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Analysis of alternative configurations of heat recovery process in small and medium scale combined cycle power plants

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ABSTRACT

In the paper various configurations of the heat recovery process in combined gas and steam cycle power plants of complex structures are examined. Proposed modifications concern mainly hot side temperature profile. It has been assumed that two gas turbines will be installed in the system with a common single pressure heat recovery steam generator. Exhaust gas from the boiler is introduced into the low-temperature Rankine cycle with an organic working fluid. Two configurations of heat exchangers have been proposed, that can be considered as an alternative solution to the conventional structures currently in use. Energy and exergy efficiency values have been calculated for different parameters of steam. In addition, the temperature of exhaust gas from gas turbines was assumed to be different, which corresponds to the use of turbines of different efficiency classes. It has been shown that, with appropriately high steam parameters and appropriately selected gas turbines, the proposed alternatives lead to an improvement of the system performance.

1. Introduction

Due to increasing influence of intermittent renewable energy sources on the work of energy systems of European countries, global optimization of their configuration and operating parameters is nowadays an important issue. Flexibility of the energy system is becoming a new criterion for design of energy conversion plants. In this light the distributed small and medium scale modular Combined Cycle Power Plants (CCPP) can be an interesting alternative. According to Welch et al. [1] distributed, relatively small, more flexible modular CCPPs, that are located closer to the actual loads, can help to improve system flexibility, reliability and security of supply as well as to reduce capital expenditure on capacity expansion/augmentation. A disadvantage in this case is the limited energy conversion efficiency, ranging from 42% to 52% for systems with a power output of up to 50 MW [2]. This is relatively low value comparing to the efficiency of 60% achieved in modern CCPPs of electric power higher than 400 MW. Nevertheless commercial offer for small-scale CCPPs of the power output below 50 MW is growing.

Traditional CCPP consists of gas turbine (GT), heat recovery steam generator (HRSG) and steam turbine (ST). The HRSG is the critical element integrating Brayton and Rankine thermodynamic cycles within the plant. There are many different configurations but the most common are: (a) 1 GT + 1 HRSG + 1 ST; (b) 2 GTs + 2 HRSGs + 1 ST. There are also configurations where 2 or more gas turbines are connected to a single HRSG As common practice, the HRSG is tailored specifically for each gas turbine unit and for each specific plant [3]. Typically the improvement of HRSG and thus the entire CCPP performance is achieved by introduction of several water evaporation pressures and steam reheaters within the HRSG. Two or three-pressure steam cycles achieve better efficiency than the single pressure systems, but their installed cost is higher. They are the economic choice when fuel is expensive or if the duty cycle requires a high load factor [4]. In the case of low nominal power output of the plant single pressure HRSGs are used. Typical steam parameters are: temperature up 540 °C and pressure up to140 bar.

Until today several approaches for improvement of performance parameters of small and medium scale CCPPs have been presented in the literature. Franco [3] studied performance of supercritical HRSG structures and evaluated real perspectives of using this technology for the development of combined CCPPs in the power range of 50–120 MW. Khaljani et al. [5] and Anvari et al. [6] proposed bottoming of the recuperated GT based combined cycle plant with an Organic Rankine Cycle (ORC) modules. The plants produced electric power and saturated steam for industrial use. The ORC working fluid was R123. Nami et al. [7] proposed a system that is combination of the conventional gas turbine Brayton cycle, the supercritical CO_2 recompression Brayton cycle and an ORC using the waste heat from the supercritical CO_2 recompression Brayton cycle. Turbomach introduced modular plant concept with two GT/HRSG trains, single steam turbine and absorption chillers for turbine inlet air cooling [8].

Till now only a few authors presented studies focused on

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Nomenclature

$\dot{B}$	exergy flux, kW
CO	condenser
D	drum
DA	deaerator
DSH	desuperheater
e	specific exergy, kJ/kmol
EV	evaporator
h	specific enthalpy, kJ/kmol
H	heater
$\dot{H}$	enthalpy flux, kW
$\dot{n}$	molar flow rate, kmol/s
p	pressure, kPa
P	pump
R	universal gas constant (R = 8314 J/kmol K)
RGT	recuperated gas turbine
s	specific entropy, kJ/kmol K
SGT	simple gas turbine
SPH	superheater
ST	steam turbine
T	temperature, K
z_i	molar fraction of gaseous component i

Greek symbols

η_E	energy efficiency
η_B	exergy efficiency

Subscripts

a	at ambient conditions
g	exhaust gas
in	at inlet
l	liquid phase
o	organic fluid
out	at outlets steam
v	vapor phase
w	water

modification of the HRSG hot gas side temperature profile. Copen et al. [9] introduced the concept of Complementary Fired Combined Cycle (CFCC), that is based on fractionally sized gas turbines, with their exhaust ducted into the HRSG at different entry points. This system is also subject to US patent No. US 20070130952 A1 titled “Exhaust heat augmentation in a combined cycle power plant”. Gonzalez Diaz at al. [10] a sequential supplementary firing in the heat recovery steam generator. Both of the cited works take into account large scale CCPP and are focused mainly on their power output augmentation.

In this paper possible modifications of small and medium class CCPP plant structure are examined theoretically. The concept is based on a bigger number of power generation modules and modified configuration of the heat recovery steam generator, resulting in changed hot side temperature profile. The main design assumption within this work is an integration of high efficiency gas turbines such as Recuperated Gas Turbine (RGT) with Simple Gas Turbine (SGT) by a HRSG of an innovative arrangement of heat exchangers. Alternative structures can be also configured using large reciprocating engines such as GE J920 or Wärtsilä 18V50SG or vacuum expansion gas turbines. In each case the exhaust gas temperature is low, and therefore traditional HRSG and steam cycle arrangement would result in a relatively low power generation efficiency of the entire plant.

2. Alternative configurations of CCPP

Within the proposed modification a highly efficient RGT will deliver energy for water evaporator whereas high temperature of exhaust gasses required for steam superheating will be provided by the SGT. Due to constraints of pinch point temperature difference (PPTD) low temperature of exhaust gas at the inlet of HRSG results in relatively high temperature at its outlet. This higher enthalpy of exhaust gas can be further utilised within an ORC with a working fluid of high critical point temperature, such as hexamethyldisiloxane (MM) or octamethyltrisiloxane (MDM). In this way a two pressure heat recovery system can be established. As the ORC is driven with exhaust gasses of relatively low temperature the direct heat exchange is assumed between exhaust gas and working fluid without intermediate thermal oil cycle. In practice the direct heat exchange is quite challenging process due to issues related to chemical stability of the fluid and potential leak ignition [11]. On the other side manufacturers have been continuously working on this solution claiming that direct heat recovery from hot gases at the temperature level of 600 °C is possible [12].

Taking into account that traditional CCPP can be also bottomed by ORC three different configuration options have been examined. In the first one (case C-1) traditional arrangement of CCPP is taken into account and this is the reference case to study the results of proposed modifications. Schematic diagram of the plant in case C-1 is presented

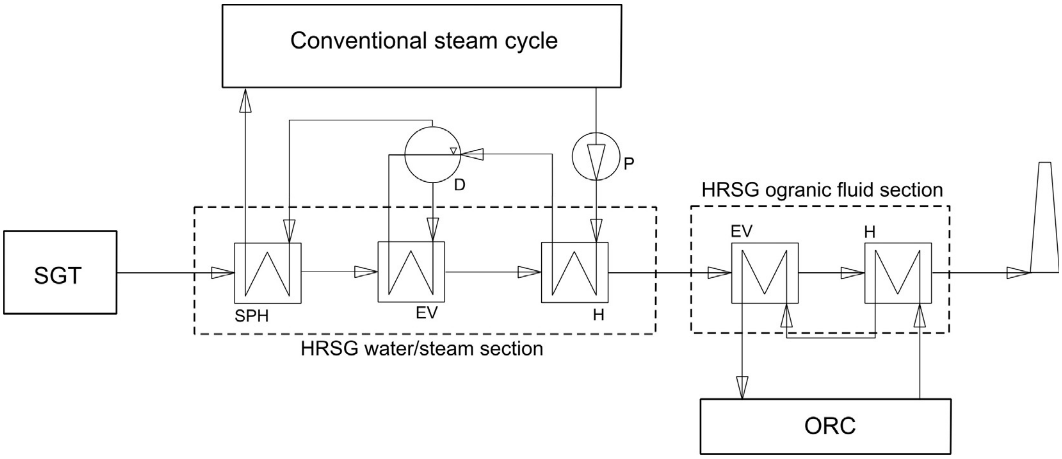

Fig. 1. CCPP with one GT, single pressure HRSG and bottoming ORC module (configuration C-1).