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Article

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Determination of the optimum extraction pressure in a steam power cycle with only one bleed

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Abstract

In the years to come, a spectacular increase in electricity usage is foreseeable, partly due to the expansion of digital technologies and electric vehicles. Additionally, humankind must face the challenge of sustainable development. In this type of scenario, a significant proportion of electricity may be still generated by steam power cycles, but the usage of renewable energies, waste fuels and heat as energy sources will probably become more common. For some heat sources and depending on their characteristics, less regenerative cycles, i.e. with a lower number of steam extractions than those of the coal-fired power plants, are needed. In general, steam cycles have low thermal efficiency and a high number of hours of operation, which is why establishing an adequate criterion and method for choosing their parameters in the design conditions is of the utmost importance. Thus, with the design of plants in mind, the aim of this research is to propose an equation for choosing the pressure of the steam extraction of a regenerative steam power cycle with only one bleed that is driven to a deaerator. Based on a combination of thermal efficiency and economics, an equation that optimizes the pressure of the steam extraction has been obtained.

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Keywords: Deaerator; Extraction pressure; Net power; Steam power cycle; Thermal efficiency

1. Introduction

It is likely that the electricity usage will reach 40% of the rise in final energy use up to 2040 [1]. However, sustainable development needs significant and profound changes in the current energy system during the next decades, process known as energy transition. Thus, the future generation scheme will also require a significant contribution of renewable energies, an important decentralization of the system and a more efficient way of transforming primary energy into end-use energy. Among the technologies that do this transformation efficiently, combined heat and power production (CHP) has to be highlighted, since, in this type of plants, usable heat and

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Nomenclature

C	Yearly income for selling the electricity
I	Yearly cost associated with the acquisition of the biomass
LHV	Lower heating value of the biomass
P	Net power of the steam cycle
P_{cond}	Condenser pressure
P_{opt}	Optimum extraction pressure
P_{ss}	Superheated steam pressure
η	Thermal efficiency of the steam cycle

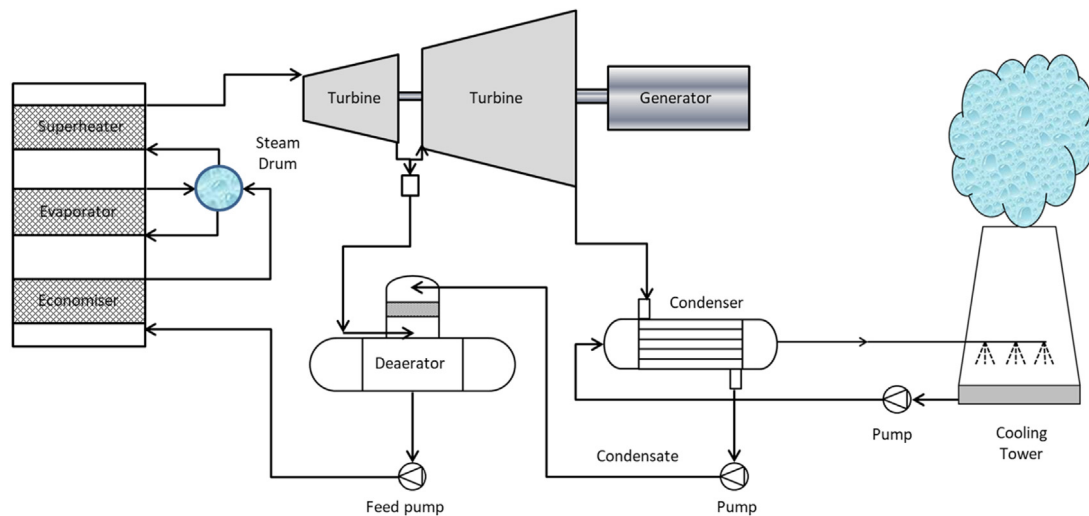


Fig. 1. Steam power cycle with one bleed.

electricity are generated in the same process. The CHP plants that use biomass as fuel often produce electricity by means of a steam power cycle [2]. Biomass-fueled small-scale CHP plants are a very interesting option in the future energy scenario, since they use a renewable energy, are adequate for a decentralized production scenario and transform energy efficiently. These small-scale plants have a net power ranging from 1 MWe to 20 MWe and some of them have relatively simple steam Rankine cycles with one steam extraction. Accordingly, due to their interest, their design optimization is a key aspect. Thus, the objective of this work is to find an expression for establishing the optimum pressure of the steam extraction easily.

2. Reference cycle

Fig. 1 shows the flow diagram of a steam power cycle that can use biomass as fuel. As can be seen in Fig. 1, the superheated steam from the steam generator flows to the turbine, where it expands to the condenser pressure. However, at an intermediate pressure, some steam is driven to the deaerator, in order to heat the feedwater, prior to its introduction into the steam generator. The condensate is pumped out of the condenser, to flow through the deaerator.

The thermodynamic behavior of the reference cycle has been simulated with Engineering Equation Solver (EES) [3] and THERMOFLEX [4] at several design conditions.

3. Criterion for establishing the optimum steam extraction pressure

The criterion chosen to determine the optimum pressure of the steam extraction to the deaerator is economic and based on thermal efficiency of the cycle and its net power. Thus, this pressure must be close to the one that

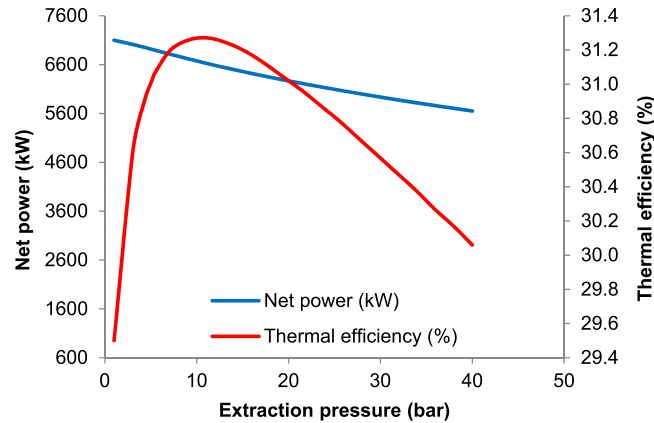


Fig. 2. Variation of the net power and the thermal efficiency of the reference cycle.

maximizes thermal efficiency but, additionally, a significant decrease in net power must be avoided. The simulations have shown that variables with a considerable impact on the optimum steam extraction pressure are the superheated steam pressure and the condenser pressure. Thus, a superheated steam temperature of 510 °C and a main steam flowrate of 7.9 kg/s have been chosen as fixed parameters for all the simulations [5], with these values the cycle net power is around 6 MW. Fixed values of the isentropic efficiencies of the turbine and the pumps (both condensate and feedwater) have been considered, these values being 0.9 and 0.8, respectively. For properly designed turbines, isentropic efficiency ranges from 85 to 90% [6]. On the other hand, the value for the isentropic efficiency of the pumps agrees with that assumed by other researchers [7–9]. No pressure drops in the steam generator, the condenser or the ducts have been considered.

For a superheated steam pressure of 60 bar and a condenser pressure of 0.68 bar, Fig. 2 shows how the steam extraction pressure to the deaerator alter thermal efficiency (η) and net power (P) of the cycle.

In Fig. 2, the maximum thermal efficiency corresponds to an extraction pressure of 11.3 bar. However, for this pressure, the decrease of the net power compared to that for an extraction pressure of 1 bar is quite important. Thus, not only a criterion based on efficiency should be considered, but an economic one. To apply an economic criterion, a biomass price of 4.5 \$/GJ has been chosen [10]. The exchange rate of 1 € to 1.1353 \$ has been used. However, it should be noted that biomass prices are highly variable, depending on the country, the type of biomass, the net power and the number of operation hours of the biomass plant. On the other hand, the electricity price is also very variable depending on the country and its power generation structure, the meteorological conditions and the balance between supply and demand. The average price of electricity for the year 2018 in the Spanish electricity market was around 57.3 €/MWh [11]. The maximum average monthly electricity price was 71.27 €/MWh, while the minimum average monthly price was 40.18 €/MWh [12]. Additionally, Khorshidi et al. [10] have reported an electricity price of 40 \$/MWh for a coal-biomass co-firing plant with a Renewable Energy Certificate in Australia. In this work, an electricity price of 58 €/MWh has been considered. The yearly income from selling the electricity (I) and the yearly cost associated with the acquisition of the biomass (C) have been calculated by the following equations:

$$I \left(\frac{\text{€}}{\text{year}} \right) = \frac{P \text{ (kW)} \cdot 0.99 \cdot 4500 \text{ (h)}}{10^3 \left(\frac{\text{kW}}{\text{MW}} \right)} \cdot \text{electricity price} \left(\frac{\text{€}}{\text{MWh}} \right) \quad (1)$$

$$C \left(\frac{\text{€}}{\text{year}} \right) = \frac{P \text{ (kW)} \cdot 4500 \text{ (h)}}{\eta \cdot LHV \left(\frac{\text{kWh}}{\text{kg}} \right) \cdot 10^3 \left(\frac{\text{kg}}{\text{t}} \right) \cdot 0.9} \cdot \text{biomass price} \left(\frac{\text{€}}{\text{t}} \right) \quad (2)$$

In Eq. (1), 0.99 is the electric generator efficiency [13], whilst 4500 is the equivalent number of hours per year that the plant operates at the rated power. In Eq. (2), LHV is the lower heating value of the biomass. In Eq. (2), 0.9 is the energy efficiency of the boiler [7]. A biomass LHV of 14 MJ/kg was considered [10].

For the above fixed values (biomass and electricity prices and biomass LHV), the maximum profit ($I - C$) is achieved for a deaerator extraction pressure of around 70% of the one that maximizes the thermal efficiency of the

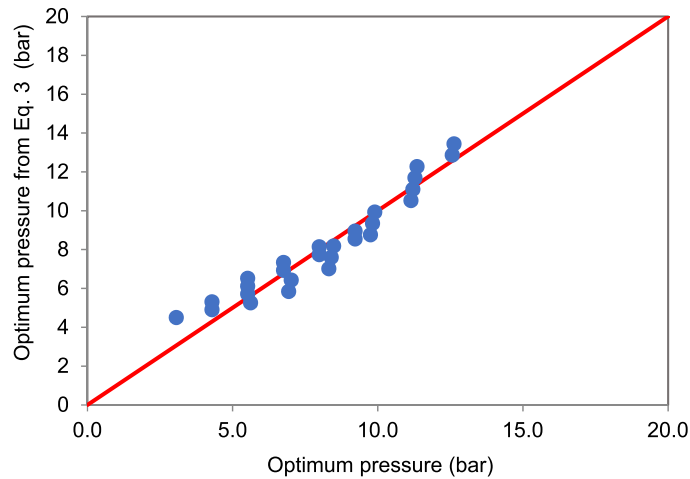


Fig. 3. Optimum steam extraction pressures calculated from Eq. (3) versus those obtained with EES software.

cycle. Nevertheless, if the biomass price decreases or its LHV increases, the maximum benefit shifts to a lower pressure. If the electricity price decreases, it shifts to a higher pressure. Therefore, it is difficult to establish the extraction pressure that maximizes profit. However, in order to avoid a significant decrease of the net power and thermal efficiency from their maximum values, the optimum extraction pressure value (p_{opt}) was defined as 60% of the one that maximizes the thermal efficiency of the cycle. For the specific case described in this section, the p_{opt} defined by means of this criterion is 6.8 bar, the relative decrease of thermal efficiency with respect to its maximum is 0.3%, and the relative decrease of net power with respect to its value with an extraction pressure of 1 bar is 3.9%.

4. Optimum pressure of the deaerator

4.1. Variables that affect the optimum pressure of the deaerator

As was previously mentioned, the variables that affect optimum extraction pressure are the respective pressures of the condenser and of the superheated steam. In order to determine the optimum extraction pressure, with the chosen criterion (60% of the one that maximizes the thermal efficiency of the cycle), the thermodynamic model of the cycle was run with EES for different values of superheated steam pressure for a constant condenser pressure. The relationship between the optimum extraction pressure (p_{opt}) and the superheated steam pressure (p_{ss}) was found to be linear ($R^2 > 0.9$). The results were also tested with THERMOFLEX.

Condenser pressure also has a significant impact on the pressure that maximizes the thermal efficiency of the cycle. Analogously, for a constant superheated steam pressure, there is also a linear relationship between p_{opt} and the condenser pressure (p_{cond}) ($R^2 > 0.9$).

4.2. Equation for determining the optimum steam extraction pressure

Taking into account the criterion explained in the previous sections, the optimum extraction pressure to the deaerator can be determined by Eq. (3) as a function of the superheated steam and condenser pressures (bias $-6.78 \cdot 10^{-9}$).

$$p_{opt} = 1.4 + 0.04 \cdot p_{ss} + 2.924 \cdot p_{cond} \quad (3)$$

In Eq. (3), p_{opt} , p_{ss} and p_{cond} are expressed in bar.

Fig. 3 contrasts the extraction pressure to the deaerator as determined by the chosen criterion with that calculated by Eq. (3). It shows that this equation fits satisfactorily.

The fact that the optimum extraction pressure was chosen as a fixed percentage of the one that maximizes the thermal efficiency can be generalized to all steam cycles with this configuration. Therefore, Eq. (3) can be applied

to steam power cycles with only one bleed, independently of the fuel used in the plant to produce electricity. Alexis [14] analyzed a cogeneration that has a steam power cycle with the configuration studied in this work. This cycle has a superheated steam pressure of 20 bar, a condenser pressure of 0.2 bar and an extraction pressure to the deaerator of 3 bar. Applying these values to Eq. (3), an extraction pressure to the deaerator of 2.8 bar is obtained, which shows that this equation may be adequate for choosing the extraction pressure.

5. Conclusions

For a steam power cycle with a single bleed to a deaerator, thermal efficiency and net power show different relationships to steam extraction pressure. Thermal efficiency shows a maximum, while net power decreases with this pressure. Therefore, it is important to establish the appropriate design pressure of steam extraction. The determination of this pressure based on an economic criterion is difficult, since fuel and electricity prices are highly variable depending on the circumstances of the moment and the country where the plant will be located. For this reason, a fixed percentage of 60% of the pressure that maximizes the thermal efficiency was chosen as criterion for establishing the optimum pressure of the steam extraction. This way, the decreases of both thermal efficiency and net power with respect to their maximum values are not so significant. It was observed that the parameters that most significantly affect the optimum pressure are superheated steam pressure and condenser pressure. Applying the chosen criterion, a linear equation to determine the optimum pressure from these two parameters was obtained.

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