2021

# The Life and Legacy of William Rankine

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## ABSTRACT

Professor William Rankine, who was born on July 5 1820, made a substantial contribution to the science of heat and power and his influence in refrigeration and air-conditioning is still apparent today. This paper gives a short overview of Rankine's life and work and then considers how his legacy is relevant to the challenges facing refrigeration, air conditioning and heat pump engineers in the 21st century. These include system efficiency, expansion methods, alternative cycles and novel working fluids.

## 1. INTRODUCTION

William J.M. Rankine, also known as Macquorn Rankine, was one of the greatest scientists and engineers to be born in Scotland, but unlike his predecessor James Watt or his contemporaries Lord Kelvin and James Clerk Maxwell he is relatively unknown. He was the Regius Professor of Civil Engineering and Mechanics at the University of Glasgow from 1855 until his untimely death at the age of 52 in 1872 and for almost his whole tenure he fought vigorously to have engineering recognized as a degree subject in its own right. Prior to Rankine's campaign people who worked as engineers studied natural philosophy (now called physics) or a general arts degree. During this period Rankine wrote several major textbooks which became standard required reading for engineering students around the world for decades after his death. These covered Applied Mechanics (1858), Steam Engines and other Prime Movers (1859), Civil Engineering (1861), Shipbuilding (1866) and Machinery & Millwork (1869). In his "Memoir" of Rankine, written in 1880, Professor Peter Guthrie Tait wrote that "*Rankine's works on applied Mechanics, on the Steam-Engine and on Engineering contain many valuable and original methods; and while the publication of any one of them would have established the fame of one of our average scientific men, that on the steam-engine could not have been produced by any but an original discoverer of a higher order*." (Guthrie Tait, 1880)

Rankine's inaugural address to the University of Glasgow when he was appointed to the Regius chair summarises his philosophy well. He wrote "*The words 'theory' and 'practice' are of Greek origin; they carry our thoughts back to the ancient philosophers by whom they were contrived, and by whom they were also contrasted and placed in opposition, as denoting two conflicting and mutually inconsistent ideas….Rational and practical mechanics (as Newton observes in his preface to the* Principia*) were considered as in a measure opposed to each other, the latter being an inferior branch of study, to be cultivated only for the sake of gain or some other material advantage*." (Rankine, 1856)

The desire to reunite theory and practice by applying pure science to real world engineering problems runs as a recurring theme through much of Rankine's work. His own output was at times intensely practical, such as the recognition of the mechanism of metal fatigue in an investigation of the failure of railway axles, or the development of a method of laying out curves in the construction of railway lines. On other occasions he showed a remarkable gift for abstract "thought experiments" for example in perhaps his greatest work, the analysis of the science of heat and work which we now know as "thermodynamics" – the term coined by Rankine for the laws which were formulated by Clausius, Thomson and Rankine working independently in the late 1840s. Rankine's explanation of the absolute zero of the temperature scale (which bears his name) was based on the image of atoms being miniature vortices with the effect of temperature on internal energy being caused by changes to the vortex motion.

## 2. RANKINE'S LEGACY IN EDUCATION

Rankine's post at the University of Glasgow was that of Regius Professor, meaning that the chair had been endowed by the reigning monarch, and therefore that he had been appointed by Queen Victoria, not by the University Senate. This caused some resentment and a degree of snobbery among the traditionalists in the senate who argued that the funds used to support this chair would be better employed in more established subjects such as study of the classics. The University Professors in those days all lived on campus in houses provided by the establishment but the Regius Professor was never afforded this privilege and his post was viewed as a second class appointment. The chair had been created in 1840 and the first incumbent, Professor Lewis Gordon, was a successful consulting engineer with a thriving practice split between Glasgow and London. Rankine acted as an associate of Gordon in the early 1850's, representing him in the London office for a few years, but in 1855 he delivered a short series of engineering lectures at the University as a substitute for Gordon, to enable the Professor to devote more time to his business interests. This course was so successful, and clearly appealed to Rankine's desire to teach and develop younger students, that Gordon resigned his post later that year and Rankine was appointed, in a rather hurried and apparently underhand way. Professor William Thomson (later Lord Kelvin) wrote in November to his brother, James (Thomson, 1855), who was a consulting Civil Engineer in Belfast, deploring the fact that the post had not been advertised and candidates had not been invited to apply but Rankine's selection had been announced in September. Thomson wrote in quite forthright terms that his brother was undoubtedly the most suitable for the post and how unfair the sneaky approach had been. He went on to write "*The system the government follows in such cases is a disgrace to the country. It is a wonder that a good appointment is ever chanced on. The present I consider to be very good, but not the best if you had been a candidate, and most unjust to all more or less qualified looking for such situations as well as to the public who has a right to expect that a careful choice of the person most likely to be useful.* ". However towards the end of the letter he somewhat grudgingly admitted that if anyone else were to be appointed he supposed that Rankine was the most appropriate of the others, concluding that "*by chance I think that Rankine is not only the best that could be got unless you would have taken it, but positively good, and I expect much from his perseverance and ambition, in a good and permanent class being formed*". Other members of the University Senate were not so open-minded. The Professor of Midwifery campaigned for the funds released by Professor Gordon's resignation to be reallocated and "*be devoted to purposes of greater and more immediate importance in connection with the higher branches of University Education*" (Small, 1957). It is not clear which branches he had in mind.

Almost as soon as he was appointed Rankine set down his lecture notes in a clear and logical manner and within three years had started publishing his famous text books. These take the form of concise "articles" stepping through the subject in a very clear progression. For example Article 1 of the Manual of Applied Mechanics (Rankine, 1858) states "***Mechanics** is the science of rest, motion and force. The laws, or first principles of mechanics are the same for all bodies, celestial and terrestrial, natural and artificial. The methods of applying the principles of mechanics to particular cases are more or less different, according to the circumstances of the case. Hence arise branches in the science of mechanics*." The text book then proceeds in steps all the way to Article 705 on ***Electrodynamic Engines,*** with each article varying in length from a few words to a few pages, but always presenting the technical detail couched in simple terms with interesting anecdotes about the origins and derivations of the information and useful rules of thumb to help the pupil to apply the theory in practice.

At about the same time (the late 1850s) Rankine started to campaign to the University senate and other ruling bodies to have Engineering recognized as a degree subject in its own right. Until that time the teaching of engineering was covered by the Faculty of Arts, but it did not count towards the award of a degree so the majority of Rankine's students were studying for an Arts degree and took engineering as an elective. In 1859 the university Senate agreed to consider a proposal from Rankine that a Diploma in Engineering Science should be awarded to students who completed a more formal course of study. The Senate passed this question to the Universities Commissioners who concluded in 1861 that Universities could only award full degrees and that Engineering was "*not a proper department in which a degree should be conferred*." (Small, 1957) Despite this judgement from the national governing body, Rankine persuaded the Senate to agree to a modified proposal for the award of a Certificate of Proficiency in Engineering Science. This was presented to Arts graduates alongside their degree, provided they had completed a structured course and had satisfied the examiners as to their competence.

Rankine continued to campaign for the recognition of the Certificate of Proficiency as a degree in its own right. The matter was considered again in 1870 but was rejected by the University after legal opinion was presented in opposition. However Rankine cited the Representation of the People (Scotland) Act of 1868 which made provision for the grant of Bachelor of Science degrees, although none were awarded at Glasgow at that time. The Senate took this on board and in 1872 established the B.Sc. degree at Glasgow, not just for Engineering Science but for all sciences. The engineering degree established under this program was the first to be offered in the United Kingdom, possibly in the world, although Glasgow was relatively slow to set up a separate Faculty of Engineering, not doing so until well into the 20th century.

Rankine's influence in engineering education was far reaching. In 1872 he was asked by representatives of the Emperor of Japan to recommend someone who could set up a new college in Tokyo to teach engineering after the Glasgow model. Rankine recommended one of his final year students, Henry Dyer, who took up post as Principal of the Imperial College of Engineering from its founding in October 1873 until 1882. Teaching at ICE followed Rankine's format of balancing theory and practice and formed strong links between the institutions in Scotland and Japan that survive to the present day.

Rankine's textbooks continued to be revised and updated for decades after his death, mainly by William Millar who was one of Rankine's students and served as Secretary of the Institution of Engineers in Scotland for 25 years from its foundation in 1857. They still serve as a model of clear technical writing.

Rankine died at the relatively young age of 52 on Christmas Eve 1872. His successor was James Thomson, who finally joined his brother as a professor at Glasgow. It was James who had the task of nurturing Rankine's ideas on engineering education and ensuring that the curriculum went from strength to strength. His tenure as Regius Professor of Civil Engineering and Mechanics at Glasgow was almost as long as Rankine's, from 1873 until he retired in 1889.

In 1939 the journal of the American Society of Refrigeration Engineers (the forerunner of the ASHRAE Journal) carried an announcement that a fund-raising effort was being co-ordinated by Professor William H Rasche of the Virginia Polytechnic Institute in Blacksburg, Va. The following reasons were given for this effort, almost seventy years after Rankine's death:

1) *"That since Rankine was chief among the founders of modern scientific engineering, he has been of incalculable service to engineering and thus also of very great service to all mankind. Hence he richly deserves not one, but many fine memorials*
2) *His writings have unquestionably played an enormously important part in the marvelous industrial development which has taken place in this country in the last fifty or sixty years and which has so fabulously enriched us; thus the United States is heavily indebted to Rankine and ought to honor him gladly and even eagerly*
3) *There are memorials to many men whose contribution to the progress of engineering are not so impressive as Rankine's are, but there is no real memorial to this great pioneer engineer anywhere in the world."*

(Refrigerating Engineering, 1939)

Professor Small summarized Rankine's contribution to engineering education in his commemorative paper on the 100th anniversary of the founding of the Institution of Engineers in Scotland, writing

"*…it is yet possible that at the bar of history he will be judged to have been greatest in his development of the education of the engineer and his elevation of the dignity of the engineer's studies. We have already seen that he had a clear vision of the place of engineering as a university discipline and of the aims the engineering teacher had to keep before him…the work he did for the teaching of engineering in Glasgow was a work from which engineering education everywhere has benefitted*."

(Small, 1957)

## 3. RANKINE'S LEGACY IN THERMODYNAMICS

Throughout the 1840s there were many investigations of the science of heat in progress across Europe. In Paris Victor Regnault, a graduate of the Ecole de Mines, was appointed Professor of Physics at the Collège de France in 1841, having previously served as Professor of Chemistry at the University of Lyon. In Salford, near Manchester in England, James Joule started investigating the equivalence of heat and work in 1843 and presented his initial findings to the British Association in Cork, Ireland that year. His ideas were so radical that his presentation was met with complete silence. In Glasgow Professor William Thomson was appointed to the chair of Natural Philosophy at the University of Glasgow in 1846. Thomson heard Joule speak on the mechanical equivalence of heat at the British Association meeting in Oxford in 1847 and was intrigued by his fresh approach to the twenty year old Carnot heat engine technology. In 1848 a young Prussian physicist, Rudolph Clausius, gained his doctorate from the University of Halle and two years later took up the physics chair at the Royal Artillery and Engineering School in Berlin. Later that year, 1850, he published his first paper on the nature of heat and work, at the age of 28.

According to his notebooks, Rankine first appeared to be attracted to the scientific study of heat in 1842 while still a pupil of Macneill in Ireland, studying the practical aspects of civil construction works (Lewis, 1875). However he set aside this train of thought as there was not sufficient data on the properties of steam for him to complete his analysis. Once he was established in a civil engineering consulting practice in Glasgow he was able to gather additional information and presented his analysis of heat in 1849.

It is likely that Rankine first met James Joule in 1843. They both attended the British Association's meeting in Cork, Ireland, and both presented papers on the relatively unfashionable topic of heat. These ought to have been delivered in the Physical Science section of the meeting but it was filled with investigations of electro-magnetism, which was all the rage at the time. As a result the two young men (Joule was 24 and Rankine was 23) were relocated to the Chemistry section, which was not a good fit for their subject matter. As they were, in effect, amateur scientists not attached to any university or other academic establishment and pursuing unorthodox theories on their own it was presumably easy to push them to one side like this. Joule continued to refine and develop his ideas on the mechanical equivalence of heat, presenting again to the British Association, which met every second year, in 1845 and 1847.

These five men of science, a Frenchman, an Englishman, a Scotsman, a German and an Irishman each brought their own unique insight to the investigation of the new science of heat. Regnault, the eldest by eight years, provided remarkably accurate measurements on the physical properties of steam and other gases, which served as the benchmark against which the others tested their theories. Joule had the vision to see that the received wisdom of the day, the caloric theory of heat, was flawed and had the courage to say so in the face of almost universal scorn. When he presented his first British Association paper in Cork the press wrote "*We cannot point out one remarkable scientific fact which is entirely novel.*" (Cardwell, 1989). Joule's status as an amateur without tenure in a university was perhaps in his favour in this respect; he was his own master and was free to pursue whatever took his fancy, driven by his own worldview and financed by his own wealth. Rankine was, like Joule, independent, but had no family riches to support his investigations. His work on heat in the 1840s was almost entirely in his mind, developing imaginative metaphors for the physical processes that provided a unique insight. Although many people later derided Rankine's thought experiments as misguided or ill-founded, this rather misses the point that they still hold good as metaphors and enable detailed engineering analysis to be performed quickly and accurately. Indeed Rankine's analysis was sufficiently accurate to identify, entirely on the basis of his thought experiment and subsequent calculation, that the previously accepted value for the specific heat of air based on Carnot's theory was inaccurate. It was only once Regnault published his detailed measurements that Rankine had the raw data to prove the validity of his method of calculation. He went on to tabulate the density of steam at various pressures, based on his method of calculation, for the benefit of the students in his engineering classes; the first time such steam tables had been created.

Thomson spent a year working in Regnault's laboratory in Paris from mid-1845 to mid-1846 between graduation from Cambridge and his appointment to the chair of Natural Philosophy in Glasgow. He took the concept of the mechanical equivalence of heat (Joule's revolutionary idea) and subjected it to intense scientific scrutiny. He was, when he first heard Joule on the subject in 1847, initially skeptical but he quickly came to see that Joule's approach to the science of heat and work resolved the many discrepancies of Carnot's caloric theory. Thomson was not always rigorous in his work, for example he claimed a coefficient of performance of 35 in his description of an air-source heat pump in 1852 when the theoretical maximum achievable from an ideal machine was only 18, but he brought a breadth of vision, a depth of scientific understanding and a grasp of higher mathematics to Joule's work which moved it from the periphery to the centre of scientific investigation. It was Thomson's writing on the subject, in 1849, which first attracted physicist Rudolph Clausius to the study of heat and work. Clausius quickly identified the relevance of absolute temperature to the quality of the heat in a process. He initially called this the "equivalence value" but later gave it the name "entropy". Thomson was the first to use the term "a thermo-dynamic engine" in his 1849 paper on the Carnot engine and it was Rankine who picked up on this and described Clausius' hypotheses as "the first and second laws of thermodynamics" (Smith, 1977). Although Rankine's involvement in the development of the theories is often overlooked today he was the most practical of these five men of science and his name is now associated with the power cycle used in steam-based generation of electricity, whether it is coal, gas or nuclear. This led to the naming of the Organic Rankine Cycle, a variant of the steam cycle using a fluorinated hydrocarbon instead of water as the working fluid. The most popular of these fluids over the last 50 years has been R-245fa, followed by R-134a for lower temperature systems.

## 4. 21st CENTURY CHALLENGES

The question of energy efficiency was uppermost in Rankine's mind as he developed his theories of prime movers for his text book in 1859. When the efficiency of an engine translated into how much coal had to be carried to fuel it, and a reduction in the weight of coal increased the payload for fee-paying passengers and cargo, it was a key consideration. In the 21st century the focus is once again on efficiency, with concerns for the environment playing a key role in motivating researchers to find better ways to generate power.

A key challenge is the extension of Organic Rankine Cycle systems to make them effective at lower temperatures. Although this sometimes leads to the use of inorganic working fluids such as carbon dioxide and ammonia, the term ORC is used loosely in this paper to denote any Rankine Cycle that does not use water as the working fluid. A Rankine Cycle takes heat at a higher temperature and converts some of it to work, using an expansion engine to drive an alternator to produce electricity. The expansion engine is often a turbine, but screw, scroll or reciprocating expansion engines can also be used. The portion of the high temperature heat which is not converted to work is rejected from the cycle at low temperature in order to turn the expander outlet from gas to liquid. The liquid is then pressurized to enable it to pick up more high temperature heat from the heat source.

The proportion of high temperature heat that can be converted to work is governed by the Carnot rule, often called the Carnot efficiency. It is really a conversion ratio, not an efficiency, so in order to avoid confusion with actual efficiencies the term "conversion ratio" is used here. The Carnot conversion ratio is a function of the temperature of the heat source and the heat sink, given by the well known equation

$$C = \frac{(T_1 - T_2)}{T_1} \quad (1)$$

where $T_1$ is the source temperature and $T_2$ is the sink temperature, on the absolute temperature scale

When the heat is being rejected to ambient the design sink temperature can be taken to be relatively constant so it is evident that the conversion ratio will reduce as the source temperature falls, since the difference between source and sink diminishes faster than the absolute temperature of the source. The conversion ratios for a range of source temperatures at two fixed sink temperatures of 5 °C and 35 °C are derived from Equation (1) and shown in Figure 1 as CCR5 and CCR35 respectively,. The sink temperatures are representative of design ambient for an air-cooled system rejecting heat to ambient and a seawater cooled system.

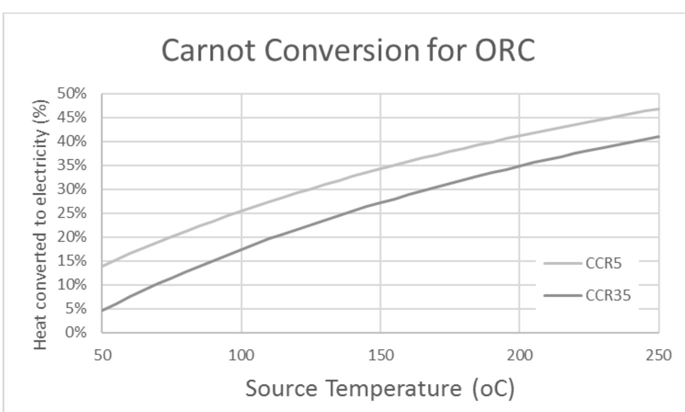


**Figure 1:** Percentage ideal conversion ratios for air-cooled and seawater cooled ORC systems

There are numerous practical challenges in designing an effective ORC system for low source temperatures, taken here to be temperatures below 100 °C. These are also known as "low enthalpy ORC" (LEORC) systems.

### 4.1 Heat exchanger thermodynamics

The ORC system depends on a volatile fluid to carry heat from source to sink. The change of phase from liquid to gas and back again in this closed cycle is essential to the operating efficiency; if the repressurizing stage of the cycle was in the gas phase then the power required to raise the pressure would be not less than the power extracted in lowering the pressure. The heat exchangers, an evaporator at the heat source and a condenser at the heat sink, therefore have a two-phase working fluid on one side and a single phase fluid (air or water) on the other. The two-phase fluid temperature remains almost constant throughout the heat transfer process but the single phase fluids temperature changes significantly, with a pinch point at the outlet on the single phase side. It follows that although the source is available at a certain temperature, extracting enthalpy from it lowers the temperature and transferring heat across the pinch point produces a further reduction to reach the evaporating temperature. Likewise in the condenser the working fluid flowing from the expander outlet has to be at a higher temperature than the heat sink, whether it is air-cooled or water-cooled. The net temperature difference in Equation (1) is therefore less than ($T_1$ - $T_2$) and the sink temperature is higher than $T_2$. Equation (1) can then be restated as Equation (2), where $T_e$ is the evaporating temperature and $T_c$ is the condensing temperature.

$$C' = \frac{(T_e - T_c)}{T_e} \tag{2}$$

If the range in the evaporator and condenser is 5 K and the approach (the pinch) is 3 K then the reduction in the Carnot conversion ratio from C to C′ ranges from 2.5 percentage points when the source is 250 °C to 5.0 percentage points when the source is 50 °C. Thus, as can be seen in Figure 1, an air-cooled LEORC system with a heat source at 50 °C would actually deliver no useful output even if the expander had 100% isentropic efficiency.

### 4.2 Expansion engine type

The Carnot conversion ratio, even if adjusted to the new base provided by the evaporating and condensing temperatures $T_e$ and $T_c$ will be higher than that which can be achieved in practice because the expander will have a certain isentropic efficiency due to irresversible losses within the machine. It might be possible to get a turbo-expander with an isentropic efficiency of 85% but a screw expander is likely to be more like 70% efficient. However a turbo-expander probably requires the inlet gas to be superheated in order to ensure that there is no possibility to create liquid during the expansion process, so the benefit of increased efficiency would be offset by a further reduction in the conversion ratio. Hence, although screw expanders are likely to be less efficient they may enable a higher power output to be achieved from a low temperature heat source than a turbo-expander.

### 4.3 Choice of working fluid

The working fluid influences the overall efficacy of the ORC system in several ways. Low pressure fluids such as R-245fa require a much larger swept volume which tends to favor turbo-expanders. Lower swept volume dictates the use of a higher pressure fluid such as ammonia, but this increases the pump power required to deliver the condensed liquid back to the evaporator inlet because the pressure lift is greater. The latent heat of evaporation is also a factor. High latent heat, as with ammonia, requires a larger heat exchanger for a given mass flow. The ideal working fluid would have a low latent heat and moderate pressure lift. Isobutane seems to be a particularly good contender. Its conversion ratio is higher than that of ammonia, R-134a and even R-245fa, although only by a fraction of a percentage point. The required volume flowrate for isobutane is three times that required for ammonia, twice the requirement for R-134a but only half the R-245fa volume requirement.

### 4.4 Ancillary Power Consumption

It is obvious that the mechanical equipment required to transfer heat from the source to the working fluid and from the working fluid to the sink will require some power to drive it. This equipment usually comprises fans and pumps, but might also require trace heating, water treatment, filtration and other ancillaries necessary to run the equipment. These items, particularly fans and pumps, can soak up a significant proportion of the power generated, putting the economic viability in doubt at low source temperatures. The power required by pumps and fans is directly proportional to the mass flow rate of the secondary fluid. The flow rate can be reduced by increasing the temperature range through which the secondary fluid passes but increasing the range has an adverse effect on the conversion ratio. For a seawater cooled system, assuming the sea to be at 5 °C, the optimum range to balance the power output and the power requirement for the seawater pump was found to be 9 K, thus heating the seawater to 14 °C. A similar optimization exercise is required for the heat source secondary fluid pump and the working fluid pump.

### 4.5 Style of source heat exchanger

It is difficult to design large heat exchangers to be counterflow. Physical and cost constraints tend to result in a configuration that is primarily crossflow, such as a typical kettle-type flooded evaporator. This inhibits the use of imaginative system designs to reduce the required flow rate such as, for example, preheating the liquid before it evaporates, unless separate heat exchangers are used to optimize the pinch.

### 4.6 Selection of heat sink

The foregoing analysis shows that it is impractical to consider ambient air as the heat sink for a source of less than 80 °C unless the design ambient is very much lower than 35 °C. This greatly restricts the field of application of low temperature ORC so heat rejection to seawater or river water is strongly preferable. If a demand for very low grade heat can be found that can provide a requirement for megawatts of heating below 25 °C then there is a prospect for a combined heating and generating but such applications are very uncommon.

### 4.7 Consideration of the local and global environment

One implication of the low conversion ratio is that the quantity of heat rejected to the ambient becomes a high multiple of the power generated. The consequences of this high multiple need to be carefully considered. For example extracting geothermal heat from deep underground and turning a small portion of it, perhaps less than 5%, to electricity and then warming the surroundings with the remainder could create significant distortion of the local environment. This might be able to be harnessed for good, for example in fish farming or plankton generation but it could also have severe adverse side effects. At a local level unwanted algal bloom or weed growth could cause problems and at a global level increasing sea temperatures could accelerate the release of carbon dioxide from deep oceans or accelerate the melting of ice caps. It is easy to dismiss these concerns by saying that ORC generation could not ever be on a large enough scale to do such damage but it is harder to completely banish the thought that this technology might be creating a climate challenge for our great-grandchildren that is just as intractable as that which was presented to us by our great-grandparents.

The actual conversion ratio, denoted $C^*$, can be calculated as shown in Equation (3), where the ancillary power required to operate the evaporator, the condenser and the working fluid pump are deducted from the power generated by the expander after accounting for the isentropic efficiency of the expander, $\eta_i$ and the electrical efficiency of the generator and power electronics required to transform the alternator output to a form suitable for export to the mains electrical network, $\eta_g$.

$$C^* = \frac{W_n}{Q_e} = \frac{\eta_g \eta_i C' Q_e - (W_e + W_c + W_p)}{Q_e} \tag{3}$$

For a practical system with $T_1$ = 70 °C, $T_2$ = 5 °C seawater, an approach of 3 K in the evaporator and condenser and a range of 18 K in the evaporator and 9 K in the condenser the actual conversion ratio was calculated. The expander $\eta_i$ and the generator $\eta_g$ were taken as 75% and 95% respectively and the working fluid selected was isobutane. Under these conditions $W_e$ was 11.9 kW, $W_c$ was 21.7 kW and $W_p$ was 8.6 kW. C′ was 9.9% and so $C^*$ is calculated to be 5.7%, meaning that if 1 MW is extracted from the heat source only 57 kW will be exported to the grid but 926 kW has to be rejected to the heat sink and 17.25 kW is dissipated through internal losses and ancillary devices. The losses and ancillaries account for 30% of the actual power output. It is important to understand the effect that such a low conversion ratio would have on the local and global environment.

Table 1 shows the key statistics for the United States of America and the United Kingdom with regard to land area, population, electrical generation capacity and heat flux to a heat sink assuming the entire electrical demand was delivered by low enthalpy Rankine cycle, for example from industrial process heat or deep geothermal sources. It is assumed for both USA and UK that the actual conversion ratio from these heat sources is 6% and that 92% of the heat extracted from the source is rejected to air as the heat sink, with the other 2% being otherwise dissipated to atmosphere. Although the energy use per head of population is much higher in the USA, the population density in the UK is higher, so the heat flux over the full area of the country would be 0.75 W $m^{-2}$ in the USA and 2.33 W $m^{-2}$ in the UK. In contrast, solar insolation at the upper atmosphere is about 1350 W m$^{-2}$ and reduces to between 200 W m$^{-2}$ and 400 W m$^{-2}$ at ground level on average at mid-latitudes. Hence generation of electricity in this way would not add significantly to the existing heat flux from sunlight, even at such low conversion ratios.

**Table 1:** The national environmental effect of total generation by low enthalpy ORC

| | Area of country (km$^2$) | Population | Population Density (p km $^2$) | Annual Electricity Generation (GWh) | Energy use per Person (kWh p $^1$) | Heat flux from ORC (W m $^2$) |
|---|---|---|---|---|---|---|
| **USA** | 9,800,000 | 328,200,000 | 33.4 | 4,162,000 | 12,681 | 0.75 |
| **UK** | 242,500 | 66,700,000 | 275.1 | 323,000 | 4,843 | 2.33 |

However, since generating plants are generally collocated with population centers it is perhaps optimistic to consider the heat flux to the sink to be spread uniformly across the whole country. There is then a risk that rejecting so much heat to atmosphere could contribute to the urban heat island (UHI) effect for the city in question. To assess the significance of this a comparison was made with contribution of the heat flux due to insolation and due to other anthropogenic activity. The heat fluxes due to low enthalpy ORC for Los Angeles, California and London, UK were estimated, assuming the same generation requirement per head as in Table 1 and the results are shown in Table 2. In comparison the peak heat flux due to insolation, according to Sailor and Lu (2004) is about 350 W m$^{-2}$ and the maximum heat flux due to all anthropogenic activity, said by Sailor and Hart (2006) to comprise metabolic heat generation, heat rejection from electricity use and heat rejection from fuel use is estimated to peak between 50 W m$^{-2}$ and 90 W m$^{-2}$ depending on the city, but with wide diurnal variation.

**Table 2:** The urban environmental effect of total generation by low enthalpy ORC

| | Area of county (km$^2$) | Population | Population Density (p km $^2$) | Generation per Person (kWh p $^1$) | Annual Electricity Requirement (GWh) | Heat flux from ORC (W m $^2$) |
|---|---|---|---|---|---|---|
| **LA** | 12,310 | 10,000,000 | 812.3 | 12,681 | 126,810 | 18.0, |
| **London** | 1,572 | 9,000,000 | 5,725.2 | 4,843 | 43,587 | 48.5 |

The heat flux from ORC is less than this peak, but it would apply at a steady rate for 24 hours per day, so in rough terms low enthalpy ORC could add approximately 40% to the urban heat island effect for a city like London, or 15% to a Los Angeles type of city. Currently the UHI effect is estimated to add 4 K to London temperatures and 10 K to Los Angeles so in both cases the use of low enthalpy ORC to supply all the city's electricity might add 1.5 K to the air temperature in major cities.

The same challenges outlined in points 4.1 to 4.7 can also be applied to refrigeration and air conditioning systems and to heat pumps, where there is a similar need to find ways to improve efficiency. To date insufficient attention has been paid to topics such as the use of expanders, the choice of working fluid and the configuration of heat exchangers for optimal efficiency, so there is certainly scope for further improvement. The challenge is to find ways to do so at an acceptable capital cost. This means that the performance of the system, whether refrigeration or heat pump, needs to be improved but the margin generated for the manufacturer in selling it also needs to be improved. Margin improvement is achieved by either cutting production cost or increasing price with the proviso that sales volume must also be considered. A high priced product selling in relatively small numbers can generate more margin than a mass produced item on a very thin profit margin, but the ability of large volume production to support further product development because the investment per unit is very low is also a significant factor. Much of Rankine's work, particularly in the engineering of railroads, locomotives and ships, was strongly influenced by economic factors, balancing them against technical considerations to develop designs that were optimized for minimum cost of ownership.

## 5. FOLLOWING RANKINE'S EXAMPLE

If he had been faced with the technical challenges presented by the improvements in efficiency and cleanliness now required of our power generation and refrigeration systems, Rankine would have undoubtedly applied the principles that served him well throughout his career. He would take as broad a view of the problem as possible, drawing on a wide range of experiences to develop a range of mental pictures and analogies to encapsulate the essence of the challenge. He would use these images to construct a detailed mathematical model and where existing mathematics was insufficient to provide a solution he would invent his own to suit. He would ensure at all points however, no matter how abstruse the theories became, that this was embedded in a solid practical foundation. His systems would be feasible and his machines would be buildable, operable and maintainable. Above all, he would communicate with good humor and grace, pitching his message to the right level for his audience, and he would never fail to recognize the contribution of his co-workers, colleagues and even his competitors. It is notable that at the end of his first term as President of the newly founded Institution of Engineers in Scotland in 1859, William Thomson, James Joule and Rudolph Clausius were all inducted as Honorary Fellows of the Institution, an honor which was most recently accorded to Professor Eckhard Groll of Purdue University.

## 6. CONCLUSIONS

Rankine explained his view of engineering and science in his introductory lecture to the University, "On the Science of the Engineer" in November 1856 with the following words

"*Let the young engineer then be convinced that the profession which he studies is not a mere profitable business, but a liberal and a noble art, tending towards great and good ends, and that to strive to the utmost to perfect himself in that art, and in the sciences on which it depends, is not merely a matter of inclination or of policy, but a sacred duty*." (Chambers and Thomson, 1875)

Continuing to seek improvements in refrigeration systems, whether for cooling, heating, conditioning or generation is a modern day imperative worthy of the liberal and noble art of which Rankine spoke. There appears to be a need for a greater integration of theoretical science and practical engineering so that the excellent technical innovations being developed and tested at places like Purdue University can be applied in practice to the greatest advantage. Rankine's example suggests that this requires a greater focus on the commercial aspects of the idea at the laboratory stage and a greater attention to the detail of the technical development when it is being installed and operated. The American civil engineer Arthur M Wellington[+] summarized this dilemma when he wrote

"*It would be well if engineering were less generally thought of, and even defined, as the art of constructing. In a certain important sense it is rather the art of not constructing; or, to define it rudely but not inaptly, it is the art of doing that well with one dollar, which any bungler can do with two after a fashion.*" (Wellington, 1887).

He went on to point out that for skilled engineering activity "*the definition given is literally applicable, for the economic problem is all there is to it.*" In the past it seems that this economic problem has been used as an argument against the progression to more efficient systems on the basis that better performance cannot be achieved because the additional cost required is economically unacceptable. We need to get better at "*the art of not constructing*" as Wellington put it. In other words we need to find ways to improve upon the exceptional performance that could be achieved with a two-dollar design but by only spending one.

[+] Note this quotation is often attributed in a slightly different form to Arthur Wellesley, Duke of Wellington, as "*The art of engineering is to do for ten shillings what any fool can do for a pound*" While this version is slightly classier than the quote from AM Wellington, it is probably bogus. There is no evidence that the Duke ever said this but it is in the introduction to his namesake's treatise on the economics of railroad construction, first published twenty five years after the Duke's death. The subtlety of the 1887 quote is that it requires the job to be done well for a dollar.

## NOMENCLATURE

| | | |
|---|---|---|
| C | Carnot Conversion Ratio | (–) |
| C′ | Reduced Conversion Ratio | (–) |
| $C^*$ | Actual Conversion Ratio | (–) |
| Q | Heat transferred | (kW) |
| W | Work transferred | (kW) |
| η | efficiency | (–) |

**Subscript**

| | | | |
|---|---|---|---|
| 1 | heat source | 2 | heat sink |
| c | condenser | e | evaporator |
| g | generator | i | isentropic |
| p | working fluid pump | | |

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## ACKNOWLEDGEMENT


The author would like to thank the directors of Star Refrigeration Ltd for permission to work on this study and publish the findings and also to acknowledge with thanks the Members, Fellows and Council of the Institution of Engineers in Scotland for their support and encouragement.