

Efficiency of utilization of heat of moisture from exhaust gases of heat HRSG of CCGT

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Abstract. The paper discusses the technology of utilizing the heat of exhaust gas moisture from heat recovery steam gases (HRSG) of combined-cycle gas turbine (CCGT). Particular attention focused on the influence of the excess air factor on the trapping of the moisture of the exhaust gases, as in the HRSG of the CCGT its value varies over a wider range than in the steam boilers of the TPP. For the research, has been developed a mathematical model that allows to determine the volumes of combustion products and the amount of water vapor produced according to a given composition of the burned gas and determine the amount of moisture that will be obtained as a result of condensation at a given temperature of the flue gases at the outlet of the condensation heat exchanger (CHE). To calculate the efficiency of the HRSG taking into account the heat of condensation of moisture in the CHE an equation is derived.

1 Introduction

CCGT of the utilization type currently has the highest net efficiency in the generation of electricity, which at the most powerful and perfect CCGT 9.02.02 of GE Power has reached 63.7%. The working medium of the steam turbine unit of this CCGT is water. The ways to further increase the efficiency of the CCGT are given in following work [1]. This is an increase in the initial temperature in front of the gas turbine and a decrease in heat losses in the steam turbine cycle and HRSG. At the same time, a decrease in heat loss in HRSG is the simplest way.

The combustion of a hydrocarbon fuel, depending on the type of fuel in the exhaust gases is formed about 10-15% moisture vapor. To prevent condensation of this moisture in the flues and the chimney so that there is no corrosion and destruction of the equipment, the exhaust gases are withdrawn at a temperature above the dew point. In this case, the heat of condensation of water vapor is lost and the atmosphere is contaminated with them.

The technology of cooling off gases in boilers below the dew point using condensation heat recovery units is now recognized as one of the most energy efficient [2-6].

This technology is especially important for HRSG of CCGT, their efficiency is not more than 90% due to the low temperature of the gases entering the boiler. At the same

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time, HRSG of CCGT operate with an excess air factor α greater than 2, and the articles on this topic consider the operation of boilers with $\alpha < 2$. For cooling of flue gases in CHE, can be used low-boiling substances and can be obtained additional generation of electricity based on the Rankine organic cycle with an air condenser [7–10].

To evaluate the effect on the amount of moisture captured and on the efficiency of the HRSG fuel characteristics, the operating parameters of the flue gases and the air excess factor, a mathematical model is worked out for the operation of the HRSG with a CCGT.

2 Mathematical model of calculating the HRSG with CHE

The mathematical model of the HRSG with CHE represents a system of equations for calculating the parameters and indicators of its operation.

The initial data:

- gas composition;
- air moisture content d_{air} , kg/kg.dry;
- temperature t_0 , °C and pressure P_g , Pa exhaust gases at the input of the recovery boiler t_1 and t_2 ;
- coefficient of excess air in the HRSG α .

The following constants are used in the model:

Molar mass (kg/mol): water $\mu_{H_2O} = 18.016$; nitrogen $\mu_{N_2} = 28.013$; oxygen – $\mu_{O_2} = 32.0$; argon $\mu_{Ar} = 39.95$; carbon dioxide – $\mu_{CO_2} = 44.0$.

$R = 8314.41$ J/(mol·K) – universal gas constant;

Take volume fractions of elements of dry air: nitrogen $r_{dryN_2}=0.7812$; oxygen $r_{dryO_2}=0.2096$; argon $r_{dryAr}=0.0092$. Because of the low content, don't take into account the fraction of carbon dioxide. Molar mass of dry air: $\mu_{dry,air}=\mu_{N_2}r_{dryN_2}+\mu_{O_2}r_{dryO_2}+\mu_{Ar}r_{dryAr}=28.96$ kg/mol.

Ratio $\mu_{H_2O}/\mu_{dry,air}=0.622$.

Volume fraction of moist air: moisture $r_{mH_2O}=d_{air}/(0.622+d_{air})$; nitrogen $r_{mN_2}=0.622r_{dryN_2}/(0.622+d_{air})$; oxygen $r_{mO_2}=0.622r_{dryO_2}/(0.622+d_{air})$; argon $r_{mAr}=0.622r_{dryAr}/(0.622+d_{air})$.

2.1 Calculation of the composition of combustion products and it enthalpies at the input of the HRSG

Table 1. Equations for properties of combustion products at the input of the HRSG.

In- dex	Determined rate	Equation
1	Theoretical volume of air required for complete combustion of fuel under normal conditions	$V_0=0.0476(0.5CO+0.5H_2+1.5H_2S+2CH_4+3.5C_2H_6+5C_3H_8+6.5C_4H_{10}-O_2)$, nm^3/nm^3
2	Theoretical volume of nitrogen in the combustion of 1 nm^3 of fuel	$V_{0,N_2} = 0.79V_0 + 0.01O_2$, nm^3/nm^3
3	Theoretical volume of nitrogen in the combustion of 1 nm^3 of fuel	$V_{0,RO_2} = 0.01(CO+H_2S+CH_4+2C_2H_6+3C_3H_8+4C_4H_{10})$, nm^3/nm^3
4	Theoretical volume of H ₂ O in the combustion of 1 nm^3 of fuel	$V_{0,H_2O}=0.01 \cdot (H_2S+H_2+2CH_4+3C_2H_6+4C_3H_8+5C_4H_{10})+1.61V_0$, nm^3/nm^3
5	Theoretical volume of gases during combustion of 1 nm^3 of fuel	$V_g = V_{0,N_2} + V_{0,RO_2} + V_{0,H_2O} + (\alpha-1)V_0$, nm^3/nm^3
6	Actual volume of H ₂ O in the combustion of 1 nm^3 of fuel	$V_{H_2O} = V_{0,H_2O} + 0.0161(\alpha-1)V_0$, nm^3/nm^3
7	Volume of dry gases during combus-	$V_{dry,g.} = V_g - V_{H_2O}$, nm^3/nm^3

	tion of 1 nm ³ of fuel	
8	Volume fractions of the combustion products at the entrance HRSG exclude their content in excess air	$r_{0,N2} = V_{0,N2}/V_g; r_{0,RO2} = V_{0,RO2}/V_g; r_{0,H2O} = V_{0,H2O}/V_g$
9	Volume fraction of air in the combustion products at the input of the HRSG	$r_{0,Air} = 1 - r_{0,N2} - r_{0,RO2} - r_{0,H2O}$
10	Volume fractions of the combustion products at the entrance with the HRSG content of excess air:	$r_{1,N2} = r_{0,N2} + r_{mN2}r_{0,Air}; r_{1,RO2} = r_{0,RO2}; r_{1,O2} = r_{mO2}r_{0,Air};$ $r_{1,Ar} = r_{mAr}r_{0,m}; r_{1,H2O} = r_{0,H2O} + r_{mH2O}r_{0,Air}$

The enthalpy of flue gases at the input of the HRSG is determined from the proportions of combustion products obtained in (10) and the set temperature t_0 and the pressure of the P_g using the function of the REFPROP program [11]

$$h_0 = \text{enthalpy}(\text{"nitrogen";}; r_{1,N2}; \text{"CO2";}; r_{1,RO2}; \text{"oxygen";}; r_{1,O2}; \text{"argon";}; r_{1,Ar}; \text{"water";}; r_{1,H2O}; \text{"TP";}; \text{"SI";}; t_0+273,15; P_g). \tag{11}$$

2.2 Calculation of the composition of the combustion products and it enthalpies at the input and outlet CHE

Table 2. Equations for properties of combustion products at the input and outlet of CHE.

Index	Determined rate	Equation
12	Saturation pressure of water vapor, Pa	$P_{S1} = f(t_1), P_{S2} = f(t_2)$
13	Partial water vapor pressure, Pa	$P_{1,H2O} = P_g r_{1,H2O}, P_{2,H2O} = P_g r_{2,H2O}$
14	Dewpoint temperature, °C	$t_{dp1} = f(P_{1,H2O}), t_{dp2} = f(P_{2,H2O})$
15	Relative humidity water vapor, %	$\phi_1 = 100P_{1,H2O}/P_{S1}, \phi_2 = 100P_{2,H2O}/P_{S2}$
16	Volume fraction of dry gases	$r_{1,dry,g} = 1 - r_{1,H2O}, r_{2,dry,g} = 1 - r_{2,H2O}$
17	Partial pressure of dry gases, Pa	$P_{1,dry,g} = P_g r_{1,dry,g}, P_{2,dry,g} = P_g r_{2,dry,g}$
18	Molar mass of dry flue gases, kg/mol	$\mu_{1,dry,g} = \mu_{N2}r_{1,N2} + \mu_{O2}r_{1,O2} + \mu_{CO2}r_{1,CO2} + \mu_{Ar}r_{1,Ar};$ $\mu_{2,dry,g} = \mu_{N2}r_{2,N2} + \mu_{O2}r_{2,O2} + \mu_{CO2}r_{2,CO2} + \mu_{Ar}r_{2,Ar}$
19	Gas constant of dry flue gases, J/(kg·K)	$R_{1,dry,g} = R/\mu_{1,dry,g}, R_{2,dry,g} = R/\mu_{2,dry,g}$
20	Coefficient	$K_{d1} = R_{1,dry,g}/R_{H2O}, K_{d2} = R_{2,dry,g}/R_{H2O}$
21	Flue gas moisture content, kg/kg.dry	$d_1 = K_{d1}P_{1,H2O}/(P_g - P_{1,H2O}), d_2 = K_{d2}P_{2,H2O}/(P_g - P_{2,H2O})$
22	Volume fraction of water vapor at the outlet of the CHE	$r_{2,H2O} = r_{1,H2O} - \Delta d/(K_d + \Delta d)$
23	Volumetric fractions of elements of dry flue gases at the outlet of CHE	$r_{2,i} = r_{1,i}K_d/(K_d + \Delta d)$
24	Enthalpy of flue gases at the inlet of the CHE, kJ/kg	$h_1 = \text{enthalpy}(\text{"nitrogen";}; r_{1,N2}; \text{"CO2";}; r_{1,RO2}; \text{"oxygen";}; r_{1,O2}; \text{"argon";}; r_{1,Ar}; \text{"water";}; r_{1,H2O}; \text{"TP";}; \text{"SI";}; t_1+273,15; P_g)$
25	Drop of moisture content in the CHE, kg/kg.dry	$\Delta d = d_2 - d_1$
26	Enthalpy of flue gases at the outlet of the CHE, kJ/kg	$h_2 = \text{enthalpy}(\text{"nitrogen";}; r_{2,N2}; \text{"CO2";}; r_{2,RO2}; \text{"oxygen";}; r_{2,O2}; \text{"argon";}; r_{2,Ar}; \text{"water";}; r_{2,H2O}; \text{"TP";}; \text{"SI";}; t_2+273,15; P_g)$
27	Enthalpy of the exhaust gases at	$h_{15,1} = \text{enthalpy}(\text{"nitrogen";}; r_{1,N2}; \text{"CO2";};$

	a temperature of 15°C in the HRSG without CHE,kJ/kg	$r_{1,RO2}$; "oxygen"; $r_{1,O2}$; "argon"; $r_{1,Air}$; "water"; $r_{1,H2O}$; "TP"; "SI"; 15+273,15; P_g).
28	Enthalpy of the exhaust gases at a temperature of 15°C in the HRSG with CHE,kJ/kg	$h_{15.2}$ = enthalpy("nitrogen"; $r_{2,N2}$; "CO2"; $r_{2,RO2}$; "oxygen"; $r_{2,O2}$; "argon"; $r_{2,Air}$; "water"; $r_{2,H2O}$; "TP"; "SI"; 15+273,15; P_g).
29	Efficiency HRSG without CHE	$\eta_{HRSG.1} = (h_0 - h_1) / (h_0 - h_{15.1})$
30	Efficiency HRSG with CHE	$\eta_{HRSG.2} = (h_0 - h_2) / (h_0 - h_{15.2})$
31	Incrementation of efficiency HRSG	$\Delta\eta_{HRSG} = \eta_{HRSG.2} - \eta_{HRSG.1}$

The model is implemented by the program in the Excel package with the calculation of the parameters of water, fuel and flue gases according to the functions of the REFPROP base [9].

3 Results and analysis

With this program, the calculations were carried out with the following input data:
 Composition of gas fuel, %: CH₄ = 98.9; C₂H₆ = 0.94; C₃H₈ = 0.08; C₄H₁₀ = 0.08.
 Moisture of air d_{air} = 0.01 kg/kg.dry.
 The temperature of the gases at the input of the HRSG t_0 = 550°C.
 The gas pressure in HRSG P_g = 10100 Pa.
 The temperature of flue gas at the input of the CHE t_1 = 100°C.

Table 3. Summary.

Temperatur e, °C; r, kJ/kg	Properties	α						
		1	1.5	2	2.5	3	3.5	4
$t_0 = 550$	h_0 , kJ/kg	1258.6	1145.9	1087.4	1051.6	1027.4	1010.0	996.9
$t_1 = 100$	h_1 , kJ/kg	718.2	623.8	574.8	544.8	524.6	510.0	499.0
	d_1 , g/kg.dry	151.5	106.3	84.3	71.3	62.7	56.5	52.0
	t_{dp1} , °C	60.4	54.0	49.8	46.8	44.5	42.7	41.2
	ϕ , %	20.0	14.8	12.1	10.4	9.2	8.4	7.7
	$h_{15.1}$, kJ/kg	622.9	531.1	483.5	454.4	434.7	420.5	409.8
	$\eta_{HRSG.1}$, %	85.0	84.9	84.9	84.9	84.8	84.8	84.8
$t_2 = 50$; $r = 2382$	h_2 , kJ/kg	509.9	517.4	522.7	526.5	529.2	531.3	532.9
	Δd , g/kg.dry	67.7	21.6	-0.8	-14.1	-22.9	-29.2	-33.9
	$h_{15.2}$, kJ/kg	472.6	479.9	485.1	488.7	491.4	493.4	494.9
	$\eta_{HRSG.2}$, %	95.3	94.4	93.7	93.3	92.9	92.7	92.4
	$\Delta\eta_{HRSG}$, %	10.3	9.5	8.9	8.4	8.1	7.8	7.6
$t_2 = 40$; $r = 2406$	h_2 , kJ/kg	432.5	428.9	428.0	427.7	427.7	427.7	427.8
	Δd , g/kg.dry	104.0	58.4	36.1	22.9	14.2	8.0	3.4
	$h_{15.2}$, kJ/kg	406.6	402.8	401.9	401.6	401.5	401.6	401.6
	$\eta_{HRSG.2}$, %	96.96	96.50	96.19	95.98	95.82	95.70	95.60
	$\Delta\eta_{HRSG}$, %	11.9	11.6	11.3	11.1	11.0	10.9	10.8

$t_2 = 30;$ $r = 2430$	$h_2, \text{kJ/kg}$	387.7	378.5	374.4	372.2	370.7	369.8	369.1
	$\Delta d, \text{g/kg.dry}$	125.1	79.6	57.5	44.4	35.7	29.5	24.9
	$h_{15,2}, \text{kJ/kg}$	372.4	363.1	359.0	356.8	355.3	354.4	353.6
	$\eta_{\text{HRSG},2}, \%$	98.3	98.0	97.9	97.8	97.7	97.6	97.6
	$\Delta\eta_{\text{HRSG}}, \%$	13.3	13.1	13.0	12.9	12.9	12.8	12.8
$t_2 = 20;$ $r = 2454$	$h_2, \text{kJ/kg}$	359.0	346.8	341.0	337.7	335.6	334.1	332.9
	$\Delta d, \text{g/kg.dry}$	137.2	91.9	69.8	56.7	48.1	41.9	37.4
	$h_{15,2}, \text{kJ/kg}$	353.9	341.7	336.0	332.6	330.5	329.0	327.8
	$\eta_{\text{HRSG},2}, \%$	99.4	99.4	99.3	99.3	99.3	99.3	99.2
	$\Delta\eta_{\text{HRSG}}, \%$	14.4	14.4	14.4	14.4	14.4	14.4	14.4

Figure 1 shows the dependence of the increase in the efficiency of the HRSG on α and t_2 , and in Fig. 2 - dependence of the decrease in moisture content in the CHE from α and t_2 .

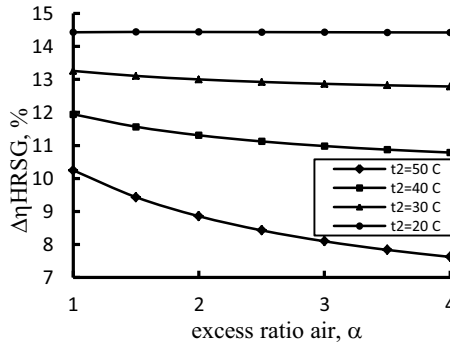


Fig.1. Dependence of the efficiency gains of HRSG.

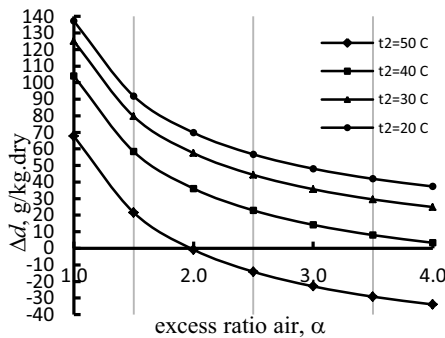


Fig. 2 –Dependence of decrease in moisture content in CHE.

The calculations based on the model showed that, depending on the temperature of the gases emerging from the CHE, the increase in the efficiency of the HRSG at the gas temperature at the outlet of the CHE 20 °C is 14.4% and is independent of the air excess ratio α . At a temperature of 30°C, the efficiency gain drops slightly with an increase in the excess air coefficient from 13.3% at $\alpha = 1$ to 12.8% for $\alpha = 4$. At a temperature of 40°C, the efficiency gain decreases from 11.8% at $\alpha = 1$ to 10.8% for $\alpha = 4$. At a temperature of 50°C, the increase in efficiency gain decreases from 10.2% at $\alpha = 1$ to 7.6% at $\alpha = 4$. A strong drop in efficiency at a temperature of 50 °C is due to the fact that for $\alpha > 1.9$ the

temperature of the outgoing gases becomes higher than the dew point, so if the contact point is of the contact type, then there is no condensation of moisture, but evaporation.

References

1. A. Gabdullina, N. Galashov, S. Tsbuisky, D. Melnikov, I. Asanov, A. Kiselev, Promising Direction of Perfection of the Utilization Combine Cycle Gas Turbine Units, **91**, 01004 (2016)
2. D.V. Gvozdyakov, V.E. Gubin, Chemical and Petroleum Engineering, **51**, 201 (2015)
3. S.A. Yankovsky, V.E. Gubin, A.A. Tolokolnikov, A.V. Zenkov, Strategic Technology (IFOST), 299 (2016)
4. S. Xiaojun, C. Defu, A. Brian, G. Jianmin, Int. J. Heat Mass Transfer, **54**, 606 (2011)
5. K. Hwang, C. Song, K. Saito, S. Kawai. Applied Thermal Engineering, **30**, 2730 (2010)
6. N. Galashov, S. Tsibulskii, A. Matveev, V. Masjuk, EPJ Web Conf. **110**, 01019 (2016)
7. Hazell D., *Modeling and Optimization of Condensing Heat Exchangers for Cooling Boiler Flue Gas* (Ph.D. Dissertation, Lehigh University, 2011)
8. N. Galashov, S. Tsibulskiy, A. Kiselev, MATEC Web Conf. **72**, 01029 (2016)
9. N. Galashov, S. Tsibulskiy, T. Serova, EPJ Web Conf. **110**, 01068 (2016)
10. E. Lemmon, M. Huber, M. McLinden, REFPROP, standard reference database 23, version 8.0, National Institute of Standard and Technology (2007)