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Rankine cycle efficiency gain using thermoelectric heat pumps

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HIGHLIGHTS

- Rankine cycle electrical power plant fuel load reduced by over 1.5
- Thermoelectric heat pumps are used to increase the efficiency of the Rankine cycle.
- We scavenge the enthalpy released in the condenser for preheating the return water.
- We measure with a new test rig the optimum COP for maximum efficiency increase.
- We show a cost-benefit analysis of applying the system to a thermal power plant.

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ABSTRACT

The Rankine cycle remains the dominant method of thermal plant electricity generation in the world today. The cycle was described over 150 years ago and significant performance advances continue to be realised. On-going metallurgy research has enabled the operating pressure and temperature of the boiler and turbine to be increased, thereby improving the cycle efficiency. The ubiquitous use of the Rankine cycle on a massive scale in conjunction with fossil fuels as the energy source continues to motivate further efficiency improvements in the cycle.

Previous work established a theoretical basis for the use of thermoelectric heat pumps (THPs) in the condensation process of the Rankine cycle to positively impact cycle efficiency. The work presented here experimentally validates this prior work and provides performance metrics for current commercially available THPs and quantifies how their use can increase the efficiency of the Rankine cycle as implemented in a large power plant.

A commercial THP is characterised to obtain its Coefficient of Performance (COP) variation with input current and the amount of thermal energy transported. A larger-scale system comprising of a multistage thermoelectric heat pump is then considered, demonstrating that using commonly available THPs a fuel load reduction of over 1.5% is achievable for a typical 600 MW_e generating set whilst simultaneously increasing the overall plant cycle efficiency from 44.9% to 45.05%.

The paper concludes with a cost-benefit analysis of the system, showing that over a four year period the saving in fuel used can easily re-coup the capital cost incurred by the addition of the condenser heat pump.

1. Introduction

Globally, Rankine-cycle based power plants are the dominant means of electrical power generation. Large thermal power plants utilise high pressure and temperature steam to maximise the thermal to electrical energy conversion with, for modern plant, a cycle efficiency approaching 50% [1]. However, the majority of these plants derive their thermal energy from the combustion of fossil-fuels and, in doing so, emit large amounts of CO_2 [2]. This CO_2 release is the focus of EU policy and the European Commission's 'Roadmap for moving to a low-carbon economy in 2050' [3] presents the motivations to achieve an 80% reduction in greenhouse gas emissions by 2050.

CO_2 capture and sequestration (CCS) technologies will almost certainly be required in fossil-fuelled thermal power plants to achieve the reductions sought [4]. Three methods of CCS are widely regarded as being suitable for this task: (i) pre-combustion capture; (ii) post-combustion capture; and (iii) combustion in oxygen. All three processes are energy intensive and contribute to a significant reduction in overall plant cycle efficiency [5]. CCS is the

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Nomenclature

ΔT_{Cu}	temperature difference at Copper blocks in contact with the 'hot' and 'cold' surfaces of a thermoelectric heat pump
Δt	time (in seconds)
ΔT_w	temperature difference of water at the inlet and outlet of the water block
ΔT_{THP}	temperature difference between the 'hot' and 'cold' sides of the thermoelectric heat pump
$\dot{m}$	mass flow (kg/s)
$\dot{P}_{THP}$	electrical power supplied to the thermoelectric heat pump ($W_{e,electrical}$)
AC	Alternating Current
C_p	specific heat capacity at constant pressure
CAD	Computer Aided Design
CAPEX	Capital Expenditure
CCS	CO_2 Capture and Sequestration
$COP_{h,c}$	Coefficient Of Performance of heating or cooling
DC	Direct Current
$I_{max,opt}$	maximum and optimum currents applied to the thermoelectric heat pump (A)
IGCC	Integrate Gasification Combined Cycle
ORC	Organic Rankine Cycle
PCCC	Post Combustion CO_2 Capture
PID	Proportional Integral Derivative
PSU	Power Supply Unit
PWM	Pulse Width Modulation
Q_C	thermal energy absorbed by the 'cold' side of the thermoelectric heat pump ($W_{th,thermal}$)
Q_H	thermal energy generated by the 'hot' side of the thermoelectric heat pump ($W_{th,thermal}$)
TE	Thermoelectric
TEC	Thermoelectric Cooler
TEG	Thermoelectric Generator
THP	Thermoelectric Heat Pump
V_{max}	maximum applied voltage to the thermoelectric heat pump

primary technology necessary to meet present and future energy demands at acceptable carbon emission levels, however, other improvements in the thermal power plant must also be made to limit increasing costs [6]. Beer [7] examines the impact of reducing CO_2 emissions from thermal power plants and the associated penalties each of the various configurations introduce; these are summarised in Table 1.

The Carnot cycle describes the theoretical relationship between the temperature difference in the heat process and the maximum amount of work that can be extracted from the process [8]. The reduced efficiency of the Rankine cycle with respect to the Carnot cycle is a consequence of the lower average temperature of the heat input to the Rankine cycle. The Rankine cycle is always below this limiting condition due irreversibilities and losses inherent in the physical realisation of the process. However, the absolute electrical output and thermal efficiency of a Rankine cycle power plant can still be improved in a number of ways. Examples include varying the steam inlet pressure and temperature [9] and lowering the condenser pressure [10]. From a commercial perspective there is also the economic cost of cycle enhancements to be considered. A recent study of plant located in China [11] concluded that cost efficiency improvements are a significant driver in plant development and the reduction of CO_2 emissions. Similarly, the use of reheat cycles to increase the practically attainable efficiency is well documented [12,13], and investigation of the performance losses attributable to the cooling circuit directly impacts the up-time and availability of the plant [14].

The most commonly used heat transport fluid in the conventional Rankine cycle is pure H_20 for high temperature plant; for lower temperature or low-grade thermal sources organic fluids with a much lower boiling point may be substituted and are frequently referred to as Organic Rankine Cycles (ORC). Efficiency improvements can be achieved by applying the ORC to the plant in specific locations where energy is lost to the environment – so-called "bottoming cycles" – and these have been extensively investigated [15–21]. All, to a greater or less extent, improve the intrinsic cycle efficiency but at a financial cost.

Table 1
Summary of the impact on cycle efficiency of various CCS configurations.

	Subcritical plant	Supercritical plant	(*i*) IGCC	(*ii*) PCC	(*iii*) Oxycombustion
Cycle efficiency	34.3%	43.4%	31.2%	34.1%	30.6%

1.1. Heat pumps

Conventional heat pumps have been previously identified as a technology that can potentially aid the reduction in CO_2 emissions, while improving the net efficiency of energy intensive processes [22–25]. Further, there have been several applications of heat pumps in the literature of THP's replacing conventional heat pumps for air conditioning and refrigeration applications [26–28]. However, to date, little is available in the literature which considers the use of condenser heat pumps as an alternative to bottoming cycles and the authors are not aware of any investigations published which examine the use of thermoelectric heat pumps in this role.

Thermoelectric modules consist of *n*- and *p*-type semiconductors arranged in usually square arrays that can be used in two different ways: in heat pumping mode they utilise the flow of an electrical current through the module to produce a thermal gradient according to the Peltier effect, while in power generating mode they generate an electrical current in an external circuit from an imposed temperature difference, exploiting the Seebeck effect [29,30]. In the latter case they are usually referred to as thermoelectric generators (TEGs) and for the former, as thermoelectric heat pumps (THPs). The coefficient of performance in heating mode, COP_h, where the electrical input power is transported to the 'hot' side of the device is defined as the ratio of heat pumped (Q_H) to power input ($\dot{P}_{THP}$), and is expressed in Eq. (1).

$$COP_h = \frac{Q_H}{\dot{P}_{THP}}; \quad COP_c = \frac{Q_C}{\dot{P}_{THP}} \tag{1}$$

Thermoelectric devices do not use any harmful refrigerants, have no moving parts, are electrically and mechanically robust, are silent in operation and have a high inherent reliability [31]. These attributes make them an attractive option for power plant use where continuous service is a primary consideration.

Thermoelectric devices have been applied to refrigeration cycles [32] and some investigation of their application to electrical power generation in thermal power plants has been conducted [33–35]. However, for power generation from waste heat the output obtained is either so low as to be unviable, or their use has resulted in a net decrease of the overall plant efficiency, due principally to the low thermal to electrical conversion efficiency of the TEGs.