International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 3 Issue 11 ǁ November. 2015 ǁ PP.01-06

Analysis of the Thermal Efficiency of Condensing Wall-Hung Boiler

HANG Xin[1], CHEN Yu[1]
[1](College of Mechanical Engineering, Shanghai University of Engineering Science, China)

Abstract: *To analyze the impact of the outdoor temperature and humidity on thermal efficiency of the condensing boiler, the experimental platform is set up based on the condensing boiler and low-temperature radiantfloor heating system. Using the method of experiment, it's measured that amount of natural gas, the temperature of supply and return water, the outdoor temperature and humidity etc. The thermal efficiency is calculated in different outdoor temperature and humidity. Also it is analyzed that the impact of that the change of the outdoor temperature and humidity on thermal efficiency. The results show that, when the outdoor temperature is 8~15 ℃ and humidity is 30%~70%RH, the impact of the outdoor humidity on thermal efficiency is very poor. But the impact of outdoor temperature on thermal efficiency is more remarkable. Thermal efficiency is the higher when the outdoor temperature is the higher.*
Keywords*:* *condensing boiler, outdoor temperature,outdoor humidity,radiant floor heating, thermal efficiency*

I. INTRODUCTION

With the intension of the global energy and deteriorative environment, natural gas has been applied to the every field as a kind of clean and efficient resource. Compared with other fossil fuel, natural gas has high thermal values, and do not produce dust after burning. It has advantages in efficiency and economy. The natural gas will play an important role in the social and economic development in the future.

As one of the most developed cities, Shanghai is in the forefront in consuming the energy. With the development of transporting the natural gas from the west to the east and other gas source project, the supply of natural gas in Shanghai has been increasing perfect. At present, the gas sources are mainly the natural gas from the west to the east, the East China Sea, Sichuan to the east, and LNG. It is equationted backbone network, providing an important guarantee for a smooth and orderly supply for the city.

With the development of urban natural gas, Gas-fired boilers have been used universally. Chinese scholars have done more research in thermal efficiency of boilers. For example, Wang Jianguo got the reasonable thermal efficiency of the boiler by analyzing the impact of various heat loss of the gas boiler to thermal efficiency, providing a reference for the selection of the configuration of the boiler[1]. Zhang Wensheng, MengJianqiong etc. analyze the relationship among the gas boiler thermal efficiency and smoke temperature and heat loss, and they derive the estimation equation of thermal efficiency[2]. Through the theoretical analysis and calculation, Wang Zhiyong etc. find that lowering flue gas temperature has a major impact to improve thermal efficiency, and flue gas temperature decrease from 195℃ to 40℃, thermal efficiency will increase about 8%[3]. Aimed at that the test of thermal efficiency is not easily operated, BaiYufang and Su Xiaoguang design thermal efficiency test system based on the C ++ builder. It has practical and cost-effective in practice[4]. As heat source, condensing boiler has high efficiency and could protect the environmental in the stand-alone residential heating equipment. So it has become the research object currently. Due to the requirement of the temperature of supply and return water, low-temperature floor radiant heating system can more sufficiently improve the efficiency of the condensing boiler[5].

Based on the condensing boiler and low-temperature floor radiant heating system, this article analyzes the condensing boiler combustion characteristics and the impact of climate parameters outdoor conditions on thermal efficiency. It will provide users with operating parameters to achieve the purpose of energy saving and economic operation.

II. Calculation of natural gas heat value and the properties of smoke

In this article, the condensing boiler uses the natural gas from the west to the east. Its components and volume fraction of composition is in the table.1[6].

Table.1 Components of Natural Gas

Component	CH_4	C_2H_6	C_3H_8	iC_4H_{10}	nC_4H_{10}
Volume fraction%	96.207	0.740	0.094	0.011	0.011
Component	iC_5H_{12}	nC_5H_{12}	CO_2	N_2	He
Volume fraction %	0.003	0.003	2.741	0.161	0.029

2.1 Calculation of the ideal natural gas

According to the conditions of combustion and measurement, the heat value of gas ideal can be found in various documents. From national standard, the natural gas reference conditions that Chinese used are the combustion reference conditions (20℃,101.325kPa) and metering reference conditions (20℃,101.325kPa)[7]. Combined with the volume fraction of the natural gas respective components, the mole fraction can be calculated. So the high and low heat values are found and could be calculated through the hybrid rules. Results are calculated as follows.

$$H_h^0 = \sum H_{(h)i} r_i = 36.24 \mathrm{MJ/m^3}, \quad H_l^0 = \sum H_{(l)i} r_i = 32.65 \mathrm{MJ/m^3}$$

2.2 Calculation of the actual heat value

As the actual natural gas is not the ideal gas. It should be amended according to the actual gas when calculating the volume heat. The amendment of actual heat value is mainly completed by the compression factor and it can be referred to the GB/T 11062-1998 which contains natural gas heat, density, Wobbe index and relative density [8].Through the associated table and a series of the calculations, it can be derived that the summation factor of the natural gas respective components. The compression factor Z=0.9982. And the actual high and low heat values are calculated through the compression factor Z. The calculation is following.

$$H_h = \frac{H_h^0}{Z} = 36.31 \mathrm{MJ/m^3}$$

$$H_l = \frac{H_l^0}{Z} = 32.71 \mathrm{MJ/m^3}$$

2.3 Amount of air required for combustion

O_2 required for the combustion is generally obtained directly from the air. In the condition of the ideal case, the volume fraction of dry air contains 21% of O_2 and 79% N_2.

Then the practical amount of air required for combustion is following.

$$V_o = \frac{1}{0.21}\left(\sum\left(m + \frac{n}{4}\right) r_{C_mH_n}\right) \tag{1}$$

Among the Equation (1), $r_{C_mH_n}$ means the volume fraction of C_mH_n, and V_o means the practical amount of air. The calculation is $V_o = 9.3174 m^3/m^3$.

Because of the gas and air is difficult to mix uniformly, the amount of air supplied is generally greater than the theoretical amount of air in the actual combustion process. Here it takes the excess air coefficient α=1.15. Eventually the actual amount of air $V = \alpha \times V_o = 10.7150 m^3/m^3$.

2.4 Calculation of the combustion products

The theoretical flue gas produced can be calculated by the combustion reaction equation. As part of the combustion products are influenced by the parameters outside. So we take the calculation of combustion products here in the condition of that the outdoor temperature is 13.1℃ and the outdoor humidity is 52.6%.

2.4.1The theoretical amount of the flue gas (α=1)

Through the component of the natural gas, the flue gas mainly contains CO_2 and H_2O after combustion. Then the volume of CO_2 is following.

$$V_{CO_2} = 0.01\left(r_{CO_2} + \sum m r_{C_mH_n}\right) = 1.0083 m^3/m^3$$

And the volume H_2O is following.

$$V_{H_2O}^0 = 0.01 \times \left[\sum \frac{n}{2} r_{C_mH_n} + 126.6 \times \left(d_g + V_0 d_a\right)\right] = 2.0095 m^3/m^3$$

d_a ——The moisture content of the gas

d_g ——The moisture content of the gas

126.6——The specific volume of water vapor in the ground state

$d_a = 0.622 \frac{\varphi p_s}{p - \varphi p_s}$, φ——Relative humidity of moist air, p——Atmospheric pressure, p_s ——The saturated pressure of water vapor corresponding to air temperature. Here we take the moisture content of the gas $d_a = 0$.

The volume of N_2 is following.

$$V_{N_2}^0 = 0.79V_0 + 0.01r_{N_2} = 7.3623m^3 / m^3$$

The volume of He is following.

$$V_{N_2}^0 = 0.79V_0 + 0.01r_{N_2} = 2.9 \times 10^{-4} m^3 / m^3$$

So the total volume of the flue gas is following.

$$V_f^0 = V_{CO_2} + V_{H_2O}^0 + V_{N_2}^0 + V_{He} \quad (2)$$

4.2.2 The actual amount of flue gas(α=1.15)

α=1.15 is substituted for calculating CO_2, water vapor, N_2, He, and the volume of excess oxygen. Therefore the results of the theoretical and actual combustion products as follow.

Table.2 Natural Gas Combustion Products Results Summary

Products	Unit	Theoretical values	Practical values
CO_2	m^3/m^3	1.0083	1.0083
H_2O	m^3/m^3	2.0095	2.0181
N_2	m^3/m^3	7.3623	8.4665
He	m^3/m^3	2.9×10^{-4}	2.9×10^{-4}
O_2	m^3/m^3	0	0.2935
Air moisture content	g/m^3	4.9	4.9
Dry gas moisture content	g/m^3	0	0
The total volume of flue gas	m^3/m^3	10.3804	11.7867

III. Measuring the experimental parameters of the condensing boiler-low temperature floor radiant heating system

3.1 Introduction of the principle of the experiment system

The Fig.1 is structural schematic diagram of the system. The system is composed of the condensing boiler, manifolds, floor heating coil, Valves, etc. As shown in Fig.1, the condensing boiler is the heat source and the hot-water is heat medium. Through the heating coil, the hot-water radiates heating to the room.

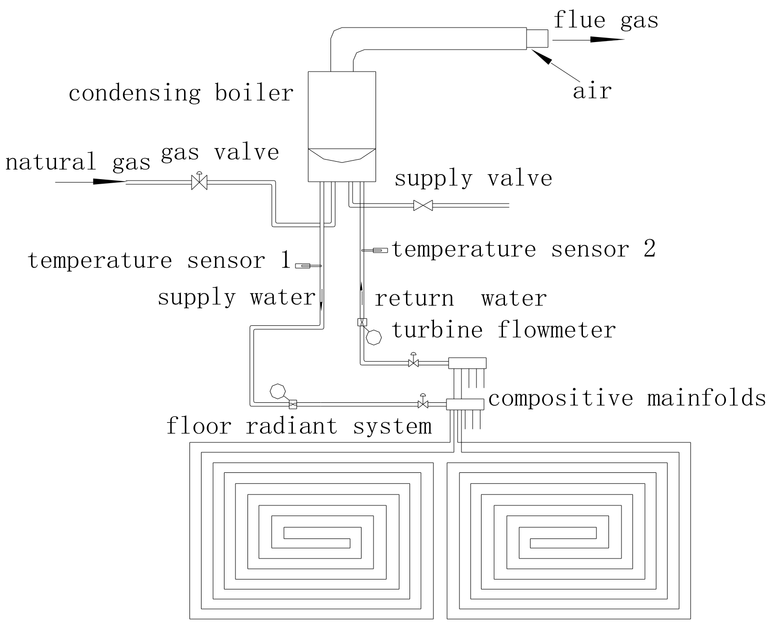

Fig.1 The structure diagram of the system

In this experimental system, the natural gas is transported to the condensing boiler. So the amount of the natural gas can be read through the gas meter and its flow can be calculated in different water supply and return temperature. The measuring cylinder is used to collect the condensate water and read the value of condensate water. And other equipment is used to gather the signal of temperature, humidity and flow. At the beginning of the experiment, the temperature of supply water is set 50℃ and the experimental parameters are recorded and measured at the same time. When the system reaches the steady state, the parameters are recorded and measured about 2~3h continuously to get more sufficient experimental data.

Similarly, the temperature of supply water is adjusted to 55℃, 60℃, 63℃, 67℃, 71 ℃,75℃ respectively and measure the parameters.

3.2 Laboratory equipment

Based on the requirements of the experimental parameters, it's needed to purchase the equipment procurement and collect the wire. The equipment and functions of the system is shown in Table3.

Table.3 equipment and functions

equipment	functions
Turbine flowmeter	Measuring flow signal of the water supply and return
Temperature Sensor	Measuring the water supply and return water temperature signal
Temperature and humidity sensor	Measuring outdoor temperature and humidity signal
Graduate	Measuring the amount of the condensate water
PLC and each module	Transforming the analog signal into the digital signal to obtain the measurement parameters

IV. Analysis and Calculation of thermal efficiency

4.1 A brief analysis of thermal efficiency

Thermal efficiency of the condensing boiler is defined as the ratio of useful heat obtained by heating the water and chemical heat

$$\eta = \frac{Q_w}{Q_{gc}} = \frac{Q_a + Q_g + H_l - Q_f - Q_c - Q_d}{H_l} \tag{3}$$

Q_a——The physical heat that air take in, kcal/m^3, Q_g——The physical heat that the natural gas take in, kcal/m^3, Q_{gc}——The chemical heat of the natural gas, kcal/m^3, H_l——LHV of the natural gas, kcal/m^3, Q_f——The total heat that the flue gas take away, kcal/m^3, Q_c——The heat that shell and pipe wall dissipate, kcal/m^3, Q_d——The heat that incomplete combustion take away, kcal/m^3, Q_w——The effective heat that the heated water obtained, kcal/m^3.

Due to the fact that the sealing and insulation of the condensation boiler casing and external piping are better, so the heat loss is relatively less and can be negligible in the calculation. $Q_c = 0$. Besides, since the condensing boiler uses the premix combustion, the natural gas combustion can be considered complete. $Q_d = 0$. So, the Equation (3) can be simplified as Equation (4) as follow.

$$\eta = \frac{Q_w}{Q_{gc}} = \frac{Q_a + Q_g + H_l - Q_f}{H_l} \tag{4}$$

The above Equation (4) shows that: one of the main effects of thermal efficiency is the heat that flue gas takes away.

4.2 Thermal efficiency calculation

When the heating system runs to the thermal equilibrium condition, the parameters are measured at different supper water temperatures. According to the experimental data of system, thermal efficiency is calculated through the following equation.

$$\eta = \frac{M \times C(t_1 - t_2)}{V \times Q_1} \times \frac{273 + t_g}{273} \times \frac{101.3}{P_a + P_g - P_s} \times 100\% \tag{5}$$

η——Thermal efficiency,%; M——The amount of hot water，kg/min; C——The specific heat capacity of water，4.2×10^{-3}MJ/(kg·℃); t_1——supper water temperature, ℃; t_2——return water temperature, ℃; V—

—natural gas flow rate, m^3/min; Q_1 ——natural gas LHV, MJ/m^3; t_g ——natural gas temperature, ℃; P_a —— Atmospheric pressure, kPa; P_g ——natural gas pressure, kPa; P_s ——saturation vapor pressure when the natural gas temperature is t_g , kPa.

$$P_s = 10^{\left(7.203 - 1735.74/\left(t_g + 234\right)\right)}$$

Besides, from another point of view, Equation (4) shows that the flue gas heat recovery is the main factor influencing thermal efficiency. So some objective factors can be neglected and the combustion heat and recovery heat recovered by the condensation are just taken into the consideration. Then the actual thermal efficiency calculation is following.

$$\eta = \frac{Q_{gas} + Q_{qr}}{Q_{gas}} \tag{6}$$

Q_{gas} ——Low calorific value gas heat released, kJ; Q_{qr} ——recovery heat recovered by the condensation, kJ.

Through two different calculations of thermal efficiency, the error can be compared to choose a more suitable calculation.

4.3 Calculation results

When return water temperature is stable, it is measured that the amount of natural gas and the temperature of supply & return water. Thermal efficiency is calculated by Equation (5). For example, when the supply water temperature is 50℃ and the outdoor temperature and humidity are 13.1℃ and 52.6%RH respectively, the calculation is following.

After the experimental measurement, the data is collected and calculated, as follows.

The water flow is $M = 8.083kg/min$. $tg = 13.1$℃, $t1 = 33.58$℃, $t2 = 30.63$℃, the gas flow is $V = 3.05\times10^{-3} m^3/min$, $Q_1 = 32.71 MJ/m^3$, $P_a = 101.325kPa$, $P_g = 2kPa$, $P_s = 1.49kPa$. So thermal efficiency is$\eta \approx 104.67\%$.

In the same way, thermal efficiency is $\eta \approx 103.90\%$ by Equation (6). The error between Equation (5) and Equation (6) is $\Delta\eta = 0.77\%$. So the Equation (6) can be used to calculate thermal efficiency approximately.

4.3.1 Analysis of relation between outdoor humidity and thermal efficiency

In the outdoor weather conditions, the humidity has some influence on the thermal efficiency. According to the Equation (6), it shows that the condensation water has impact on thermal efficiency. And the main factors affecting the amount of water is the moisture content of condensed fumes.

When the outdoor temperature and humidity are 13.1℃ and 52.6%RH respectively, other conditions are kept the same and the humidity is just changed. Then it's necessary to analyze thermal efficiency in different humidity.

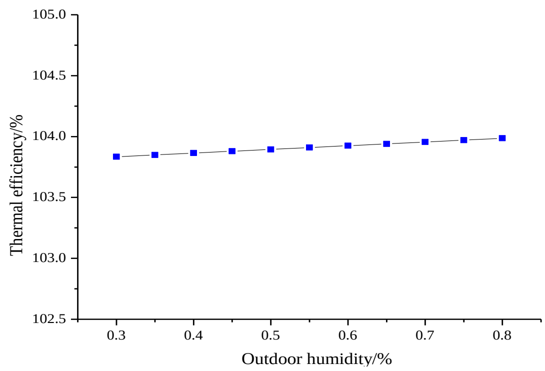

Fig.2 Outdoor humidity and thermal efficiency curve

As the Fig.2 shows, when the supply water temperature is 50℃ and outdoor temperature remains unchanged, with the increase of outdoor humidity, thermal efficiency gradually moderate increase. When outdoor humidity increases of 10%, thermal efficiency will increase about 0.03%. While outdoor humidity rises from 30% to 80%, the thermal efficiency increases of 0.15%. Thermal efficiency increases marginally, and maintained at between 103.9% and 104%. It can be inferred that the outdoor humidity has little effect on thermal efficiency. So as one of the factors affecting thermal efficiency, the outdoor humidity can be ignored. Next, the outdoor temperature should be focused on the effect on thermal efficiency.

4.3.2 Analysis of relation between outdoor temperature and thermal efficiency

Outdoor temperature mainly affects gas temperature and air temperature, which has an impact on thermal efficiency. During the experimental period, the outdoor temperature is varied between 8℃ and 15℃. When the supply water temperature remains constant, the outdoor temperature has a little change during the experimental measurements. So the number of thermal efficiency is less in different outdoor temperature. They are summarized as shown in Table 4.

Table.4 relationship between outdoor temperature and thermal efficiency

Supply water temperature/℃	Outdoor temperature/℃							
	8	9	10	11	12	13	14	15
50	/	/	/	/	104.16	104.65	104.68	105.09
55	/	103.63	103.62	103.72	104.03	104.67	104.62	104.82
60	102.80	103.22	103.53	/	/	/	/	/
63	102.25	102.46	/	/	/	/	/	/
67	/	101.76	101.9	/	/	/	/	/
71	/	/	100.92	/	/	/	/	/
75	/	/	100.55	100.39	100.33	100.18	/	/

Obviously, efficiency thermal of condensing boiler declines with the increase of supply water temperature in the condition of the same outdoor temperature. When the supply water temperature continue to rise from 60℃, thermal efficiency decline faster. When the supply water temperature remains constant, thermal efficiency increases with the rise of outdoor temperature. There is a certain nonlinear relationship between them. When the supply water temperature rises to 75℃, thermal efficiency hardly changes, and maintains at 100.18%~100.55%. The reason is that the latent heat recovering from water vapor is negligible.

V. Conclusion

Through the experimental analysis of heating system, the factors—the outdoor temperature and humidity affecting thermal efficiency condensing boiler are calculated and analyzed. And the following conclusions can be gotten.

1. The influence that outdoor humidity on thermal efficiency of the condensing boiler is less. When the humidity increases by 60%, thermal efficiency will increase just only 0.15%. So the humidity as the factors affecting thermal efficiency can be negligible.
2. The impact that outdoor temperature on thermal efficiency is more remarkable. Thermal efficiency is the higher when the outdoor temperature is the higher.

Because of the experimental period is short and small changes in outdoor temperature conditions, some data are not fully measured. So thermal efficiency affected by different outdoor temperature is required to have a further detailed analysis. And the experimental parameters in different conditions need to be measured, which will be explored in future experiments.

Reference

[1] WANG Jian-guo.The analysis of gas boiler thermal efficiency.*District the heating,5,* 2005,25~27.

[2] ZHANG Wen-sheng, MENG Jian-qiong, ZHANG Shu-lin, etc. Estimation of Thermal Efficiency of Medium &Minitype Gas-Fired Boiler[J]. *Energy conservation technology,23(129),*2005,91~93.

[3] WANG Zhi-yong, LIU Chang-long, WANG Han-qing, etc.Discussion on Condensing Heat Recovery of Oil-fired Boiler.*Building Energy & Environment, 29(3),* 2010,78~80.

[4] BAI Yu-fang, SU Xiao-guang. Study on Wall-mounted Boiler Thermal Efficiency Measurement System.*Industrial Control Computer.27(4),* 2014, 1~3.

[5] SUI Yun-liang, JI Yong-fei. The Advantages of Combination of Condensing Boiler and Floor Heating Systems.China Construction Heating &Refrigeration, (4), 2010,42-43.

[6] SUN Hui. *Analysis of Operation for Trunk Network of Natural Gas in Shanghai*.Tongji University,Shanghai, ME, 2007.

[7] YAN Shi-xin, WANG Wei-na, XIA Qing-yang.Energy Measurement of Natural Gas and Calculation of Volume Calorific Value.*Energy and energy conservation,10,* 2013,94~96.

[8] TANG Meng, XIA Chao-bin.*GB/T 11062-1998Natural gas—Calculation of calorific values, density, relative density and Wobbe index from composition*. Beijing: China Standard Press,1998.