Waste heat recovery potential from industrial bakery ovens using thermodynamic power cycles

Jahedul Islam Chowdhury[a*], Faisal Asfand[a], Yukun Hu[b], Nazmiye Balta-Ozkan[a], Liz Varga[b] and Kumar Patchigolla[a]

[a] School of Water, Energy and Environment, Cranfield University, Bedford, UK, (J.I.C: J.Chowdhury@cranfield.ac.uk; F.A: Faisal.Asfand@cranfield.ac.uk; N.O: n.ozkan@cranfield.ac.uk; K.P: k.patchigolla@cranfield.ac.uk)
[b] Department of Civil, Environmental and Geomatic Engineering, University College London, London, UK, (Y.H: yukun.hu@ucl.ac.uk; L.V: l.varga@ucl.ac.uk)
[*]Corresponding author

Abstract:

This paper investigates the potential for waste heat recovery from industrial bakery ovens and its conversion into electricity using thermodynamic power cycles. Three prominent cycles: supercritical CO_2 Brayton cycle (s-CO_2), trilateral cycle (TLC) and organic Rankine cycle (ORC) are selected and optimized for maximum net power to demonstrate the cycles' performance under steady heat input conditions. This study is extended to perform sensitivity analysis of the cycles' performance against a set of input variables. Results show that a higher thermal efficiency of 26.5% is achievable in the case of ORC cycle with n-pentane as a working fluid compared to s-CO_2 and TLC with a cycle thermal efficiency of 22.1% and 18.8%, respectively. Results also show that the ORC, the most preferable cycle, can avoid around £23,204 of annual electricity cost if the cycle is integrated with an industrial oven that generates waste heat at a mass flow rate and temperature of 1 kg/s and 250 ºC, respectively.

Keywords:

Waste heat recovery, Supercritical CO_2 Brayton cycle, Trilateral cycle, Organic Rankine cycle, Thermodynamics, Energy efficiency.

1. Introduction

The UK is legally bound to reduce its greenhouse gas (GHG) emissions by both national and international regulations, of which the most radical target was set to reduce 80% emissions by 2050 [1]. This ambitious target has to be met by cutting emissions and reducing energy demand from all energy consuming sectors. In UK, industrial energy use is responsible for 25% of total GHG emissions in 2016 which equates to 100 $MtCO_2e$, of which 8% is from the food and drink sector [2]. The food and drink sector is a highly heat intensive and diverse sector that consists of many sub-sectors: grocery, bakery, meat and poultry, beverage, fish processing, etc. Among them bakery has the highest energy consumption (approx. 15%) due to extensive burning of natural gas for heat in ovens that produces an estimated 4.1 billion units of breads, bakery snacks and other bread products per year, and has an estimated market value of £3.6 billion/year [3]. Bread is made from dough, which is a mixture of flour and water, through baking. The details of the bread making process are shown in Fig. 1. The entire manufacturing process is a heat intensive process that is controlled carefully, particularly the baking process which takes place at a temperature of 230-270 ºC for around 25 minutes [4]. A significant amount of heat from ovens is ended up as waste with temperatures up to 250ºC [5]. The waste heat at this temperature provides an opportunity for waste heat recovery through in-process recovery, e.g. air preheating for combustors, sub process recovery such as heat to prover, and heat to electricity conversion using thermodynamic power cycles [6]. Although the waste heat from bakery ovens for air preheating purpose is commonly known and partially implemented in UK bakeries, previous research on industrial bakery ovens has not examined opportunities for on-site waste heat recovery through heat to electricity conversion cycles. Therefore, this paper focuses on energy efficiency improvement potential offered by waste heat from an industrial bakery oven through thermodynamic power cycles.

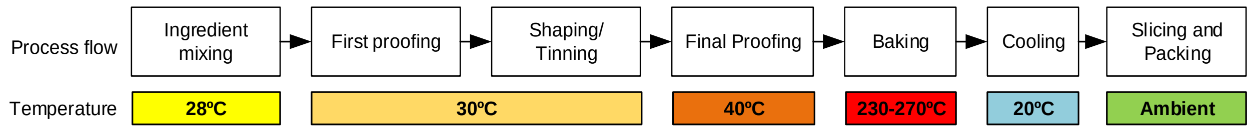

Figure 1. Flow chart of commercial baking processes

2. Methodology

There are many thermodynamic power cycles that can be used for heat to electricity generation such as traditional Rankine cycle, organic Rankine cycle, Kalina cycle, Otto cycle, Stirling cycle, etc. Due to temperature limitations, not all cycles are suitable for all types of heat recovery applications. More specifically, the selection of power cycles for a particular application is to be made according to heat source temperatures along with nominal efficiency of cycles. Since waste heat from bakery ovens are low to medium grade energy (up to 250ºC), this research considers three promising power cycles: supercritical CO_2 Brayton cycle (s-CO_2), Trilateral cycle (TLC) and organic Rankine cycle (ORC). Schematic diagram and temperature-entropy diagram of the cycles are shown in Fig. 2. All the selected cycles have the potential for high thermal efficiency and are suitable for waste heat recovery with temperatures at this level which is supported from literatures [7–12].

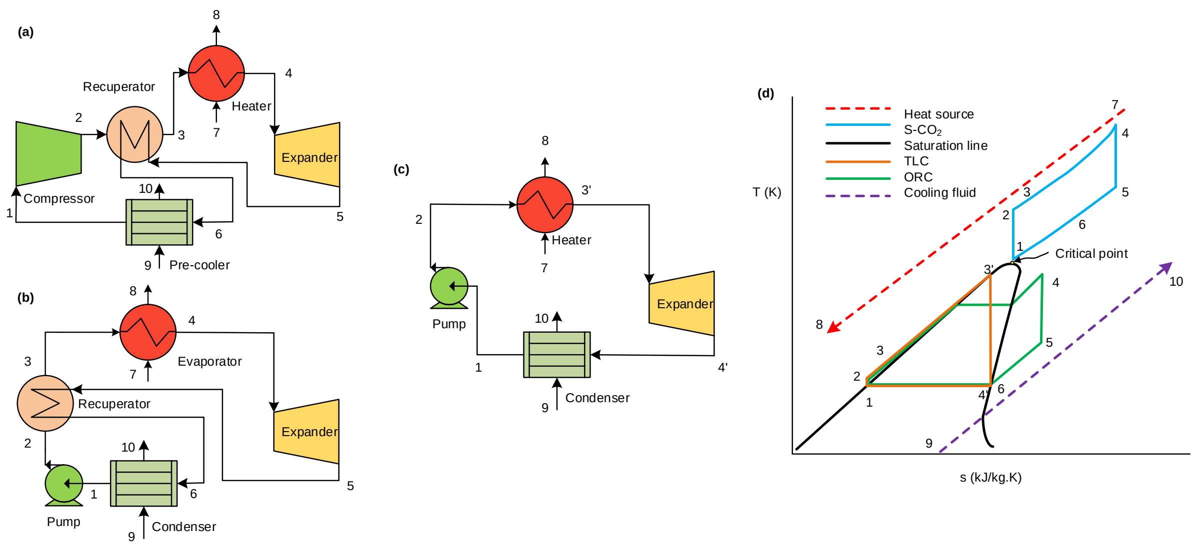

Figure 2. Cycle configurations: (a) Supercritical CO_2, (b) ORC, (c) TLC and (d) T-S diagram of all cycles

In case of s-CO_2 and ORC, the cycles comprise of a pump or compressor, an evaporator or heater, a recuperator, an expander or turbine and a condenser, as shown in Fig. 2(a),(b). Both the s-CO_2 and ORC are expected to operate at a superheated condition at the inlet of the turbine/expander. The TLC, however, is limited to operate at a saturated liquid condition at the inlet of expander. This boundary limit for the TLC provides a higher potential for heat recovery due to a better thermal match between a working fluid and heat sources [13]. The operation principles of the s-CO_2 and ORC and TLC are similar except that the former cycle uses a compressor instead of a pump. A working fluid at the pump/compressor is pressurized from a state point 1 to 2 (see Fig. 2 (d)), then the fluid is heated up (points 2-3) at the recuperator by the superheated fluid from the exhaust of the expander (points 5-6) before the fluid is superheated (points 3-4) by a waste heat source (points 7-8) and expanded in the expander (points 4-5). The working fluid from the recuperator is cooled at the condenser to its sub-cooled state (points 6-1) by cooling water (points 9-10). The design and operation principle of the TLC is similar to other cycles except that it has no recuperator as can be seen in Fig. 2(c). It was found that a recuperator, which recovers the latent heat from the expander exhaust, in such a cycle can improve the heater/evaporator performance and increase the thermal efficiency of the cycle [14, 15]. However, since the expansion of the TLC takes place from a saturated liquid state, the expander exhaust (points 4' in Fig. 2(d)) offers no potential heat to recover at the recuperator. Therefore the recuperator in the TLC was ignored in this study.

Individual components of the selected cycles are modelled thermodynamically where mass and energy conservation equations are applied as follows:

The mass conservation equation:

$$\sum \dot{m}_i - \sum \dot{m}_o = 0 \tag{1}$$

The energy conservation equation:

$$Q - W = \sum \dot{m}_f h_f - \sum \dot{m}_i h_i \tag{2}$$

The net work output:

$$W_{net} = W_{\exp} - W_p \tag{3}$$

The cycle efficiency:

$$\eta_{cy} = \frac{W_{net}}{Q_i} \tag{4}$$

where $\dot{m}$ is the mass flow rate in kg/s, Q is the heat input in kW, W is the work output in kW, h is the specific enthalpy in kJ/kg, and subscripts $i, o, f, \exp, p$ represent the inlet condition, outlet condition, final condition, expander or turbine, pump or compressor, respectively.

The working fluids and the operating conditions presented in Table 1 are used for the simulation of the selected cycles. The selection of working fluid, particularly, for TLC and ORC is very important as it influences the cycle efficiency, equipment sizing requirement and cycle configuration arrangement. The working fluid selected for this work was n-pentane for both the TLC and ORC and CO_2 for s-CO_2 cycle. N-pentane is a dry fluid and has good thermo-physical properties that are suitable for low and medium grade heat recovery applications. Thermodynamic simulation of the selected cycle was performed in Thermoflex simulation tool, while the REFPROP database was used to calculate the thermodynamic properties of s-CO_2 and n-pentane. In the simulation a constant pinch value of 5 K was assumed for all heat exchangers used in the cycles.

Table 1. Base case operating parameters of s-CO_2, TLC and ORC.

Cycle	Working fluid	Maximum pressure (bar)	Minimum pressure (bar)	Heat source temperature (°C)	Pump/ compressor efficiency	Expander efficiency
s-CO_2	CO_2	250	76	250	0.85	0.9
TLC	n-pentane	30	1	250	0.85	0.9
ORC	n-pentane	30	1	250	0.85	0.9

3. Results and discussions

The steady state thermodynamic models of the selected cycles developed in the previous section is simulated with a waste heat (exhaust gas) from an industrial bakery oven at a temperature and mass flow rate of 250 °C and 1 kg/s, respectively. The exit temperature of the waste heat from the power cycles was restricted to 110 °C to prevent the gas being cooled below acid dew point temperature and any formation of acid. Thermodynamic analyses were first performed for the base case. A sensitivity study was then carried out to investigate the impact of heat source temperature and flue gas mass flow rate on the cycle thermal efficiency and net power generation. The sensitivity analyses include a variation of mass flow rate and temperature of exhaust gas at 0.5-1.5 kg/s and 230-270 ºC, respectively. The performance of the cycles were optimized in all conditions and the base case results are presented in Table 2, while the sensitivity analyses results are shown in Figs. 3-5. It can be seen from Table 2 that a higher thermal efficiency (26.51%) is achieved in the case of ORC with n-pentane as a working fluid compared to the TLC (18.77%) and s-CO_2 (22.09%) cycle. The reason for a lower efficiency in the case of TLC is that the turbine inlet condition was fixed at a saturation liquid state due to its thermodynamic design limitation as shown in Fig. 2(d). Moreover, a recuperator was not used in the case of TLC because of a lower temperature at the turbine exhaust which make the cycle less efficient. However the capital cost of the TLC tends to be lower because of fewer components.

Table 2. Performance of s-CO_2, TLC and ORC under base case scenario.

Cycle	Heat input (kW)	Net power output (kW)	Thermal efficiency (%)	Annual energy saving (kWh) (avg. operating hours: 7000)	Annual cost saving (£) (based on 10.10p/kWh)
s-CO_2	142.5	31.11	22.09	217770	£21995
TLC	142.5	22.32	18.77	156240	£15781
ORC	142.5	32.82	26.51	229740	£23204

Industrial bakeries in the UK run around 7000 hours per year without any waste heat to electricity conversion technologies. Once the proposed cycles are integrated with a single oven of an existing plant, an estimated annual cost saving for electricity could be up to £23,204 for the ORC, £21,995 for the s-CO_2 and £15,781 for the TLC. However, this economic saving does not take into account the capital investment cost of the power cycle. Since industrial bakeries have more than one baking line and therefore multiple ovens, the annual savings can be increased further with the integration of more power cycles to their baking lines.

Fig. 3 shows the effect of flue gas temperature on the net power output. As expected, the net power of all three cycles increases with the increase in exhaust flue gas temperature. A 50% increase in the net power is observed in the case of ORC and s-CO_2 cycle whereas net power increases by 35% in the case of TLC when the flue gas temperature is increased from 230 °C to 270 °C. Thermal efficiency of the ORC and s-CO_2 cycle also increases with the increase in heat source temperature as shown in Fig. 4. However in the case of TLC the efficiency remains constant which is because of the fixed saturated liquid condition at the turbine inlet. With the increase in heat source temperature, although the turbine inlet condition is fixed however more amount of refrigerant is expanded hence a higher net power is achieved in the case of TLC.

Sensitivity studies were also carried out to investigate the effect of flue gas mass flow rate on each cycles' performance. Fig. 5 shows the effect of flue gas mass flow rate on the cycles net power output. A linear increase in the net power is achieved in the case of all the three cycles when the flue gas mass flow rate is varied from 0.5 kg/s to 1.5 kg/s. It is worthy of note that the thermal efficiency of all three cycles remains constant as the turbine inlet condition doesn't vary when the flue gas mass flow rate is varied. With the increase in flue gas mass flow rate more amount of refrigerant can be expanded at the same operating conditions and hence a higher net power is achieved in all the cases.

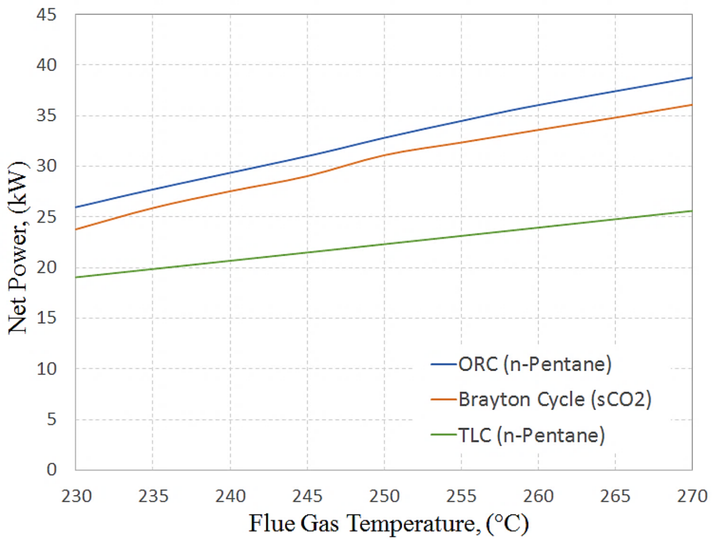

Figure 3. Effect of heat source temperature on net power output

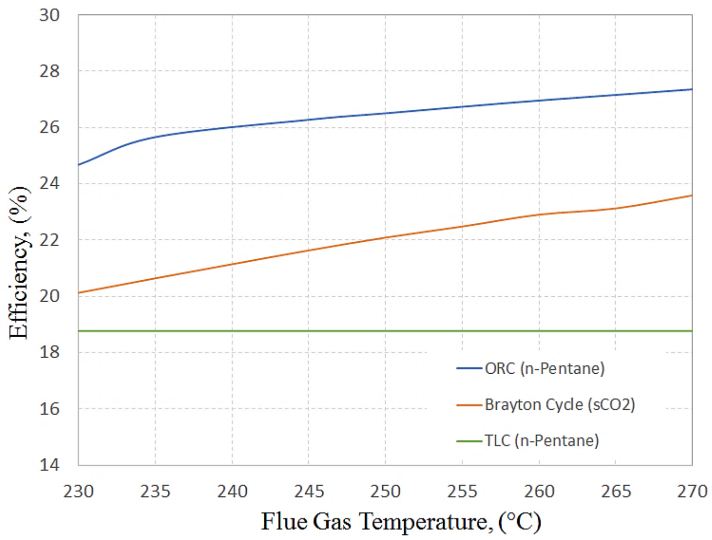

Figure 4. Effect of heat source temperature on cycle efficiency

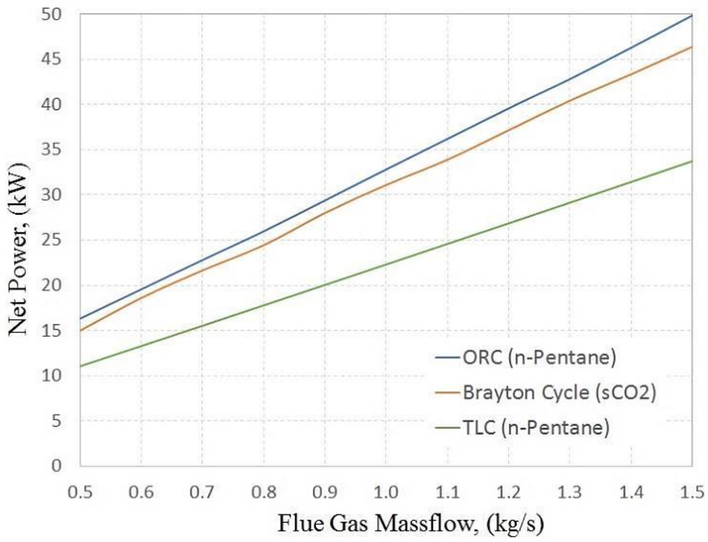

Figure 5. Effect of flue gas flow rate on net power output

3. Conclusions

This paper investigates the potential for waste heat recovery from industrial ovens with s-CO_2, TLC and ORC power cycles at their optimized conditions. The optimized results show that ORC has a higher potential for generating more net output at a higher thermal efficiency leading to a higher annual electricity cost avoidance than the other cycles. In contrast, the performance of the TLC is found to be the lowest. Although the TLC has a lower efficiency compare to other cycles, the benefit of each cycle will be realized with exergy and techno-economic analyses, which will be key tasks for further research.

Acknowledgments

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC, EP/P004636/1, UK).

Nomenclature

Abbreviation

s-CO_2	Supercritical CO_2 Cycle
TLC	Trilateral Cycle
ORC	Organic Rankine Cycle
GHG	Greenhouse Gas

Symbols

$\dot{m}$	Mass flow rate, kg/s
Q	Heat input, kW
W	Work, kW
h	Specific enthalpy, kJ/kg
η	Efficiency, %

Subscripts

i	inlet or initial
o	outlet
f	final condition
exp	expander

p	pump
cy	cycle

References

[1] Parliament of the United Kingdom. Climate Change Act 2008. London: 2008.

[2] Committee on Climate Change. Meeting Carbon Budgets: Closing the policy gap: 2017 Report to Parliament. London: 2017.

[3] Federation of Bakers UK. About the federation of bakers. https://www.fob.uk.com/about-the-federation-of-bakers/ (accessed January 10, 2018).

[4] Carbon Trust. Industrial Energy Efficiency Accelerator: Guide to the Industrial Bakery Sector. London: 2010.

[5] Mukherjee S, Asthana A, Howarth M, McNiell R. Waste heat recovery from industrial baking ovens. Energy Procedia 2017;123:321–8.

[6] Chowdhury JI, Hu Y, Haltas I, Balta-Ozkan N, Matthew GJ, Varga L. Reducing industrial energy demand in the UK: A review of energy efficiency technologies and energy saving potential in selected sectors. Renew Sustain Energy Rev 2018;94:1153–78.

[7] Varma GVP, Srinivas T. Power generation from low temperature heat recovery. Renew Sustain Energy Rev 2017;75:402–14.

[8] Zhang Y, Yao Y, Li Z, Tang G, Wu Y, Wang H, et al. Low-grade heat utilization by supercritical carbon dioxide Rankine cycle: Analysis on the performance of gas heater subjected to heat flux and convective boundary conditions. Energy Convers Manag 2018;162:39–54.

[9] Iglesias Garcia S, Ferreiro Garcia R, Carbia Carril J, Iglesias Garcia D. A review of thermodynamic cycles used in low temperature recovery systems over the last two years. Renew Sustain Energy Rev 2018;81:760–7.

[10] Chowdhury JI, Nguyen BK, Thornhill D, Hu Y, Soulatiantork P, Balta-Ozkan N, et al. Fuzzy Nonlinear Dynamic Evaporator Model in Supercritical Organic Rankine Cycle Waste Heat Recovery Systems. Energies 2018;11:901.

[11] Chowdhury JI, Nguyen BK, Thornhill D. Modelling of Evaporator in Waste Heat Recovery System using Finite Volume Method and Fuzzy Technique. Energies 2015;8:14078–97.

[12] Chowdhury JI. Modelling and Control of Waste Heat Recovery System. Queens University Belfast, 2017.

[13] Lecompte S, Huisseune H , Den Broek MV, Vanslambrouck B , De Paepe M. Review of organic Rankine cycle (ORC) architectures for waste heat recovery. Renew Sustain Energy Rev 2015; 47: 448-461.

[14] Ajimotokan H , Sher I. Thermodynamic performance simulation and design optimisation of trilateral-cycle engines for waste heat recovery-to-power generation. Appl Energy 2015; 154: 26-34.

[15] Quoilin S , Broek MVD, Declaye S, Dewallef P, Lemort V. Techno-economic survey of Organic Rankine Cycle (ORC) systems. Renew Sustain Energy Rev 2013; 22: 168-186.