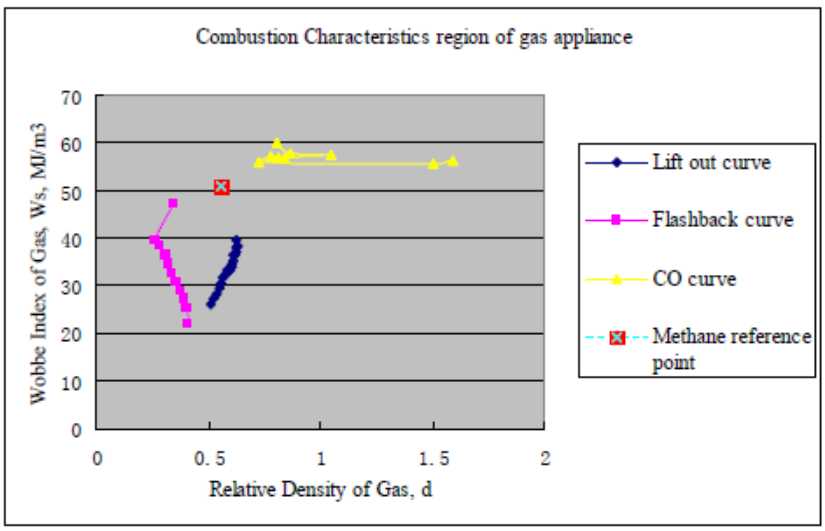

Fig. 3 Limit curves of Wobbe Indexes versus relative densities of limit gases of the 1st cooking appliance

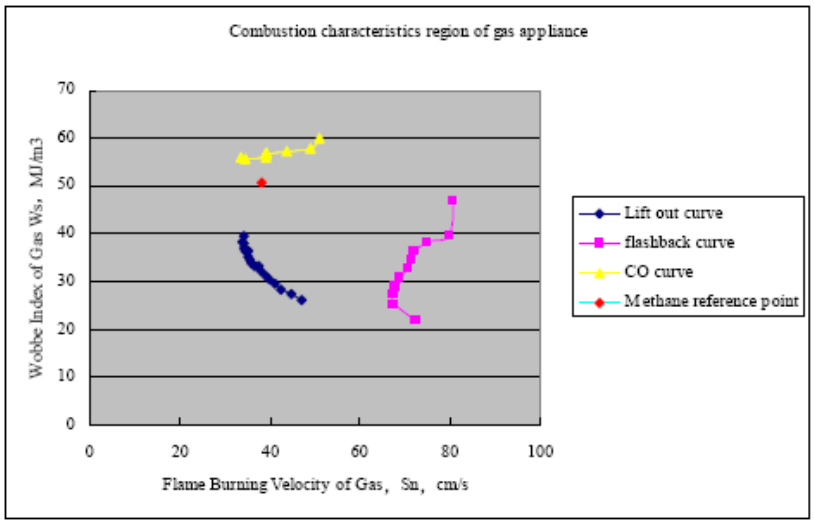

Fig. 4 Limit curves of Wobbe Indexes versus flame burning velocities of limit gases of the 1st cooking appliance

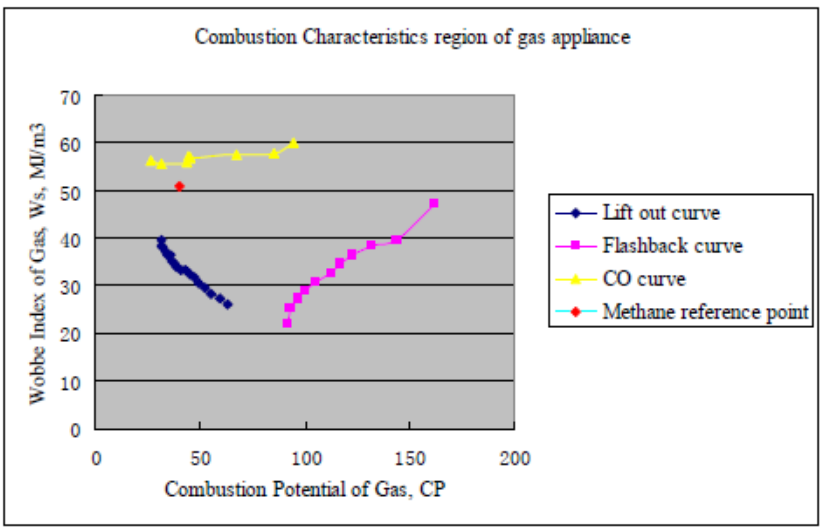

Fig. 5 Limit curves of Wobbe Indexes versus Combustion Potentials of limit gases of the 1st cooking appliance

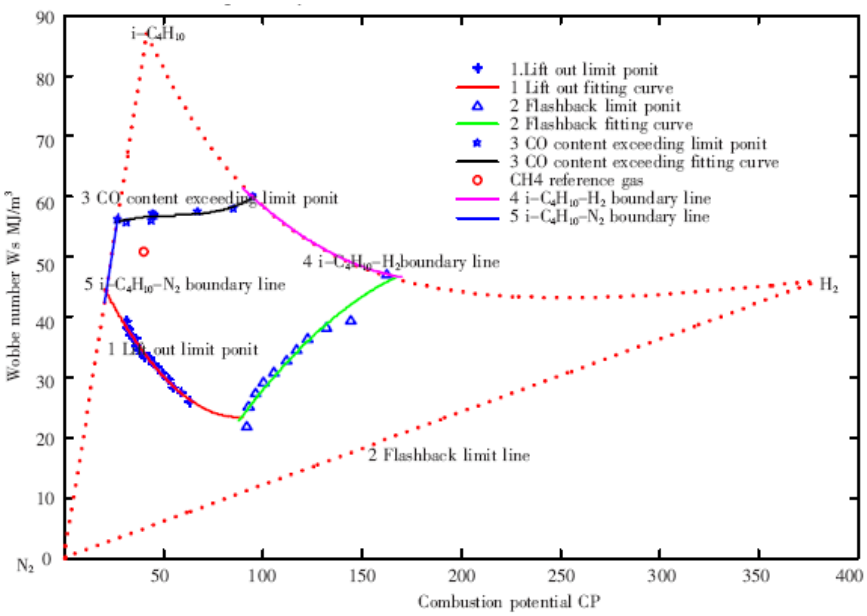

Fig. 6 Limit curves of Wobbe Indexes versus Combustion Potentials of limit gases of the 1st cooking appliance in the range of i-C_4H_{10}, N_2, H_2 blending-gas distribution

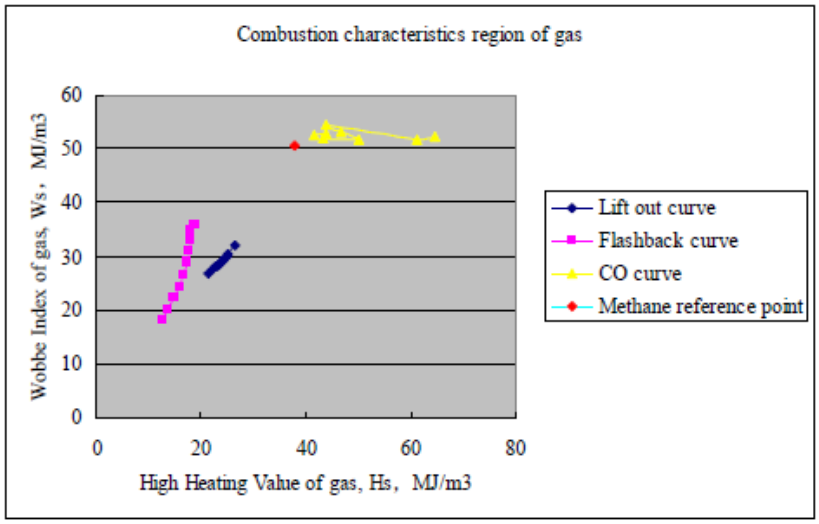

Fig. 7 Llimit curves of Wobbe Indexes versus High Heating Values of limit gases of the 2nd cooking appliance

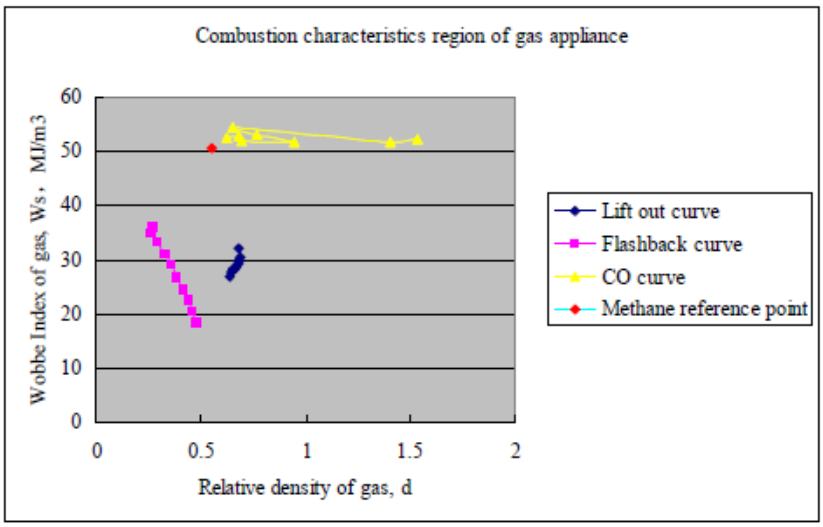

Fig. 8 Limit curves of Wobbe Indexes versus relative densities of limit gases of the 2nd cooking appliance

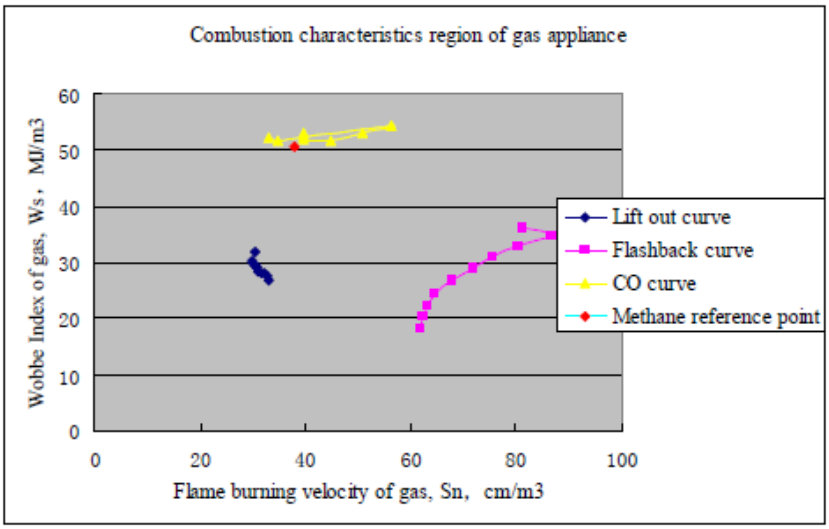

Fig. 9 Limit curves of Wobbe Indexes versus flame burning velocities of limit gases of the 2nd cooking appliance

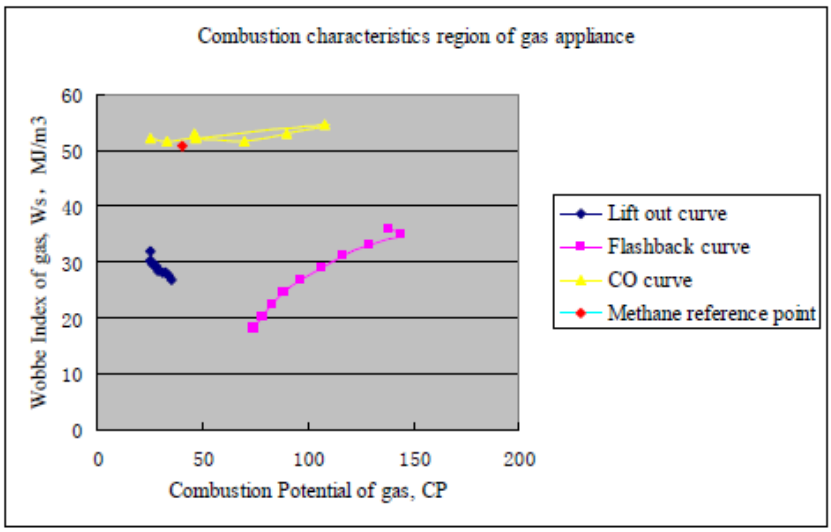

Fig. 10 Limit curves of Wobbe Indexes versus Combustion Potentials of limit gases of the 2nd cooking appliance

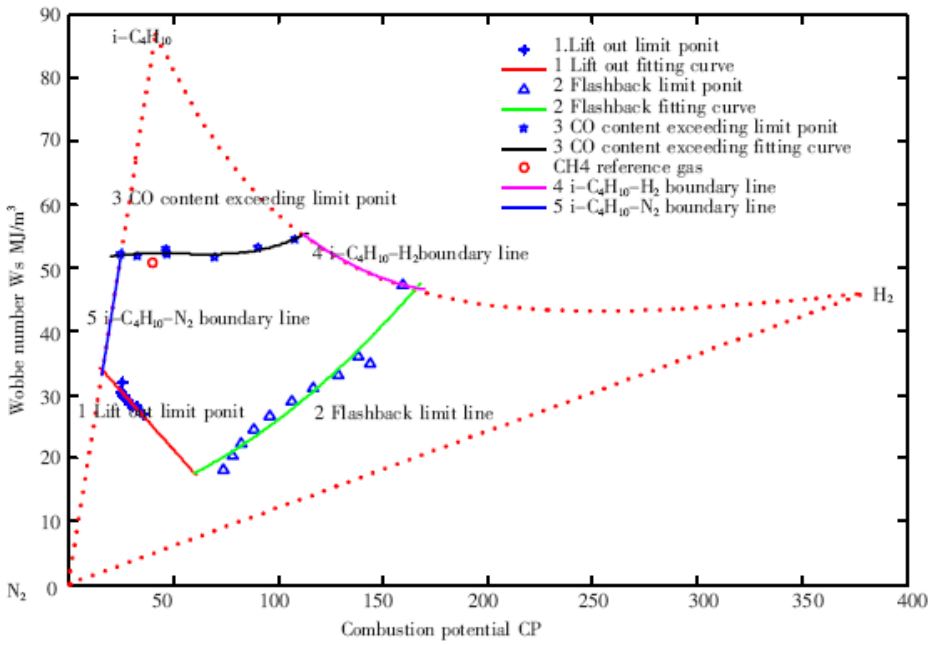

Fig. 11 Limit curves of Wobbe Indexes versus Combustion Potentials of limit gases of the 2nd cooking appliance in the range of i-C_4H_{10}, N_2, H_2 blending-gas distribution

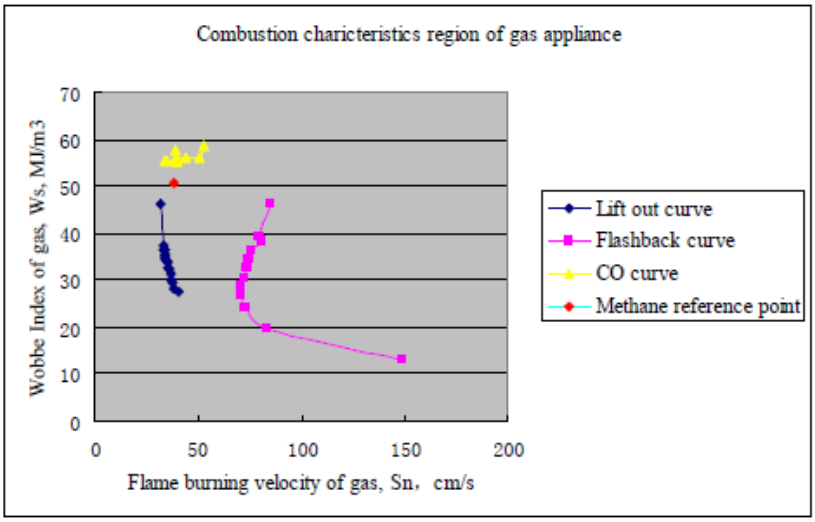

Fig. 12 Limit curves of Wobbe Indexes versus flame burning velocities of limit gases of the 3rd cooking appliance

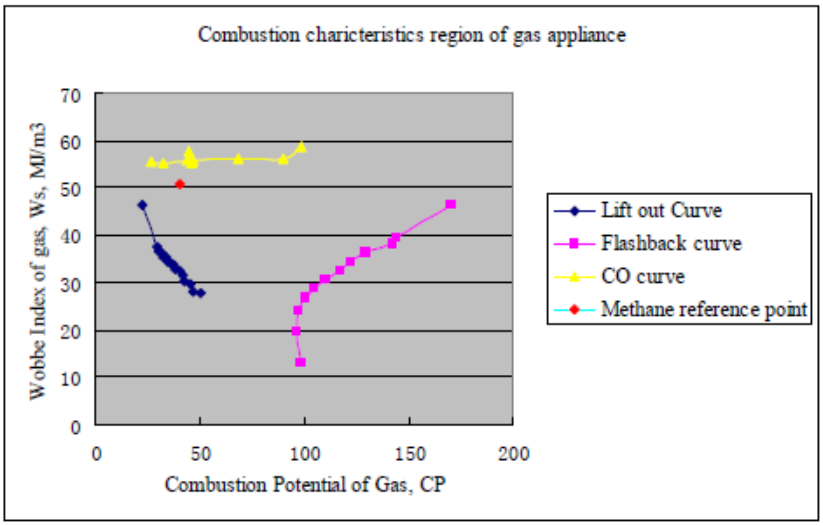

Fig. 13 Limit curves of Wobbe Indexes versus Combustion Potentials of limit gases of the 3rd cooking appliance

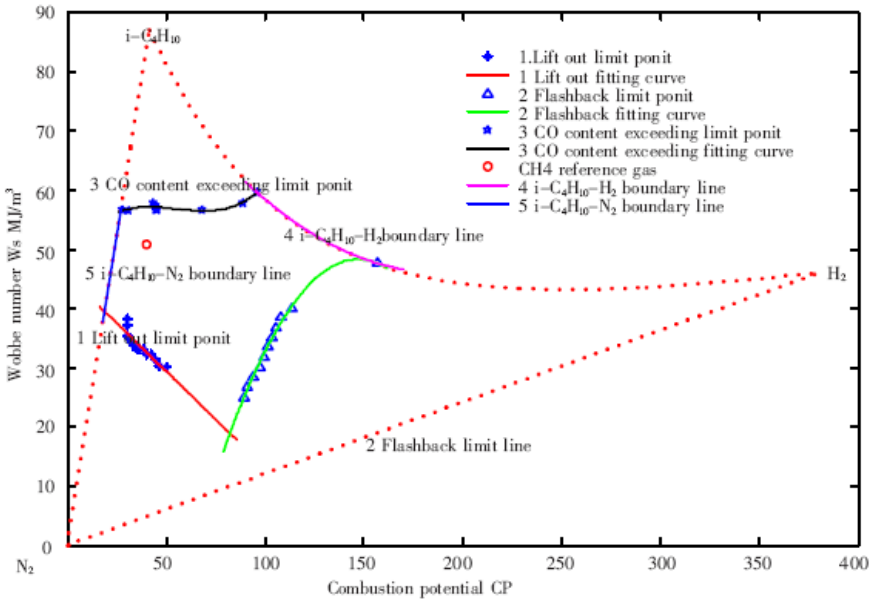

Fig. 14 Limit curves of Wobbe Indexes versus Combustion Potentials of limit gases of the 3rd cooking appliance in the range of i-C_4H_{10}, N_2, H_2 blending-gas distribution

Figure 2-Figure 14 show that for the combustion characteristics indexes of the gas with a high Wobbe number (Ws), a high heating value (Hs), relative density (d), flame burning velocity (Sn), combustion potential (CP), when choose the characteristics parameters of Ws versus Hs or Ws versus d to illustrate limit curves of the three sample gas cookers, the curves plotted are unsmooth and irregular, when select the parameters of Ws versus Sn, the limit curves with two of the three sample cookers are more regular, but the shape of CO limit curve is much shorter and not stretchable; while the three cooking appliances, in the choice of parameters of Ws versus CP, the three limit curves of Lift out, Flashback and CO content exceeding the standard are smooth and regular with natural extending trend. Therefore, when we researched gas appliance adaptability of atmospheric type and carry out practice of equivalent experimental gas-blending, it was reasonable and scientific to choose the two key characteristics parameters of Wobbe number and combustion potential of gases. Taking into account the possibility of substituting LPG mixed with air for natural gas, which is easy to produce yellow tip flames, we added the yellow tip index to control and eliminate the phenomenon.

(3) Basic range of gas blending distribution

Due to the diversity and complexity of city gas supply, it is impossible to have the appropriate gas sources needed in the various aspects such as distribution and application of gas, production and regulation of gas appliance, combustion and testing of gas, and so on. Therefore alternative or substitute gases are required. To ensure the substitute gas has the same chemical properties and thermal performance of the reference gas, we should control the gas blending process required for multi-component material gases, research and design

the optimum gas blending method. Thus, conventional gas-consuming units such as gas appliance manufacturers, fuel gas consuming enterprises and high-precision gas appliance test centers, may produce test gases possessing the same properties of certain city gases with several material gases according to national standards. Then gas-consuming enterprises can use the technology of gas blending with certain principle and achieve a variety of substitute gases equivalent to that of reference gases.

Based on the principle of interchangeability , the practice of equivalent gas blending usually use the three essential components of methane, hydrogen and nitrogen, or propane (butane), hydrogen and nitrogen as the material gases. The controlling principle is to keep the key combustion characteristics parameters such as Wobbe number, combustion potential, yellow tip index of test gases equaling to that of the reference gases. According to the material gases used for gas blending, we can carry out the work of gas blending design with the main controlling indexes of Wobbe number, combustion potential [7], and we can obtain the overall range of gas blending distribution. In the Cartesian coordinate system with Wobbe number, combustion potential as their function variables, and with the combination of the three material gases such as methane, hydrogen and nitrogen, or propane, hydrogen and nitrogen, or butane (normal butane, isobutene), hydrogen and nitrogen, the common gas blending range derived by the three-gas-combination mentioned above shown in figure 15.

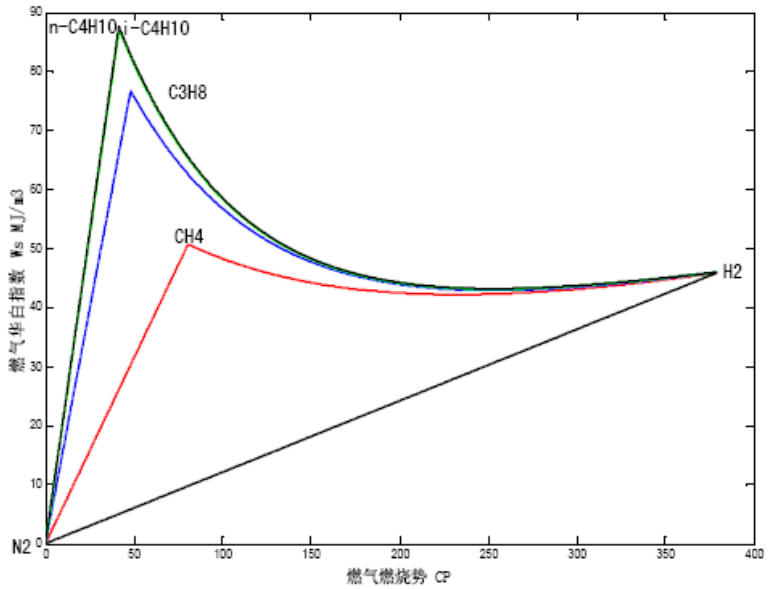

Fig. 15 The common gas blending distribution range derived by the three-gas-combination of methane, hydrogen, nitrogen or propane, hydrogen, nitrogen or butane, hydrogen, nitrogen

It can be seen from Figure 15, the gas blending range of each three components combination and the common gas blending distribution, the boundary line is not all straight lines; the boundary line is exponential curve with either of the two combustible gases; while the boundary line is straight when formed by nitrogen with the other combustible gas.

3.1.2 Summary of gas interchangeability research with fully-premixed combustion type burners

(1) Expansion of research field

The contents above mainly focus on domestic gas appliances, and introduce determination indices of gas interchangeability. The combustion performance and emission targets has adapted to these indices and methods in atmospheric (that is partial pre -mixed type) combustion burner for a long period of time.

Further research found that equivalent substitute gases derived from gas blending method by controlling the key parameters such as Wobbe number (W), combustion potential (CP) and so on based on the principle of interchangeability, can get better working performance in the current atmospheric burners of gas stove, gas water heaters etc. But in a fully premixed combustion burner , there is a greater difference in combustion effect and emissions performance. With gas terminal utilization equipments becoming more diverse and complex, fully premixed burners are in a growing market share today, it is an urgent technical issue need to be figured out that whether we can continue to use combustion performance indices accommodated to atmospheric burners, in the aspects of gas interchangeability and experimental gas blending, to meet the practical requirements of improving combustion utilization efficiency and low-carbon, reduced-nitrogen emission.

(2) Characteristics of fully premixed combustion type

All the fuel gas and air required premixed at stoichiometric ratio (primary air ratio ≥ 1), the combustible mixture undergoes instantaneous combustion process in the steady flame device is called fully premixed combustion [10]. Premixed combustion burner mainly used in the popular products such as domestic condensing gas water heater, gas dual oven, industrial furnaces, gas turbines, gas engines and others. Because of their big gas load, they are the main equipment for city gas consuming.

The combustion type has many advantages, such as the features of strong burning intensity, short flame can reduce the furnace height, and require no secondary air, thus eliminate the secondary air entrance area; the combustion has a large area and volume of heat intensity, can reduce the volume of combustion equipment; the flame front can near the heat exchanger, thus can increase the heat transfer coefficient, increase thermal efficiency; combustion products can be effused from beneath the flame surface, which downwards the heat flow, is conducive to condensing water heater and to process requirements of downward radiation; under the fully premixed combustion conditions, the combustion products levels of CO and NOx are relatively low.

Fully premixed combustion, in manner of all the gas and air required for complete combustion are pre mixed, before they entered into the combustion chamber (or cylinder) and burned out.

The combustible medium being gas and air, with air and fuel gas pre-mixed, fully burned in a fixed flame stability device (such as the combustion chamber), and the conversion pattern between thermal energy and power is through heating or volumetric expansion to power production by flue gas. Thus, combustion characteristics and emissions performances of fully premixed combustion are closely related the factors such as gas composition, calorific value, volume of theoretical air required for complete combustion, antiknock performance indexes of gas octane number or methane number, flame burning velocity, the components, volume, pressure and temperature distribution of flue gas.

3.2 Research on allocation of city gas sources and methods of multi -gas interchangeability

Allocation of city gas sources is directly related to the combustion performance of gas appliances "in use" in cities. There are different requirements for all gas users such as the domestic, industrial, commercial and gas power plants, and so on, due to the difference between combustion processes and combustion manners, It is not always the same that the gas burners and terminal utilization equipment tolerate the changes and fluctuations in gas composition and quality. Therefore, the research group developed technologies of interchangeability and conversion of multi-gas sources supplied to cities, proposed originally technical methods for determining interchangeability range of city gas and adaptability range of gas appliance in China.

We chose the technical route of combining theoretical analysis of gas interchangeability with combustion characteristics test of gas appliance. For the first time, we advanced the method of determining reference gas in city in the guiding principles of matching gas interchangeability and gas appliance adaptability, harmonizing economy and rationality, which greatly expanded the application field of gas interchangeability, provided new technical guidelines and methods for cities supplying natural gases encountered with the questions of inadaptability when other new gas sources entered into existing pipeline networks.

When the research group researched on urban gas sources allocation and multi-gas interchangeability, we extended gas combustion utilization fields to full-premixed combustion users such as gas power plants, industrial users, commercial and other users with more stringent requirements for gas quality, for all gas users in cities including domestic, industrial, commercial, gas power plants, gas cars, and so on, based on combustion characteristics of specific equipment, and the differentiated demands for gas composition and quality, we established distinguishing programs and methods for gas sources application, conversion, scheduling and allocation for all users; made basic research on the means of multi-gas source supplying, gas mixing feasibility and operation stability in identical pipelines, advanced possible composition and fluctuating range of reference gas; investigated gas exchange feasibility under different gas sources; analyzed and proposed the technical route and strategy options to ensure stable operation of gas pipelines, thus can provide technical basis

for government and enterprises to select reference gas, alternate gases and peak shaving gases.

Supported by the research results of subjects in this field, we fiound application to engineering practice. For gas users within the city, we put forward the balanced composition and fluctuating range of reference gas on basis of technicality and economy, and raised proposals for gas sources utilization, scheduling and allocation, in order to utilize reasonably the natural gas resources, optimize combustion effects, and to obtain good economic and social benefits.

3.3 Experimental gas blending and gas appliance adaptability

Considering the control targets of combustion safety, energy efficiency, emissions performances of gas appliances, the research group boldly developed the standards of current gas classification and gas appliance product, and proposed methods to determine the limit adaptability of gas appliances to gas component fluctuation through experimental determination, thus pointed out the research direction of adapting to development trends of multi-gas sources and quality improvement of gas appliance products in China. We also established and developed test device and software of high precision, multi-index, quantitative analysis based on this new thought, which formed a complete technical implementation platform, and laid a solid foundation of promotion and application of technical achievements.

On basis of studying deeply the theory of gas interchangeability, the group doubted the prevalent approach of experimental gas blending through controlling the index Wobbe number and combustion potential of test gas equivalent to that of the reference gas, and verified it through large number of experiments; then proposed control method of experimental gas blending with "multi-component, multi-index" (such as the three-index method representative of Wobbe number, combustion potential, yellow tip index).

For the sake of better research results on this field; we have built a system to test gas blending and gas appliance adaptability, tested and determined the adaptability of gas appliance and interchangeability of city gas; proposed the design technology of experimental test gas-blending based on the principle of interchangeability.

The technology of research on adaptability of gas appliance to city gas quality closer to the actual operating conditions of gas appliance, filled the gap effectively in gas appliance performance testing and solved the problems of the combustion quality can not be quantified and there is no detection experiment platform to them. It is important for the development of testing standards and improvement for equipment or production in gas appliance factory and generally product quality enhancement for the industry. The result of gas blending method "multi-component, multi-index" has been successfully applied to famous companies in gas industry, and has played a leading and exemplary role. The research result of

interchangeability of city gas and adaptability of gas appliance has been published in national conferences or public journals in gas industry, and has been accepted by the industry and emerging industrial influence [12-15]. Experimental test device has been available for the China Quality Supervision and test Center for Gas Appliances (CGAC). Figure 16 gives the photos of the test devices, figure 17 and figure 18 are the combustion characteristics regions of cooking appliance 4 and 5 tested by the test device above.

Fig. 16 Experimental test device of combustion characteristics of gas appliances used in CGAC

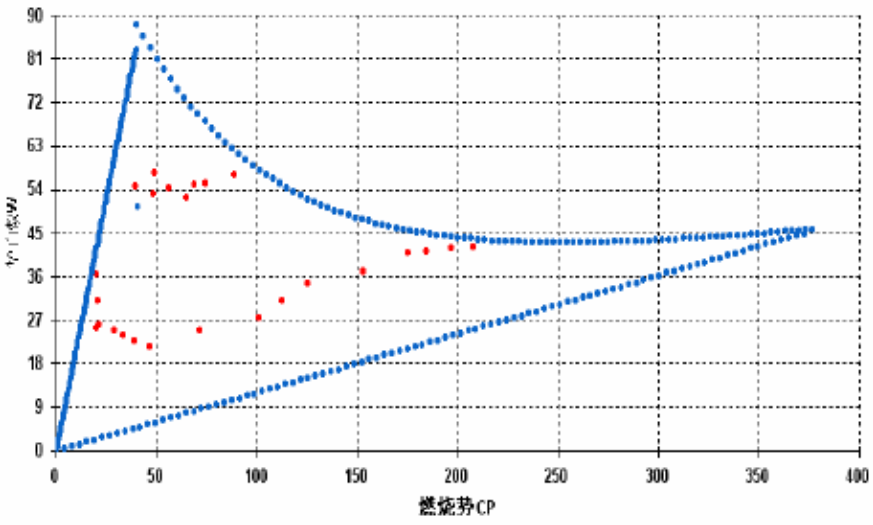

Fig. 17 Combustion characteristics region of cooking appliance 4 derived from test device above

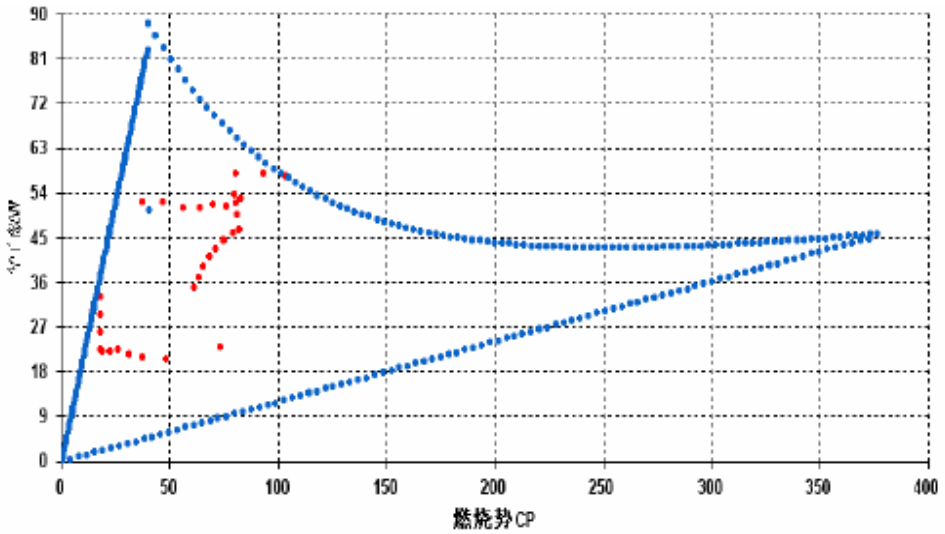

Fig. 18 Combustion characteristics region of cooking appliance 5 derived from test device above

3.4 Adaptability of gas appliance

The research group has determined the distribution range of adaptability of gas appliance (adaptability range) and interchangeability of city gas through experimental tests, formed a complete approach and technical route to determine "common range of interchangeability" of city gases; and proposed a quantitative, scientific testing technique of gas interchangeability range. Based on three series of gas appliance samples, the group tested the adaptability of the samples, obtained the limit range of combustion characteristics parameters of each appliance, established the common adaptability range of gas appliances in gas blending distribution field surrounded by the boundary lines of three material gases isobutene, hydrogen and nitrogen, as shown in Figure 19. Also the typical gases used in China distributed in common adaptability range of gas appliances shown in Figure 20, which successfully lined out several types of natural gas beyond the limit curves boundary.

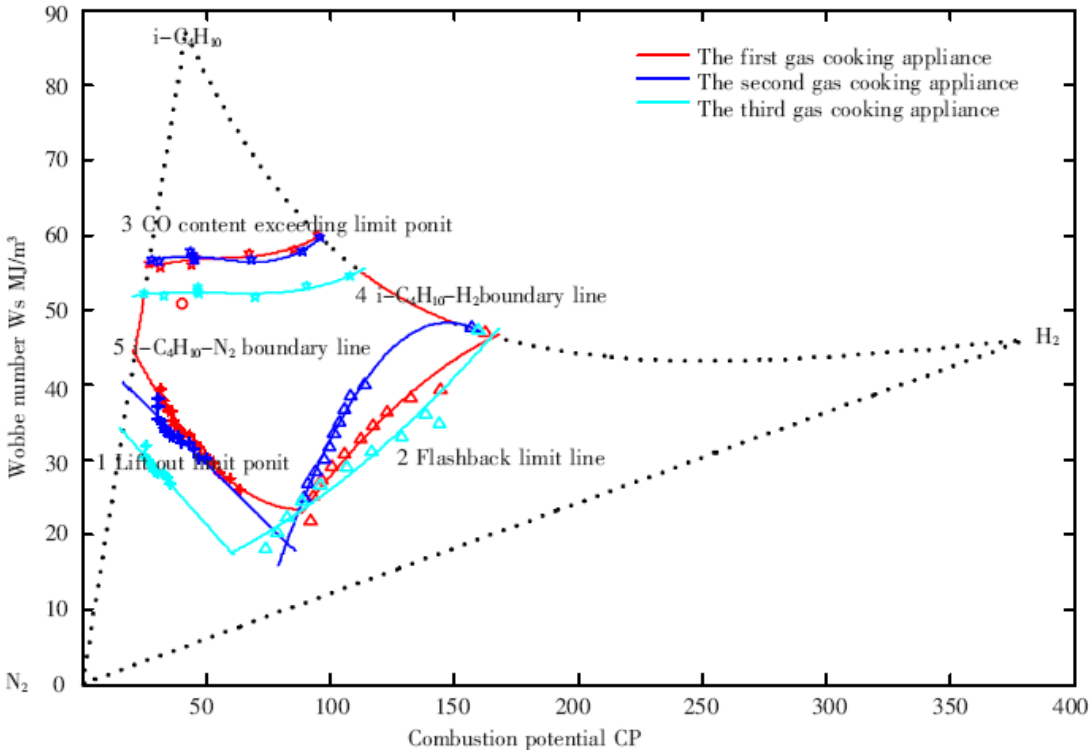

Fig. 19 the common combustion adjustability region of the three cooking samples above

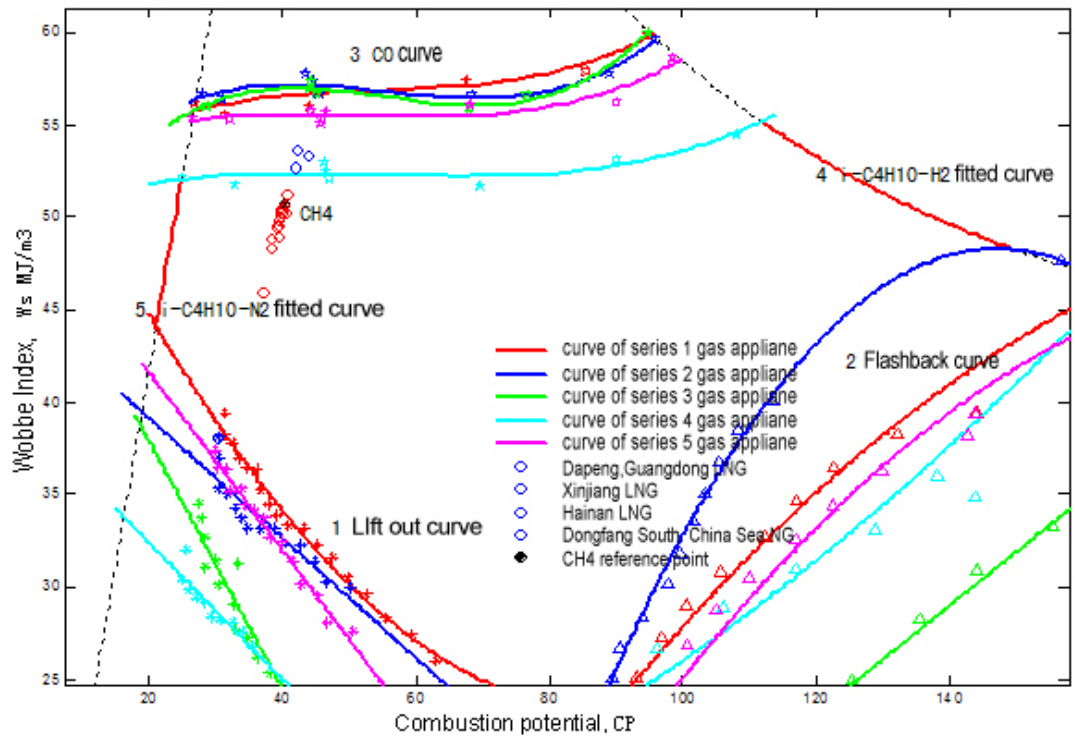

Fig. 20 Typical gases used in China distributed in common adaptability range of different series of gas appliances

3.5 Technical and economical evaluation on city gas interchangeability

When there are a variety of gas sources can be selected in a city, it is usually to choose one or several types of gases the main parameters of gas composition and combustion characteristics closest to the reference gas. The main factors to consider include: content of methane in gas component, content of inert gas components, content of heavy hydrocarbon components, Wobbe number, combustion potential, yellow tip index, density (relative density), heating value, gas flame burning velocity, and so on. There are a number of gas utilization terminals, such as users of domestic, industrial, public welfare, gas cars, gas power plants, LNG production, and chemical, while the requirements of gas quality to different end-use terminals are not always consistent,. Thus it is urgent for us to select reasonable methods and feasible controlling technical parameters of multi—gas-source interchangeability. When determination of gas interchangeability and its range according to gas quality requirement of the strictest user, it will make the city the most stable gas components, the smallest changes in gas composition and the higher or highest operating cost; while investigating interchangeability range of city gas from the most extensive gas users in its number and impact (such as domestic users), the gas composition can fluctuate within a certain range, which may lead to combustion instability to a small number of gas users with more stringent requirements to gas quality, but that will result in a reduced or minimum running costs in city gas. All of this requires environment-concerned treatment, scientific selection and careful analysis.

It is required for relevant departments or gas operating companies of the city to research scientifically gas sources scheduling, peak shaving gas allocation, and interchangeability of multiple gases, to determine the composition and fluctuation range of reference gas, and to select combustion characteristics parameters of different combustion types reasonably. Gas companies should make objective and comprehensive analysis of overall operating costs and the risk of irregular working of the gas appliance can bear based on different types of gases, select the appropriate reference gas composition and allowable range, form scientific "component map of gas interchangeability" of the city or local area, so as to carry out the practice reasonably of city gas allocation and the research of multi-gas interchangeability.

The specific technical route of city gas interchangeability is generally that , to study the methods for interchangeability of multiple gas sources; to classify reasonably the type of gas users; to select typical test samples of urban gas appliance; to determine the appropriate parameters for combustion based on burner types and combustion manners of gas appliance; to test the adaptability of gas appliance to different gases; to determine the common interchangeability range of city gases considering the common adaptability range of gas appliance; to obtain rational composition and fluctuation range of reference gas through technical and economic analysis and evaluation; and to select optimal program of pipeline network scheduling, gas source allocation, to determine the standby gas, peak shaving gas supply, and so on.

4. Results

In summary, the main results of urban multi-gas interchangeability researches in China are as follows:

(1) Rational, scientific determining method for urban reference gas.
The technical route of combining theoretical analysis of gas interchangeability with gas appliance testing has been selected. The method of determining reference gas in city in the guiding principles of matching gas interchangeability and gas appliance adaptability, harmonizing economy and rationality has advanced, which provided a new guidance and technical approach to solve the inadaptability issues of conversion other new gases with former gases in cities.

(2) The experimental determination method of the adaptability range of gas appliances and interchangeability range of city gases
The interchangeability of city gas and adaptability of gas appliance is organic and unified, as the two aspects of one question. The interchangeability range of city gases in one city can be obtained through determining adaptability range of gas appliances used in the gas pipeline network end. The experimental determination methods and programs of adaptability range of gas appliances and interchangeability range of city gases are established and proposed, which forming a complete technical implementation platform. We also built the experimental test device, and tested the appliance samples. The research provided scientific and reasonable technology support for the engineering practice of conversion and interchangeability of urban multi-gas sources.

(3) Experimental determination of main parameters characterization of atmospheric combustion burners.
A Cartesian coordinate system with the combustion characteristics parameters Wobbe number Ws, combustion potential CP can be received, by judging the relative positions in the closed bounded region formed by the curves of lift out, flashback and CO exceeding the standard with the reference gas point. We can define and evaluate the combustion performance of gas appliances. The gas blending controlling indexes have been studied and analyzed and the "multi-component, multi-index" experimental method for gas blending proposed based on the principle of gas interchangeability; also the experimental gas blending design approach of adaptive testing of gas appliances developed.

(4) The establishment of urban multi-gas interchangeability research route with technicality and economy balanced.
Experimental testing method should be adopted to research accurately interchangeability of city gas and adaptability range of gas appliance to gas quality fluctuation, in order to improve scientifically decision-making level and ability, make cost - risk analysis and allocate rationally

the resources with good economy and excellent technicality, so as to protect the supply security, reliability, and economy of city gas energy.

(5) Research fields are more global, while research methods are more extensive.
The research focus began to shift from atmospheric combustion burners to fully premixed combustion burners. With the diversification of gas utilization terminal equipment, the feasible and scientific indexes of gas interchangeability and gas blending controlling parameters should be selected according to specific gas combustion equipments and the way the gas mixed with air in the burners. For fully premixed combustion burners , religious gas interchangeability tests should be carried out, with the results of associated key characteristics parameters with combustion performance and emission requirements, in order to adapt to the development and change of current gas end-use equipments.

5. Summary/Conclusions

In recent years, a number of useful researches and explorations have been done in the field of city gas interchangeability in China, followed by some scientific results. The experimental and theoretical researches mainly focused on the both aspects of city gas interchangeability and gas appliance adaptability.

Key results include test determination of main parameters characterization of atmospheric combustion burners; test determination method for adaptability region of gas appliances and interchangeability region of city gases; rational and scientific determining method for urban reference gas; the establishment of urban multi-gas interchangeability research route with technical and economic balance; research fields are more global, and research methods are more extensive.

With the diversification of gas combustion and combustion end-use models, technical parameters and controlling indexes of gas interchangeability should be reasonably chosen. More experimental researches and technical feasibility studies should be carried out, in order to build a comprehensive and scientific technology system of city gas interchangeability.

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