Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 75 (2015) 627 – 632
Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Experimental application of thermoelectric devices to the Rankine cycle

J. Siviter[a]*, A. Montecucco[a], A. Knox[a]

[a]Electronics and Nanoscale Research Division, School of Engineering, University of Glasgow, Glasgow, G12 8LT, UK

Abstract

Thermal plants operating on the Rankine cycle are by far the most common method of global electrical power generation. The Rankine cycle, first developed in the late 19th century, continues to this day to be one of the most important practical implementations of a heat engine. Innovation and enhancement of this cycle continue and today's emphasis is directed towards reduced carbon emissions from the combustion of fossil fuel as well as improvement of the absolute cycle efficiency. This paper presents a technique to increase in the Rankine cycle efficiency through reducing the waste heat rejected during the condensation phase by use of a thermoelectric heat pump. Firstly, this work derives a theoretical statement of the required Coefficient of Performance for viable economic operation. This is followed by an experimental investigation to determine if the calculated performance is available using today's thermoelectric technology.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: thermoelectrics; peltier effect; Rankine cycle; heat pump; cycle efficiency improvement

1. Introduction

1.1. Electricity generation and CO_2 emissions reduction

The global energy consumption is rising and according to the International Energy Agency (IEA) World Energy Report 2013 [1] the demand is set to increase from 4900 Mtoe (million tonnes of oil equivalent) to 8200 Mtoe by 2035. If world power generation needs continue according to current estimates (around 61%) then the Compound Annual Growth rate of CO_2 emissions will increase by 1.2% per annum. This level of increase is above the levels that are acceptable to mitigate a rise in global temperature [2]. Increasing levels of GHG and CO_2 emissions, and methods of mitigating these increases has been the subject of reviews, *e.g.* [3], and they conclude that reducing the impact of electricity-driven CO_2 emissions is critical to reducing such harmful emissions.

* Corresponding author. Tel.: +44-141-330-2180.
E-mail address: jonathan.siviter@glasgow.ac.uk.

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.472

Nomenclature

ΔT_{THP}	Temperature difference across a thermoelectric heat pump.
$COP_{h,c,}$	Coefficient of Performance of heating (h) or cooling (c).
Q_h	Thermal energy at the 'hot' side of the THP.
ΔT_W	Temperature difference measured across the water at the 'hot' side of the THP.
I, I_{max}	Current applied to the THP and the maximum current.
T_{wi},T_{wo}	Temperature of the water at the inlet and outlet at the 'hot' side of THP.
$Q_{e, process}$	Energy values in Rankine plant (electrical output, fuel thermal input energy)
η_{eff}	Cycle efficiency of the Rankine plant (%)

1.2. Thermoelectric Devices

Thermoelectric devices can be used in two operating modes: in heat pumping mode ("Thermoelectric Heat Pump"; THP) they utilise an electrical current to produce a thermal gradient according to the Peltier effect, while in power generating mode ("Thermoelectric Generator"; TEG) they generate an electrical current from a temperature difference, exploiting the Seebeck effect.

In order to experimentally assess the performance of a THP, the variation of the heat pumping (or cooling) capacity and the Coefficient of Performance ($COP_{h,c}$) with ΔT_{THP} across the device needs to be measured. At low temperature difference the $COP_{h,c}$ is larger because less energy is required for a specific heat flux. However, as the temperature difference increases, the amount of power required to shift the heat through the thermal gradient increases at a faster rate meaning that the relationship between input electrical power and resultant thermal power is not linear, but follows an exponential decay.

Using the experimental setup described in [4] and [5] the thermal energy at the "hot" side of the heat pump (Q_h) was measured as a function of the increase in water temperature used to remove the thermal energy from the apparatus (ΔT_W). As the ΔT_{THP} increases, so the electrical input power must increase and hence the COP_h curve peak moves to the right along the x-axis, corresponding to an increased value of I/I_{max}, where I_{max} is the value of electrical current flowing in the THP which yields the greatest heat transport through the device. The experimental data obtained in [6] shows that the greatest COP_h available from the heat pump is in the region between $0.1I/I_{max}$ and $0.3I/I_{max}$ where I/I_{max} is the normalized current ratio independent of the maximum heat pumping power achieved during testing.

2. Modification to the Rankine cycle

The regenerative cycle applied to the Rankine cycle adds thermal energy to the returning feedwater, resulting in increased plant efficiency [7], [8]. The work presented here investigates the potential for recovering useable thermal energy in the condenser of the Rankine cycle. The proposed solution uses a heat pump to capture a portion of the enthalpy released as low-grade thermal energy in the isothermal conversion of the low pressure steam to liquid after the last turbine stage in the power plant. By redirecting this energy back to the process, rather than rejecting it to the environment, the scavenged energy is used to raise the temperature of feedwater returning to the boiler, thereby displacing some of the plant's fuel load. Thermoelectric heat pump devices are considered suitable for this application because they do not use any harmful refrigerants and are known to be reliable with a very long working life [9].

A frequent application for thermoelectric devices is the refrigeration cycle [10]. Others [11] have investigated the performance of a TEG system placed in the flow of flue gas exiting the boiler of a $10MW_e$ Rankine cycle thermal power plant. The use of 'topping' cycles is well documented in the literature [12], [13]. Reheat and regeneration cycles are also implemented in current generation Rankine cycle thermal power plants and, despite extracting thermal energy from the plant, they return a net improvement in efficiency. There are further examples in the literature [14], [15] where the Organic Rankine Cycle (ORC) is applied in conjunction with fluid circulating from a solar collector to replace the steam traditionally bled for feedwater heating. However, these systems add mechanical complexity and a focus of the work presented here is to experimentally evaluate a system that does not potentially reduce the plant reliability.

There is some work [16]–[18] in the literature on ‘bottoming’ cycles with the condenser serving as the evaporator in the ORC. Kyono et al. [19] have shown the application of TEGs to the condenser of the Rankine cycle, specifically on the surface of pipes that are open to the exit of the low pressure turbines able to generate 0.78% of the electrical output of the plant but at the expense of an impractically large number of thermoelectric generators with very high associated cost. The application that we have already presented in [5], [20], however, focuses on a thermoelectric heat pump. By using the THP in the condenser the low-grade enthalpy of condensation can be extracted and converted to an increase in thermal energy at the opposite side of the THP, thereby reducing the fuel load of the plant. The scavenged energy can then be transferred to the water returning to the boiler for reheating. The work presented here extends the application of a THP to the condenser of a thermal power plant in order to increase the overall process efficiency. To this end a small-scale experimental model of a regenerative steam cycle that incorporates a steam expansion stage and condenser-mounted thermoelectric heat pump has been developed to explore the effect of thermodynamic modifications to the Rankine cycle.

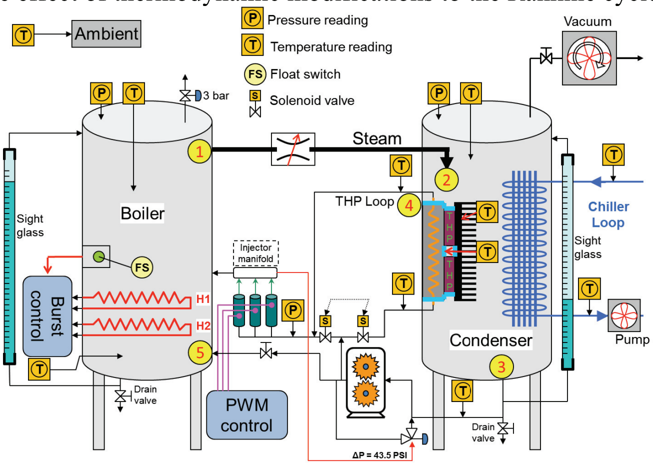


Fig. 1: Model of the small scale Rankine cycle

A fundamental requirement for viable use of condenser heat pumping is to ensure that the input power does not exceed the point at which use of the system detracts from the overall cycle efficiency. Prior work [20] has determined theoretically that the point at which the heat pump becomes beneficial is when the COP_h exceeds the reciprocal of the cycle efficiency, shown in equation (1). The aim of the work presented here is to experimentally validate this result.

$$COP_{min} = \frac{Q_{process}}{Q_e} = \frac{1}{\eta_{process}} \tag{1}$$

3. Experimental setup of a THP to the Rankine cycle

The apparatus developed and shown in Fig. 1 has approximately $6kW_{th}$ of heating power. This is around 200,000x smaller than a conventional thermal power plant generating $660MW_e$ of electrical power. This scaled reduction exacerbated some effects which are present but would not normally be an issue in the full-scale plant. The working fluid is water and the whole system is sealed relative to atmospheric pressure. In order to closely approximate the larger-scale power plant condenser operation, the model’s steam conditions are matched: the operating temperature and pressure at cycle equilibrium are 33°C and 45mbar-absolute.

With reference to Fig. 1, for the ‘standard’ Rankine cycle operation steam is generated in the boiler and exits at point (1). Steam is then expanded through a gate valve and enters the condenser at point (2) at reduced pressure. Within the condenser the latent heat of condensation of the steam is removed by it coming into contact with pipes of a refrigeration loop and the fins of the THP heatsink, both held below the ‘dew’ point. The condensate drops by gravity to the bottom of the condenser at point (3) and flows to a positive displacement pump located below the base of the condenser[†]. Steady-state in this context is defined as the condition where the mass flow of steam leaving the boiler exactly equals the mass flow to the boiler, at point (5). A modified internal combustion engine fuel injection system provides the metering of the flow returning to the boiler. The thermoelectric heat pump input power, along with numerous other variables including time, pressures and temperatures, are monitored by a software program (Agilent VEE Pro). The software also stabilises the boiler to maintain a constant boiling state by regulating the input power.

4. Experimental results using Rankine cycle test apparatus

The energy consumption in the Rankine cycle test apparatus is quantified by how much the process water changes in energy and enthalpy at each point in the system. The system is brought to steady state conditions, the boiler was held at 63°C, 230 mbar-abs and the condenser was held at 45mbar-abs giving a water boiling temperature of 35°C. The vacuum pump was used only during the start-up phase to remove non-condensable air from the boiler and condenser vessels.

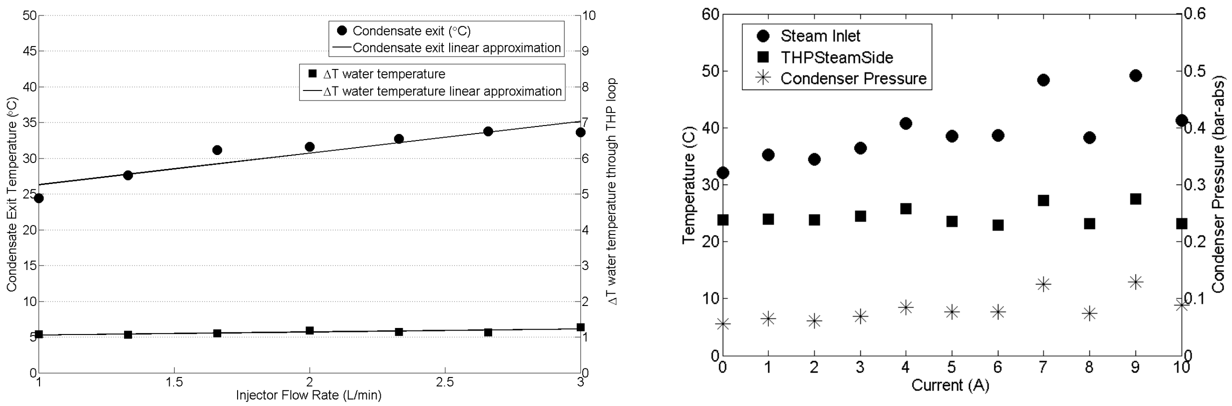


Fig. 2 (a): Increasing flow rate with the THP disconnected; (b) Condenser pressure and temperature at increasing current to the THP

The heat pump fluid circuit was switched in but the THP itself remained off in order to characterize the temperature rise in the THP loop for various flow rates as an unavoidable consequence of thermal energy from the condenser leaking into the loop. Fig. 2 (a) presents the resultant averaged data for several experimental runs. At low injection rates the water temperature at the condensate exit (which feeds the THP loop directly) remains constant around 23°C therefore any rise in the THP loop can be attributed to thermal energy leaking inside the condenser through the pipework supporting the THP. Therefore a flow rate of 1L/min was selected for operation of the THP loop with the THP enabled. The graph of water temperature difference in the THP loop (T_{wo}-T_{win}) shows the presence of an offset of 1°C ±5% and, as expected, is subject to a decrease as the injector flow rate increases. The THP loop was then enabled and the input electrical current to the THP was incremented in steps of 1A up to 10A. Fig. 2 (b) shows the prevailing conditions for condenser pressure, steam inlet and the steam side (‘cold’ side) temperature of the THP for each current value at a flow rate of 1L/min through the injectors.

† In the experimental apparatus the vertical distance between the base of the condenser and the pump was less than a metre. Coupled with an operating pressure of 45mBara, this initially caused pump cavitation – something not experienced in the full scale plant.

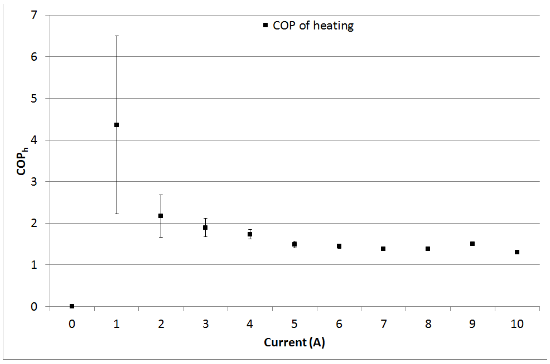


Fig. 3: COP in heating mode with adjusted ΔT_w measured at flow rate=1L/min.

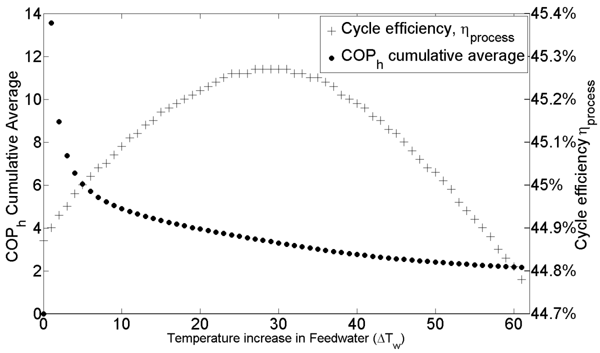


Fig. 4: Cumualtive COP_h average and optimum plant efficiency (η_{eff}) at increasing feedwater temperature increments (ΔT_w)

Steam is condensed on to the fins of the heat-sink in response to power being applied to the THP. In order to calibrate the data, the water temperature from the test with no THP is combined with the offsets from Fig. 2 (a) and subtracted from the measured water temperature in the THP where current is applied. The data in Fig. 3 shows the characteristic peak of high COP_h at low current followed by a gradual decay to a COP_h of unity at high heat pump power where Joule heating dominates the behaviour.

5. Results analysis

The COP_h curve in Fig. 3 follows the general shape of the COP curves noted previously by the authors [6]. The absolute values are somewhat different, due to the apparatus in use, but the trend remains the same. Despite careful attempts to mitigate errors and unwanted effects introduced by the extreme scale reduction of the test apparatus compared to actual power plant there is a deviation from idea performance in the results obtained. The principal causes of error are attributed to the proximity of the condenser coils and the THP system and the difficulty in thermally isolating the THP loop from the steam supply in a physically confined condenser volume.

The primary finding of importance is that the minimum COP_h to be met which dictates if the THP would be beneficial to the plant is exceeded so long as the COP_h remains above 2.2 for a 44.9% efficient Rankine cycle plant. Further, by breaking the THP system in to a series of steps it is possible to attain a higher temperature increase in the feedwater returning to the boiler.

There are three modes of operation that make this beneficial to the plant: the first is maintaining an above-breakeven cumulative average COP_h and the second is maintaining the minimum useful benefit condition. The above-breakeven point is described in equation 1 as 2.2 and gives a maximum feedwater temperature of 59°C, 26°C above the condensate temperature. As a result, 27.49MW_{th} is retained in the Rankine cycle giving an efficiency increase of 0.4%. The 'minimum useful benefit' condition is attained by the THP devices pumping larger feedwater temperatures, but at successively lower COP's. As the COP_h of a THP approaches unity this remains beneficial to the plant and provides useful heating effects. The maximum temperature difference that can be attained is 57°C, resulting in a feedwater return temperature of 89°C. These two situations break the THP block into a series of smaller stages and result in a higher temperature rise as more THP devices are added. This is akin to higher compressor efficiencies attainable as more small stages are added in series, rather than implementing the whole compression ratio in a single stage. This is also the method employed in feedwater heaters in current plant. The third mode of operation is, however, potentially of the greatest interest to plant operators – that which maximizes the overall efficiency gain of the heat pump series. The graph in Fig. 4 shows the overall cycle efficiency as a function of the ΔT on the feedwater ΔT_w. The last-stage COP_h for the maximum value has dropped to 1.69 but the cumulative average is a COP_h of 3.36. The peak cycle efficiency is 45.27% - an improvement of 0.4%.

6. Conclusions

This paper has experimentally verified that there is potential to improve the cycle efficiency of a thermal power plant by harvesting thermal energy normally rejected by the condenser. Today's thermoelectric materials have attained the performance level that makes them a viable technology to apply this solution. The economic feasibility of using large number of THP devices does not form part of this work and remains to be investigated, noting that the rapid expansion of the use of thermoelectric materials by the automotive industry is quickly driving down material prices. Further work will detail the implementation of a $100kW_{th}$ Rankine cycle experiment that replicates power plant steam conditions and examines the mechanical implementation required. The economic case for a plant of this size will also be investigated and depends ultimately on the performance of future thermoelectric devices, based on Manganese Oxides and other materials with higher efficiencies. However, using today's materials and devices the technical and economic case for condenser heat pumping has been proven and could lead to a further 0.4 points of cycle efficiency in a modern supercritical power station.

References

[1] IEA, "World Energy Outlook 2013," pp. 1–82, Nov. 2013.

[2] V. K. Arora, J. F. Scinocca, G. J. Boer, J. R. Christian, K. L. Denman, G. M. Flato, V. V. Kharin, W. G. Lee, and W. J. Merryfield, "Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases," *Geophys. Res. Lett.*, vol. 38, no. 5, pp. 3–8, Mar. 2011.

[3] S. Pacala and R. Socolow, "Stabilization wedges: solving the climate problem for the next 50 years with current technologies.," *Science*, vol. 305, no. 5686, pp. 968–72, Aug. 2004.

[4] A. Montecucco, J. Buckle, J. Siviter, and A. R. Knox, "A New Test Rig for Accurate Nonparametric Measurement and Characterization of Thermoelectric Generators," *J. Electron. Mater.*, vol. 42, no. 7, pp. 1966–1973, Mar. 2013.

[5] J. Siviter, A. Knox, J. Buckle, and A. Montecucco, "Megawatt scale energy recovery in the Rankine cycle," in *ECCE2012*, 2012, pp. 1374–1379.

[6] J. Siviter, a. Montecucco, and a. R. Knox, "Rankine cycle efficiency gain using thermoelectric heat pumps," *Appl. Energy*, vol. 140, pp. 161–170, Feb. 2015.

[7] J. M. Salazar, U. Diwekar, E. Constantinescu, and V. M. Zavala, "Stochastic optimization approach to water management in cooling-constrained power plants," *Appl. Energy*, vol. 112, pp. 12–22, Dec. 2013.

[8] A. Borsukiewicz-Gozdur, "Exergy analysis for maximizing power of organic Rankine cycle power plant driven by open type energy source," *Energy*, vol. 62, pp. 73–81, Dec. 2013.

[9] D. M. Rowe, "Applications of nuclear-powered thermoelectric generators in space," *Appl. Energy*, vol. 40, pp. 241–271, 1991.

[10] G. Min and D. M. M. Rowe, "Experimental evaluation of prototype thermoelectric domestic-refrigerators," *Appl. Energy*, vol. 83, no. 2, pp. 133–152, Feb. 2006.

[11] T. Furue, T. Hayashida, Y. Imaizumi, T. Inoue, K. Nagao, A. Nagai, I. Fujii, and T. Sakurai, "Case study on thermoelectric generation system utilizing the exhaust gas of interal-combustion power plant," in *Thermoelectrics, 1998. Proceedings ICT 98. XVII International Conference on*, 1998, no. 1, pp. 473–478.

[12] S. Yamaguchi, N. Kondoh, I. Yonenaga, Y. Hasegawa, and T. Eura, "New Proposal of High Temperature Thermoelectric Conversion In Power Plant," in *1999. Eighteenth International Conference on Thermoelectrics*, 2004, pp. 1–4.

[13] K. Yazawa, Y. R. Koh, and A. Shakouri, "Optimization of thermoelectric topping combined steam turbine cycles for energy economy," *Appl. Energy*, vol. 109, pp. 1–9, Sep. 2013.

[14] H. Hou, J. Mao, Y. Yang, and N. Luo, "Solar-Coal Hybrid Thermal Power Generation — an Efficient Way to Use Solar Energy in China," *J. Energy Eng.*, vol. 2, pp. 137–142, 2012.

[15] R. Yang, G. Chen, a. Ravi Kumar, G. J. Snyder, and J.-P. Fleurial, "Transient cooling of thermoelectric coolers and its applications for microdevices," *Energy Convers. Manag.*, vol. 46, no. 9–10, pp. 1407–1421, Jun. 2005.

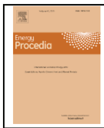
[16] C. Wang, B. He, S. Sun, Y. Wu, N. Yan, L. Yan, and X. Pei, "Application of a low pressure economizer for waste heat recovery from the exhaust flue gas in a 600MW power plant," *Energy*, vol. 48, no. 1, pp. 196–202, Dec. 2012.

[17] K. M. Mohamed, M. C. Bettle, A. G. Gerber, and J. W. Hall, "Optimization study of large-scale low-grade energy recovery from conventional Rankine cycle power plants," *Int. J. Energy Res.*, vol. 34, no. 12, pp. 1071–1087, 2009.

[18] B. Liu, P. Rivière, C. Coquelet, R. Gicquel, and F. David, "Investigation of a two stage Rankine cycle for electric power plants," *Appl. Energy*, vol. 100, pp. 285–294, Dec. 2012.

[19] T. Kyono, R. O. Suzuki, and K. Ono, "Conversion of unused heat energy to electricity by means of thermoelectric generation in condenser," *IEEE Trans. Energy Convers.*, vol. 18, no. 2, pp. 330–334, Jun. 2003.

[20] A. R. Knox, J. Buckle, J. Siviter, A. Montecucco, and E. McCulloch, "Megawatt-Scale Application of Thermoelectric Devices in Thermal Power Plants," *J. Electron. Mater.*, 2013.



Biography

J. Siviter is a Research Assistant at the University of Glasgow in the Thermoelectric Systems research group. He obtained his PhD in Electronics and Electrical Engineering 2014 and he also holds an M.Eng in Electrical Engineering obtained in 2010.