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Steam bottoming cycles offshore – Challenges and possibilities

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Abstract

This paper addresses the challenges and possibilities related to offshore steam bottoming cycles with a special focus on once-through heat recovery steam generators (HRSGs). The main focus of the paper is to investigate the compromise between weight and efficiency of the HRSG by process simulation. The cost per installed kg of equipment is high offshore. Therefore, any bottoming cycle, applied to the back-end of the gas turbine, needs to be compact, yet sufficiently efficient. Important parameters to make the HRSG compact were the number of steam pressure levels, the HRSG technology, the flue gas pressure drop in the HRSG, and the pinch-point temperature difference. While selecting the parameters as a compromise between weight and efficiency, the combined cycle net plant efficiency was found to be approximately 50% with a power output of 43 MW. The steam turbine gross power output was 11 MW or about 25% of the total combined cycle plant gross power output. These results were compared to an onshore reference plant model which utilized the same type of aeroderivative gas turbine. The weight of the offshore once-through HRSG was about one third of the onshore HRSG. The net plant efficiency was 3%-points lower for the offshore system.

Keywords: Once-through, Rankine cycle, Combined cycle, Process simulation

1. Introduction

The Norwegian government introduced a CO_2 tax for hydrocarbon fuels in offshore operations back in 1991. This led to an increased focus on energy conservation and energy efficiency. The vast majority of offshore power generation and mechanical drive applications are handled by simple cycle gas turbines (GTs) fueled by hydrocarbons and thereby subject to the CO_2 tax. One alternative to increasing the efficiency of the power plant, and thereby decreasing the CO_2 tax per generated MW, is to add a steam bottoming cycle to the gas turbine topping cycle, making it a combined cycle.

As a result of the CO_2 tax, combined cycles offshore were already discussed and, to some extent, implemented in the '90s [1–3, e.g., see]. However, as of today, widespread use of steam bottoming cycles in the offshore sector has not happened. Challenges include weight and size limitations, harsh conditions, and the need for treated feed and makeup water. Nevertheless, there are a few examples of existing offshore combined cycles.

Kloster [3] describes the three to-date existing offshore combined cycles on the Norwegian shelf. The three installations include combined cycles on platforms at 1) Oseberg, 2) Eldfisk, and 3) Snorre B. The steam cycles are, in all three cases, based on single-pressure non-reheat heat recovery steam generators (HRSGs). Kloster notes that the design of the

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HRSGs is compact compared to conventional steam generators due to the tight requirements on weight and space offshore.

This paper addresses the challenges and possibilities related to offshore steam bottoming cycles with a special focus on once-through HRSGs. Topics like water treatment and material selection will be covered. The main focus of the paper is to investigate the compromise between weight and efficiency of the HRSG by process simulation. The cost per installed kg of equipment is high offshore. Therefore, any bottoming cycle, applied to the back-end of the gas turbine, needs to be compact, yet sufficiently efficient.

The remainder of the article is divided into the following sections: Once-through technology is discussed in Section 2. A description of the process, model assumptions, and methodologies used are presented in Section 3. The results of the process simulations are presented in Section 4, and concluding remarks are given in Section 5.

2. Once-through technology

Once-through HRSG technology can be an attractive option when designing an offshore steam bottoming cycle. Its flexibility, the avoidance of steam drums, and, with the right material selection, the possibility to avoid the bypass stack while allowing for dry HRSG operation are all advantages for offshore applications.

A simple once-through heat recovery steam generator (OTSG) does not, unlike conventional drum-type HRSGs, have defined sections for economizer, evaporator, and superheater. Instead, the interface between water and steam moves freely within the tube banks, its location depending on the heat input, feedwater flowrate, and pressure. Brady [4] explains design aspects including material selection, water chemistry requirements, controls, and startup for OTSGs. At the time of writing the 2001 paper, Brady represented Innovative Steam Technologies (IST), which is an OTSG manufacturer with over 100 units sold [5]. One of their main applications is OTSGs as part of a steam bottoming cycle for the GE LM6000 gas turbine series. The material selection by IST allows for dry operation of the OTSG up to 538°C flue gas temperature.

Franke et al. [6] describe a horizontal flow, vertical tube Benson® HRSG developed by Siemens and Babcock Borsig Power. Advantages, compared to a drum-type HRSG, such as, improvements in the dynamic characteristics are discussed. Flow arrangement, pressure drops for various flow conditions, and steam temperatures during a cold start are some of the features and results shown. The Benson® HRSG design has, unlike the IST design described above, defined evaporator and superheater sections with a separator vessel in between as inherited from the Benson® boiler design. The separator, used when necessary to avoid overheating of the evaporator tube banks by recirculating water, is smaller than a drum would be in a conventional HRSG.

Mucino et al. [7] describe the modeling of both single- and dual-pressure OTSGs. Pressure drop and fouling effects are included in the analysis. Both design and off-design performance results are presented. The dual-pressure model was validated with actual plant data with satisfactory correspondence. A detailed steady-state modeling effort of an OTSG is described by Dumont and Heyen [8]. The equations and details of the model are thoroughly introduced. A comparison with a drum-type superheater and reheater is made. Ngoma et al. [9] perform both steady-state and dynamic simulations of a dual-pressure OTSG. The effects of changes in flue gas temperature and mass flow are studied. The focus of the results are directed toward changes in temperature and steam quality along the tube length. Model validation with data from a test facility is included.

2.1. Water treatment

Water treatment offshore can be a challenge since there is no natural source of fresh water available. Either fresh water has to be transported from land or a desalination plant is needed.

The chemistry for the water used in a steam cycle is controlled by means of purification of makeup water, condensate polishing, deaeration, blowdown, and chemical additives. For once-through systems, it is critical to keep the water contaminants to a minimum. In a drum-type system, enrichment of salts and other contaminants can be avoided with drum blowdowns. However, such an outlet does not exist in a once-through system. Therefore, the feedwater requirements are stricter for a once-through steam generator than for a drum-type steam generator (given a similar life expectancy and material selection).

The Babcock & Wilcox Company [10] thoroughly explains water and steam chemistry, water treatment, and corrosion issues. Boiler water treatment is also discussed in [11]. Water treatment practices in general and the all volatile treatment (AVT) in particular are described by Gabrielli and Schwevers [12]. The International Association for the Properties of Water and Steam provides technical guidance for steam cycle volatile treatment [13].

For an offshore installation, a desalination plant for the supply of fresh water to the platform could be needed. Examples include the Eldfisk platform where an evaporator for desalination of seawater is installed [2]. This desalinated water is, in addition to being utilized for fresh water supply to the rest of the platform, used as a feed to the steam cycle makeup water treatment system. If sea water is used as raw water, the following steps provide one alternative for water treatment for an offshore OTSG based bottoming cycle:

1. Desalination of sea water with an evaporator
2. Mixed-bed demineralization for both
   (a) makeup water, and
   (b) condensate polishing
3. Chemical additives for mainly
   (a) pH control, and
   (b) oxygen scavenge

In addition to the points in the listed example, deaeration would be part of a steam cycle. Deaeration essentially eliminates oxygen, carbon dioxide, argon, and nitrogen from the water. This is accomplished by heating the condensate to decrease the gas solubility and carrying away the gases with a flow of steam. Oxygen at ppb levels would still remain in the water and could be scavenged by a chemical additive like, for example, hydrazine. For pH control, ammonia could be used.

2.2. Tubing material

Typical tubing material in an HRSG are ASTM A335 grade T22 or, for the superheaters, grade T91 [14]. Carbon steel can be used further downstream in the HRSG. Fin material can be, for example, stainless steel ASTM A176 TP409 or carbon steel.

If a higher grade alloy is needed, Incoloy 800/825 can be an option. Incoloy is more expensive, but the additional material cost can, for the most part, be offset by the omittance of the bypass stack and drum. A bypass stack requires a lot of space and is heavy. Offshore, where the focus of the power plant is flexibility to adjust to the oil and gas processes, one must be able to operate the gas turbine in simple cycle mode. With a selection of high-grade materials for the once-through HRSG, there is the possibility to operate it dry for many of the aeroderivative gas turbines (with low enough exhaust temperature). Thereby, the bypass stack could potentially be omitted. Another reason for selecting a superalloy like Incoloy is that it would be more resistant to corrosion, both internally from the water and impurities in the system, and externally from the harsh ambient conditions offshore.

3. Methodology

GT PRO and PEACE by Thermoflow were used for the combined cycle process modeling, process simulations, and HRSG weight estimations [15]. The IAPWS-IF97 water and steam properties were used [16]. Key assumptions for the process models are displayed in Table 1.

The net plant power output was defined as

$$\dot{W}_{cc} = (\dot{W}\eta_m\eta_{gen})_{gt} + (\dot{W}\eta_m\eta_{gen})_{st} - \dot{W}_{aux} \quad (1)$$

where $\dot{W}_{gt}$ is the GT gross power, $\dot{W}_{st}$ the steam turbine (ST) gross power, and $\dot{W}_{aux}$ the auxiliary power requirement. η_m is the mechanical efficiency and η_{gen} the generator efficiency. Note that all the power terms were defined as their absolute values, meaning all terms were considered positive and the sign handled in the equation itself.

The net plant efficiency was defined as

$$\eta_{cc} = \frac{\dot{W}_{cc}}{(\dot{m}LHV)_{ng}} \quad (2)$$

where $\dot{m}_{ng}$ is the natural gas mass flow entering the system and LHV_{ng} the lower heating value of the natural gas.

The following models were built and simulated:

Table 1: Process model assumptions

Site	
Ambient T,°C	15
Ambient pressure, bar	1.013
Ambient relative humidity, %	60
Frequency, Hz	60
Cooling water system	direct water cooling
Cooling water	sea water
Cooling water T, °C	10
Cooling water ΔT, K	10
Gas turbine	
Model type	GE LM2500+G4
GT fuel	methane
GT inlet Δp, bar	0.010
GT exhaust Δp, bar	0.005

1. Oseberg combined cycle based on [3] for modeling calibration purposes.
2. Onshore steam bottoming cycle with dual-pressure drum-type HRSG (2P drum). This was used as reference plant.
3. Single inlet drum-type HRSG with design criteria based on Oseberg model (1P drum). This model represented existing offshore combined cycle technology.
4. Combined cycle with OTSG and *free* steam cycle design parameters (1P ot). This model represented possible improvements compared to existing offshore combined cycles.

As the first modeling step, the Oseberg combined cycle described in [3] was modeled in GT PRO. This was done to ensure that the methods, tools, and assumptions used for the process models were valid. As a reference plant, an onshore dual-pressure system was modeled as described in point 2. This model would represent current state-of-the-art without the tight requirements on space and weight as with an offshore plant. The model described in point 3 represents existing offshore combined cycle technology. Finally, an OTSG based combined cycle was modeled and simulated, in which the process parameters, such as live steam pressure, live steam temperature, condensing pressure, pinch-point temperature difference, and flue gas pressure drop, were selected without considering the Oseberg model parameters. Instead, the parameters were selected to obtain an acceptable compromise between weight and efficiency.

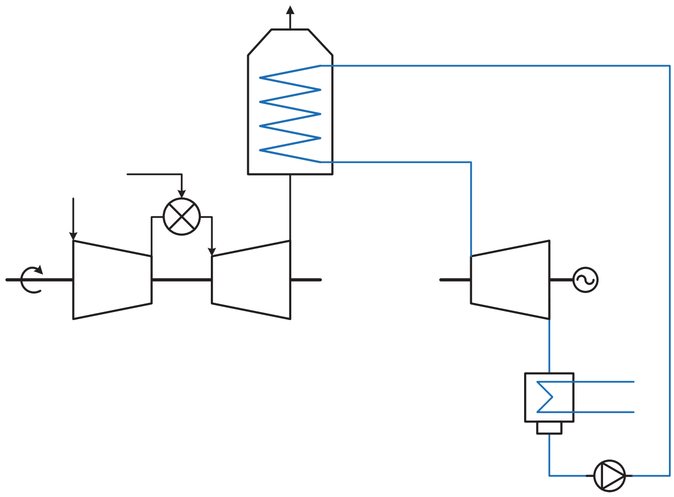

Figure 1: Simplified layout of offshore combined cycle with once-through HRSG

3.1. Process description

A schematic of a combined cycle with a single-pressure OTSG is shown in Fig. 1. In addition, both single-pressure and dual-pressure drum-type systems were analyzed in a combined cycle setup. The dual-pressure system, used as a reference plant to be able to compare a typical onshore and the offshore systems, is shown in Fig. 2.

As the first modeling step for calibration purposes, as described in point 1 above, the Oseberg combined cycle described in [3] was modeled in GT PRO. The combined cycle on the Oseberg Field Center has two GE PGT25+ gas turbines [17] and a double-inlet drum-type HRSG. The gas turbines drive gas compressors. One interesting aspect is that the HRSG skid and the ST skid (includes condenser) are placed on separate platforms. This leads to very long main steam and condensate lines, 400 m each. According to [3], the steam cycle on Oseberg produces 15.8 MW electricity at the design point with no steam extraction. The design point is at 88% relative gas turbine load and an ambient temperature of 7.6°C. The steam pressure at the steam turbine inlet

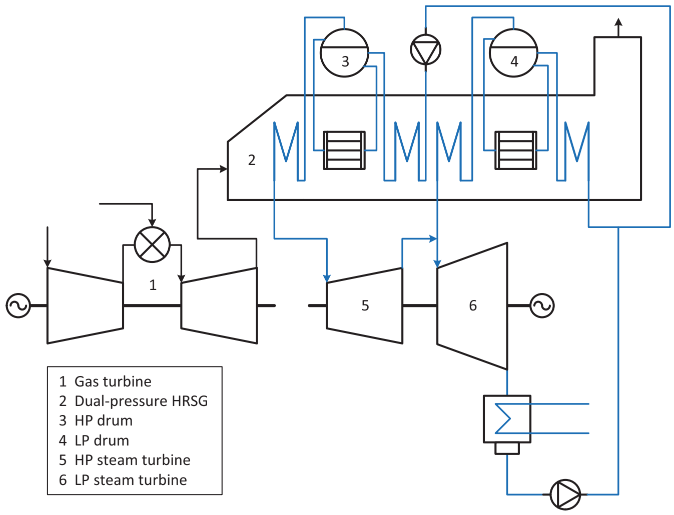

Figure 2: Simplified layout of onshore combined cycle with dual-pressure drum-type HRSG

was 17.5 bar (assumed a live steam pressure of 18 bar in the process model) with a live steam temperature of 430°C.

After the calibration step, three combined cycle models were designed. In all three setups, the GE LM2500+G4 (60 Hz) was selected as gas turbine. Common for the three setups was that for one GT there was one HRSG. ISO ambient conditions were assumed. Direct water cooling condenser with sea water at an inlet temperature of 10 °C was assumed. Pure methane was used as fuel for the GT combustor. For the single-pressure drum system, a live steam pressure of 18 bar was selected with a live steam temperature of 430°C based on the Oseberg steam parameters. The live steam pressure and temperature were selected at 25 bar and 450°C respectively for the single-pressure once-through system. For the onshore dual-pressure system, the steam pressures were set at 55/7 bar and the corresponding temperatures at 510/260°C.

4. Results and discussion

The model calibration with the existing Oseberg combined cycle led to simulation results within 0.1% of the Oseberg documented steam turbine power output while matching the live steam pressure and temperature. These results were deemed satisfactory.

Results from the simulations, excluding the calibration model, are presented in Table 2 and Figs. 3 and 4. The reference to wet weight includes the weight of the water in the system. Dry weight is excluding the water content.

As can be seen in Table 2, the onshore combined cycle with a dual-pressure HRSG outperforms the offshore systems in terms of net plant output and net electrical efficiency. The net electrical efficiency is close to 3%-points higher for the dual-pressure system. However, the weight is significantly larger. The HRSG weight for the offshore single-pressure drum-based system is 60% lower than for the onshore dual-pressure system. A further reduction in weight from the single-pressure drum-based system of approximately 20% is possible when going to the once-through system.

A breakdown of the difference in weights between the single-pressure drum-type system and the single-pressure once-through system is shown in Fig. 3. The leftmost bar refers to the drum-type single-pressure HRSG and the rightmost bar refers to the once-through single-pressure HRSG. The increase in weight due to the heat transfer tubing, piping, and support, is mainly because of material selection and its heat transfer properties (Incoloy). However, the tubing weight increase is rather small. Weight savings are accomplished by omitting the drum for the once-through system, by allowing for HRSG dry operation and thereby avoiding the bypass stack, and by the structure avoided in connection with the drum and bypass stack. As can be seen in Fig. 3, the main weight saving is due to the removal of the bypass stack for the once-through system.

Fig. 4 shows the sensitivity of important process parameters on the once-through HRSG dry weight and net electrical efficiency for the combined cycle. It is clear that, to design an HRSG for offshore, where weight is an important factor, a high pinch-point temperature difference, and a high flue gas pressure drop in the HRSG would be desired. Condenser pressure plays a limited role in the HRSG weight, however, it has a big impact on the efficiency. It should be mentioned that the condensing pressure is important for the weight of the condenser and of the steam turbine. Therefore, it is likely that a higher than needed condensing pressure, from a cooling medium temperature standpoint, would be chosen for an offshore application.

Table 2: Comparison of results between combined cycles based on an onshore drum-type dual-pressure HRSG (2P drum), an offshore drum-type single pressure HRSG (1P drum) and an offshore once-through single pressure HRSG (1P ot)

		2P drum	1P drum	1P ot
GT gross power output	$\dot{W}_{gt}$, MW	32.1	32.1	32.1
GT gross electric efficiency	η_{gt}, %	38.2	38.2	38.1
ST gross power output	$\dot{W}_{st}$, MW	13.7	11.2	11.3
CC net power output	$\dot{W}_{cc}$, MW	45.3	42.8	42.9
CC net electric efficiency	η_{cc}, %	53.8	50.9	51.0
HRSG wet weight estimate	m_{hrsg}, kg	340	145	110

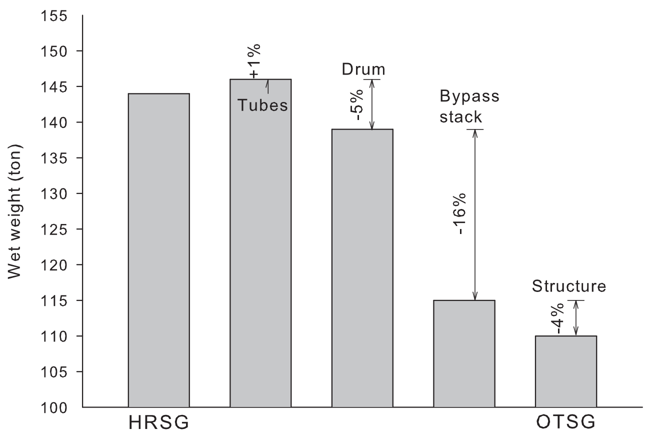

Figure 3: Breakdown of wet weight difference between a drum-type and a once-through HRSG for offshore applications

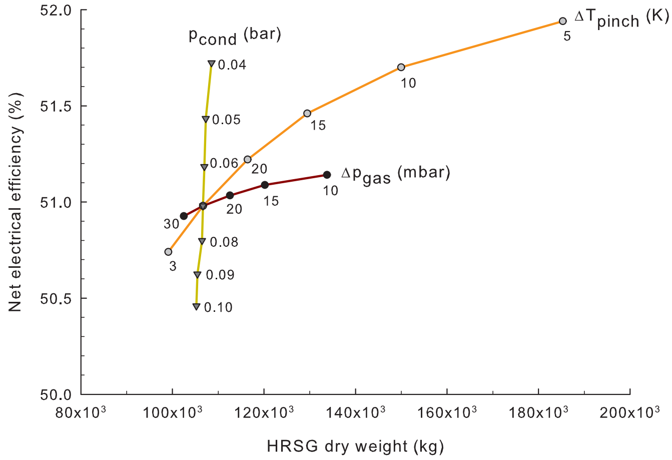

Figure 4: Sensitivity of flue gas pressure drop, pinch-point temperature difference, and condensing pressure on HRSG dry weight and net electrical efficiency

5. Conclusions

Challenges with offshore steam bottoming cycles are the limitation on space and weight, the harsh external conditions, and the need for fresh water for the steam cycle. Also, since the focus in offshore operation is on the oil and gas production, the power plant needs to be flexible. A steam bottoming cycle can be designed to be compact and of relatively low weight for offshore applications. In order to accomplish this, the net plan efficiency decreased compared to an onshore system. Important parameters to make the HRSG compact and of low weight were the number of steam pressure levels, the HRSG technology, the flue gas pressure drop in the HRSG, and the pinch-point temperature difference. To ensure operation in harsh conditions while allowing for flexible operation, the material selection for the HRSG tubing is critical. Once-through technology is an attractive option due to its flexibility, the avoidance of the steam drums, and, with the right material selection, the possibility to avoid the bypass stack while allowing for dry HRSG operation.

A suitable HRSG design for offshore applications, based on the results in Section 4 and the discussion in Section 2 could be:

- One pressure level
- Once-through technology
- No bypass stack
- Incoloy for tubing and piping material; TP409 for fin material
- Pinch-point temperature difference of 25 K; HRSG flue gas pressure drop of 25 mbar

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