Int.J. Thermodynamics,
Vol.6, (No.4), pp.143-147, December-2003

ISSN 1301-9724

Energy and economic effects of the steam-and-gas heat-and-power plant cooperating with the low-exergy heating system

Jan SZARGUT
Silesian University of Technology
Institute of Thermal Technology
Konarskiego 22, 44-100 Gliwice, Poland
Tel.: (+4832)2371661, Fax: (+4832)2372872
E-mail: itc@itc.polsl.pl

Abstract

Technical conditions for the application of a low-exergy (low temperature) heating system of buildings have been discussed. Cumulative economy of the chemical energy expected after introducing the steam-and-gas HP plant fed with natural gas has been analyzed. Approximate determination of the production cost of the useful heat in the considered system has been performed. The influence of the sell price or avoided purchase cost of the electricity has been investigated.

Key words: building heating, exergy losses, cogeneration, steam-and-gas heat-and-power plant

1. Introduction

In the systems of heating buildings three components of the exergy losses appear:

1) Exergy losses in the source of useful heat (together with the exergy losses burdening the delivery of the energy carrier feeding the source of useful heat),

2) Exergy losses connected with the transmission of useful heat to the heated rooms,

3) Exergy losses caused by the irreversible heat flow from the heated rooms to the environment, through the external walls of the building.

The third component of the exergy losses is not analyzed in the present paper. This loss might be reduced by the improvement of the thermal insulation of the considered buildings. The second component may be reduced by introducing a low-exergy (low-temperature) internal installation (floor heating, wall heating, low temperature radiators). The application of such type of the internal installation is, however, purposeful only in such case when it can simultaneously reduce the exergy losses in the heat source (Szargut, 2001)

In many cases the reduction of the second component of exergy losses causes an increase of exergy losses in the heat source. For example, the low temperature heating system could not ensure any energy advantages, if the water boiler plays the role of a source of useful heat. The mean temperature of water within the boiler influences very slightly its efficiency (Skorek and Kruppa, 2001). Also a heat and power plant equipped with an internal combustion engine (ICE) or a gas turbine could not ensure any positive energy effects, because in such HP-plant the network heat could be produced only in the cooling system of ICE and from the stream of combustion gases rejected to the environment. In both cases the amount of the produced useful heat only slightly depends on the mean temperature of the network water. Considerable positive energy effects could be attained when applying the heat pump or the steam- or gas-and-steam HP-plant. The low-exergy heating systems are recently very popular. The International Energy Agency elaborated a program of "Energy Conservation in Buildings" and initiated the edition of a bulletin LOWEX NEWS (2000, 2001). Also scientific conferences devoted to the mentioned heating systems have been organized, for example, the 50-th Executive Committee Meeting in Cracow (November 7, 2001).

2. Technical conditions for the introduction of Low-ex heating systems

The introduction of a Low-Ex heating system would be impossible in large existing systems, because it would require new internal installations by all the heat consumers. The introduction of a Low-Ex system would be possible in new systems built simultaneously with the heating network. The Low-Ex system requires an increased flow rate of heating water, because the temperature difference between the hot- and return-water are small. The introduction of the considered system would be most easy in large public buildings (hospitals, hotels, schools, administration buildings).

Because of the ecological requirements, the application of liquid or gaseous fuels would be necessary in these cases. Therefore, the application of a gas turbine would be preferable, but because of a high price of fuel, the system should be supplemented with the steam turbine, fed from the heat recovery boiler of the gas turbine.

The pressure of the heating steam would be considerably lower than the atmospheric one. Hence, the steam turbine would operate similarly to a condensation turbine with a worsened vacuum in the condenser.

The qualitative regulation system would be not convenient in the low-ex system. Because of the small temperature difference between the network water and the heated rooms, the interval of the temperature changes of the network water would be very small too, and the regulation of the heat output would be most convenient by means of the changes of the flow rate of the network water. In the low-ex system also the central delivery of domestic hot water would be difficult because of the required relatively high temperature of that water.

3. Cumulative economy of chemical energy

Figure 1 presents the scheme of a steam-and-gas HP plant cooperating with the gas turbine. The preliminary preheating of the network water proceeds in the waste-heat boiler of the gas turbine. It has been assumed that the final temperature of the combustion gases rejected to the environment is not lower than their dew point (whose value is about 40^{o}C). The preliminary preheating of the network water improves the energy efficiency of the heat recovery boiler.

The preheating of air before the compressor (Figure 1) would operate in the case of ambient temperature lower than 0oC, to avoid the icing of the compressor inlet (Gebert et al., 1998). Approximate calculations indicate a very small consumption of heat for this purpose.

Taking into account a small power of the considered HP-plant, only one stage of evaporation has been assumed. Figure 2 presents a temperature distribution in the heat recovery boiler. The cumulative economy of the chemical energy attainable in the total system thanks to the cogeneration may be expressed as:

$$-\Delta \dot{E}^*_{ch} = \frac{\dot{E}_{el\,g} + \dot{E}_{el\,s}}{\eta^*_{Eel}} + \frac{\dot{Q}_u}{\eta^*_{Eb}} - \frac{\dot{E}_{ch\,F}}{\eta^*_F} = \frac{\dot{E}_{el\,s}}{\eta^*_{Eel}} + \dot{E}_{ch\,F}\left(\frac{\eta_{Eg}}{\eta^*_{Eel}} - \frac{1}{\eta^*_F}\right) + \frac{\dot{Q}_u}{\eta^*_{Eb}} \qquad (1)$$

where:

$\dot{E}_{el\,g}, \dot{E}_{el\,s}$ electric power produced by the gas turbine and steam turbine

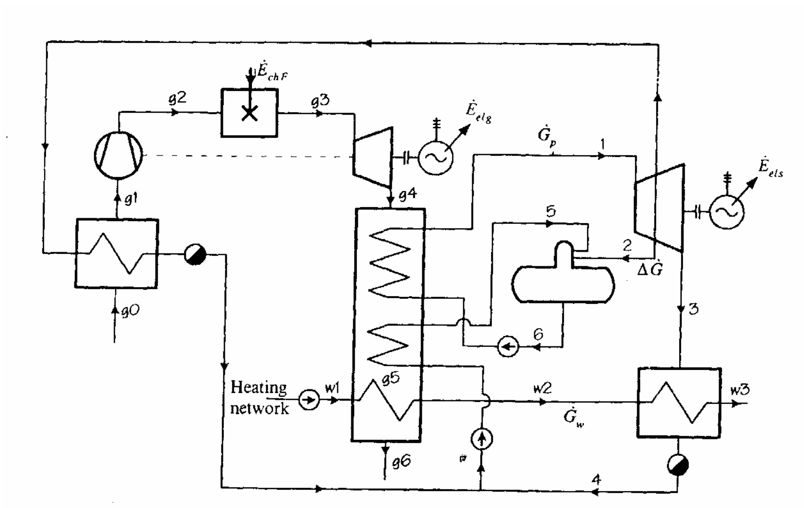

Figure 1. Scheme of the steam-and-gas HP plant; 1-6 states of steam and condensate; g0-g6 states of working fluid in the gas turbine; w1-w3 states of network water, $\dot{G}_p, \dot{G}_w$ - flow rate of live steam and network water

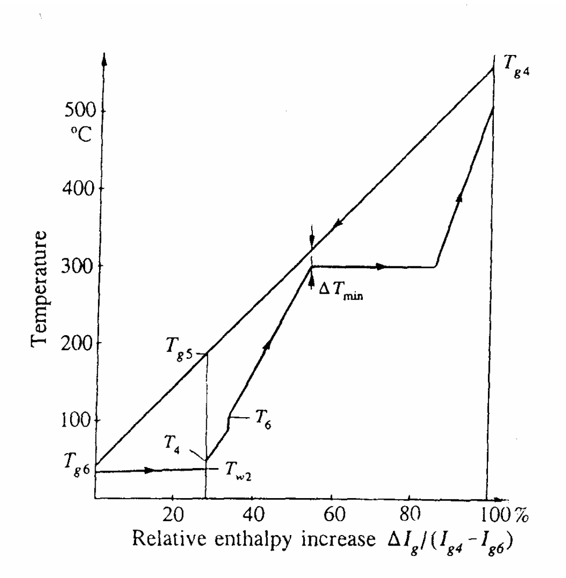

Figure 2. Temperature distribution in the heat recovery boiler of the gas turbine

$\dot{Q}_u$ heat stream delivered to the heated building

$\eta_{E\,g}$ energy efficiency of the separately operating gas turbine

$\eta^*_{E\,el}$ cumulative energy efficiency of the delivery of electricity from a professional power plant

$\eta^*_{E\,b}$ cumulative energy efficiency of the replaced water boiler

η^*_F cumulative energy efficiency of the delivery of fuel to the considered HP plant.

The cumulative energy efficiency takes into account not only the immediate energy consumption in the considered link, but also the energy consumption in preceding links, for example at fuel extraction and transportation.

In equation (1) the energy consumption in the air preheater in front of the compressor has been neglected. Using the energy balance of the degasifier and of the hot part of the heat recovery boiler, the electricity production in the steam turbine set may be determined:

$$\dot{E}_{els} = \dot{Q}_u\, \eta_{mes} \frac{T_{w3} - T_{w2}}{T_{w3} - T_{w1}} U_1 \tag{2}$$

where:

T_{w1}, T_{w2}, T_{w3} temperature values of the network water (Figure 1)

$\eta_{me\,s}$ electro-mechanical efficiency of the steam turbine set

$$U_1 = \frac{(i_2 - i_5)(i_1 - i_3) - (i_6 - i_5)(i_2 - i_3)}{(i_3 - i_4)(i_2 - i_6)} \tag{3}$$

Energy balance of the system comprising the gas turbine leads to the following equation:

$$\dot{E}_{el\,g} = \dot{Q}_u \frac{\eta_{me\,g}\eta_{E\,g}}{(\eta_{me\,g} - \eta_{E\,g})\,\eta_{E\,wb}} \left(\frac{T_{w3} - T_{w2}}{T_{w3} - T_{w1}} U_1 + 1 \right) \tag{4}$$

$\eta_{me\,g}$ equivalent electro-mechanical efficiency of the gas turbine set

$\eta_{E\,wb}$ energy efficiency of the heat recovery boiler (steam generator).

$$\eta_{E\,wb} = \frac{T_{g4} - T_{g6}}{T_{g4} - T_a} \tag{5}$$

T_a ambient temperature.

The cumulative economy of chemical energy depends on the temperature T_{w2} (Figure 2). Exemplary calculations indicate that a heightening of that temperature decreases the cumulative economy of chemical energy, because it leads to a decrease of the electricity production. Assumed data for exemplary calculations are cited in TABLE I.

4. Cost of the production of network heat

The unit cost of the production of network heat can be expressed as follows:

$$k_h = \frac{1}{\dot{Q}_u}\left[\frac{\sigma}{\tau_n}(\dot{E}_{el\,g}\, j_g + \dot{E}_{el\,s}\, j_s) + \frac{\dot{E}_{el\,g}}{\eta_{E\,g}} k_{ch\,F} - (\dot{E}_{el\,g} + \dot{E}_{el\,s})\, k_{el} \right] + \frac{\sigma}{\tau_n} j_{wp} \tag{6}$$

σ annual rate of the fixed costs

τ_n annual utilization time of the nominal thermal power.

j_g, j_s investment expenditure for the gas turbine set together with the heat recovery boiler and for the steam turbine set per unit of the electric power

j_{wp} investment expenditure for the heater of the network water per unit of the thermal power

k_{el} sale price of electricity or its avoided purchase cost

Using equations (2) and (4), equation (6) may be presented in the form:

$$k_h = \left(\frac{\sigma}{\tau_n} j_g + \frac{k_{ch\,F}}{\eta_{E\,g}} - k_{el} \right) \frac{\eta_{E\,g}\,\eta_{me\,g}}{\eta_{E\,wb}\,(\eta_{me\,g} - \eta_{E\,g})} \times$$
$$\times \left(\frac{T_{w3} - T_{w2}}{T_{w3} - T_{w1}} U_1 + 1 \right) + \left(\frac{\sigma}{\tau_n} j_s - k_{el} \right) \times \quad (7)$$
$$\times \eta_{me\,s} \frac{T_{w3} - T_{w2}}{T_{w3} - T_{w1}} U_1 + \frac{\sigma}{\tau_n} j_{wp}$$

Data for exemplary calculations are cited in TABLE II, and the results in TABLE III.

5. Conclusions

The cost of heat production depends considerably on the sale price or avoided cost of electricity purchase. When this price is too low (e.g. 36 $/MWh), the cost of heat production can be higher than in classical system. Therefore, the HP-plant should operate and produce electricity mainly in the peak hours of the electricity demand, when the price of electricity is very high.

Shifting of some part of heat demand on the preliminary preheater located in the heat recovery boiler of the gas turbine, improves the efficiency of the boiler but simultaneously increases the investment expenditures of this boiler.

The avoided purchase cost of electricity would be considerably higher than the sale price if the produced electricity were used totally for own needs. The purchase price comprises a relatively high transmission fee, which would be very small for the own consumer.

The cost of heat production could be even negative in that case. This would allow to use some part of the attained financial income for the investment expenditures of the internal installation. It is worth remembering, that the internal installation is very expensive in the considered conditions.

Acknowledgement

The investigations have been sponsored by the Polish Committee of Scientific Research.

TABLE I. DATA FOR EXEMPLARY CALCULATIONS OF THE STEAM-AND-GAS HP PLANT

Symbol	Value	Symbol	Value
T_1, p_1, i_1	510 °C, 9 MPa, 3409.7 kJ/kg	T_{w1}, T_{w3}, T_a	30, 40, 2 °C
$\eta_{i\,1\text{-}2}$, $\eta_{i\,2\text{-}3}$	0.85	U_1	0.529
p_2, i_2	0.125 MPa, 2602.1 kJ/kg	$\eta_{me\,s}$, $\eta_{me\,g}$	0.98 , 0.95
p_3, i_3	0.013 MPa, 2317.6 kJ/kg	$\eta_{E\,g}$	0.354
T_4, i_4	50 °C, 209.3 kJ/kg	$\eta^*_{E\,el}$	0.31
T_5, i_5	90 °C, 377.0 kJ/kg	$\eta^*_{E\,wb}$	0.83
T_6, i_6	105 °C, 435.8 kJ/kg	η^*_F	0.98
T_{g3}, T_{g4}, T_{g5}	1200, 560, 190 °C		

TABLE II. DATA FOR THE ECONOMIC CALCULATIONS OF A STEAM AND GAS HP PLANT

Symbol	Value	Symbol	Value
σ	0.12 1/a	$k_{ch\,F}$	3.6 $/GJ
j_g, j_s	715, 430 $/kW	k_{el}	36, 48, 60 $/MWh
j_{wp}	70 $/kW	τ_n	3400 h/a

TABLE III. RESULTS OF EXEMPLARY CALCULATIONS OF THE PRODUCTION COST OF USEFUL HEAT *

Tempera- -ture T_{w2} °C	**Ratio** $\dot{E}_{el\,s} / \dot{Q}_u$	**Temperature of outlet combustion gases** T_{g6} °C	**Energy efficiency of a heat recovery boiler** $\eta_{E\,wb}$	**Specific cost of heat production** k_h \$/GJ — sale price of electricity k_{el} \$/MWh: 36	48	60
30	0.518	190	0.663	7.0	1.0	-4.8
31	0.466	162.9	0.712	6.4	0.98	-4.4
32	0.413	129.1	0.772	5.7	0.95	-3.9
33	0.363	85.6	0.850	5.1	0.90	-3.2
33,5	0.337	58.8	0.898	4.8	0.88	-3.0

* *Calculations performed by MSc Rafał Kruppa.*

Nomenclature

$\dot{E}$	flow rate of energy [W]
$\dot{G}$	flow rate of the fluid [kg/s]
I	enthalpy [J]
i	specific enthalpy [J/kg]
j	incremental investment cost [\$/unit]
k	specific cost of energy [\$/J]
p	pressure [Pa]
$\dot{Q}$	flow rate of heat [W]
T	temperature [K]
η	efficiency
σ	annual rate of fixed costs [1/year]
τ	time length of operation [h / a]

Subscripts

a	ambient
b	water boiler
ch	chemical energy
E	related to energy
el	electricity, professional power plant
F	fuel
g	gas turbine
h	heat
me	electro-mechanical
n	nominal
s	steam turbine
u	useful
w	network water
wb	heat recovery boiler
wp	network water preheater

Superscripts

*cumulative quantity

Abbreviations

HP heat-and-power plant

ICE internal combustion engine

References

Gebert, von H., Rosner, G., and Markmann, D., 1998, *Betriebserfahrungen mit dem Kombi-Kraftwerk HKW Mitte, Berlin*. VGB Kraftwerkstechnik Nr 7, pp. 31-36.

International Energy Agency, 2000 (No.1), 2001 (No.2, No.3 and No.4), “Low-Ex News Bulletin”, *Energy Conservation in Buildings and Community Systems Programme*, Annex.37 working group, Finland.

Skorek J., Kruppa R., 2001, “Analysis of Exergy Losses in Domestic Heating Systems”, *Energy Conservation in Buildings and Community Systems*, 50. Executive Committee Meeting, Cracow, pp.81-89

Szargut J., 2001, “Low-exergy heating systems— when can they be profitable”, *Energy Conservation in Buildings and Community Systems*, 50.Executive Committee Meeting. Cracow, pp.75-88