

Performance Analysis of an Absorption Heat Pump System for Waste Heat and Moisture Cascade Recovery from Flue Gas

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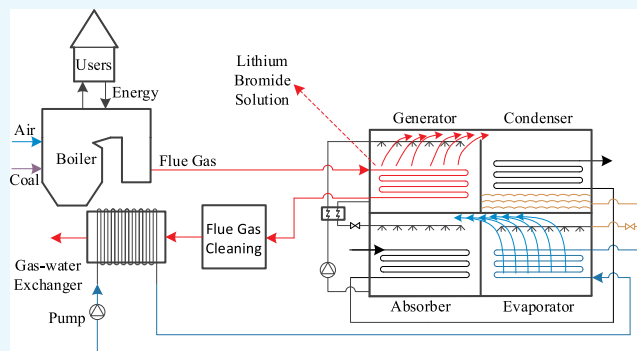
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ABSTRACT: The typical flue gas exhaust temperature of coal-fired boilers is up to 150 °C. There is a considerable amount of waste heat that cannot be efficiently recovered. This study describes a zero-energy consumption absorption heat pump system that can improve the thermal efficiency and recover moisture. In the proposed system, lithium bromide solution serves as the recyclable heat-transfer medium, which absorbs sensible heat at the outlet of the air preheater by a generator. The latent heat of the flue gas is absorbed by an evaporator, and the condensate water appears. Theoretical investigation and mathematical models are built. Meanwhile, the operating parameters of the system are displayed. The results showed that the acid dew point of flue gas is related to the water content. The sorption heat pump efficiency (coefficient of performance) increased to 1.64. Compared with the two-stage heat exchanger system, 24.4 t/h condensate water and 47.21 MW waste heat were recovered. The flue gas temperature at the chimney entrance was reduced by 4.18 °C.



1. INTRODUCTION

1.1. Background. Coal-fired boilers are widely used for power generation at the district level. In 2021, the installed capacity of power generation in China was 2376.92 million kilowatts, of which the installed capacity of coal-fired power plants was 1296.48 million kilowatts, accounting for 54.54%. The total energy generated was 8112.18 billion kW h, of which 5770.27 billion kW h was generated by coal-fired power plants, amounting to 71.13%. At the same time, the per capita volume of water resources in China was only 2090.47 m³/per person.¹ The temperature of flue gas at the outlet of the air preheater from coal-fired boilers is generally 150 °C. The heat loss of the exhaust gas accounts for 4~8% of the fuel heat and is carried to the atmosphere when large or medium sized boilers operate in the normal state, making it the most significant component of the heat loss.^{2,3} It is estimated that the water vapor content of flue gas from coal-fired boilers is 4~13%. However for gas-fired boilers, the content is approximately 15~20%.⁴

Waste heat in the flue gas exhaust includes sensible heat and latent heat, and the latent heat usually accounts for the majority of the total heat. This can be recovered only when the coolant temperature is lower than the dew point of the flue gas.^{5–7} Figure 1 illustrates the variation in the surplus heat proportions of the coal-fired boiler. The data source in Figure 1 is the ratio of sensible and latent heat calculated from the temperature at the outlet of the air preheater under different working conditions of a 330 MW coal-fired unit in China. The steam flow rate is 1866 t/h. Between the outlet of the air

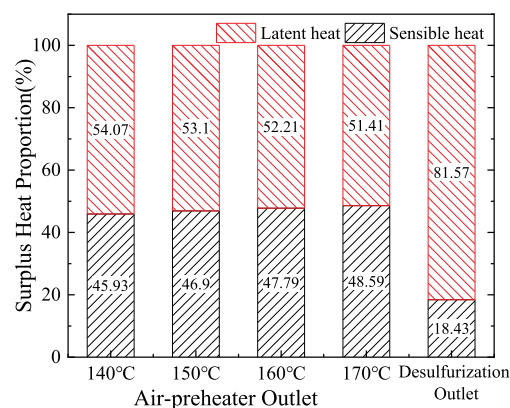


Figure 1. Variation in surplus heat proportion.

preheater and the inlet of the desulfurization tower, the flue gas is not saturated, and the water vapor volume fraction of the flue gas is about 7%. In the desulfurization tower, the flue gas absorbed a lot of water and reached saturation at the outlet of

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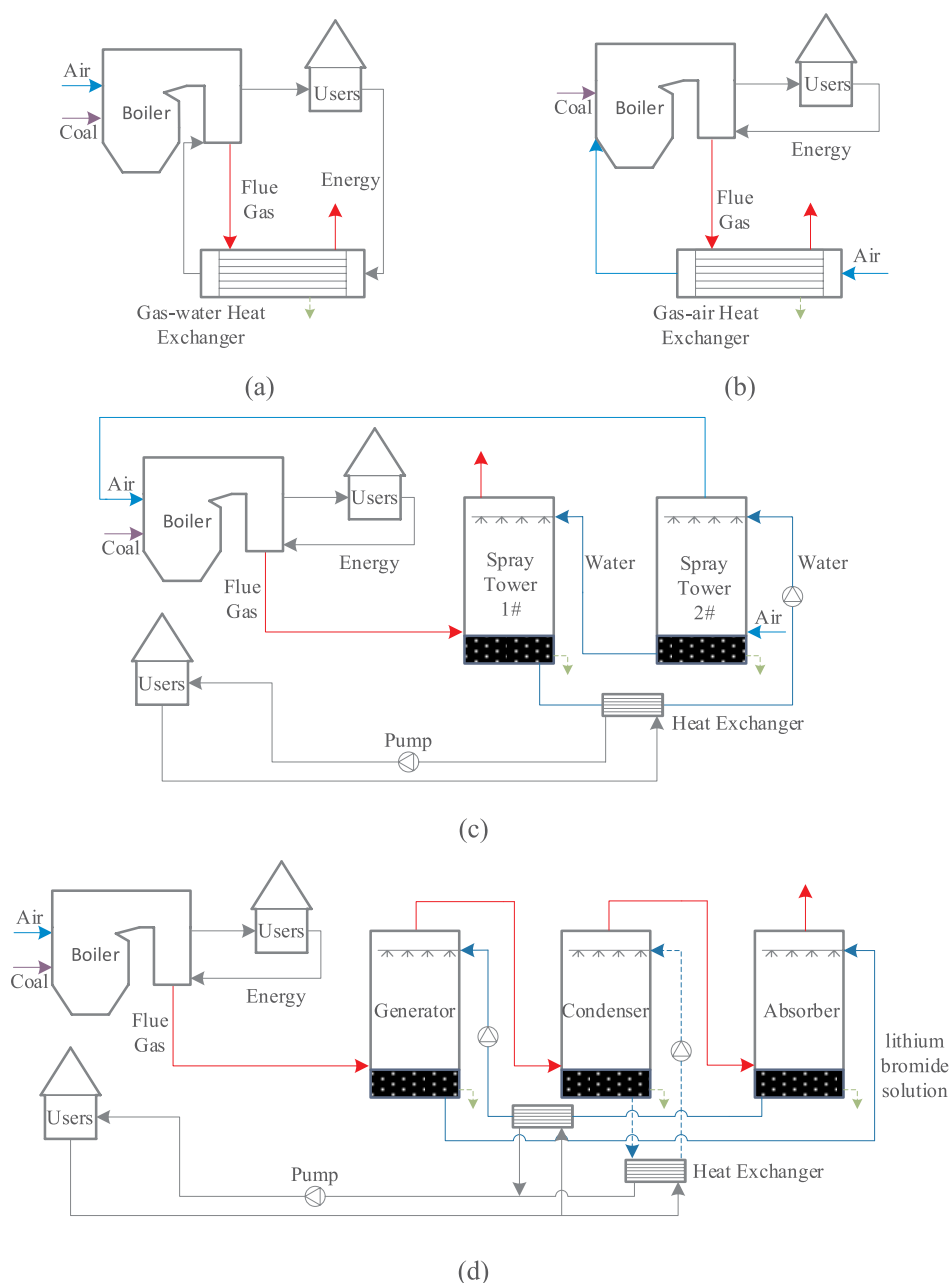


Figure 2. Schematic of flue gas surplus heat recovery for coal-fired boilers using (a) economizers, (b) air-preheaters, (c) contact economizer systems, and (d) a novel full-open absorption heat pump.

the desulfurization tower, at which time the volume fraction of water vapor was about 12%. The percentage of latent heat in flue gas is as high as 81.57%. If the flue gas temperature falls below the dew point, the water vapor could condense, and both the sensible heat and latent heat of the flue gas can be recycled along with capturing the water vapor in the flue gas. Therefore, it is important to reduce the heat loss through flue gas as well as recycle the flue gas moisture.⁸

1.2. Research on Waste Heat and Water Recovery from Flue Gas. In order to recover the latent heat in the flue gas, the temperature of the cooling medium must be lower than the dew point of the flue gas. Recently, several researchers focused on economizers and air preheaters which are common methods for waste heat recovery from flue gas. Figure 2a depicts the waste heat recovery system from flue gas with economizers.^{9–11} It uses the return water of the heat supply

network system as the cooling medium for the condensing heat exchanger. The results show the possibility of obtaining a high efficiency when the temperature of the exhaust gas is maintained within 50–60 °C. However, the return water temperature is generally 55–60 °C, near the dew point temperature of flue gas. Thus, flue gas cannot get deep cooled and vapors in the flue gas cannot get condensed. The flue gas releases only a limited amount of latent heat.

Figure 2b depicts the flue gas heat recovery system with air preheaters. It uses the ambient cold air as the cold source.^{12,13} The heat recovery capability is also limited due to the incompatible thermal capacity between the air and flue gas. During the sensible heat recovery, when the vapor does not condense, the thermal capacities of the air and flue gas are compatible, and the temperature variations are almost the same in flue gas and air. However, when the flue gas vapor

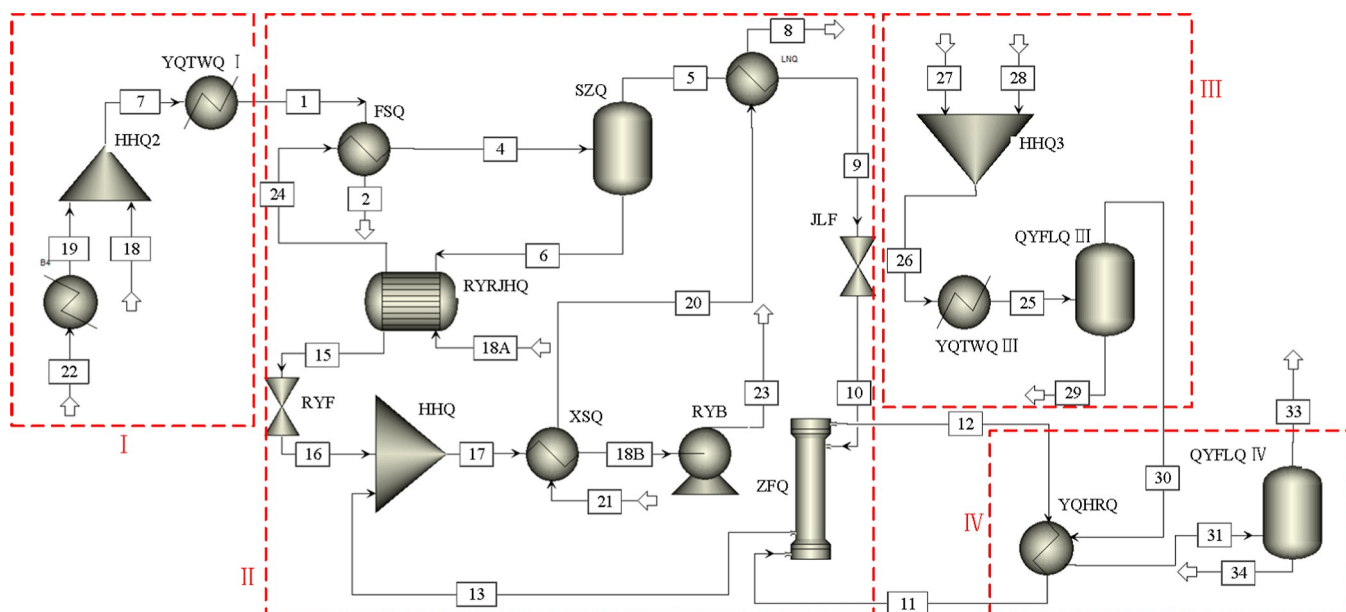


Figure 4. Modeling of the ZCAHP system.

is the standard state density of dry flue gas, kg/m^3 (standard condition); p_g is the actual flue gas density, kg/m^3 (standard condition).

Another key parameter is the dew point temperature of acid vapor, as shown in eqs 4–7.

$$t_{\text{DP}} = t_{\text{DP}}^0 + \frac{\beta(K_s S_{\text{sp}})^{1/3}}{1.05^n} \quad (4)$$

$$S_{\text{sp}} = S_{\text{c,ar}} \times \frac{4182}{Q_{\text{net,ar}}} \quad (5)$$

$$n = \alpha_{\text{fly}} A_{\text{sp}} \quad (6)$$

$$A_{\text{sp}} = A_{\text{ar}} \times \frac{4182}{Q_{\text{net,ar}}} \quad (7)$$

where S_{sp} is fuel converted sulfur; n is the index (degree of influence of fly ash content on the acid dew point); α_{fly} is the fly ash share (pulverized coal furnace = 0.8–0.9); A_{sp} is the fuel conversion ash; β is the coefficient (in general engineering calculation $\beta = 125$).

When flue gas is denitrified by selective catalytic reduction (SCR) flue gas, a new SO_3 conversion rate is formed due to SCR catalysis. The increase of acid dew point temperature of flue gas can be estimated by the following eq 8

$$\Delta t_{\text{DP}} = 26 \lg[(K_{\text{SO}_3} + K_{\text{SCR,SO}_3})/K_{\text{SO}_3}] \quad (8)$$

where K_{SO_3} is the SO_3 conversion rate (for pulverized coal-fired boiler 0.005–0.02); $K_{\text{SCR,SO}_3}$ is the SO_3 conversion rate through SCR catalysis (generally, it can be selected by 1%).

2.3. Thermal Process. After the air preheater, the flue gas sensible heat is absorbed by the generator in the ZCAHP system. As shown in eq 9

$$Q_{\text{ge}} = m_{\text{fl}} h_{\text{fl}}^1 - m_{\text{fl}} h_{\text{fl}}^2 \quad (9)$$

After the wet desulfurization tower, the flue gas latent heat is absorbed by the evaporator in the ZCAHP system. As shown in eq 10

$$Q_{\text{ev}} = m_{\text{fl}}' h_{\text{fl}}' - m_{\text{fl}}'' h_{\text{fl}}'' + m_{\text{con}}^2 h_{\text{con}}^2 \quad (10)$$

Through the absorber with a series condenser in the ZCAHP system, the heats of solution and condensation are recycled. As shown in eq 11

$$Q_{\text{ab}} + Q_{\text{con}} = m_{\text{me}}^2 h_{\text{me}}^2 - m_{\text{me}}^1 h_{\text{me}}^1 \quad (11)$$

The ZCAHP system follows the law of conservation of energy, and the total energy absorbed by the generator and evaporator is exactly equal to the total energy released by the absorber and condenser. As shown in eq 12

$$Q_{\text{ev}} + Q_{\text{con}} = Q_{\text{ge}} + Q_{\text{ev}} \quad (12)$$

2.4. Thermodynamic Evaluation Indices. To quantitatively measure the performance of the system for flue gas surplus heat and moisture recovery, several evaluation indexes are introduced below. The moisture recovery efficiency of the ZCAHP system is defined as eq 13. This is the ratio of the recollected amount of moisture and the maximum recollected moisture. It is used for assessing the latent heat recovery efficiency of the system.

$$\xi = m_{\text{re}}/m_{\text{to}} \quad (13)$$

The system waste heat recovery proportion is defined as in eqs 14–16. There are two physical significances of waste heat recovery. The sensible heat recovery rate of flue gas refers to the partial heat for generators of surplus heat recovery in the ZCAHP system. Second, it refers to the latent heat recovery rate of the flue gas, which is the heat source of the absorption heat pump evaporator. Thus, the total waste heat recovery includes the sensible heat and latent heat in the ZCAHP system.

$$\tau_1 = Q_{\text{se}}/Q_{\text{a-p}} \quad (14)$$

$$\tau_2 = Q_{\text{la}}/Q_{\text{de}} \quad (15)$$

Table 1. Block/Stream Corresponding to Device Name

block/stream	device name	block/stream	device/substance name
FSQ + SZQ	generator	YQHRQ	flue gas exchanger
LNQ	condenser	QYFLQ IV	gas–liquid separator IV
JLF	valve	QYFLQ III	gas–liquid separator III
ZFQ	evaporator	7/1/2/26/25/30/31/33	flue gas
HHQ + XSQ	absorption	24/4/6/15/18A/16/17/18B	lithium bromide
RYP	solution valve	22/19/27	dry flue gas
YQTWQ III	thermolator III	18/13/28/5	vapor water
YQTWQ I	thermolator I	9/10/11/12/21/20/8/34	liquid water

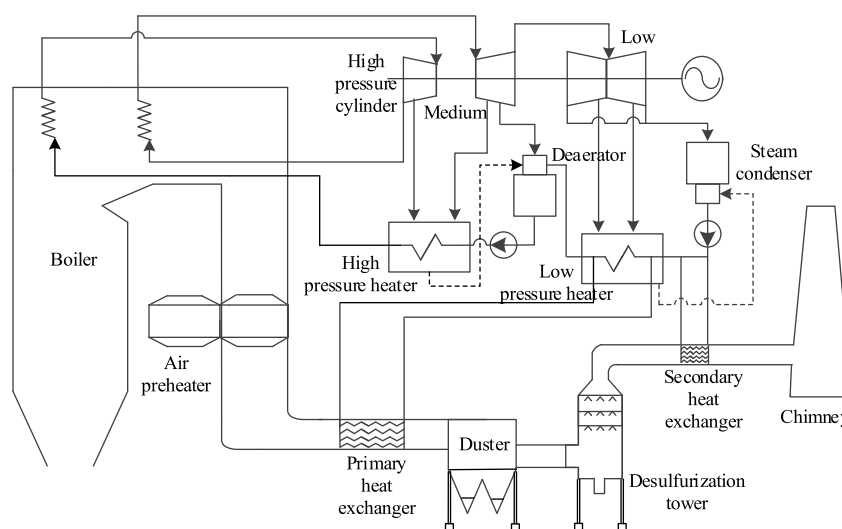


Figure 5. Schematic diagram of two-stage heat exchangers system for recovering waste heat.

$$Q = Q_{la} + Q_{se} \quad (16)$$

The performance of absorption heat pumps is quantified using the coefficient of performance (COP) as in eq 17

$$\text{COP} = \frac{Q_{con} + Q_{ab}}{Q_{ge}} = 1 + \frac{Q_{ev}}{Q_{ge}} \quad (17)$$

3. SIMULATION PROCESS

3.1. Simulation Modeling. Aspen Plus is a process simulation software set, which is widely used in the modeling of power generation, chemical processes, and other applications. A large number of researchers have performed thermal process modeling and analysis by Aspen Plus.²⁴ In this work, Aspen Plus is used to research the ZCAHP system. Figure 4 shows the modeling of the ZCAHP system using Aspen Plus. Subsystem I is used to simulate the sensible heat flue gas located at the air preheater outlet; subsystem II is used to simulate the lithium bromide absorption heat pump; subsystem III is used to simulate the latent heat of flue gas located at the wet desulfurization tower outlet; subsystem IV is used to simulate the flue gas discharge and water recovery at the end of the system. The names corresponding to the components in Figure 4 are shown in Tables 1.

3.2. Simulation Conditions. Online simulation is carried out with the history data of a 330 MW subcritical coal-fired power plant. The boiler in the case study is characterized by a single furnace, pulverized coal combustion with one reheating, balanced draft and an opposed combustion, condensing steam turbine system. The boiler is equipped with four low-speed

coal mills. The pressure and temperature of the main steam under the boiler rated load (BRL) are 17.32 MPa and 813.15 K. The sampling time of the DCS history data is set to 15 s. Figure 5 shows the schematic diagram of a two-stage heat exchanger system for recovering waste heat from flue gas. The primary heat exchanger is used to recover the sensible heat; the secondary heat exchanger is used to recover latent heat from flue gas. Parameters of the coal-fired boiler are listed in Table 2.

3.3. Input Parameter. Table 3 shows the flue gas input parameters of the ZCAHP system. Except for N₂, CO₂, O₂, and H₂O, other gases are negligible and do not influence the simulation. Thus, these gases have been neglected.

From the equation, the dew point temperature of water/acid vapor is calculated and shown in Table 4. As can be seen from

Table 2. Ultimate Analysis of the Fire Coal in Boiler

as received basis	unit	design coal	check coal
net calorific value	$Q_{net,ar}$ MJ/kg	22.96	20.15
total moisture	M_t %	22.96	20.15
air-dried basis moisture	M_{ad} %	5.21	6.84
dry ash-free basis volatile matter	V_{daf} %	33.65	39.02
ash	A_{ar} %	15.15	15.91
carbon	C_{ar} %	62.49	55.26
hydrogen	H_{ar} %	3.75	3.32
oxygen	O_{ar} %	7.4	11.4
nitrogen	N_{ar} %	0.66	0.62
sulfur	$S_{t,ar}$ %	0.75	0.69

Table 3. Flue Gas Input Parameters of the ZCAHP System

item	unit	30% BRL
dry flue gas component	N ₂	78%
	O ₂	7%
	CO ₂	15%
dry flue gas mass flow		1339.16 t/h
water vapor mass flow	air-preheater outlet	74.75 t/h
	desulfurization tower outlet	112.09 t/h

Table 4. Dew Point Temperature of Water/Acid Vapor

		design coal	check coal
t_{DP}^0	°C	39.84	41.74
S_{sp}		0.11	0.10
n		1.95	2.05
A_{sp}		2.16	2.27
t_{DP}	°C	86.24	86.67
Δt_{DP}	°C	7.83	7.83

the table, the dew point temperature of water vapor in the flue gas is much lower than that of acid dew point. That is to say, in order to effectively avoid flue corrosion, the lowest flue gas temperature after limiting the air preheater is worth the acid dew point temperature. The minimum limit of temperature is set at 100 °C in this study.

4. SIMULATION RESULTS AND DISCUSSION

4.1. System Performance Parameters. Since the boiler equipped with the new absorption heat pump system involves several heat and moisture transportation processes, a typical case study is illustrated in Table 5. Table 5 shows the thermal parameters at each critical point in the ZCAHP system.

Subsystem I: The flue gas flows from the boiler into FSQ. The temperature of the flue gas decreases from 150 to 100 °C. This part of waste heat in flue gas is used to heat the lithium bromide solution. The temperature of the solution is changed

from 80 to 123.11 °C. The vapor fraction of lithium bromide solution is 7.82% at the generator outlet.

Subsystem II: Through XSQ and LNQ, the network backwater is heated from 65 to 78.22 °C. Also, the internal circulating water transfers the latent heat of flue gas from YQHRQ to ZFQ.

Subsystem III: The flue gas flows from the desulfurizing tower into YQHRQ. The temperature is lower than 50 °C, but the moisture content of flue gas is raised to saturation.

Subsystem IV: The flue gas is cooled to 46.81 °C. A part of vapor water is condensed into liquid water, so the vapor fraction is reduced by the internal circulating water. There is 15 tons of water which flows out from QYFLQ.

4.2. Analysis of Influencing Factors. As shown in Figure 6, it can be found that the outlet flue gas temperature of air preheating is 160 °C, and the energy flow is 130.02 MW. Approximately, 19.3% of the energy flow is used to drive the absorption heat pump, while the remaining part of the flow enters the wet desulfurization tower. When the flue gas passes through the desulfurization tower, it absorbs moisture, and hence the moisture content of flue gas reaches the saturation state. Subsequently, 11.2% of the latent heat in flue gas is used to become a low-temperature heat source; however, the energy flow of the other parts is drained into the environment.

When the composition of the flue gas is unchanged, there is a certain relationship between the flue gas pressure and the flue gas condensation temperature. Figure 7 represents the characteristics of saturated water vapor at different temperatures. As can be seen from Figure 7, the saturated vapor pressure and water vapor density decrease with the decrease in the flue gas temperature. Hence, the tail flue gas of the coal-fired thermal power plant is desulfurized by the wet method to remove sulfide. The flue gas temperature at the outlet of the desulfurization tower is relatively low. However, its water vapor content is saturated, and a considerable amount of low-grade latent heat of vaporization is discharged into the atmosphere

Table 5. Thermal Parameters at Each Critical Point in the ZCAHP System

subsystem	stream	substance	temperature (°C)	pressure (kPa)	flow ratio (t/h)	vapor fraction (%)
I	1	flue gas	150	96.45	1413.91	100
	2		100	96.45	1413.91	100
II	11	circulating water	45	101.325	1239.03	0
	12		37.19	101.325	1239.03	0
	5		refrigerant water	123.11	50	18.04
	9	80		50	18.04	0
	10	26.60		3.5	18.04	9.16
	13	40		3.5	18.04	100
	4	dilute solution		123.11	50	334.28
	18B		72.12	8.20	334.28	0
	23		72.13	49.20	334.28	0
	24		80	50	334.28	0
6	concentrated solution		123.11	50	316.24	0
15		118.62	50	316.24	0	
16		74.84	6	316.24	5.08	
21		hot water	65	101.325	2130.95	100
20			73.38	101.325	2130.95	100
8	78.22		101.325	2130.95	100	
IV	33	flue gas	46.81	96.45	1435.87	100
	30		49.39	96.45	1451.24	100
	31		46.81	96.45	1451.24	98.29
	34	condensate water	46.81	96.45	15.37	0

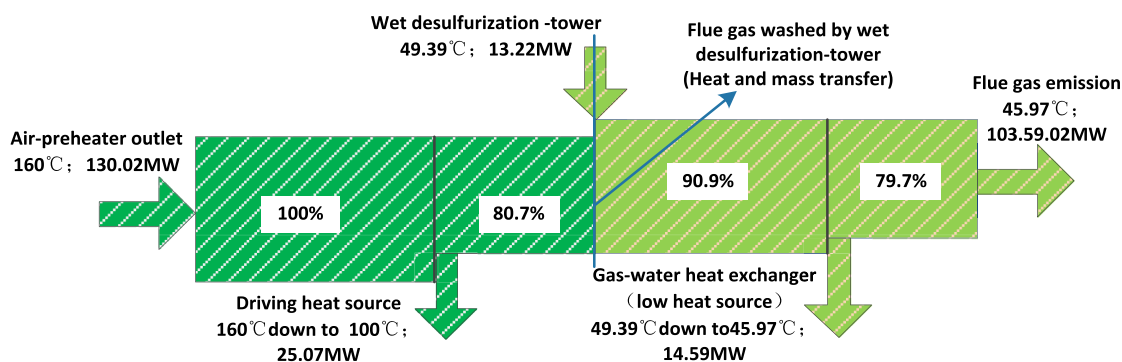


Figure 6. Energy flow under 160 °C of flue gas.

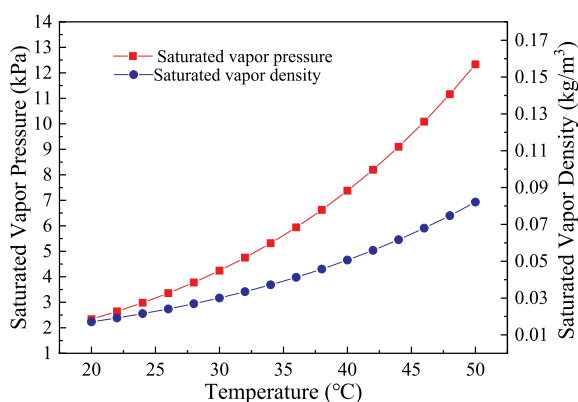


Figure 7. Effect of temperature change on saturated water vapor parameters.

with the flue gas. If the flue gas temperature can be further reduced, the waste heat and moisture can be effectively recovered. As shown in Figure 8, considering the example

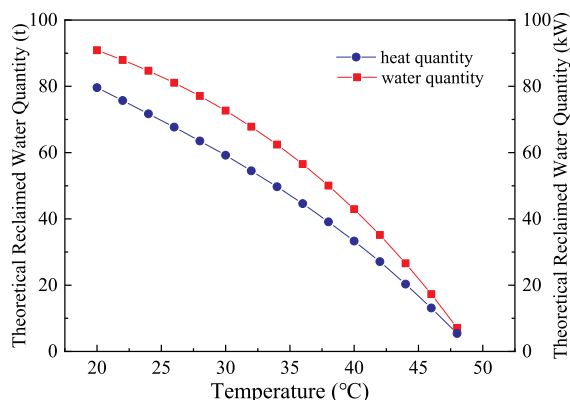


Figure 8. Effect of temperature change on the theoretical reclaimed water/heat quantity.

system, the flue gas temperature can be reduced. Reducing the temperature of flue gas leads to the condensation of some water vapor into liquid and releases the latent heat of vaporization. With the increase in the discharge temperature, the trend of the reclaimed water is increased. This is consistent with the variation trend of the partial pressure of saturated water vapor. However, the rate of change of theoretical heat recovery is comparatively consistent because the latent heat of vaporization of water vapor decreases with the decrease in temperature.

In Figure 9, the inlet temperature of flue gas decreases from 49.39 to 20 °C, and the temperature changes from 49.39 to 20

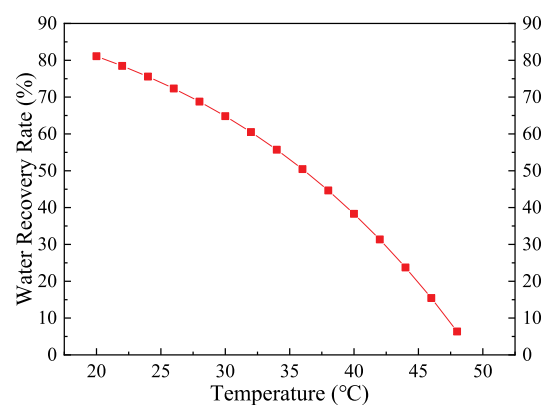


Figure 9. Effect of temperature change on the water recovery rate.

°C. The phenomenon shown in Figure 9 occurs, that is, the water recovery rate increases with the decrease of temperature, which can be explained by Figure 7. Because the saturated vapor pressure is different at different temperatures and the difference is not linear, with the decrease of temperature, the decrease rate of saturated vapor pressure slows down, that is, the moisture content of flue gas shows the same trend with the change of temperature, so the data curve as shown in Figure 9 is drawn. Figure 9 shows that if the recovery rate of water is 60%, the temperature of the flue gas must be reduced to 32 °C. As shown in Figure 10, from the heat exchange and water recovery in the system, the sum of heat of generator and

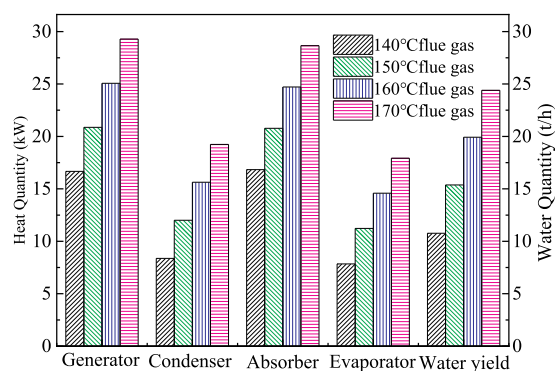


Figure 10. Heat exchange in different parts and recovery water quantity.

evaporator is approximately equal to the sum of heat of condenser and absorber. Especially, with the increase in the flue gas temperature, the amount of recovered water increased significantly because a higher flue gas temperature has a larger driving energy flow, as shown in Figure 10. It demonstrates the flue gas energy flow. It can be found that the flue gas temperature does not have a significant effect on the flue gas energy flow at the outlet of the desulfurization tower because the mass flow rate of dry flue gas is constant. Other energy flows increase linearly with temperature because the flue gas temperature is proportional to enthalpy. Compared with other energy flows, the driving energy flow is smaller. Because the driving heat source is the sensible heat of flue gas, the temperature of the flue gas decreases from 150 to 90 °C. However, there is a problem of energy flow mismatch that stipulates that a smaller driving energy flow cannot recover the latent heat of flue gas in large quantities and allows only for limited water recovery.

Due to the different working principle of the refrigerant, the performance coefficient of the absorption heat pump is lower than that of the compression heat pump. The effect of temperature change on the COP of lithium bromide absorption heat pump and the temperature of the hot water outlet is shown in Figures 11 and 12. When the mass flow rate

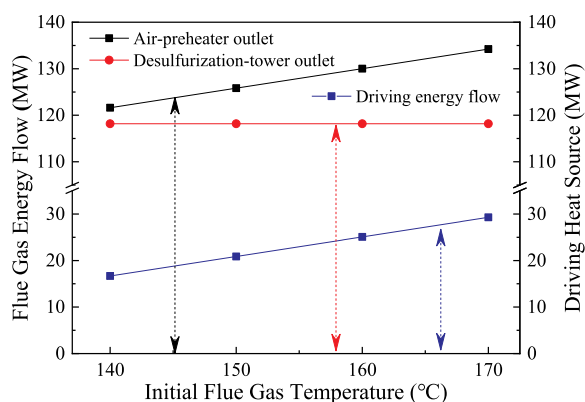


Figure 11. Effect of temperature change on energy flow.

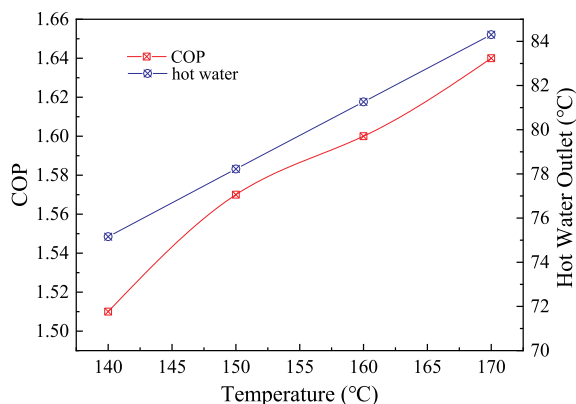


Figure 12. Effect of temperature change on the COP and the temperature of the hot water outlet.

of hot water is constant, the outlet water temperature increases linearly with the flue gas temperature. Because of the emphasis on energy conservation, the increased heat is reflected in the outlet temperature. Meanwhile, the COP is always greater than

1.5 and increases with the temperature of flue gas from the air preheater outlet. Because more water vapor is produced by more driving heat in the generator, a larger amount of condensation heat and absorption heat is released. This part of heat can be used to heat the condensate water or heat the supply network water.

4.3. Benefit Analysis of Energy Conservation. In this paper, a two-stage heat exchanger is installed at the tail of a coal-fired utility boiler to recover waste heat from flue gas. Figure 13 shows that the operation effect of the ZCAHP

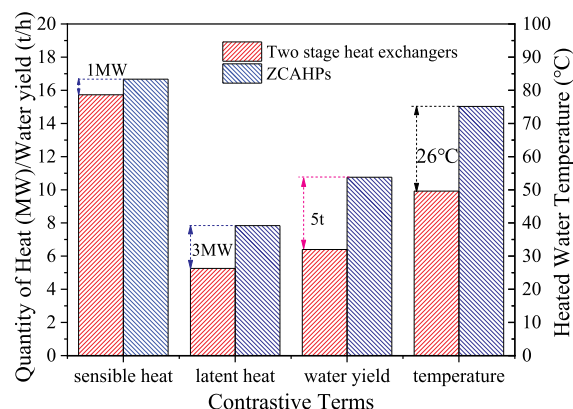


Figure 13. Comparisons of operation results in different systems.

system is better than the two-stage heat exchanger system in the reuse of waste heat and water recovery. Through the ZCAHP system, the recovery of waste heat increased by 4 MW, the recovery of water increased by 5 t/h, and the temperature of hot water heated by latent heat of flue gas increased by 26 °C.

Under design conditions, 20.86 MW flue gas sensitive heat and 11.23 MW flue gas latent heat can be recovered by the ZCAHP system. According to the utilization of 4354 h of thermal power equipment in China in 2021, 504.61 million MJ waste heats from the flue gas can be recovered by the ZCAHP system. That is equivalent to saving 17218.04 tons of standard coal per year. The air pollution of coal-fired power plants can be controlled significantly, and the emissions of major pollutants can be controlled effectively. Analysis of coal components with recovered waste heat by the ZCAHP system shows annual reduction of carbon dioxide of 39451.73 t, annual reduction of nitrogen oxide of 372.8, and annual reduction of sulfur dioxide of 39451.73 t. At the same time, 15.39 t/h of water is recovered and 67136.36 t/year of water from the flue gas is recovered. The absorption heat pump model RHP263 is used in the reference literature.²⁵ The initial investment of the ZCAHP system equipment is 15.21 million yuan. In 2021, the standard coal price was 1022 yuan/ton, and it can save 17.59 million yuan in fuel consumption throughout the year.²⁵ With reference to the tap water price of 4.1 yuan/ton, in the same year, it can save 0.275 million yuan per year. The payback period is 0.85 years. This recovery cycle only considers the investment cost of heat pump equipment but does not consider the operation cost.

5. CONCLUSIONS

This paper describes a fundamental study of the ZCAHP system. Based on a typical 330 MW coal-fired power plant, study of the operation parameters and thermodynamic analyses

were performed, and the following important conclusions were obtained.

- (1) This paper reveals the nature of the ZCAHP system, and a mathematical model has been established to quantitatively characterize the ZCAHP system. Subsystem I is used to recover the sensible heat of flue gas; subsystem II is used to recover the latent heat of flue gas; subsystem III is used to separate and recover the condensate moisture.
- (2) By applying the ZCAHP system, the temperature of flue gas that enters the desulfurization tower could be reduced from 150 to 100 °C when the sensible heat of flue gas was recovered by 20.86 MW; at the same time, the temperature of flue gas entering the chimney could be reduced from 49.39 to 46.81 °C when the latent heat of flue gas was recovered by 11.23 MW.
- (3) Compared with a two-stage heat exchanger system, the COP of the absorption heat pump increased up to 1.64. From the perspective of energy saving and emission reduction, water loss as condensate water discharge in flue gas is reduced by 24.4 t/h.
- (4) The available driving heat flow accounts for a small proportion. Proper increase in flue gas temperature at the outlet of the air preheater can improve latent heat and moisture recovery of flue gas. However, the mismatch between the driving energy flow and the low-temperature heat source is a considerable problem, and if this can be effectively solved, the effect of flue gas waste heat and water recovery will be significantly improved.

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Notes

The authors declare no competing financial interest.

NOMENCLATURE

m mass flow of flue gas or water (t/h)

Q heat exchange capacity (MW)

τ_1 sensible heat recovery rate

SUBSCRIPTS AND SUPERSSCRIPTS

'	desulfurization tower outlet
1	inlet
bu	burn
coa	coat
ai	air
ge	generator
fl	flue gas
ev	evaporator
con	condensate
me	medium temperature heat source
ZCAHP	zero-energy consumption absorption heat pump
COP	coefficient of performance
<i>h</i>	enthalpy of flue gas or water (kJ/t)
ξ	water recovery rate
τ_2	latent heat recovery rate
"	chimney entrance
2	outlet
re	recover
to	total water content
se	sensible heat
a-p	air preheater
la	latent heat
de	desulfurizing-tower
ab	absorber

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