archives
of thermodynamics
Vol. **31**(2010), No. 4, 15–24
DOI: 10.2478/v10173-010-0024-7

Thermodynamic analysis of a new conception of supplementary firing in a combined cycle

JANUSZ KOTOWICZ
ŁUKASZ BARTELA*
ADRIAN BALICKI

Silesian University of Technology, Institute of Power Engineering and Turbomachinery, Konarskiego 18, 44-100 Gliwice, Poland

Abstract The paper analyzes a new concept of integration of combined cycle with the installation of supplementary firing. The whole system was enclosed by thermodynamic analysis, which consists of a gas-steam unit with triple-pressure heat recovery steam generator. The system uses a determined model of the gas turbine and the assumptions relating to the construction features of steam-water part were made. The proposed conception involves building of supplementary firing installation only on part of the exhaust stream leaving the gas turbine. In the proposed solution superheater was divided into two sections, one of which was located on the exhaust gases leaving the installation of supplementary firing. The paper presents the results of the analyses of which the main aim was to demonstrate the superiority of the new thermodynamic concept of the supplementary firing over the classical one. For this purpose a model of a system was built, in which it was possible to carry out simulations of the gradual transition from a classically understood supplementary firing to the supplementary firing completely modified. For building of a model the GateCycle^{TM} software was used.

Keywords: Combined cycle; Supplementary firing systems; Thermodynamic analysis

*Corresponding author. E-mail address: lukasz.bartela@polsl.pl

1 Introduction

Classically understood supplementary firing in combined cycle systems consist in combusting of additional portion of fuel in the specially provided for this purpose installation located in the duct connecting the expander of the gas turbine with a heat recovery steam generator. Combustion of gaseous fuel in the supplementary firing installation proceeds only in the atmosphere of exhaust gases and is possible due to a significant share of oxygen in their composition [1]. Supplementary firing leads to an increase of exhaust gas temperature, which allows for higher steam superheating. Increase of the heat flux supplied to the steam cycle contributes to the increase of the steam turbine power, but also usually to a decline in overall system efficiency. Decrease in efficiency is a consequence of resignation from one stage of conversion for additionally introduced chemical energy of fuel, and thus results from the partial abandonment of the advantages of a combined cycle. The decrease in efficiency in the case of classically understood supplementary firing is not usually counteracted by the possibility of increasing of the temperature of superheated steam.

In the case of combined cycles major impact of integration with supplementary firing installation on the efficiency of the whole system has the class of the gas turbine used in this cycle. Class of turbines to the greatest extent is associated with the level of exhaust gases temperature supplied to the expander, which in turn results from thermal resistance of materials and expanders blades cooling solutions. Figure 1 shows, adapted from [2], results of calculations of thermal efficiency of gas-steam cycle, which were obtained for the specific assumptions, for four temperature levels at the inlet to the gas turbine expander. Efficiency is expressed as a function of the degree of supplementary firing q, which is defined as the ratio of heat supplied to the system through the supplementary firing installation ($\dot{Q}_{SF}$) to the total heat flux supplied to the system ($\dot{Q}_{CCH} + \dot{Q}_{SF}$):

$$q = \frac{\dot{Q}_{SF}}{\dot{Q}_{CCH} + \dot{Q}_{SF}} \,. \tag{1}$$

As it can be seen, the integration of the system with the supplementary firing installation may even lead to increased efficiency, but only for lower values of flue gases temperature reaching expander.

In the presence of high temperature exhaust gases, which are achieved in modern gas turbines constructions (even above 1450 °C) at present, the decisions regarding the use of supplementary firing in combined cycles are the

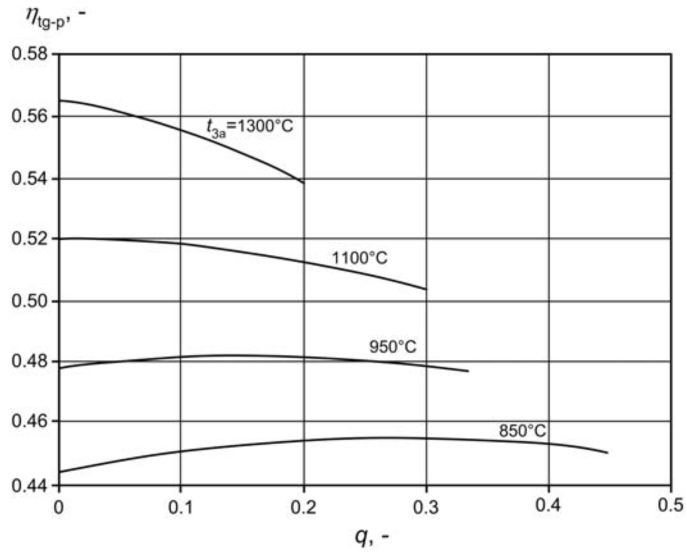

Figure 1. Thermal efficiency of the combined cycle as a function of the degree of supplementary firing for different temperature levels at the inlet to the gas turbine expander [2].

result of a compromise between the advantage resulting from the increase of load flexibility and of the power of the unit, and the disadvantage of such integration in the form of decreased efficiency of electricity generation.

Currently re-observed increase of the interest in supplementary firing installations is linked primarily to the growing interest in combined cycle systems in the context of their use as systems of combined electricity and heat production. In these systems, especially working for the municipal district heating networks, very important is the opportunity to work with the widest range of loads, which is possible exactly due to the use of supplementary firing [3,4]. It is estimated that the supplementary firing will be more and more often used, also due to the more frequently observed popularization of new technologies, in which taking advantage of this system is extremely desirable, including integrated gasification combined cycle and with carbon capture and storage (CCS) installations, combined cycles, in which apart from high-quality natural gas there is a cost-effective possibility of burning of extra low-quality fuels, the conception of combined cycle systems within which supercritical heat recovery steam generators are operating [5,6].

2 New conception of supplementary firing

The main feature of the solutions analyzed in the present paper is the location of the system of burners incorporated only on part of the flue gases reaching heat recovery steam generator. Diagram of the integration of the system with a heat recovery steam generator is shown in Fig. 2. This arrangement allows the utilization of a smaller amount of fuel in relation to the quantity which would be required to achieve the same steam temperature as in the case of classical solutions of supplementary firing. This gives the opportunity to reduce the efficiency decrease resulting from the resignation, for the additionally supplied heat, from the advantages of combined cycle. Moreover, in the case of a new conception even for systems, where higher class gas turbines operate, it is possible to achieve the growth of efficiency of electricity production. Initially, the new conception of the solution of system integration with a combined cycle was presented in [7].

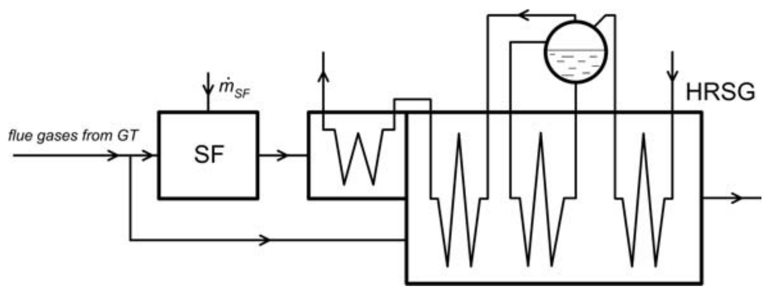

Figure 2. New conception of supplementary firing system.

3 Model of the system

In order to analyze the modified supplementary firing installation a reference combined cycle system was chosen (Fig. 3), for which the fundamental characteristic parameters were determined. It was decided here to use a gas turbine model, which corresponds to the characteristics of the Westinghouse 501G turbine. Among the most important features of the machine, the following can be mentioned:

- power ratio: 228.7 MW;
- efficiency: 0.3824;

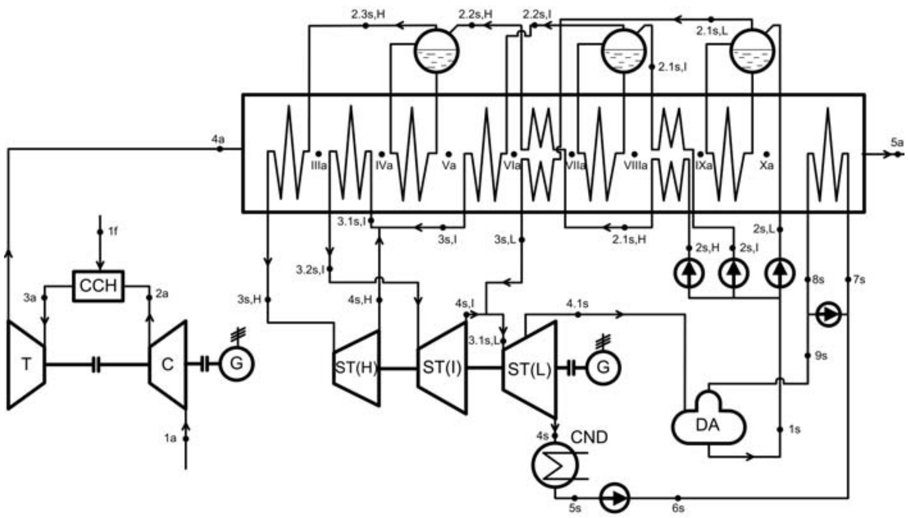

Figure 3. Scheme of the reference unit.

- temperature of the flue gases after combustion chamber: 1429.8 °C;
- exhaust gases temperature after expander: 597.3 °C;
- pressure ratio: 19.19.

As about steam part of the system, it was decided here to use the triple-pressure structure with extraction-condensing steam turbine. Among the most important characteristic quantities of steam cycle following can be mentioned:

- temperature of high-, medium- and low-pressure steam as well as reheated: 557.3 °C, 315.3 °C, 303.5 °C, 458.8 °C;
- pressure of high-, medium- and low-pressure steam: 16.0 MPa, 5.0 MPa, 0.3 MPa;
- minimum temperature differences in the high-, medium- and low-pressure part of heat recovery steam generator (pinch point): 8 K, 10 K, 15 K;
- isentropic efficiency of high-, medium- and low-pressure section of steam turbine: 0.90, 0.90, 0.86;
- isentropic efficiency of pumps operating in the system: 0.85.

In the case of the reference system, despite the fact that it uses a gas turbine, which is characterized by high temperature exhaust gases, it is not possible to obtain steam at temperature higher than 560–570 °C (despite the fact that the strength of the materials currently used in the construction of steam superheater enables its higher superheating). The application of supplementary firing allows to increase the exhaust gases temperature at the inlet to the heat recovery steam generator, however, in the case that the supplementary firing is applied on the whole exhaust stream it will negatively affect the efficiency of the entire system. Therefore, the possibility of supplementary firing on the part of the exhaust stream should be considered and its impact on the system performance should be determined.

For the reference system both the classical conception of supplementary firing, as well as being subjective in this article modified supplementary firing were examined.

For the thermodynamic evaluation of the transition from classical supplementary firing to a modified one, the system based on the reference block was built. Modification of the system consist in building of the supplementary firing installation on the exhaust stream, which feeds the second, additional section of the high-pressure superheater. The exhaust gases after the transfer of the heat to steam in the exchanger are mixed with the part of the exhaust gases, which were not subjected to supplementary firing. The stream of exhaust gases goes to the first section of the high-pressure steam superheater. The scheme of the additionally built installation together with the first and the second section of steam superheater is given in Fig. 4.

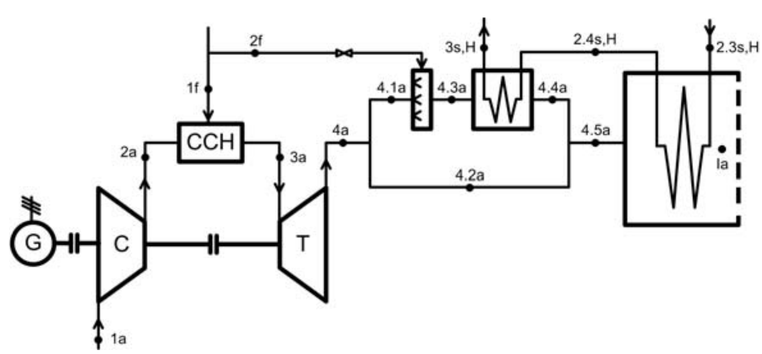

Figure 4. The structure of the system with two supplementary firing installations.

It was assumed that the installation allows to increase the temperature of high-pressure steam by 40 K compared to the reference case, i.e., to

597.3 °C. For steam superheaters – the first section of high-pressure superheater and an additional section of this heat exchanger – the same levels of differences temperatures on the hot ends, i.e. 40 K, were assumed.

In the analyses as a decision variable a ratio of the exhausts stream going to the supplementary firing installation to full exhausts stream ($m_{4.1a}/m_{4a}$) was adopted. This quantity took values from 0 (total stream of exhaust gases bypasses the supplementary firing installations, what leads to the reference system) to 1 (entire stream reaches the supplementary firing installation, which leads to a system based on the classic concept of supplementary firing). Conducting of the calculations for streams ratio $m_{4.1a}/m_{4a}$ from 0 to 1 allowed for the determination of optimal flow of the exhaust gases going to supplementary firing installation, for which the best thermodynamic effect is obtained. Realization of the system in accordance with the model shown in Fig. 4 and in accordance with the set of assumptions for the low ratio $m_{4.2a}/m_{4.1a}$ is in practice impossible because of the need for large surface of heat transfer in the additional section of steam superheater. In the calculations limit value of thermal efficiency for this heat exchanger was assumed at 99%.

4 Results of calculations

Figure 5 shows the results of calculations of the net efficiency of the system as a function of the selected decision variable. As shown, by using a modified supplementary firing installation in the analyzed system, it is possible to achieve higher efficiency of the system compared to the reference one. What is important, efficiency in case of using of the classical solutions of supplementary firing is lower than the efficiency obtained for the reference case by 0.315%. Efficiency increase by introducing modifications in relation to the efficiency of the reference system is possible only for a specific range of stream ratios $m_{4.2a}/m_{4.1a}$, ranging from 0.185 to 0.317, while for lower of these values the maximum efficiency is achieved, i.e. 56.385%. Occurring in this case restriction is assumed here maximum efficiency of the second section of steam superheaters.

In a similar approach as in Fig. 5, in Fig. 6 net power ratio of the entire system is presented. As it can be seen, modification of the supplementary firing system, regardless of the assumed decision variable value, contributes to reducing of the system power in relation to the case of the classical solution of supplementary firing, but at the same time allows the increase

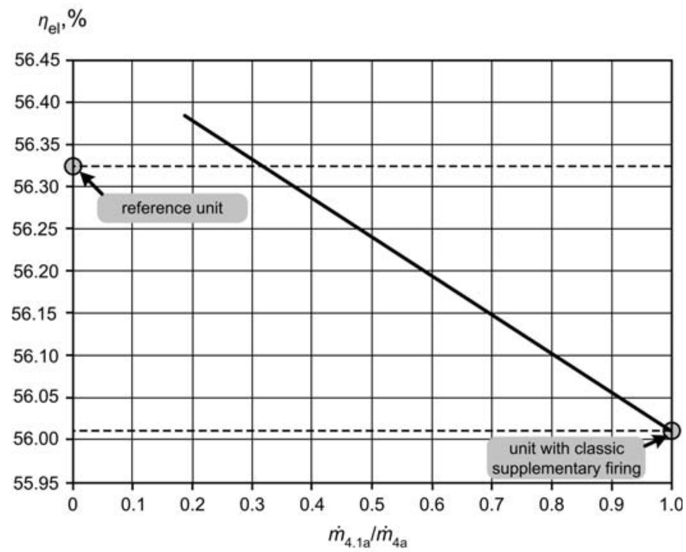

Figure 5. Net efficiency of the system as a function of stream ratio $m_{4.2a}/m_{4.1a}$.

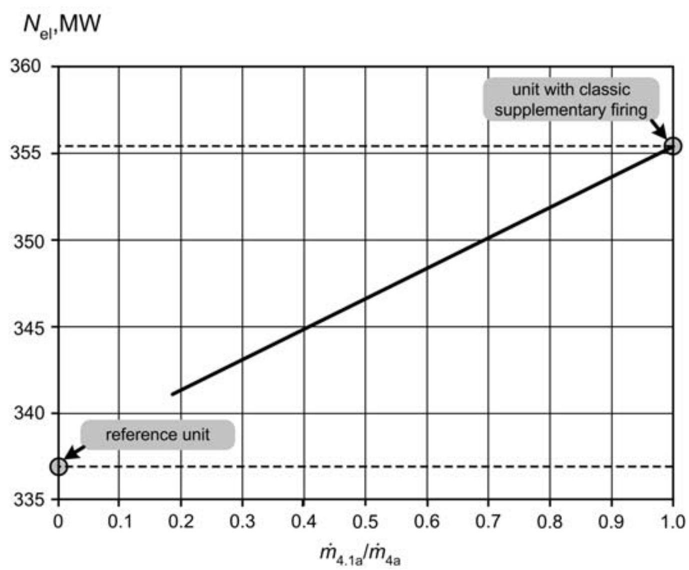

Figure 6. Net power ratio of the system as a function of stream ratio $m_{4.1a}/m_{4a}$.

of power in relation to the reference system. In the optimum case, for the system with a modified firing installation, i.e., for $m_{4.2a}/m_{4.1a}$=0.185, power at the level of 341.1 MW was achieved, what in comparison to the reference system gives a higher by 4.1 MW value, but lower by 14.3 MW as compared to the system with the classic solution of supplementary firing installation.

5 Summary

Current supplementary firing installations are considered primarily for combined cycle heat and power plants. They allow there, first of all, for a very flexible operation over a wide load ranges. In addition, due to the desirable use in heat and power plants of gas turbines of lower generation, supplementary firing does not cause such significant degradation of production efficiency.

It should be assumed that in the near future supplementary firing systems may also return to the role of components of systems for electricity generation only. Such premises are associated with conceptions and prepared implementation of technologies that are primarily a response to the essential revaluation in the energy legislation.

The conducted analysis showed that even in case of a relatively modern gas turbine it is possible to use supplementary firing installation without significant negative effect of reducing the efficiency of the system. When optimally modified solution of supplementary firing installation selected, it is possible to achieve increased efficiency while increasing the electric power of the system, but this increase will not be as high as is the case of conventional firing systems.

Thus, in light of the observed pro-ecologic trends in environmental legislation of the European Union the use of modified supplementary firing installation may also bring environmental benefits.

In the present paper the economic analysis was not undertaken, which can give an answer to the justification of the application of modified supplementary firing system concept.

Received 28 August 2010

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