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Experimental study of the flow and heat transfer of a gas–water mixture through a packed channel

Xiaolei Zhu · Xiaofeng Sui · Yan Zhao · Ji'an Meng · Zhixin Li

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Abstract Waste heat recovery from the flue gas of gas-fired boilers was studied experimentally by measuring the flow and heat transfer of air and water through six kinds of packing with saturated humid air as the simulated flue gas. The experiments measured the effects of inlet air temperature, inlet air velocity and circulating water flow rate on the flow and heat transfer. The results show that higher inlet air temperatures and lower inlet air velocities lower the flow resistance and increase the heat transfer coefficient. The stainless steel packing had better surface wettability and larger thermal conductivity than the plastic packing, which enhanced the heat transfer between the water and the saturated moist air. When both the flow resistance reduction and the heat transfer enhancement were considered, the experimental results gave an optimal packing-specific surface area. A packed heat exchanger tower was designed for waste heat recovery from the flue gas of gas-fired boilers based on the experimental results which had better flow and heat transfer characteristics with lower pump and fan power consumption, more stable system operation and less thermal fluctuations compared with a non-packed heat transfer system with atomized water.

X. Zhu · J. Meng (✉) · Z. Li
School of Aerospace, Tsinghua University, Beijing 100084, China
e-mail: mja@mail.tsinghua.edu.cn

X. Sui · Y. Zhao
Beijing Yuanshen Energy Saving Technology Co., Ltd., Beijing 100142, China

Y. Zhao
Thermal Research Institute, Tianjin University, Tianjin 300072, China

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1 Introduction

Over 50 % of industrial waste heat is exhausted to the atmosphere by flue gases. Heat losses in the exhaust gases from boilers are still as high as 8 %–20 % [1], with the main pollutant being NO_x, which is one of the main pollutants raising $PM_{2.5}$ levels during the heating season. Analyses indicate that the exhaust gas heat losses decrease by 0.5 %–0.6 % for every 10 °C decrease in the exhaust gas temperature [2], and the boilers thermal efficiency can be increased by more than 10 % when the latent heat loss is recovered as the exhaust gas temperature drops below the dewpoint [3]. The waste heat in flue gases can be divided into moderately high-temperature waste heat with flue gas temperatures higher than 200 °C and low-temperature waste heat with temperatures lower than 200 °C. Waste heat recovery becomes harder as the waste heat source temperature decreases. At present, boilers flue gas temperatures are gradually falling as more new energy saving techniques being developed. Hence, high-efficiency flue gas waste heat recovery methods are needed.

There have been many studies of waste heat recovery technology. For the higher-temperature waste heat recovery, DeWerth and Waters [4, 5] theoretically and experimentally studied vapor condensation in flue gas from condensation-type boilers and the energy conservation and pollutant removal characteristics. DeVries [6] cooled 72,000 Nm^3/h (here N means standard state) flue gas exhausted from an urban garbage incineration power plant from 220–270 to 180 °C with waste heat boilers. The recovered waste heat was used for regional central heating and reduced the power plant energy use by 20 % and the operating costs by 40 %. Han et al. [7] simulated a 600-MW flue gas pre-drying system to study the effects of various structural and thermal parameters for using the waste heat to dry lignite, with the thermal power plant efficiency increased by 1.51 %. Chawla [8] developed a heat exchanger for waste heat recovery, which also removed the dust from the flue gas by the vortex flow generated by the staggered flow channels that increased the heat transfer coefficient. The waste heat was used to heat steam for a turbine or an absorption refrigeration system. An 1-MW demonstration plant was set up to show that the exhaust gas temperature could be reduced from 600 to 150 °C. Kilkovsky et al. [9] optimized the thermodynamic and hydraulic heat exchangers designs for flue gas waste heat recovery from incinerators and combustors. Carcasci et al. [10] recovered the waste heat from the flue gas of gas turbines in an organic rankine cycle (ORC) with four working media: toluene, benzene, cyclopentane and cyclohexane, and they were compared to find the best efficiency. The results showed that the efficiency with each working medium depended on the working temperature, with low working temperature cyclopentane having the best efficiency while at high working temperatures, toluene was the best. Cimini et al. [11] simulated the pollutant absorption and waste heat recovery from flue gases from solid waste incinerators using Aspen Plus and a complicated gas–solid reaction model, and the results showed that this method was feasible and efficient. For the low-temperature waste heat recovery, Cohen et al. [12] developed a multi-effect distillation plant with flue gas as the heat source to study a flushing chamber and a back pressure turbine, their economic analysis of the water consumption, rectification cost and internal loss rate showed that the system was feasible and saved a considerable amount of energy. Zhou et al. [13] set up a waste heat recovery system based on an ORC, which absorbed waste heat from the flue gas of liquefied petroleum gas boilers with R123 as the working medium and finned tube heat exchangers as the evaporator. The system recovered waste heat from the flue gas at 90–220 °C with a maximum output power of 645 W, a cycle efficiency of 8.5 % and a heat recovery efficiency of 22 %. Wang et al. [14] designed a heat recovery system for high humid flue gas to recover both latent and sensible heat based on a nanoporous ceramic membrane for capillary condensation and separation. With gas-fired package boilers, the system recovered 40 % of the steam with the thermal efficiency increased by 5 % and the recovered water could be used as supplemental makeup water for almost all industrial processes. Jin and Li [15] and Jin et al. [16] used a LiBr absorption refrigerator driven by flue gas waste heat to produce cooling water, and studied the effects of the inlet and outlet flue gas temperatures, wall temperature and working medium temperature to compare the LiBr system COP for different system designs. The results showed that the COP of the two-stage flue gas waste heat double-effect LiBr–H_2O absorption refrigerator system could reach 1.2 and the exhaust gas temperature was decreased to 150 °C. Qiu et al. [17] studied a liquid drying and cooling system driven by biomass boilers flue gas waste heat to recover the waste heat by regenerating a concentrated desiccant solution using concentric helical wire heat exchangers in the smoke stack. The system reduced the indoor temperature by 4 °C in the fall with a refrigeration capacity of 2381 W and the humidity reduced by 13 %. Yong et al. [18] studied the advantages and difficulties of using heat pipes to recycle flue gas waste heat in a power plant, and they numerically predicted the temperatures, pressures and flow rates to find the optimal operating conditions. Xu et al. [19] designed four waste heat recovery systems using heat pipes for the waste heat recovery of flue gas from 1000 MW coal-fired boilers. The work produced and the coal consumption were used to study the economics to optimize the working conditions with the exhaust gas temperature reduced from 150 to 98 °C. Wang et al. [20] installed a low-pressure economizer before the exhaust flue gas entering the flue gas desulfurization (FGD) to recover waste heat from the exhaust flue gas of a 600-MW plant, with the condensed water heated by finned serpentine pipes. The results showed that the coal consumption could be reduced by 2.31 gec/kWh but that low-temperature corrosion may be a problem. Pan et al. [21] designed a condensation-type flue gas waste heat exchanger for a gas-fired vacuum hot water boiler, which increased the thermal efficiency of the water boiler by 6.6 % for a heat load of 69.78 kW with the CO_2 emissions reduced by 0.34 m^3/h. However, desulfurizers would have to be installed to avoid pipeline corrosion and atmospheric pollution.

The flue gas from gas-fired boilers has lower exhaust gas temperatures than that from coal-fired boilers, with a larger relative humidity so the latent heat accounts for a larger percentage of the waste heat. Typical conditions for flue gas from heating boilers in Beijing are exhaust gas temperatures of 60–80 °C and relative humidity of up to 70 %, and hence, the waste heat recovery conditions are very different from those of coal-fired boilers. Such systems have lower heat transfer coefficients and low-temperature corrosion resulting from low exhaust gas temperatures and high relative humidity. Both Zhou et al. [22] and Zhao et al. [23] studied flue gas waste heat recovery from gas-fired boilers. Both papers described a new waste heat recovery system with direct contact spray-type heat exchangers for the heat exchange between the flue gas and the circulating water and absorption heat pumps driven by