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Comparative Analysis of ORC and Condensing Heat Engines for Low Grade Waste Heat Recovery

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Abstract: The re-use of low-grade waste heat has the potential to contribute significantly to a better energy efficiency of our economies. There is a resource of around 100 TWhr per year in this area in Europe alone. The technology development in this area is still ongoing. Organic Rankine Cycle systems are considered the most promising technology. However, a nearly forgotten technology, the condensing engine (CE), was recently re-discovered. CEs use water as working fluid, with an operating temperature of 100°C at atmospheric pressure. The water is evaporated, and then condensed in the engine, where the arising vacuum is employed to generate power. Condensing engines were built until the late 19th Century, and then disappeared. Results from tests conducted in 1885 with a 0.735 kW commercial engine showed a mechanical efficiency of 3.7%, with a second law efficiency of 24.7%. For comparison, four typical experimental studies of Organic Rankine Cycle systems with power ratings between 0.5 and 1.4 kW were reviewed. Their thermal efficiencies ranged from 4.2 to 6.8%. The ORC systems' second law efficiencies ranged from 20 to 35%, with an average of 27.5%. The comparative analysis showed that the CE's performance is comparable to modern systems. Theoretical work suggests that it has significant further development potential. The CE's simplicity combined with good efficiency, the use of a very simple working fluid, reduced safety requirements and the development potential makes this a technology which can become important again.

Keywords: Condensing Engine, Thermal Efficiency, Second Law Efficiency, Waste Steam

1. Introduction

Low-grade heat constitutes a significant resource and is present both as waste from industry as well as from renewable sources. In industry as much as 20 to 50% of all input energy is wasted in the form of heat [1]. This can be categorised by temperature, with anything below 230°C being considered low grade. A study reported in [2] found there to be around 100TWh/yr of waste heat potential below a temperature of 200°C in Europe. There appears to be a large potential energy source in waste steam, more than 40,000 gigawatt hours (GWh) of energy is lost globally every year through waste steam [3]. Re-use of low-grade heat for electricity generation would displace fossil fuel use, reducing associated costs and environmental burdens. In addition to waste heat from industry, low grade heat is generated by biomass plants, solar thermal collectors and geothermal sources. The use of this heat to provide electricity offers alternative renewable energy systems. However, the utilisation of energy in this temperature range is difficult, especially for very small power ratings from 0.5 to 10 kW, with complexity and expense being the key barriers.

Currently, the principal technology employed for the re-use of low-grade heat for electricity generation is the Organic Rankine Cycle (ORC). In Organic Rankine Cycle systems, a working fluid with an evaporation temperature well below 100°C is employed, evaporated by the low-grade waste heat source. The vapour passes through an expander to produce mechanical work, before being condensed and pumped back to the evaporator. As a result of the thermodynamic properties of typically chosen working fluids, ORC systems can have operating temperatures as low as 60°C.

The use of low-temperature heat for power production is however not a new development, it began in the 18th

Century. In 1769, James Watt patented the condensing engine (CE). This employs the condensation of steam at atmospheric pressure and a temperature of 100°C, and the arising near vacuum, as driving force for work generation, see e.g. [4]. The CE employs a Rankine cycle very similar to that of the ORC engines. The system consists of a boiler or evaporator, the piston or expander where the work is done, a condenser where the evaporated fluid is condensed and a vacuum pump which recirculates the condensed fluid into the evaporator. This is shown in Figure 1.

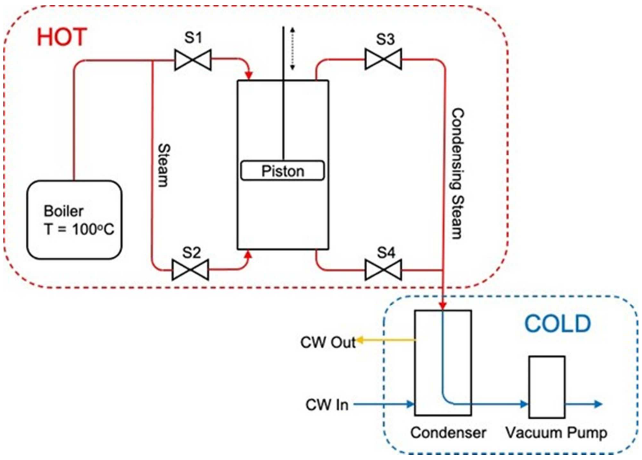


Figure 1. *The condensing cycle without expansion. Red and blue lines show CE hot and cold process flows respectively. S1/S2=Steam inlet valves. S3/S4=Steam outlet valves. CW=Cooling Water.*

First, steam is produced in the boiler and drawn into the cylinder at atmospheric pressure. When the piston reaches the lowermost position, the steam valve S1 is closed and the condenser valve S3 opened. The condenser pressure is near vacuum, associated with the heat sink temperature. The steam is drawn into the condenser, where it changes phase so that the pressure remains low. The condenser valve S3 is then closed, the steam valve S2 opens, the steam at atmospheric pressure acts on the other side of the piston, and the cycle repeats itself. This technology operated at working temperatures of 100°C and at atmospheric pressure. If waste steam, e.g. from industrial processes, is directly employed as a heat source, then the CE does not require a boiler or evaporator. The efficiencies were estimated at around 3%, e.g. [4]. The condensing engine disappeared in the early 19th Century, when high pressure steam engines became available. The last condensing engine, a 0.735 kW machine, to be produced commercially was manufactured by Hathorn, Davey and Co. / Leeds from around 1878 to 1895 [5, 6].

However, despite low efficiency, the reasons for the CE's original popularity are again relevant today. The engine is a simple technology, utilises water as a safe and sustainable working fluid, and operates at low temperature and pressure reducing safety and maintenance requirements and costs significantly. As a result, the technology is being re-evaluated at the University of Southampton [7]. This is made possible by employing modern thermodynamic theory (not existent at Watt's time) to better understand the engine, as well as modern materials and electronics to optimise valve control and engine performance, and to reduce energy losses through better insulation. This review paper presents and compares modern ORC and historic CE performance data, combined with an analysis of potential modern improvements in performance.

2. Efficiency Definitions

The analysis of ORC and CE engines presented in this article relies to a large extent on the comparison of efficiencies. The parameters and efficiencies used are defined as follows.

2.1. Thermal Efficiency (η_{th})

Useful power output, W_{out}, as a percentage of thermal energy input, Q_{in} (1). The useful power output can be mechanical or electrical. To ensure comparability of results only mechanical power output, $W_{(out\_m)}$, will be used for final analysis in this paper.

$$\eta_{th} = \frac{W_{out\_m}}{Q_{in}} \tag{1}$$

When thermal efficiency using an electrical power is given in literature instead, η_{th_e}, this is converted using an assumed electrical generator efficiency of 80%.

2.2. Net thermal Efficiency (η_{net})

Net useful power divided by thermal energy input Q_{in} (2) Net useful power is the useful engine power, W_{out}, minus energy requirements of system components such as working fluid pumps, W_p, which are essential for the operation of the system.

$$\eta_{net} = \frac{W_{out} - W_p}{Q_{in}} \tag{2}$$

2.3. Carnot Efficiency (η_C)

The maximum theoretical efficiency of a heat engine defined using only the heat source and sink temperatures (3). T_{co} and T_{evap} are condenser and evaporator temperature respectively, given in Kelvin.

$$\eta_C = 1 - \frac{T_{co}}{T_{evap}} \tag{3}$$

2.4. Second Law Efficiency (η_{II})

Thermal efficiency as a percentage of the Carnot efficiency; see (4). This represents the given system's ability to convert the available thermal energy into a useful output. It therefore allows for a direct comparison of effectiveness between different technologies operating in different temperature levels and ranges.

$$\eta_{II} = \frac{\eta_{th}}{\eta_C} \tag{4}$$

3. Review

3.1. Low Temperature, Low Power ORC Systems

There is a substantial amount of work reported on the development of ORC systems, including at low powers and low temperatures. This section of the paper presents the results of experimental investigations with working parameters close to those of Hathorn & Davey's condensing engine. An extensive review described in [8] gave compiled data from over 100 experimental ORC studies. The review shows that ORC systems operating with heat source temperatures of 75 to 150°C and/or power outputs of 0.5 to 10 kW have average thermal efficiencies ranging between 5 to 10%. The associated second law efficiencies ranged from approximately 15 to 33%.

Data from four typical ORC studies with operating conditions close to that of Hathorn & Davey's engine, and where all relevant data is available, is also given in Table 1.

Table 1. *Example ORC studies in literature collated data. [E]=Electrical. [M]=Mechanical. WHR=Waste Heat Recovery.*

	[9]	[10]	[11]	[12]
Heat source	Steam	Oil (WHR)	Solar/ Water	Oil (WHR)
Working fluid	R-245fa	R-123	R-245fa	R-236fa
Expander type	Scroll	Turbine	Piston	Rotary
Evaporator inlet pressure (bar)	8.95	4.55	6.70	12.7
Net power (kW)	0.46	1.00	1.43*	1.16*
Evaporator temp. (°C)	101	101	78.0	98.3
Condenser temp. (°C)	16.1	28.3	14.0	36.1
ΔT (K)	84.9	72.7	47.0	62.2
Thermal eff. (%) [E]	3.6	3.0	-	-
Thermal eff. (%) M]	4.6*	6.8	4.2	6.5
2nd law eff. (%) *	20.1	35.0	23.0	31.8

* Calculated by authors using available data

The evaporator and condenser temperatures in Table 1, required for determining the second law efficiency, are defined using the working fluids' outlet streams. This sets the maximum and minimum working fluid temperatures in the cycle used to generate power. Absolute operating pressures were taken at the expander inlet. Efficiencies were taken as net values in all cases, with second law efficiencies calculated from the available data.

The chosen studies offer a variety of ORC working fluids, expander types, and heat sources. Of most interest in the context of this analysis are ORC tests which use steam as a direct heat source. Steam is available as a direct form of waste heat in industry, see Figure 2. It has also been mostly neglected in the literature, e.g. [9], and is a source of energy which can be directly used by the CE without an intermediate heat exchanger. This suggests a reduction in complexity and cost compared with e.g. ORC systems.

Figure 2. *Wet steam emissions from a paper and cardboard factory. 1 m^3 of steam per second contains a thermal energy of 1.56 MW (Image: G. Muller).*

3.2. The Safety Engine from Hathorn, Davey and Co

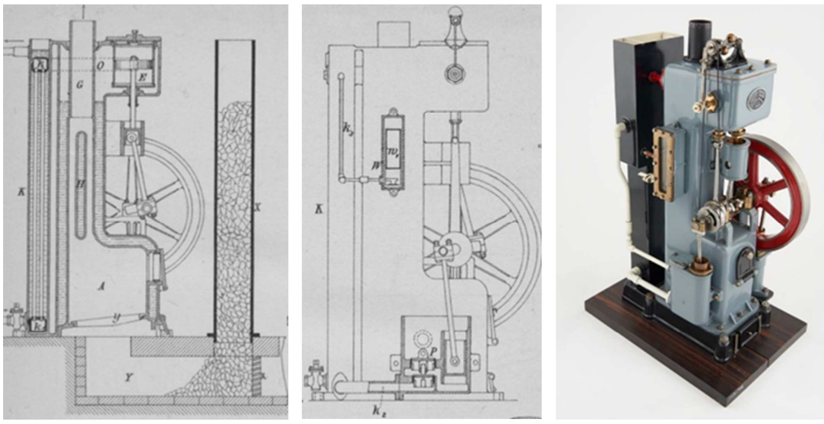
Around 1878 the company of Hathorn, Davey & Co. of Leeds / England started to manufacture a "Safety Engine" with 1 bhp (0.735 kW) nominal power output [5, 6]). The Safety Engine was a condensing engine, which employed the condensation of steam at atmospheric pressure and the arising near vacuum as driving force.

The engine had a double-acting cylinder with a bore diameter of approximately 150mm and a stroke of 175 mm, a footprint of around 0.9 x 0.9 m, and a height of 1.80 m. It operated with a boiler pressure at, or slightly below, atmospheric. This meant that there was no danger of boiler explosion or steam scalding, and the engine could be employed e.g. in residential buildings without any safety precautions. This, plus the simplicity, reliability, low maintenance and low costs, were the main sales arguments. In Figure 3a, a cross section of the engine is shown. 'A': fire box, 'E' cylinder, 'H' boiler tubes, 'K' Condenser and heat exchanger, 'G' stove pipe, 'O' exit pipe from cylinder to condenser, 'X' coal store, 'Y' fire pit. The vacuum pump 'P' is shown in Figure 3b. Figure 3c shows a scale model built for the Science Museum London, which gives a good impression of the compactness of the complete engine, including boiler and condenser. The engine was manufactured under licence in France by Albaret S. A. / Liancourt and in the USA by Ch. P. Willard und Comp. / Chicago, which indicates the success of the design. To determine the actual performance, a series of engine tests was conducted in France.

Table 2. *Test results for the Hathorn & Davey safety engine [5].*

Test Nr	**1**	**2**	**3**	**4**
Test duration (minutes)	108	240	221	600
Weight on lever arm (kg)	6	6	6	6
Length of lever arm (m)	1	1	1	1
Total nr of revolutions	12782	31822	27310	75428
Revolutions per minute (rpm)	118.3	132.5	123.6	125.7
Power (bhp)	0.99	1.11	1.03	1.07
Power (kW) *	0.74	0.83	0.77	0.80
Total fuel consumption (kg)	12	25.5	21	53
Fuel consumption per hour (kg/hr)	6.73	5.745	5.530	5.040
Water usage in boiler (kg)	70	144	120	300
Water volume condenser (kg)	1310	2756	2400	7600
Water demand for boiler (kg/bhp·hr)	39.3	32.4	31.6	28.5
Water demand for condenser (kg/bhp·hr)	736	620	632	723
Temperature at condenser entry (°C)	20	20	20	20
Temperature at condenser exit (°C)	45	47	48	44
Temperature for boiler feed water (°C)	27	40	35	35
Temperature of steam (°C)	100	100	100	100
Time required for start-up	30	20	30	37
Net thermal efficiency, η_{th} [M] (%) *	2.7	3.3	3.3	3.7
2nd law efficiency, η_{II} (%)*	18.3	23.2	23.7	24.7

*=Value determined by the authors from available data.



(a) (b) (c)

Figure 3. *Hathorn, Davey & Co.'s Safety Engine (a) Cross section, (b) Side view [6], (c) Scale model [13].*

The results were published in the journal *Revue Industrielle* [5]. Table 2 shows the test results. The thermal efficiency was calculated from the volume of water evaporated as thermal input as well as the mechanical power output and ranged from 2.7 to 3.7%. Engine warm-up affecting efficiency was attributed to the lower efficiency of 2.7% to 3.3% in tests 1 to 3. For the further analysis, the value of 3.7%, recorded in test 4 which had the longest run time, is taken as representative.

3.3. Condensing Engine Development Potential

3.3.1. Steam Expansion

The condensing engine described in [5] did not employ steam expansion, with which the efficiency of the engine can be increased significantly.

For steam expansion, the steam inlet valve is closed at mid stroke, allowing contained steam to expand against the piston, thus recovering more work from the given steam. Isentropic ideal gas laws, also corroborated with non-ideal gas law methods, can be applied in order to understand possible efficiencies with steam expansion, e.g. [7]. This is shown in Figure 4 for expansion ratios (ER's) of 1:1 (i.e. no expansion) to 1:10 with a heat source temperature of 100°C and heat sink temperature of 20°C.

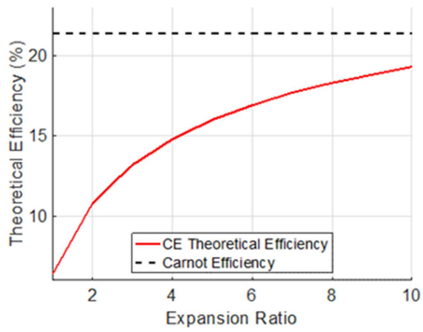


Figure 4. *Theoretical efficiency of the CE with varying expansion ratio. Heat source and sink of 100°C and 20°C respectively.*

3.3.2. Extended Operating Temperatures (70 to 110°C)

The CE is a system where the evaporation temperature is a function of the system pressure. This means that lowering the system pressure reduces the evaporation temperature. If in a real engine the boiler temperature is at say 70°C, it can be envisaged that once the piston starts to move from the top position, the pressure will reduce until the evaporation pressure for that boiler temperature is reached. The engine itself creates the sub-atmospheric operational pressure. Whilst a reduction in working temperature reduces the efficiency, it allows heat sources with temperatures between 70 and 100°C to be exploited by the modern CE.

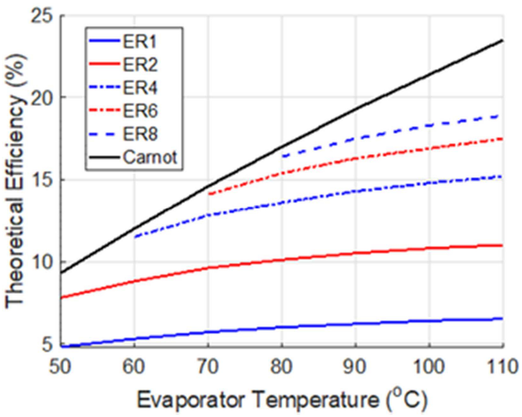


Figure 5. *Theoretical efficiency of the CE with extended heat source temperatures. Heat sink temperature of 20°C.*

Similarly, the CE can also use higher operating temperatures. Assuming operation with saturated steam, this results in a pressure above that of atmospheric. It is envisioned that the CE would be used up to a temperature of 110°C and an associated pressure of around 1.5 bar. This limit is set by the regulations in many countries, which require higher manufacturing, safety, and inspection standards for pressures exceeding 1.5 bar [14]. With operating pressures above atmospheric, the energy of the pressurised steam can also be employed as driving force. Figure 5 shows the efficiency as a function of operating temperature for different expansion ratios and a heat sink temperature of 20°C, calculated using isentropic ideal gas laws.

3.3.3. Materials and Insulation

The Hathorn & Davey engine did not have any thermal insulation. Adding insulation or using thermally insulating materials can be expected to reduce losses and increase the efficiency. Modern low-friction materials can also be used, for example in valves, to reduce mechanical losses.

3.3.4. Control and Engine Configuration

Modern electronic control will not only allow use of steam expansion, but also the ability to adjust ER during operation. This will increase the efficiency, as shown in Figure 4, and reduce the complex mechanical valve operation. Alternative engine configurations, such as uniflow, allow use of evacuation ports to minimise pressure losses as well as reducing the required number of valves.

4. Discussion

4.1. System Comparison

Table 3 shows the comparison of the test results from ORC systems reported in the literature as well as the results of Hathorn & Davey's condensing engine, summarised from Tables 1 and 2.

With an overall conversion efficiency of η_{th}=3.7%, the Hathorn & Davey engine has a relatively low thermal efficiency. However, a direct comparison of the thermal efficiency values is misleading, since both operating temperatures and temperature differences vary considerably, Table 3. The second law efficiency η_{II} is instead used to compare technologies. Hathorn & Davey's engine achieves a second law efficiency of η_{II}=24.7%. which compares quite well with the median η_{II} values of the ORC studies of 24% and 27.5%. The comparison with [9] is of interest due to use of the steam as a direct heat source. Here, the Hathorn & Davey engine has a higher second law efficiency; 24.7% compared to 20.1%, despite the technology being over 100 years older.

Furthermore, modernisation of the technology allows for the use of steam expansion. Figure 4 shows that the CE's theoretical efficiency increases from 6.4% for an ER of 1:1 to 19.3% for an ER of 1:10. It can be seen that this approaches the Carnot efficiency, further justifying the potential of the CE. Whilst technical limitations may limit practical operation to an ER of 1:4, this can still achieve a theoretical thermal efficiency of 14.8%. It is an ideal efficiency not achievable in practice. The practical efficiency of 3.7% reported in [5] represented around 60% of the ideal efficiency of 6.4%, at an ER of 1:1, shown in Figure 4. If this conversion rate is extrapolated to an ER of 1:4, the modern CE could be expected to practically achieve a net thermal efficiency as high as 9%. This would result in an associated second law efficiency of around 40%, exceeding current ORC systems of similar scale and at similar operating temperatures.

Table 3. *Comparison of test results.*

	[8]	[9, 10, 11, 12]	[5]
Working Fluid	Various	R-245fa, -123, -236a	Water
Operating pressure (bar)	Various	4.55 – 12.7	Atmosph.
Heat source temp. (°C)	75 - 150	78 - 108	100
Heat sink temp. (°C)	Various	14.0 - 36.1	44
dT (K)	Various	47.0 - 90.5	56
Thermal efficiency (%)	5 - 10	4.2 – 6.8	3.7
2^{nd} law efficiency (%)	15 – 33	20.1 – 35.0	24.7
Median 2^{nd} law eff. (%)	24.0	27.5	24.7

Tests conducted at Southampton University with a condensing engine had shown efficiencies of up to 5.5% for an expansion ratio of 1:4 [7]. These tests confirmed the theoretical predictions, and the development potential of the engine. Whilst the Hathorn & Davey engine only operated with a 100°C heat source, the technology can also be applied to wider heat source temperatures. Analysis suggests a theoretical maximum efficiency of 13.9% when operating the CE with a heat source of 75°C; see Figure 5. In [7], the operation of an engine is reported with a boiler pressure of 0.746 bar and a boiler temperature of 90°C. The modern CE can also operate up to a heat source temperature of 110°C without regulatory approval, with theoretical efficiencies as high as 20.0%.

The CE has several other advantages when compared with ORC systems. For example, it uses water as a non-corrosive, non-flammable, non-toxic and cost-effective working fluid. ORC systems employ organic refrigerants, which are more problematic because of the fluids' Global Warming Potential (GWP) and the unavoidable leakages in such systems [15, 16]. This also means that the fluids have to be recycled or disposed of carefully during end-of-life decommissioning, which adds to the operational costs.

The CE operates at atmospheric pressure, so that no additional safety measures, certification or inspections are necessary. Operating pressures in ORC systems reviewed in this paper range from 4.55 to 12.7 bar, so that these systems are subject to all regulations for pressurised systems such as required e.g. in [14] whereas the CE is not. Reduced pressure therefore allows for a reduction in system cost. The CE is a less complex technology in comparison to the ORC, again implying cost effectiveness. The ability to remove the need for an evaporator in the case of waste steam emission also reduces complexity.

4.2. CE Application Potential

The CE has not seen any application since Hathorn & Davey's engine was built. The disappearance of the CE was largely caused by its low efficiency, and the advent of the electric motor. In the modern world however, new demands for energy economy have arisen and several roles can be envisaged for the CE:

1. Direct energy conversion from waste steam.
2. Energy conversion from low-grade waste heat, e.g. from biomass, geothermal energy or solar thermal power.
3. Combined power generation and desalination using solar thermal power. This is achieved through the distillation process present in the CE's cycle.

The scale of the Hathorn & Davey CE implies that the conclusions drawn from the test results will be valid for commercially sized units. The CE has however limitations regarding the power output range, caused by the increasing cylinder dimensions and costs. Therefore, the main area of future applications of a commercial condensing engine is seen in the small power ratings from 1 to 50 kW and for operating temperature ranges between 70 and 110°C. At Southampton University, an ongoing research programme aims at the development of the CE as a practical solution for low grade heat conversion. The analysis of the data from the Hathorn & Davey Engine provided a baseline, establishing that the technology can be competitive even in its most basic form.

5. Conclusions

Reported test results of small-scale ORC systems for operating temperatures between 75 to 150°C and power ratings from 0.5 to 10 kW were compared with measurements of a one b.h.p. (0.735 kW) condensing engine (CE) with similar parameters reported in the historic engineering literature. The CE is a simple machine, which uses water as working fluid with an operating temperature of 100°C at atmospheric pressure. It was found that:

1. Low temperature, small scale ORC systems have thermal efficiencies ranging from 5 to 10%. Second law efficiencies were found to range from 15 to 33%.
2. The analysis of four typical ORC systems with a temperature range similar to the CE's showed thermal efficiencies from 4.2 to 6.8% and 2nd law efficiencies from 20 to 35%.
3. The CE had a thermal efficiency of 3.7%, and a second law efficiency of 24.7%, this is comparable with modern ORC systems.
4. The CE has considerable development potential, with steam expansion the 2nd law efficiency could reach 40%.
5. Theory indicates that the CE's operating temperature can be extended to 70°C to 110°C. Modern control systems, insulation and materials would improve performance further.
6. The simplicity of the CE, when compared with the ORC systems, suggests the potential for significant cost advantages. The operation with water at pressures below 0.5 bar means that safety and regulatory requirements as well as environmental impacts are minimal.

The analysis of historic engineering literature in the context of today's changed demand structures led to a re-assessment of a near forgotten technology which has a surprisingly good performance, combined with a significant development potential. An ongoing research programme aims to develop the technology further.

Acknowledgements

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References

[1] BCS (2008). Waste Heat Recovery – Technology and Opportunities in the U.S. Industry. U.S. Department of Energy.

[2] Papapetrou, M., Kosmadakis, G., Cipollina, A., Commare, U. L., Micale, G. (2018). Industrial waste heat: Estimation of the technically available resource in the EU per industrial sector, temperature level and country. Applied Thermal Engineering, 138, 207-216.

[3] Armitage C. (2017). How waste steam is helping firms to go green. Recycling and Waste World Sept. Issue. https://www.recyclingwasteworld.co.uk/in-depth-article/how-waste-steam-is-helping-firms-to-go-green/160999/ (accessed 31.01.2021).

[4] Farey, J. (1827). A Treatise on the Steam Engine Historical, Practical, and Descriptive. By John Farey. Illustrated by Numerous Engravings and Diagrams. Longman, Rees, Orme, Brown, and Green.

[5] Josse H. (Ed.) (1885). Moteur Domestique – Système Hathorn, Davey and C^{ie}. Revue Industrielle. Paris. No 10 (3), 93-94. https://gallica.bnf.fr/ark:/12148/bpt6k97674548/f105.image.

[6] Dingler, G. (Ed.) (1886), Ueber Neuerungen an Klein-dampfmaschinen. Polytechnisches Journal. Band 259 (S. 1–9). http://dingler.culture.hu-berlin.de/article/pj259/ar259001.

[7] Müller, G., Chan, C. H., Gibby, A., Nazir, M. Z., Paterson, J., Seetanah, J., Yusof, F. (2018). The condensing engine: A heat engine for operating temperatures of 100°C and below. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 232 (4), 437-448.

[8] Landelle, A. Tauveron, N., Haberscill, P., Revellin, R. & Colasson, S. (2017). Organic Rankine cycle design and performance comparison based on experimental database. Applied Energy, 204, 1172-1187.

[9] Muhammad, U., Imran, M., Lee, D. H., & Park, B. S. (2015). Design and experimental investigation of a 1 kW organic Rankine cycle system using R245fa as working fluid for low-grade waste heat recovery from steam. Energy Conversion and Management, 103, 1089-1100.

[10] Pei, G., Li, J., Li, Y., Wang, D., & Ji, J. (2011). Construction and dynamic test of a small-scale organic rankine cycle. Energy, 36 (5), 3215-3223.

[11] Wang, X. D., Zhao, L., Wang, J. L., Zhang, W. Z., Zhao, X. Z., & Wu, W. (2010). Performance evaluation of a low-temperature solar Rankine cycle system utilizing R245fa. Solar Energy, 84 (3), 353-364.

[12] Cipollone, R., Bianchi, G., Battista, D. D., Contaldi, G., & Murgia, S. (2014). Mechanical energy recovery from low grade thermal energy sources. Energy Procedia, 45, 121-130.

[13] Science Museum (2021). Science Museum Group. Model of a Hawthorn Davey Safety Domestic Engine a. 1998-756 Science Museum Group Collection Online. Accessed January 13, 2021. https://collection.sciencemuseumgroup.org.uk/objects/co468557/model-of-a-hawthorn-davey-safety-domestic-engine-a-model-safety-domestic-steam-engine.

[14] Pressure Equipment Directive (PED) (2014): European Directive 2014/68/EU, https://ec.europa.eu/growth/sectors/pressure-gas/pressure-equipment/directive_en (accessed 30.01.2021)2440-2454.

[15] Li, G., (2019) Organic Rankine cycle environmental impact investigation under various working fluids and heat domains concerning refrigerant leakage rates. Int. J. Environ. Sci. Technol. 16, 431–450. https://doi.org/10.1007/s13762-018-1686-y.

[16] Wang, S., Liu, C., Li, Q., Liu, L., Huo, E., & Zhang, C. (2020). Selection principle of working fluid for organic Rankine cycle based on environmental benefits and economic performance. Applied Thermal Engineering, 178, 115598.