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# Some Experiences, Thoughts, Ideas and Open Questions Relating to Applied Thermodynamics

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# Some Experiences, Thoughts, Ideas and Open Questions Relating to Applied Thermodynamics*

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**Abstract**

In this paper I present some of my thoughts and experiences relating to 'applied thermodynamics' over my career so far. I explain my interest in thermodynamics, describe some topics I have worked on, point out some questions that appear still to be open and outline some ideas for work that could be done.

I describe how I was inspired to pursue the area of applied thermodynamics, with reference to a glass, opposed-piston internal combustion engine. I put my heat pump research in the late 1970s briefly into today's context. Some of my research has been in relation to compressors, which are work input devices: progress was made in understanding what happened to the work. Perhaps some conventions in thermodynamics can be challenged, e.g. the convention of taking both 'heat in' and 'work out' as positive. Exergy analysis, rational efficiency, finite time thermodynamics and simulation are mentioned. I describe my work on zero-emissions cycles, which was inspired by Evgeny Yantovski. Recently I have worked on the Stirling cycle and cycles for high-performance, 'low thermal efficiency' heat engines. I have a Stirling cycle concept that I would like to develop. All of these things are connected. Symmetry is mentioned and I provide references to some relevant publications, including ones where I have been an author or co-author.

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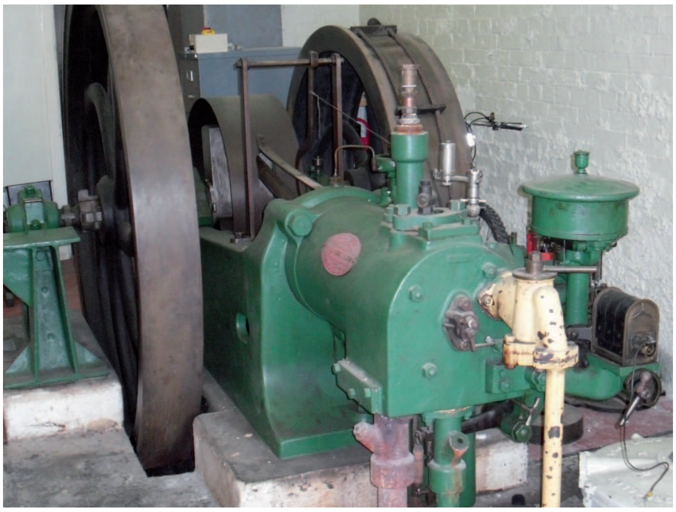

Figure 1: Crossley gas engine at Dublin Institute of Technology, Bolton Street, 2010. The engine is complete, but is not connected to a gas supply and is not in use.

## 1 Why Thermodynamics?

My career-long interest in and involvement with applied thermodynamics commenced through the inspirational lectures and labs of the late Professor Seamus G. Timoney (1926–1991) at University College Dublin. The first course I took with him, in the third year (1973–1974) of the Mechanical Engineering degree programme, was Thermodynamics and the second, in my final year, was Internal Combustion Engines. Seamus Timoney explained the fundamentals clearly and supported technical understanding by working through extensive calculations. Then, as is still the case now, learning Thermodynamics required painstaking attention to detail. For instance, my classmates and I plotted thermodynamic property diagrams on graph paper, taking data from steam tables under Professor Timoney's guidance.

The lectures were supported by laboratory experiments, where understanding and mastering the fundamentals were further emphasized. In Thermodynamics we carried out tests on a steam boiler, on a dual-fuel (oil and gas) reciprocating internal combustion engine (somewhat similar to the Crossley engine shown in Figure 1) and on a twin-turbine steam power plant. As far as I can recall, we also tested a reciprocating steam engine (which was an even more historical artefact than the dual fuel engine. For these engines a mechanical or a mechanical-electrical (spark-tracer type) indicator was used to obtain pressure-versus-volume diagrams for the determination of indicated power. Figure 2 shows a mechanical indicator. Variations between cycles were considerable and it was necessary to take the average 'mean effective pressure' from a number of indicator diagrams. Indicator di-

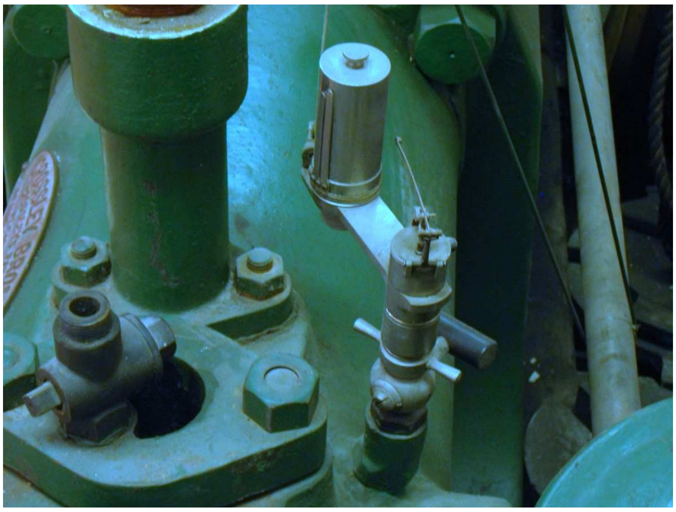

Figure 2: Engine indicator on the Crossley gas engine. A cord, in tension, linked to the connecting rod of the engine provided the oscillating motion of the chart-holding cylinder.

agrams characterize and quantify the work processes of positive displacment machines (such as engines, compressors and expanders) and, whether measured or determined by simulation, continue to be very important. Figure 3 is an indicator diagram from my own 1988 Ph.D. thesis [1].

Seamus Timoney was a highly enthusiastic and talented Mechanical Engineer. His personal work-rate was enormous and he had many engineering achievements. He was an inventor, e.g. a patent entitled 'Internal combustion engines' with seven claims [2], and he had the skill and the drive to implement his ideas. Figure 4, which is a diagram from the patent, is a concept for an opposed-piston engine in which the compression ratio could be varied dynamically. A great dream of Seamus Timoney's was the concept of an adiabatic ('no coolant') *ceramic* reciprocating internal combustion engine [3]. In talking about it, Seamus Timoney sometimes referred to it as a *glass* engine, which made it seem all the more tantalizing. He saw the opposed piston configuration as ideally suited to the perceived requirement that all ceramic components be designed to be in compression. Had he realized his dream of a viable adiabatic engine, the temperature of the exhaust gas would have been increased significantly compared to the exhaust temperature of a non-adiabatic engine. The potential would have been created for the achievement of a higher thermal efficiency from any bottoming cycle that might have been used. I believe the dream lives on.

In case I am misunderstood, I want to be clear about my attitude to historical engines and scientific artefacts. I am very interested in inspecting these items and studying them. It is important that they are recorded and

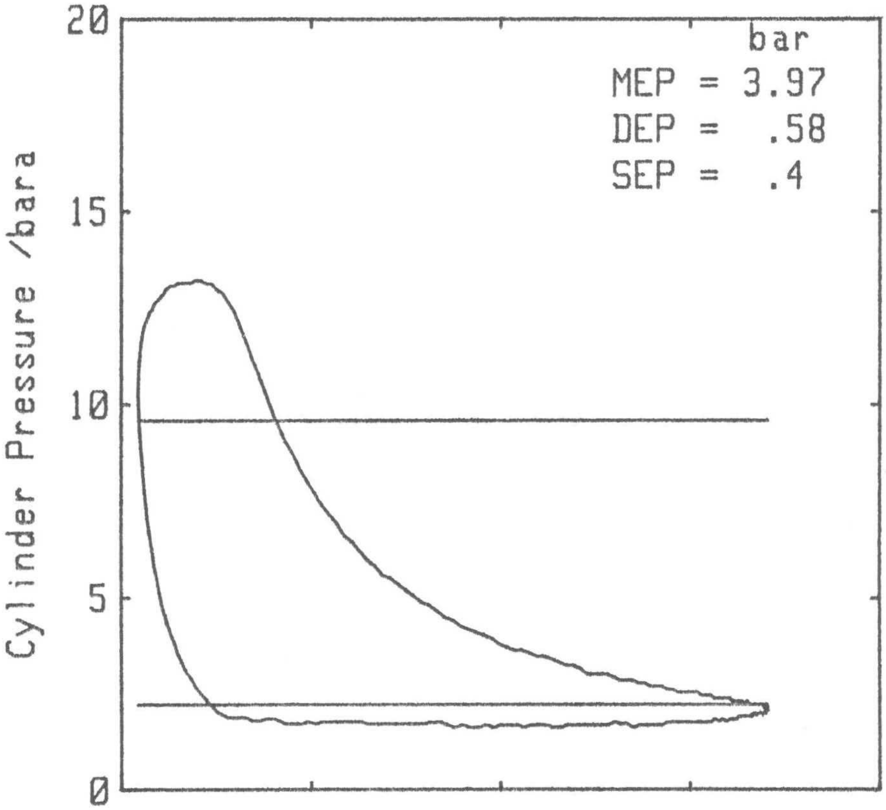


Figure 3: $p$-$V$ diagram for a reciprocating refrigerant compressor [1]

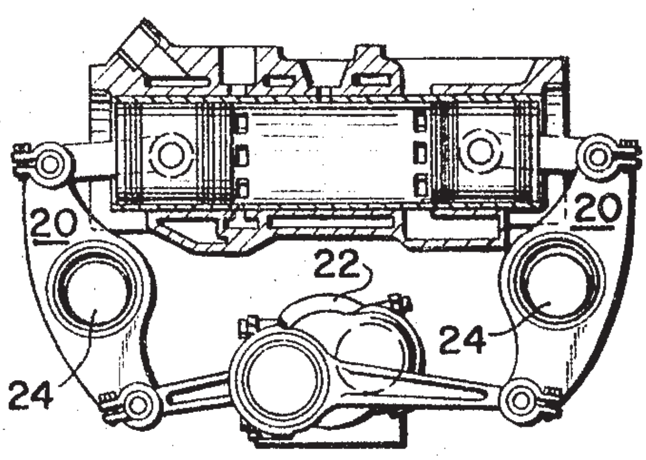


Figure 4: Diagram of a variable compression opposed piston engine from a patent by Prof. Seamus Timoney [2]

are preserved in museums. However, I am not in favour of using them for regular instruction of undergraduates. This is because priority needs to be given to current equipment and technologies. However, visits to museums can be very educational. On my web site a have a children's story [4] that relates to an excellent and under-appreciated steam museum at Straffan, Co. Kildare, in Ireland.

## 2 Heat Pumps

Having completed my bachelor's degree in 1975 I undertook research for a Master of Engineering Science degree under the supervision of Professor Timoney. The title was 'Heat pump evaluation and design for the Irish climate' [5] and the degree was conferred in 1977. The air-to-air heat pump that I tested was capable of a coefficient of performance of between 1 and 1.7, depending on the operating conditions (outside temperatures from $-10\,^{\circ}\mathrm{C}$ to $15\,^{\circ}\mathrm{C}$ and room air temperatures from $15\,^{\circ}\mathrm{C}$ to $25\,^{\circ}\mathrm{C}$).

The particular air-to-air heat pump that I tested would have had a very low seasonal COP of about 1.2. I estimated that, with design improvements, a seasonal COP of 1.7 was achievable for a heat pump of the same configuration. A basic computer simulation model of the heat pump was developed and the program listing in the thesis is an early example of such a simulation program.

Thirty-five years later, heat pumps are still uncommon in Ireland for domestic space heating. It is only very recently that buildings are being built, or upgraded, to have a sufficiently low heating demand that heat pumps have some chance of being economically viable. Where heat pumps are installed they are likely to be of the air-source or ground-source type and the sink is likely to be hot water for space heating and domestic hot water. Low-operating-temperature 'radiators' or underfloor heating are used to allow condensation in the heat pump circuit at a reasonably low temperature. Seasonal COP values of perhaps 3 can be realized. Heat pumps still fall far short of the ideal described by William Thomson in 1852: a COP of about 35 for heating outside air at $10\,^{\circ}\mathrm{C}$ to $27\,^{\circ}\mathrm{C}$ [6].

From about September of 1978 to August of 1979 I worked at University College Galway on a research project entitled 'The optimization of electrically driven heat pumps for the heating of houses with the aim of a minimum seasonal energy consumption.' This project involved testing and performance monitoring of heat pumps and, on my part, a large amount of computer modelling with the objective of understanding the interaction between the heat pump and the fabric of the building that was being heated. Today in Ireland buildings are required to have a formal energy rating, which is calculated using standardized software. For the present, this software does not take account of the dynamic performance of the fabric of the building.

## 3 Refrigerant Compressors

In 1981 I joined the University of Dublin, Trinity College, as a lecturer in Mechanical Engineering, having already completed two years as a lecturer at what was then Carlow Regional Technical College. I lectured mainly in the areas of Thermodynamics and Fluid Mechanics. As a staff member I undertook research on refrigerant compressors and was awarded a Ph.D. degree in 1988 for my thesis, which had the title 'On refrigerant compressors' [1]. This research involved compressor testing and simulation. In the thesis I presented new ways of looking at the utilization of shaft power and of volume displacement.

My refrigerant compressor research for the Ph.D. degree caused me to reflect on the Second Law of Thermodynamics and I became interested in 'exergy analysis', which was commonly described as 'availability analysis' at that time. The following sentences are from the conclusions of my Ph.D. thesis:

> The use of 'rational efficiency' and the 'rational efficiency for compression and heat rejection' are described and justified in chapter 3 and experimental values are given in chapter 7. This concept, if taken to its conclusion, would involve the attribution of losses in shaft power availability to specific causes, such as heat transfer within the cylinder, suction valve throttling, etc.

The quantification and localization of the instantaneous rates of exergy destruction in a compressor through simulation was subsequently achieved and described in conference papers [7, 8], in a Ph.D. thesis by my former graduate student, Shane Harte [9], and in a journal paper [10].

## 4 The Conventional Directions for Heat and Work in Thermodynamics

Traditionally, heat transfer into a system and work done by a system have both been taken as positive in Thermodynamics. The science of thermodynamics developed as engineers attempted to understand the factors that limited the conversion of 'heat transfer into a system' into 'net work done by the system' when the system itself undergoes no net change [11, 12], Figure 5. Had the most significant problem at the time been to understand the conversion of 'net work into a system' to 'heat transfer out of a system,' where the system itself undergoes no net change, the reverse convention might well have been adopted. However, had there been a much wider range of 'heat engine' problems involving useful heat inputs and outputs at various temperature levels and ranges, as well as multiple work inputs and outputs, perhaps a simpler convention, or no convention, would have

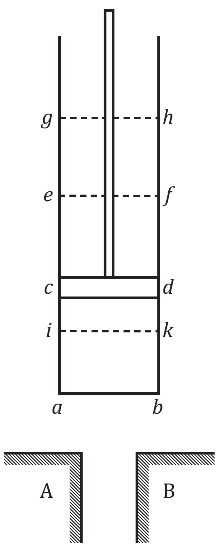


Figure 5: Sadi Carnot's diagram (redrawn) for a reversible heat engine to produce a net work output [11].

resulted. There would have been no reason to prioritize one particular direction for heat transfer and a different direction for work. On my web site, under the pen name Leo Nest [13], I have explained my view that the convention is unhelpful in explaining the principles involved. When exergy analysis is added to a conventional first law analysis it becomes impossible to maintain any reasonable consistency between the 'positive heat in, positive work out' convention and whatever convention might be adopted for the positive direction of exergy that crosses a system boundary.

Straightforward versions of the familiar 'non-flow energy equation' and 'steady flow energy equation' are presented below. In Equation 1, the $Q$ and $W$ variables are the net input energy amounts as heat and work respectively. In Equation 2, $q_{\text{in}}$ and $w_{\text{in}}$, which are the the gross input energy amounts per unit mass as heat and work respectively, are included on the left hand side. The corresponding gross output amounts are included on the right hand side.

$$Q + W = \Delta U \tag{1}$$

$$q_{\text{in}} + w_{\text{in}} + h_1 + v_1^2/2 + gz_1 = q_{\text{out}} + w_{\text{out}} + h_2 + v_2^2/2 + gz_2 \tag{2}$$

In 1994 I had the pleasure of spending a three-month sabbatical working within the research group of the late Professor Pierre Le Goff (1923–2005) at the Laboratoire des Sciences du Genie Chimique at the University of Nancy in France. I was very proud to co-author a paper with him concerning the use of positive and negative signs in exergy analysis and the definition of exergetic efficiency [14].

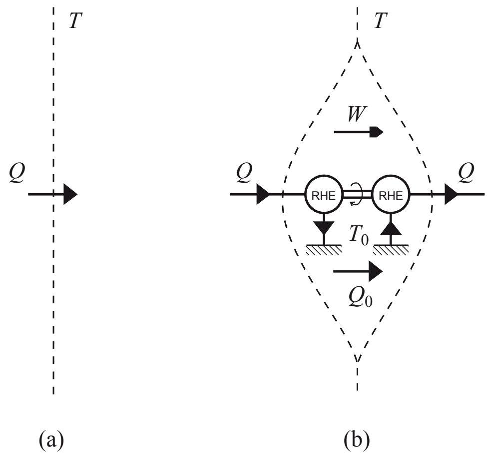


Figure 6: (a) Heat transfer through a boundary at temperature $T$. (b) A virtual ideal device, which shows the equivalent transfer of shaft work with heat transfer at a reference temperature, $T_0$.

# 5 Conceptual Devices for Exergy Analysis

A former graduate student of mine, Francis O'Toole, and I described conceptual devices that could help to envision exergy flow or transfer at boundaries [15], e.g. Figure 6.

Conceptual devices of this general type were applied to the analysis of a steam/air ejector and to a combined heat and power plant [16]. In a subsequent Ph.D. thesis [17], under my supervision, Francis O'Toole presented a new methodology for exergy analysis of flow network plant and introduced the concept of a flow constraint system. Considerable effort has been expended by researchers in this area, but even now, in 2011, it appears that consensus has not yet been reached about the methodologies that should be used. Dealing with exergy that is recycled within a plant [18] is also still problematical.

In 1997 Brian Smyth completed a master's thesis entitled 'Exergy analysis of a multi-effect evaporation unit for seawater desalination' [19] under my supervision. The analysis was based on a solar powered desalination plant in Almeria, Spain. The first two conclusions within the thesis are: 'Distillation technology is inherently irreversible' (the multi-effect distillation system tested had a rational efficiency of just over 2%) and 'With regard to the exergy destruction within the MED unit, the heat exchangers are the greatest offenders.' This thesis also contains a generic treatment of the rational efficiency of a heat exchanger.

## 6 Simulation

Throughout my career in the area of applied thermodynamics, simulation has been central to my work. Simulation means representing a plant by a simplified model. The model is refined until it adequately represents all the important characteristics. My graduate students and I have modelled heat pumps, compressors, air cycle refrigeration systems, novel thermodynamic cycles, CHP plants and combined cycle plants.

Traditionally suppliers of engineering components such as pumps, boilers or turbines provided performance characteristics in the form of tables or graphs. Today it is possible to provide a software object that encapsulates all the important characteristics of the component. However, unfortunately, this is not the situation that I see. In many cases manufacturers and suppliers are reluctant to provide the full information about their products, for commercial and competitive reasons. For instance, an engine supplier might well provide the main power output, torque and fuel consumption characteristics of a particular model over the expected operating envelope, but may not provide any information about the exhaust gas temperatures and flow rates or the rate of heat rejection to the coolant. Considerable progress still needs to be made: standardized simulation modules could be used.

## 7 Zero Emissions Technology

Prof. Evgeny Yantovski has greatly impressed me by his drive, enthusiasm and engineering creativity since I first met him at a conference. I found his book 'Energy and exergy currents' [20] inspiring and delightful. We collaborated on some publications, mainly in the area of 'zero emissions' cycles of various sorts e.g. [21, 22]. One paper related directly to exergy currents: 'Mechanical work at a boundary and its associated exergy transfer' [23]. Stemming directly from Evgeny's ideas, Kirsten Foy undertook a Ph.D. [24] in the area of zero emissions power plants under my supervision. Her excellent research included significant collaboration on papers with Evgeny Yantovski e.g. [25, 26]. The recent book by Yantovsky, Gorski and Shokotov [27] contains a lot of information and a lot of ideas in relation to zero emissions cycles.

## 8 The Stirling Cycle Engine

Barry Cullen has recently completed a Ph.D., under my supervision, with the title 'The combined Otto and Stirling cycle prime-mover-based power plant' [28]. Such a plant appears to be commercially attractive for power-only or CHP use. Through our collaboration with Michel Feidt and Stoian Petrescu, e.g. [29], Barry Cullen and I became aware of the importance of

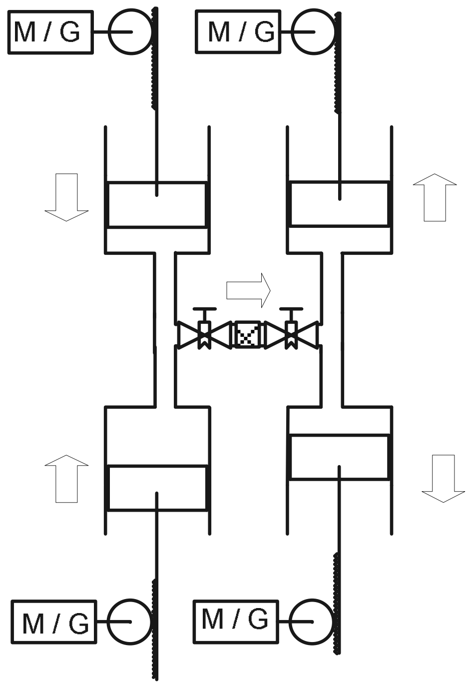


Figure 7: Schematic of the uncoupled Stirling cycle engine concept [32]

the topic of 'finite time thermodynamics' [30]. It seems to me there is a need to integrate this concept and approach fully into exergy analysis and thermoeconomics.

As an aside to the subject of Barry's Ph.D. research, I proposed that we should consider the possibility of a decoupled form of Stirling cycle engine that would break free from the constraints of particular mechanical linkages and would allow for active heat transfer enhancement through mechanical action [31, 32]. The schematic arrangement is shown in Figure 7 and the $p$-$V$ diagram is shown in Figure 8. I am keen to see this concept developed.

## 9 Low Thermal Efficiency Heat Engines

Low-thermal efficiency heat engines, such as coffee-cup Stirling engines and 'drinking birds', Figure 9, are great fun. Thermal efficiency never was a true efficiency, but an applied thermodynamicist will be happy to try to build a low-thermal-efficiency engine of high rational efficiency. This is currently a popular area of research in relation to renewable energy applications and waste heat recovery. Recently I worked with a class of master's degree students on the preliminary design of a trans-critical $CO_2$ cycle to utilize waste heat over a temperature glide from 200 °C to 100 °C. Also, I currently have an undergraduate student who is undertaking a related design project.

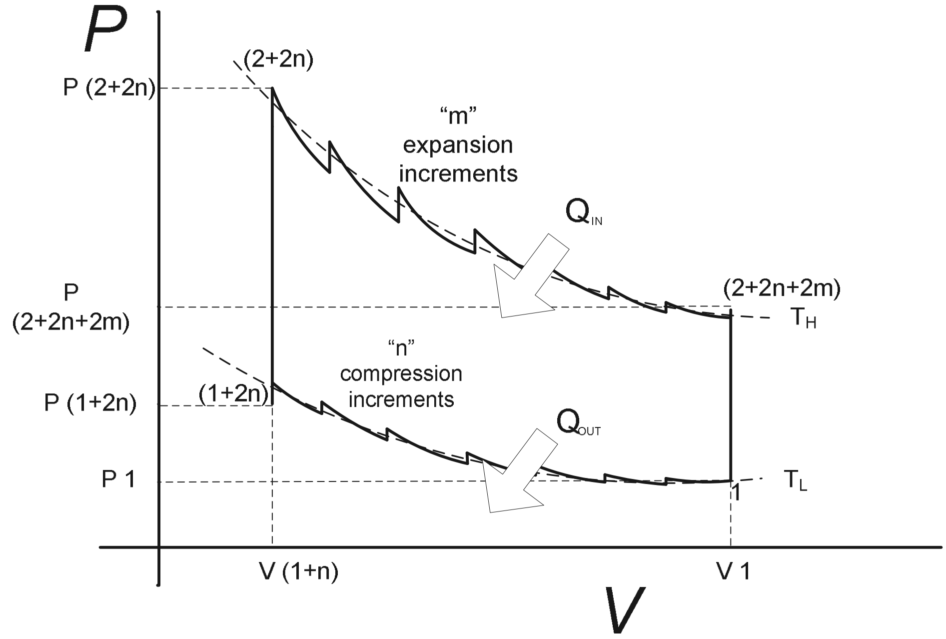


Figure 8: Uncoupled Stirling cycle $p$-$V$ diagram [32]

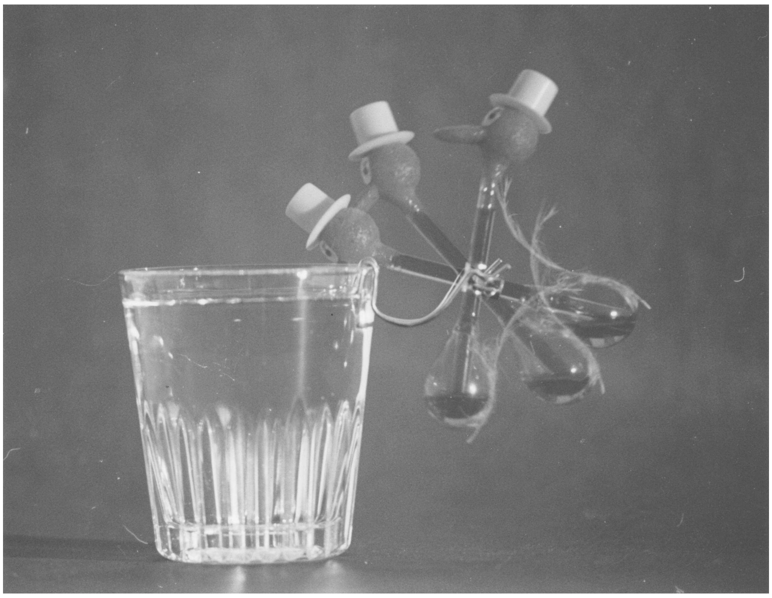

Figure 9: An old multiple-exposure photograph that was taken for me by a colleague at Trinity College Dublin. The drinking bird is a low-thermal-efficiency heat engine.

All the engineering challenges can be met.

In 1983, having searched for papers relating to the 'drinking bird,' I obtained a copy of a technical report by R.B. Murrow [33] from the Rand Corporation. I note that various papers have cited it. Some years later I drew up a competitive design brief for freshman engineering students, based on the drinking bird concept. However, I was advised by academic colleagues to consider returning to a simple toy-vehicle design-and-race concept, such as the one I had run successfully the previous year. I bowed to their better judgement.

## 10 Symmetry

Figure 10: Unstriking a match [34].

I have been fascinated by symmetry [35] and have a deep curiosity about the 'fundamentals of the fundamentals' of thermodynamics. In one paper I pushed speculation quite a distance [34]. The apparent asymmetry of time is very puzzling. Figure 10 illustrates a match being unstruck. A narrative for this is available on my web site [36].

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