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System analysis and optimisation of a Kalina split-cycle for waste heat recovery on large marine diesel engines

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ABSTRACT

Waste heat recovery systems can produce power from heat without using fuel or emitting CO2, therefore their implementation is becoming increasingly relevant. The Kalina cycle is proposed as an efficient process for this purpose. The main reason for its high efficiency is the non-isothermal phase change characteristics of the ammonia-water working fluid. The present study investigates a unique type of Kalina process called the Split-cycle, applied to the exhaust heat recovery from large marine engines. In the Split-cycle, the working fluid concentration can be changed during the evaporation process in order to improve the match between the heat source and working fluid temperatures. We present a system analysis to identify the governing mechanisms of the process, including a comparison of the efficiency of the Split-cycle and a conventional Kalina cycle and an investigation of the effects of using reheat in both cases. Results of a multi-variable optimisation effort using a genetic algorithm suggest that the Split-cycle process can obtain a thermal efficiency of 23.2% when using reheat compared to 20.8% for a conventional reference Kalina cycle. Reheat can increase the thermal efficiency by 3.4–5.9%. A simplified cost analysis suggests higher purchase costs as result of increased process complexity.

1. Introduction

Waste heat recovery (WHR) systems are able to generate mechanical power and electricity without any fuel input and associated CO_2 emissions. Hence, with rising fuel prices and increased environmental awareness, motivation is growing for integrating these systems to improve the energy efficiency of various processes.

The large marine diesel engine is particularly well suited to be coupled with a WHR system, whether it is applied for stationary small scale power production or for powering large ships. Although the diesel process is highly efficient, the engine looses a large part of the fuel energy to the environment, most importantly with the exhaust gasses which can contain about 25% of the input energy [1].

For large ships, the fuel expenses constitute about 30–55% of the total operational costs, depending on the type of vessel [2]. Hence, in times with high fuel prices, there are significant economic advantages associated with investing in a diesel engine exhaust WHR system [3]. The higher the fuel price, the larger investment in the WHR system can be allowed. Moreover, when considering very large ships, the large scale makes it feasible to consider relatively complex systems, compared to other WHR applications.

Recently, Choi et al. [4] analysed the application of an advanced WHR system for a large container vessel, consisting of a trilateral cycle and an organic Rankine cycle (ORC). It was concluded that significant reductions in fuel consumption and CO_2 emissions can be obtained. In general, WHR systems for combustion engines have received attention in the recent literature. Yu et al. [5] studied a combined cycle consisting of a diesel engine generator set and an ORC using the jacket cooling water and exhaust gas for additional power production. A 6% increase in thermal efficiency was predicted with the use of the ORC.

For the scale and heat source temperature level of application considered in the present work, both the ORC and the Kalina cycles have been studied using thermodynamic models. Bombarda et al. [6] compared the two processes applied for WHR on large marine engines and found that both cycles, when optimised, produced equal power outputs. Jonsson et al. [7] studied the Kalina cycle and two steam Rankine cycles in WHR systems for large diesel engines. It was predicted that the Kalina cycle can produce about 45% and 25% more power than a single and a dual pressure steam cycle. More recently, but utilising a heat source with a lower temperature, the economical performances of a Kalina cycle and an ORC were

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Acronyms

ORC	organic Rankine cycle
SC	Split-cycle
SUB	subcooled state
SUP	superheated state
USD	United States Dollars
WHR	waste heat recovery

Symbols

$\dot{m}$	mass flow rate (kg/s)
$\overline{U}$	overall heat transfer coefficient (W/m^2*K)
A	heat transfer area (m^2)
C	cost (USD)
h	specific enthalpy (kJ/kg)
P	pressure (bar)
q	vapour quality (−)
T	temperature (°C)
x	concentration by mass (−)

Subscripts

0	base
b	bubble point
c	cold stream
h	hot stream
i	inlet
lm	logarithmic mean
o	outlet
PP	pinch point
r	rich ammonia concentration

compared by Wang et al. [8]. The Kalina cycle was predicted to deliver power at a 15% lower cost than the ORC.

Research on the Kalina cycle is currently ongoing. In a recent study by Li et al. [9] it was proposed to substitute the traditional throttle valve with an ejector for improved efficiency. Wang et al. [8] optimised the thermodynamic and economical performance of a Kalina cycle using a multi-objective algorithm and presented a Pareto front useful for making decisions about the final process layout.

The main reason for the relatively high thermal efficiency of the Kalina cycle is the non-isothermal evaporation and condensation processes which occur because the working fluid is a zeotropic mixture of two fluids [10]. This enables a close matching of the temperatures of the heat source and the working fluid in the boiler, and between the heat sink and working fluid in the condenser(s). Among the many variations of the cycle, Alexander Kalina, the inventor of the Kalina cycle, has proposed a unique type of cycle layout that enables an even better match between the temperatures of the heat source and the working fluid. This is achieved by having an additional system of mixers and splitters to form two streams of working fluid with different mixture compositions that enter the boiler separately. A full description of this configuration, which Kalina named the Split-cycle (SC) [11], is provided in Section 2.2.

In the literature [11], the conceptual idea of the SC is described, but no thermodynamic analyses or modelling efforts are presented. Previous work by the present authors [12] investigated a method for the optimisation of this special Kalina process, finding that compared to a conventional Kalina cycle the SC process may be able to improve the thermal efficiency from 20.1% to 21.5%. However, the optimisation methodology was limited to including only the boiler and turbine components.

Further analyses showed that the potential of the process could not be found using this methodology, but an optimisation of the entire process is required. Due to the complexity of the process, a relatively large number of parameters needs to be optimised simultaneously. Thus using a comprehensive multi-variable optimisation method is required.

This study presents, first, a system analysis with the objective of identifying the governing mechanisms of the process. Second, the potential of the Split-cycle process, in terms of conversion efficiency, is investigated in the context of the marine diesel engine WHR using a genetic algorithm optimisation methodology. The performance of a reference Kalina process is compared to the Split-cycle process, and the potential effect of implementing reheat in both cycles is studied. Third, a simplified cost analysis is presented such that the cost of the additional process complexity can be evaluated against the efficiency.

Section 2 presents descriptions of the modelled processes, while Section 3 presents the methodologies of the modelling, the optimisation algorithm and the cost analysis. An analysis of the most important process mechanisms influencing the overall process efficiency is presented in Section 4 along with the optimisation results and the cost analysis. Section 5 provides a brief discussion of the findings.

2. Process descriptions

The reference Kalina process layout and the process conditions used throughout were the same as those presented in the work of Bombarda et al. [6]. Both the reference cycle and the Split-cycle were evaluated with and without using reheat in the turbine, in order to determine the influence of this technique on the processes.

In the following, the solution concentration running through the turbine is referred to as the *working solution*, and the terms *lean* and *rich* refer to a low and a high concentration of ammonia in the solution.

2.1. Reference Kalina cycle

Fig. 1 illustrates the flow diagram of the reference Kalina process with reheat. Starting from (21) to (1), the preheated working fluid is evaporated and superheated in the boiler before it enters the turbine (3). In the process layout that includes the reheat technique, the outlet stream from the turbine (3′) is heated in the boiler before entering (3″) a second turbine. When reheat is not included in the process, stream (3) runs directly from the turbine outlet (4) to Recuperator 1. From the stream (4) heat is transferred to the stream (10) in Recuperator 1. The stream (5) is then mixed with an ammonia lean stream from the separator (15) to form a leaner solution. This solution is condensed (7) and after being pumped to an intermediate pressure level, the stream (8) is divided into two streams (9) and (17). The stream (9) is heated in Recuperator 2 and in Recuperator 1 to a partially evaporated state. It then enters the separator which separates the stream into a lean liquid (12) and a very rich vapour (13). Heat from stream (13) is used to preheat stream (20) in Recuperator 3, and the stream (16) is then mixed with a leaner solution (17) to form the working solution (18). This stream is finally condensed and pumped to the boiler pressure.

2.2. Kalina split-cycle

Fig. 2 illustrates the flow diagram of the Split-cycle process. To maintain focus on the special split stream boiler, the Split-cycle