Int.J. Applied Thermodynamics, ISSN 1301-9724
Vol.2, (No.1), pp. 1-4, March-1999

Energy and Ecological Effects of the Primary Gas-Turbine Supplementing a Coal-Fired Power Plant

Jan SZARGUT
Institute of Thermal Technology
Technical University of Silesia
Konarskiego 22, 44 100 Gliwice, Poland
Phone: (4832)237 16 61, Fax: (4832)237 28 72
E-mail: itc@itc.isc.plsl.gliwice.pl

Abstract

Gas turbine fed with natural gas, introduced as a primary link of the coal-fired power plant for preheating the feed water, ensures positive energy and ecological effects. The energy effect has been expressed by means of the incremental energy efficiency, defined as the ratio of the increase of power to the chemical energy of the consumed gas. The reduction of CO_2 emission has been also characterized by means of the incremental index. Formulae have been derived and numerical examples included.

Key words: gas turbine, combined power plant.

1. Steam Power Plant with a Primary Gas Turbine

The simplest possibility of introduction of gas turbine into the scheme of the coal-fired power plant is presented in *Figure 1*. The combustion gases flowing out from the gas turbine are used for preheating the feed water entering the coal-fired boiler of the steam power plant. The regenerative bleeds of the steam turbine are partially switched off.

The comparison of the power plant before and after the introduction of the primary gas turbine has been made at constant consumption of coal. This assumption differs from that made by Szargut (1998) and simplifies the formulae.

At constant consumption of coal switching off the regenerative feed water pre-heater decreases slightly the flow rate of live steam (because after switching off the high pressure bleed the ratio of the secondarily superheated steam to the live steam becomes greater) and increases the flow rate of steam in the low pressure part of the turbine. This flow rate may be limited by the size of the flow apparatus. Such a limitation may require a decrease in the flow rate of the live steam. The mentioned limitation does not influence the energy efficiency, because the proportion of flow rates in particular points of the system remains constant. The limitation of flow rate should be taken into account only when calculating the economical effects. Therefore further considerations are made assuming constant consumption of coal. In this case the switching off of the previously operating regenerative pre-heaters increases the power of the steam turbine.

2. Incremental Energy Efficiency of the Primary Gas Turbine

The introduction of the primary gas turbine increases the energy efficiency of the entire power plant, but the positive energy effect can be better characterized by means of the incremental energy efficiency, defined as the ratio of the increase of power of the plant to the consumption of chemical energy of gas fuel (Szargut and SzlHk 1993):

$$\eta_\Delta = \frac{N_g + \Delta N_s}{\dot{E}_{ch\,g}} = \eta_{E\,g} + \frac{\Delta N_s}{\dot{E}_{ch\,g}} = \\ = \eta_{Eg} + \frac{N_s + \Delta N_s}{\dot{E}_{ch\,g}} - \beta \frac{N_s}{\dot{E}_{ch\,s}} \tag{1}$$

where,

N_g: electrical power of the gas turbine system,

N_s ,ΔN_s: initial electrical power of the steam turbine and its increase after introduction of the primary gas turbine,

$\dot{E}_{ch\,g}$, $\dot{E}_{ch\,s}$: consumption of chemical energy of gas fuel and of coal per time unit,

$\beta = \dot{E}_{ch\,s} / \dot{E}_{ch\,g}$: ratio of the streams of chemical energy of coal and gaseous fuel,

$\eta_{E\,g}$: energy efficiency of the independent gas turbine system.

Initial power of the steam turbine can be expressed by means of its initial energy efficiency:

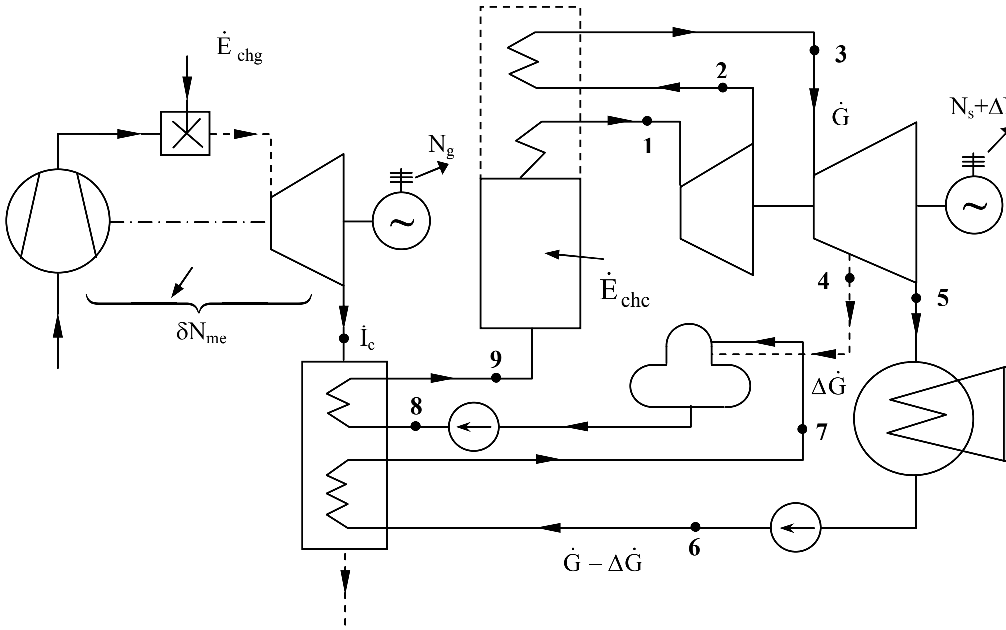

Figure 1. Scheme of the steam power plant with a primary gas turbine

$$N_s = \eta_{E\,r}\,\dot{E}_{ch\,s} \tag{2}$$

where:

$\eta_{E\,r}$: initial energy efficiency of the steam power plant

After we put Eq.(2) into Eq.(1) we obtain:

$$\eta_\Delta = \eta_{E\,g} + \beta\,\frac{N_s + \Delta N_s}{\dot{E}_{ch\,s}} - \beta\,\eta_{E\,r} = \eta_{E\,gs}(1+\beta) - \beta\,\eta_{E\,r} \tag{3}$$

where:

$\eta_{E\,gs}$: efficiency of the combined power plant (*see* Eq.16)

If the quantities $N_s + \Delta N_s, \dot{E}_{ch\,s}, \beta$ are not known from design calculations or measurements, they should be expressed by means of the parameters of working fluid. The consumption of chemical energy of gas-fuel results from the energy balance of the gas turbine complex:

$$\dot{E}_{ch\,g} = N_g + \delta N_{me} + \dot{I}_c = \frac{\eta_{E\,g}}{\eta_{me}}\,\dot{E}_{ch\,g} + \frac{\dot{Q}_r}{\eta_{b\,w}} \tag{4}$$

where:

δN_{me} : mechanical and electrical losses within the gas turbine system

$\dot{I}_c$: enthalpy flow rate of the combustion gases from gas turbine,

η_{me} : electro-mechanical efficiency of the gas-turbine system,

$\dot{Q}_r$: heat flow rate transferred to the feed water inside the waste heat boiler,

η_{bw} : energy efficiency of the waste heat boiler.

Electro-mechanical efficiency of the gas turbine system can be expressed as:

$$\eta_{me} = \frac{N_g}{N_g + \delta N_{me}} = \frac{(\alpha - 1)\,\eta_{el}}{\alpha / \eta_{mT} - \eta_{mC}} \tag{5}$$

where:

η_{mC}, η_{mT} : mechanical efficiency of the compressor and gas turbine,

η_{el} : efficiency of the electric generator,

α : ratio of the shaft power of turbine and compressor.

Assuming the exemplary data from Szargut and SzlHk (1996)

$$\eta_{mC} = \eta_{mT} = 0.99, \quad \eta_{el} = 0.98, \quad \alpha = 2$$

we obtain $\eta_{me} = 0.951$.

The heat flux transferred to the feed water:

$$\dot{Q}_r = \dot{G}\,(i_9 - i_6)\varphi \tag{6}$$

where:

$\dot{G}$: flow rate of live steam after the introduction of the primary gas turbine,

$\varphi < 1$: coefficient determining the participation of the waste heat boiler in the preheating of feed water:

where γ determines the relative decrease of the steam flow rate within the low pressure part of the turbine as a result of the use of stream $\Delta\dot{G}$ in the degasifier:

$$\gamma = \frac{\dot{G} - \Delta\dot{G}}{\dot{G}} = \frac{i_4 - i_8}{i_4 - i_7} \tag{8}$$

From Eq.(4)

$$\dot{E}_{ch\,g} = \dot{G}\,(i_9 - i_6)\;\varphi\;\frac{\eta_{me}}{(\eta_{me} - \eta_{Eg})\,\eta_{bw}} \tag{9}$$

Stream of the chemical energy of coal after the introduction of the primary link:

$$\dot{E}_{ch\,s} = \frac{1}{\eta_b}\,\dot{G}\,(i_1 - i_9 + i_3 - i_2) \tag{10}$$

where η_b denotes the energy efficiency of the steam boiler. From Eqs. (9) and (10) results the ratio of the consumed chemical energy of coal to that of gas:

$$\beta = \frac{\beta_{min}}{\varphi} \tag{11}$$

where:

$$\beta_{min} = \frac{i_1 - i_9 + i_3 - i_2}{i_9 - i_6}\;\frac{\eta_{b\,w}}{\eta_b}\;\frac{\eta_{me} - \eta_{E\,g}}{\eta_{me}} \tag{12}$$

When the value of φ increases, the ratio β becomes smaller. The value β_{min} relates to the maximal ratio of chemical energy of gas to that of coal.

3. Influence on the Power of Steam Turbine

Electric power of the steam turbine system after introduction of the primary link can be expressed by means of the enthalpy drop in particular parts of the turbine:

$$N_s + \Delta N_s = \dot{G}\,(h_W + h_S + \gamma\,h_N)\,\eta_m\,\eta_g \tag{13}$$

where:

h_W, h_S, h_N : specific enthalpy drop within the high-pressure, middle-pressure and low pressure part of the turbine,

η_m, η_g : mechanical and electrical efficiency of the steam turbine system.

After defining:

$$\chi = \frac{N_s + \Delta N_s}{\dot{E}_{ch\,s}} = \frac{(h_W + h_S + \gamma\,h_N)\,\eta_m\,\eta_g\,\eta_b}{i_1 - i_9 + i_3 - i_2} \tag{14}$$

Eq.(3) takes the final form:

$$\eta_\Delta = \eta_{E\,g} + \beta\,(\chi - \eta_{E\,r}) = \eta_{E\,g} + \Delta\eta_{E\,g} \tag{15}$$

$$\varphi = \frac{i_9 - i_8 + \gamma\,(i_7 - i_6)}{i_9 - i_6} = 1 - \frac{i_8 - i_7}{i_4 - i_7}\;\frac{i_4 - i_6}{i_9 - i_6} \tag{7}$$

where $\Delta\eta_{E\,g}$ denotes the increase of the incremental energy efficiency of the primary link in comparison with the separately operating gas turbine system.

4. Influence on the Overall Efficiency

Overall energy efficiency of the considered steam-and-gas power plant:

$$\eta_{Egs} = \frac{N_g + N_s + \Delta N_s}{\dot{E}_{ch\,g} + \dot{E}_{ch\,s}} = \frac{\eta_{Eg} + \beta\,\chi}{1 + \beta} = \frac{1}{1+\beta}\,(\beta\,\eta_{Er} + \eta_\Delta) \tag{16}$$

Overall efficiency of the combined power plant is greater than the efficiency of separately operating gas turbine complex for $\chi > \eta_{E\,g}$.

5. Ecological Effect

Reduction of CO_2-emission is the main ecological effect of the introduction of primary gas turbine. Emission of CO_2 per unit of additionally produced electricity can be expressed as:

$$\mu'' = \frac{\dot{E}_{ch\,g}\,\rho_g}{N_g + \Delta N_s} = \frac{\rho_g}{\eta_\Delta} \tag{17}$$

and per unit of the initially produced electricity:

$$\mu' = \frac{\dot{E}_{ch\,s\,0}\,\rho_s}{N_s} = \frac{\rho_s}{\eta_{E\,r}} \tag{18}$$

Ratio of CO_2 emission per unit of electricity produced in the steam power plant to that burdening the electricity additionally produced due to the primary gas turbine link distinctly indicates the main ecological effect:

$$\zeta = \frac{\mu'}{\mu''} = \frac{\rho_s\,\eta_\Delta}{\rho_g\,\eta_{Er}} \tag{19}$$

where ρ_g, ρ_s denote the specific emission of CO_2 per unit of the chemical energy feeding the gas turbine and the steam boiler.

6. Examples

6.1 According to Zaporowski et al. (1997) it has been assumed:

$$\dot{E}_{ch\,s} = 897.5\,\text{MW}, \qquad \dot{E}_{ch\,g} = 434.3\,\text{MW}$$

$$N_g = 163.5\,\text{MW}, \qquad N_s + \Delta N_s = 439.1\,\text{MW}$$

$$\eta_{Egs} = 0.453, \qquad \eta_{Eg} = 0.376$$

Additionally it has been taken:

$$\eta_{E\,r} = 0.4076$$

From Eq.(3)

$\eta_\Delta = 0.545, \quad \Delta\,\eta_{Eg} = 0.169, \quad \eta_\Delta / \eta_{E\,g} = 1.45$

The incremental efficiency of the primary gas turbine link is 1.45 times greater than the efficiency of the separately operating gas turbine complex.

6.2 For the designed power plant following data have been assumed:

Steam parameters: 14/3.1 MPa, 540/540 ^oC

Temperature values: $t_6 = 35\ ^oC$, $t_7 = 120\ ^oC$, $t_8 = 158\ ^oC$, $t_9 = 230\ ^oC$

Pressure: $p_4 = 0.6$ MPa.

Internal efficiency of the turbine:

$\eta_{i\,1\text{-}2} = 0.85,\ \eta_{i\ 3\text{-}4} = 0.88,\ \eta_{i\,4\text{-}5} = 0.77$

Other assumed values:

$\eta_{me} = 0.95,\ \eta_{E\,g} = 0.376,\ \eta_{E\,r} = 0.37$

Final calculated values:

$\varphi = 0.891,\ \ \beta = 2.146,\ \ \eta_{E\,gs} = 0.408,\ \ \eta_\Delta = 0.496$

The incremental energy efficiency is in this case 1.32 times greater than the efficiency of the separately operating gas turbine complex. The overall energy efficiency of the combined power plant is only 1.10 times greater in comparison with the coal-fired steam power plant and 1.085 times greater in comparison with the separately operating gas turbine complex.

6.3 Following data have been assumed for the calculation of ecological effects:

$\rho_g = 55$ kg/GJ, $\rho_s = 98$ kg/GJ, $\eta_{E\,r} = 0.37$, $\eta_\Delta = 0.496$

From Eq.(19) we obtain $\zeta = 2.39$. The CO_2-emission per unit of the additionally produced electricity is more than 2 times smaller in comparison with the emission in the coal-fired steam power plant.

7. Conclusions

The attained increase of the efficiency of the entire plant does not reflect the energy effect of the utilization of additionally consumed gas-fuel. The incremental efficiency of the primary gas turbine takes into account the increase of the power of the plant and the consumed chemical energy of the gas-fuel that should be also considered when determining the reduction of CO_2-emission.

The economical effectiveness of the primary gas turbine depends distinctly on the ratio of specific cost (per unit of chemical energy) of the gaseous fuel and coal and on the ecological fee for CO_2-emission. If this ecological fee is very small and the mentioned ratio is greater than the incremental energy efficiency of the primary gas turbine, the operational cost of electricity production will be greater after introduction of the primary gas turbine.

Nomenclature

$\dot{E}_{ch}$	flow rate of chemical energy
$\dot{G}$	flow rate of steam or liquid water
h	drop of specific enthalpy
i , $\dot{I}$	specific value and flow rate of enthalpy
N	electric power
$\dot{Q}$	stream of heat
p	pressure
t	temperature
α	ratio of the shaft power of gas turbine to that of compressor
β	ratio of the flow rate of chemical energy of coal to that of natural gas
γ	relative decrease of the flow rate of steam resulting from feeding the degasifier
δ , Δ	symbol of a loss and of an increase
ζ	index of the decrease of CO_2-emission thanks to the introduction of primary link
ε	ratio of the heat amount delivered per steam unit before and after the introduction of primary link
η_E , η_i , η_{me}	energy, internal and electro-mechanical efficiency
η_Δ	incremental energy efficiency of the primary gas turbine link
μ	emission of CO_2 per unit of electricity
ξ	ratio of steam flow rate in the secondary superheater to that of live steam
ρ	emission of CO_2 per unit of chemical energy of fuel
φ	fraction of the heat delivered to the feed water in the waste heat boiler
χ	ratio of the electric power of steam turbine system to the flow rate of chemical energy of coal after the introduction of primary gas turbine link.

References

Szargut, J. and SzlHk, A., 1993, "Application of the Szewalski-Cycle in the Combined Steam-and-Gas Power Plant with Additiomnal Combustion of Gaseous Fuel", *Proceedings of the conference "Problems of Fluid-Flow Machines*" IMP PAN Gdansk , pp.607-616.

Szargut, J., SzlHk A., 1996, "Energetische und oekologische Aspekte der Kraft-Wärme Kopplung in erdgasgefeuerten GuD-Anlagen", *Gaswärme International* No. 11, pp.498-503.

Szargut, J., 1998, "Energy Effectiveness of the Primary Gas-Turbine Supplementing a Coal-Fired Power Plant", *Proceedings of ECOS'98* Nancy, pp.739-745.

Zaporowski, B., Roszkiewicz, J., Sroka, K., Szczerbowski, R., 1997, "Gas-and-Steam Power and Heat-and-Power Plants Fueled with Natural Gas and Bifueled", *Proceedings of the Seminar "New Technologies of the Electricity Production from Conventional Fuels"* (in Polish), Komitet Problemów Energetyki PAN Poznan, pp.85-96.