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The Potential and Approach of Flue Gas Waste Heat Utilization of Natural Gas for Space Heating

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Abstract

After the combustion of natural gas, the flue gas contains large amounts of water vapor. The latent heat of the water vapor in the flue gas account for 10%-11% of the lower heating value of natural gas, that is, if the condensing heat of the flue gas were recovered, the energy efficiency could be improved greatly. In order to improve the efficiency of the space heating system by natural gas, the potential of waste heat of the flue gas were analyzed, and the problems of the conventional space heating system were proposed. A new approach was proposed, which could decrease the temperature of the flue gas, and recover the waste heat of the flue gas simultaneously. The flue gas outlet temperature could be reduced to below 25ºC. The different processes were proposed for gas boiler, distributed energy system, and natural gas cogeneration systems. The energy saving analysis and economic evaluation were investigated. A remarkable economic advantage can be achieved in this technology. The payback year is within 4 years. It provides the important reference for reasonable application of the technique.

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Keywords: District heating waste heat of the flue gas, Gas boiler, Distributed energy system, Cogeneration

1. Introduction

With the increase of heating demand, the problem of environmental pollution is enhanced by space heating. The use of clean energy, natural gas has become an important measure to solve the problem of environmental pollution.

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At the same time, the resource of natural gas is limited, how to use the limited resource and play the biggest role of clean energy has become an important issue.

After the combustion of natural gas, the flue gas contains large amounts of water vapor. The latent heat of the water vapor in the flue gas account for 10%-11% of the lower heating value of natural gas, that is, if the condensing heat of the flue gas were recovered, the energy efficiency could be improved greatly[1]. At present, the exit flue gas temperature of the household gas-water heater is 110ºC~160ºC,and the exit flue gas temperature of the gas boiler is about 90ºC~130ºC,and the exit flue gas temperature of the natural gas power generation plant (gas power plant, thermal power plant or the combined cooling heating and power system) is about 90ºC~150ºC.At such temperatures, the water vapor in the flue gas does not condense, and the latent heat cannot be reclaimed, which leads to a considerable heat loss. The flue gas temperature is lower, the recoverable heat is greater. Since the 1970s, condensing boilers have been developed and have found wide applications in Europe and North America [2-6]. Dann [7] concluded that the potentially high operating efficiencies offered by condensing boilers can be achieved in practice, and the condensing boiler will provide substantial savings in running costs when compared to the more conventional boiler. Searle [8] and Pickup [9] showed that many parameters of design and installation would influence the performance of condensing boilers. Various schemes for recover the latent heat in flue gas have been put forward [10, 11]. The study of the design and efficiency analysis have been done in condensing heat exchangers and system [12-14].The waste heat recovery can be used for household hot water, for heating the return water of district heating system, for regeneration the dehumidification system solution, preheating air, preheating gas etc. In the heating system, the return temperature is the key factor to affect the use of waste heat recovery. The investigation [15] showed that when the return temperature is between 40.8 and 53.3, the efficiency improvement would be 2.12%~5.76% in the use of the condenser heat exchanger. It is feasible to use the return water of a heating system as the cooling medium of the condensing heat exchanger because the return temperature varies with the ambient temperature and is lower than the dew point of the flue gas in some periods of a heating season. In China, the return temperature of the heating system is always above 50 ºC, so the flue gas temperature could not be reduced to below 50, therefore the condensing heat of the flue gas can not be fully recovered. There are two methods to solve the problem: one is to keep the return temperature not changed, and to use a heat pump to produce a low temperature environment, extracting heat from the flue gas, another is to take some technical measures to reduce the return temperature in the heating network, and use the low temperature return water as the cooling medium of the condensing heat exchanger directly to recover the waste heat of the flue gas. For gas boiler or gas engine, method one is applicable, and for combined cycle system, method one and two are all applicable, but the waste heat recovery and utilization degree is different.

In this paper, the potential of the waste heat recovery was analyzed quantitatively. A new approach was proposed, which could decrease the temperature of the flue gas, and recover the waste heat of the flue gas simultaneously. The outlet temperature of the flue gas could be reduced to below 25ºC. The different processes were proposed for gas boiler, distributed energy system, and natural gas cogeneration systems. The energy saving analysis and economic evaluation were investigated. A remarkable economic advantage can be achieved in this technology. The recovered year is within 4 years. It provides the important reference for reasonable application of the technique.

2. The potential of the waste heat in the flue gas

We all know that the excess air coefficient α could be used to describe the combustion process of ideal and actual combustion process.

$$\alpha = \frac{V_{act}}{V_0} \tag{1}$$

Where V_{act} is the actual supply air quality to burn 1 cubic meters of natural gas, and V_0 is the theoretical air quality required 1 cubic meters of natural gas for full combustion.

Corresponding to the different excess air coefficients, recoverable heat in flue gas is different, in general, the higher the excess air coefficient, the greater the recoverable heat. The excess air coefficient of gas boiler is about

1.05~1.3. The excess air coefficient of the gas internal combustion engine is about 1.5~2.0.The excess air coefficient of gas turbine of the combined cycle is about 2.6~3.1, which is higher than the natural gas boiler, so the recoverable heat is much more than the gas boiler. The relationship between the outlet temperature and the utilization efficiency of the natural gas is shown in Fig.1. The efficiency in Fig.1 means the heat recovery percentage of total lower heating value of natural gas.

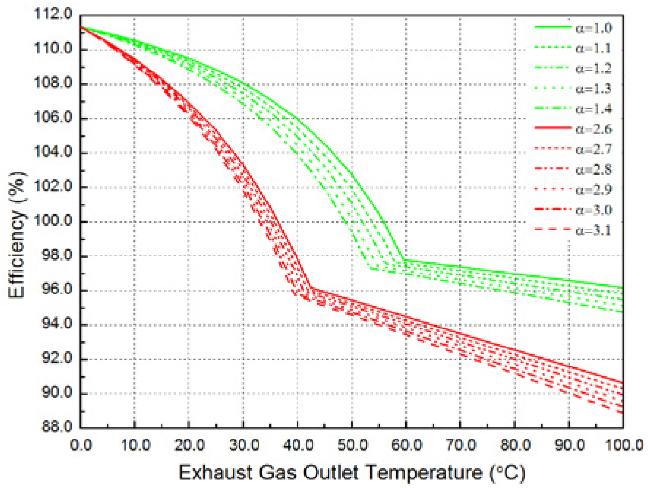

Fig. 1 Outlet temperatures vs. Utilization efficiency of natural gas.

As can be seen from the Fig.1, when the temperature of the flue gas decreased from 100 ºC to the dew point, it scales linearly with the efficiency of the natural gas, that is, only the sensible heat of the flue gas is recovered, and the recoverable heat are almost equal per temperature drop. When the temperature of the flue gas is below the dew point, the relationship between the efficiency and the temperature of the flue gas is nonlinear, that is, the sensible and latent heat of the flue gas is recovered at the same time, and the waste heat recovery per temperature drop is increased significantly. Therefore, when the outlet temperature is lower than the dew point, it comes into the condensation recovery area, and the heat quantity is very large when the temperature is decreased just 1ºC.

When the flue gas reduces the same temperature gradient, the excess air coefficient is bigger, the recoverable heat is larger. Take the combined cycle as an example, through the statistical analysis of several typical combined cycle units, such as 9E and 9F units of GE and Siemens, the potential of the waste heat in the flue gas accounts for about 48%~65% of the rated district heating capacity (extraction steam heating capacity). A typical 9E combined cycle unit as an example, when the outlet temperature of the flue gas is decreased from 90ºC to 30ºC, almost 60MW waste heat could be released for district heating. In the condensation recovery area, the temperature of the flue gas decreases 1ºC, the waste heat is up to 2MW. For the natural gas-steam combined cycle power plant, the power generation efficiency is hard to improve because of the confine of the unit characteristics, the improvement in thermal efficiency should be concerned, which has great significance to energy saving, environmental protection, economy.

As can be seen from the Fig.1, the dew point of the flue gas is between 40ºC and 60 ºC, that is, the temperature of the flue gas is reduced to below 40ºC~60 ºC, the latent heat is recovered gradually. When the temperature is reduced to 20ºC, the waste heat recovery of the gas boiler increased 14%~15% of the original boiler rated heating capacity, and the waste heat recovery of the gas engine increased 40%~50% of the original rated heating capacity, and the waste heat recovery of the combined cycle unit increased 48%~70% of the original rated heating capacity. As much as possible the recovery of the heat, which has great significance to energy saving, environmental protection, and economy.

3. The Approach of Flue Gas Waste Heat Utilization of Natural Gas for Space Heating

3.1. The flue gas heat recovery method for gas boiler

We all know that, the return temperature of the heating system is always above 50 ºC, so the flue gas temperature cannot be decreased to below 50ºC, and the condensing heat of the flue gas cannot be fully recovered. In order to recover the condensing heat of the flue gas fully, we can use a heat pump to produce a low temperature environment to extract the heat of the flue gas. The new system is shown in Fig.2.

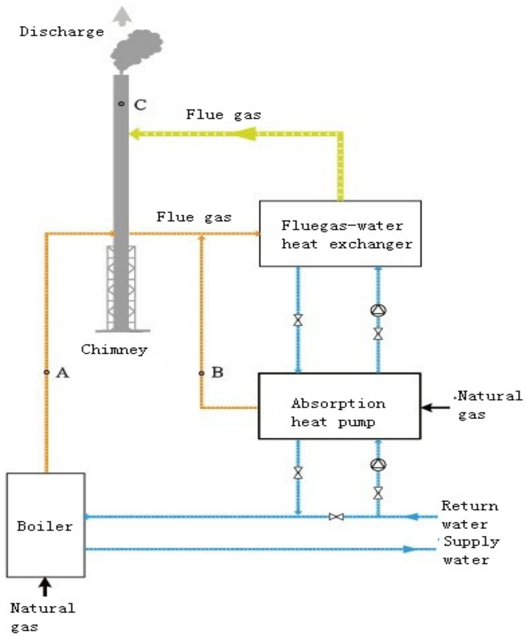

Fig.2 Schematic diagram of the flue gas heat recovery of gas boiler based on absorption heat pump.

An absorption heat pump and a flue gas-water heat exchanger are used. In the system, natural gas is used as the driving energy to drive absorption heat pump. The exhaust of the absorption heat pump and the boiler are combined together, and then are sent to the flue gas-water heat exchanger. The waste heat of the flue gas is recovered and then transferred to the medium water (15ºC/20ºC), which is used as the lower temperature heat source of the absorption heat pump. The return water of the primary heating network is heated by the absorption heat pump, and then it is heated by the gas boiler. The exhaust of the stack could be decreased to about 20ºC.

The energy utilization efficiency could be improved more than 10% [16]. Nowadays, the technology has been used in some boiler rooms in Beijing, and has achieved good energy saving effect. At the same time, it also has good environment protection effect because that the actual observation found significant role in reducing the white smoke of the stack.

In this paper, the Incremental Evaluation Method (IEM) can be used to evaluate the economics of the tri-generation system, IEM can be defined as an economic benefit analysis between the flue gas heat recovery system and reference energy system based on input and output increment analysis to meet the same heating demand. The reference energy system means that the heat is supplied by the natural gas boiler.

$$Y = \frac{\Delta C}{\Delta R} \tag{2}$$

Where, Y is the payback year of the increased investment, ΔC is the initial investment increment compared with the reference system; ΔR is the operation and maintenance cost decrement compared with the reference system.

The payback year of this kind of system is about 2~3 years.

3.2. The flue gas heat recovery method for gas engine distributed energy system

For a gas engine distributed energy system, the exhaust of the gas engine is about 400~500ºC, the typical system is shown in Fig.3. The system is composed of the internal combustion engine (ICE), the absorption heat pump(AHP), the condensing heat exchanger(CHE), and other assistant facilities. The natural gas is used to fire the ICE, which generates power on-site. In the winter, the exhaust gas (about 530 ºC) of the ICE is used to drive the AHP directly, and the exhaust (about 150 ºC) out of the AHP is sent to the CHE, and the exhaust out of the CHE could be lowered to below 25ºC. On the evaporator side of the AHP, the evaporation temperature is about 15 ºC, and the cold water flows from the CHE which recovered the condensing heat of the exhaust is directed to the evaporator side of the AHP as the low-grade heat source. On the condenser side of the AHP, the condensation temperature is about 50 ºC, and the hot water flows from the condenser side of the AHP, in conjunction with the hot water flows from the jacket water heat exchanger, is used for space heating. If the temperature of the jacket water is high (about 90~110 ºC) in some manufacturers of machine, the jacket water and the flue gas could be used simultaneously to drive the absorption heat pump to recover the waste heat of the low temperature flue gas.

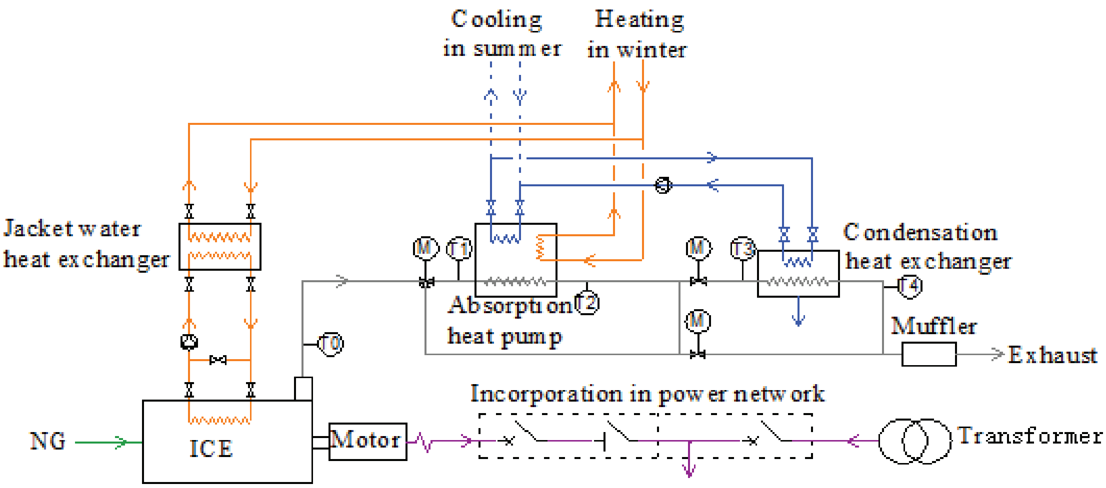

Fig.3 Schematic diagram of the flue gas heat recovery of gas engine distributed energy system.

Nowadays, the technology has been used in building energy research center and the railway station in Beijing and Tianjin, and has achieved good energy saving effect. Compared with conventional gas engine distributed energy systems, it shows that the new system could increase the heat utilization efficiency 10% in winter [17-19]. At the same time, it also has good environment protection effect because that the actual observation found significant role in reducing the white smoke of the stack. The payback year of the increased investment is about 3~4 years.

3.3. The flue gas heat recovery method for gas engine distributed energy system

3.3.1 The flue gas heat recovery method in the power plant

In the conventional thermal power plant, the steam is extracted to the steam/water heat exchanger to heat the primary heating network, and then, the heat is transferred to the heating station. In the station, the water / water heat exchanger is used to heat the secondary heating network for the buildings.

We can use the absorption heat pump in the thermal power plant which is shown in Fig.4. The steam is extracted to the absorption heat pump as the driving energy, and the exhaust are sent to the flue gas-water heat exchanger. The waste heat of the flue gas is recovered and then transferred to the medium water (15ºC/20ºC), which is used as the lower temperature heat source of the absorption heat pump. The return water of the primary heating network is heated by the absorption heat pump, and then it is heated by the steam/water heat exchanger for peak shaving. The exhaust of the stack could be decreased to about 40ºC.In the system, the irreversible loss of the conventional steam/water heat exchanger could be reduced, and the heating capacity could increase. But because the return temperature is high (above 60ºC), and the extraction is limited, the heat recovery is limited. Use a 9E gas steam combined cycle unit as an example, the recoverable waste heat is about 36MW, and the exhaust temperature is reduced to 38ºC, and the increased heating capacity improved 28% compared with the rated heating capacity, which recovered a small part of condensing heat of the flue gas, and cannot recover the waste heat totally.

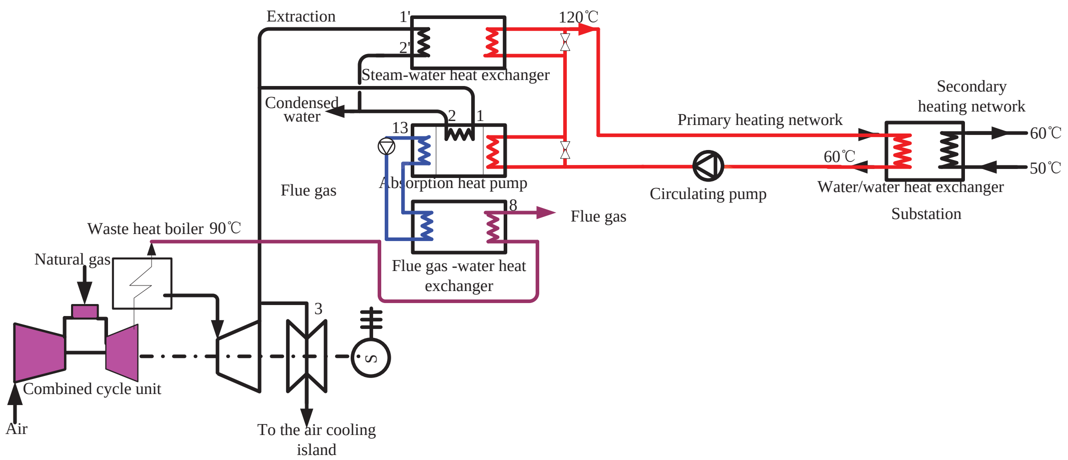

Fig.4 Schematic diagram of the flue gas heat recovery in the thermal power plant.

3.3.2 The flue gas heat recovery method based on return temperature reduction of the heating network

In general, for the heating network, the radiator area of the end user is limited, so the supply and return water temperature of the secondary heating network is not too low. The supply and return water temperature of the primary heating network is confined by the secondary heating network, so the return temperature of the primary heating network cannot be decreased, which make the condensing heat of the flue gas cannot be utilized effectively.

In order to improve the efficiency, a new kind of energy utilization method in district heating system was proposed, which has two different places compare with conventional system.

Firstly, it has some changes in the substations. Generally, the design temperature of the primary heating network is 120/60ºC, and the secondary heating network is 60ºC/50ºC or less. The huge temperature difference of heat transfer caused a lot of irreversible loss in the substations. We can use the available potential energy as driving force to realize the heat exchange between the primary and the secondary heating networks by the technique of absorption heat-exchange unit (AHE).The technology has been widely used in China[20-22].The principle is based on absorption cycles and the working fluids are Lithium bromide [23].

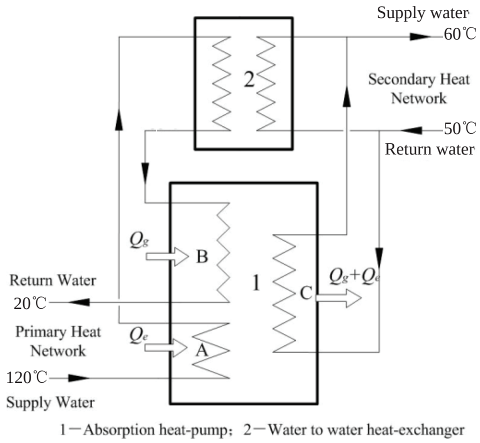

Fig.5. Schematic diagram of Absorption Heat-Exchange Unit.

The schematic diagram of AHE is shown in Fig.5. It is composed of a water-water heat exchanger and an absorption heat pump. The supply water of the primary district heating network first serves as a heat resource to drive the absorption heat pump, and then the hot water out of the generator of the absorption heat pump is used to heat one part of the return water of the secondary district heating network in the water-water heat exchanger, finally, the hot water is used as a low temperature heat resource and is cooled in the evaporator of the absorption heat pump. The return water in the secondary district heating network is divided into two parts. One part is heated in the water-water heat exchanger, and the other part is heated by the absorption heat pump. The return temperature of the primary heating network can be decreased to 20ºC which will bring the following benefits:

- The huge irreversible exergy loss decreases in the process of heat exchange.
- The heat transport capacity of the primary heating network increase and the investment reduces greatly: Because the supply/return water temperature of the primary heating network is changed from 120ºC/60ºCto 120/20ºC, the temperature drop is increased from 60ºC to 100ºC that means the heat transport capacity improved 60%. For a newly-built district heating network, the diameter of the pipe could be small and the pipe of the return water could be of no insulation, thus the investment reduced significantly.
- Low temperature conditions are created to recover the waste heat in the power plant: Because the temperature of the return water is low, it is easier to recover the low-grade waste heat in the power plant.

Secondly, there are different in the combined cycle power plant in the waste heat recovery of the flue gas.

The return water of the primary heating network (about 20ºC) is heated by the flue gas-water heat exchanger. After that, it is heated to about to 120ºCby the steam-water heat exchanger. The flue gas out of the waste heat boiler is about 90ºC, the flue gas is cooled to about 20ºC.The extraction of the turbine is used to heat the steam-water heat exchanger. Use a 9E gas steam combined cycle unit as an example, the output heat is 77MW which provided by the extraction of the turbine which accounts for about 62% and the waste heat of the flue gas which accounts for about 38%. The increased heating capacity improved 61% compared with the rated heating capacity.

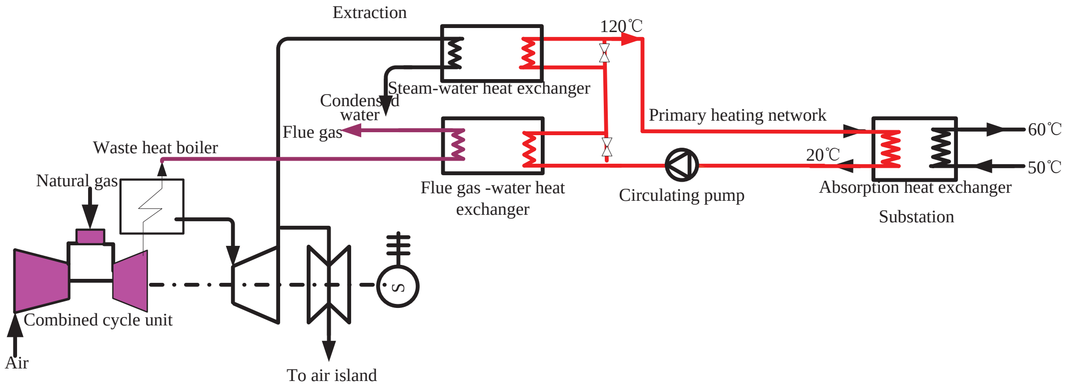

Fig.6 Flue gas heat recovery method based on return temperature reduction of the heating network.

The system can be designed differently according to the quality and quantity of waste heat of the exhaust and the flue gas. It can recover the waste heat of the exhaust firstly, and then recover the waste heat of the flue gas, it also can recover the waste heat of the flue gas firstly, and then recover the waste heat of the exhaust, or it can be divided into two flows to recover the waste respectively. The process need to be determined by the optimal analysis according to different cases.

It is worth mentioning that, the process is not the same with Fig.6 according to different configurations of the thermal power plant. When the heating parameters of the users, the steam parameters and the flue gas parameters are not the same, the system needs to determine the process optimization analysis according to different cases. In addition, the thermal power plant also has the exhaust steam which always been dissipated to the environment by the cooling tower. When we need to consider the waste heat recovery of the flue gas and the exhaust simultaneously, the process is different according to the quality and quantity of the waste heat. We can recover the waste heat of exhaust steam, and then recover the waste heat of flue gas, or we can divided the return water to two shares, one is used to recover the waste heat of exhaust steam and another is used to recover the waste heat of the flue gas. The process needs to determine the optimal analysis according to different cases. The payback year of the increased investment is generally within 4 years. At present, the technology has been developing engineering application in Beijing future technology city.

4. Conclusions

In order to improve the efficiency of the space heating system by natural gas, the quantitative analysis of the potential of the flue gas waste heat recovery was analyzed. Various new processes to recover the flue gas waste heat were proposed for gas boiler, gas engine distributed energy system, and combined cycle system. Different processes have different waste heat recovery effects. The following conclusions are obtained:

- For the natural gas boiler, the return water of the primary heating network is heated by the absorption heat pump, and then it is heated by the gas boiler. The exhaust of the stack could be decreased to about 20ºC. The energy utilization efficiency could be improved more than 10%.The new system can recover the waste heat of the flue gas deeply.
- For the gas engine distributed energy system, compared with conventional gas engine distributed energy systems, it shows that the new system could increase the heat utilization efficiency 10% in winter, and the exhaust of the stack could be decreased to about 25ºC.
- For the natural gas-steam combined cycle power plant, there are two ways to recover the waste heat. One is adding the absorption heat pump in the power plant; another is adding AHE in the substation. Using a 9E natural gas-steam combined cycle unit as an example, method one can recover 36MW waste heat, and the exhaust temperature is decreased to 38ºC, and the increased heating capacity improved 28% compared with the rated

heating capacity, which cannot recover the waste heat totally. Method two can recover 77MW waste heat, and the exhaust temperature is decreased to 20ºC, and the increased heating capacity improved 61% compared with the rated heating capacity, which can recover the waste heat totally.

The payback year of the increased investment of this kind of technology is generally within 4 years.

Nowadays, all the technology has been used gradually in Beijing of China, which has achieved good energy saving effect. At the same time, it also has good environment protection effect because that the actual observation found significant role in reducing the white smoke of the stack. A remarkable economic advantage can be achieved in this technology. The recovered year is within 4 years for all of the systems. It provides the important reference for reasonable application of the new technique.

Taking Beijing city as an example, the Potential of the waste heat of the four combined cycle power plants and distributed energy systems are about 2300MW, equivalent to the alternative 0.5 billion square meters heating area. It is planned that the heating area is 4.8 billion square meters by natural gas boiler until 2015 in Beijing, the Potential of the waste heat of the gas boiler can replace 0.48 billion square meters heating area. That is, there are about 1 billion square meters heating area which could be solved by waste heat. It can save natural gas nearly 10 billion Nm3 per year, the energy saving and emission reduction is huge. It is a sustainable energy utilization mode and will be popularized in the future.

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References

[1] Zhao X.L., Fu L., Jiang Y. The potential and method of the waste heat utilization of natural gas in space heating. District heating 2013;3:41-45(in Chinese).
[2] Field AA. Reclaiming latent heat in flue gases. Heating, Piping Air Condition 1974;46(11):85–7.
[3] Thompson RE. Condensing flue gas water vapor: another way to cut your fuel bill. Power 1983;27(5):79–82.
[4] Noir D, Houlmann N. European technology in condensing flue-gas systems. In: Symposium on Condensing Heat Exchangers Proceedings, vol. II, March 3–4, 1982, Atlanta, GA. p. 10-1–10-15.
[5] Shook JR. Recover heat from flue gas. Chem Eng Progr 1991;87(6):49–54.
[6] Thorn WF. Waste heat recovery from stacks using direct-contact condensing heat exchanger. In: Paper Presented at the 9th World Energy Engineering Congress, 1987. p. 483–95.
[7] Dann R. Domestic heating systems and controls for condensing boilers. Heat Ventilat Engr 1984;58(668):1–14.
[8]Searle M, Shiret AR. The opportunities for a new generation of high efficiency gas boiler. Gas Eng Mgmt 1986;26(7–8):200–14.
[9] Pickup G. Innovation in home heating. Gas Eng Mgmt 1983;23(5):171–8.
[10] Makansi J. Options multiply for low-temperature heat recovery. Power 1985;129(8):73–5.
[11] Kuck J. Efficiency of vapor-pump-equipped condensing boilers. Appl Thermal Eng 1996;16(3):233–44.
[12] Cirillo E, Lazzarrin R, Piccininni F. Energy analysis of a central domestic hot water heating system equipped with condensing boilers. Int J Energy Res 1990;14(1):73–81.
[13] Rosa L, Tosato R. Testing of a cheap high-efficiency combined boiler. In: Proceedings of the Intersociety Energy Conversion Engineering Conference, vol. 4, 1990. p. 37–42.
[14] McNair HP, Shiret AR. Factors that influence the annual efficiency of domestic wet central heating systems. Gas Eng Mgmt 1985;25(3):90–3.
[15] Defu C., Yanhua L., Chunyang G. Evaluation of retrofitting a conventional natural gas fired boiler into a condensing boiler. Energy Conversion and Management 2004;45:3251–3266
[16] Zhao X.L., Fu L.,Wang X., Li F., Chen C.Y., Zhang S.G.Analysis of the emission on the decreasing of the exhaust temperature of gas boiler. 13th International Conference on Sustainable Energy technologies (SET2014), 25-28th August, 2014,Geneva
[17]Fu L., Zhao X.L., Zhang S.G., Jiang Y., etal. Laboratory research on combined cooling, heating and power (CCHP) systems. Energy Conversion and Management. 2009,50(4):977-982
[18] Fu L., Zhao X.L., Zhang SG., Jiang Y., etal. Performance Study of an innovative natural gas CHP system. Energy conversion &Management. 2011, 52(1): 321-328

[19] Zhao X.L., Fu L., Wang X.. The engineering practice of a CCHP system with the condensing heat recovery of the flue gas in CHINA. Proceedings of the ASME 2013 7th International Conference on Energy Sustainability & 11th Fuel Cell Science, Engineering and Technology Conference ESFuelCell2013,July 14-19, 2013, Minneapolis, MN, USA

[20] Li Y., Fu L., Zhang S.G., Jiang Y., Zhao X.L. A new type of district heating method with co-generation based on absorption heat exchange (co-ah cycle).Energy Conversion and Management 2011;52 (2) :1200-1207.

[21] Li Y., Fu L., Zhang S.G. A new type of district heating system based on distributed absorption heat pumps. Energy 2011;(36):4570-4576.

[22] Sun F.T., Fu L., Zhang S.G., Sun J. New waste heat district heating system with combined heat and power based on absorption heat exchange cycle in China. Applied Thermal Engineering 2012;37: 136-144.

[23] Fu L., Jiang Y., Zhang S.G. District heating system based on Co-ah cycles in combined heating and power systems. Tsinghua University (Sci & Tech 2008;48(9): 1377- 1380 (in Chinese).