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Stirling myth – and Stirling reality

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1.1 Expectation

'*Stirling's is a perfect engine, and is the first perfect engine ever to be described.*' (Fleeming Jenkin, 1884). '*offering silence, long life*.' (Ross, 1977). '*... thus enabling the thermal efficiency of the cycle to approach the limiting Carnot efficiency.*' (Wikipedia 2013). *A silent, burn-anything, mechanically simple, low-maintenance, low-pollution prime mover with potential for the thermal efficiency of the Carnot cycle*. Here, without doubt, is a recipe for run-away commercial success which Lloyds of London would surely be happy to underwrite.

The reality of the modern Stirling engine is in terms of tens of thousands of 'one-offs' – prototypes or designs of different degrees of sophistication, only a tiny handful of which have been followed up by a degree of further development.

The outcome of a technological venture has much to do with expectation: Where this is unreasonably or irrationally high, the outcome falls short. The verdict – by definition – is failure. The *identical* technological outcome based on realistic expectation can amount to success.

The Stirling engine is not silent – but can be quiet relative to reciprocating internal combustion engines of comparable shaft power. There is not the remotest chance of approaching the so-called Carnot efficiency, but claims for brake thermal efficiencies comparable to those achieved by the diesel engine appear genuine. Nominal parts count per cylinder of the multi-cylinder Stirling is, indeed, lower than that of the corresponding four-stroke IC engine. On the other hand, many individual components pose a severe challenge to mass manufacture.

Supposing this more sober view to be correct, a world of limited resources and increasing environmental awareness probably has room for the Stirling engine. If so, responding to the need is going to require a lowering of expectation. This may be helped by the shedding of a substantial body of myth.

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1.2 Myth by myth

1.2.1 That the quarry engine of 1818 developed 2 hp

This can be traced back to an article in *The Engineer* of 1917 celebrating rediscovery of the patent specification – but no further. A back of envelope calculation will indicate whether further enquiry is necessary.

All power-producing Stirling engines of documented performance yield approximately the same value of Beale number N_B:

$$N_B = \frac{\text{shaft power [W]}}{\text{charge pressure [Pa]} \times \text{swept volume [m}^3\text{] and speed [cps} = rpm/60]}$$

The value is dimensionless and is typically 0.15 [–] – the 'Beale number'.

Charge pressure p_{ref} of Stirling's engine was 1 atm or 10^5 Pa. Linear dimensions cited in the 1816 patent convert to swept volume V_{sw} of 0.103 m^3. Rotational speed is not on record, but on the basis of hoop stress, the *rpm* capability of the 10-ft diameter composite flywheel has been estimated with some confidence (and with subsequent corroboration – Organ 2007) at 27.

On this basis the Beale arithmetic suggests a power output of 695 W – or 0.93 hp. The figure of 0.15, however, derives from engines operating with expansion-space temperatures T_E at or above 900 K (627 °C). Stirling is specific about a much lower value of 480 °F, consistent with limitations of materials available in 1818 (wrought iron). This converts to 297 °C, or 570 K. Performance is very much a function of temperature ratio, $N_T = T_E/T_C$, where T_E and T_C are absolute temperatures, K. Where N_T departs from the norm of $N_T = N_T{}^* = 3$, the definitive parametric cycle analysis (Finkelstein 1960a) justifies a temperature correction factor of $(1 - 1/N_T)/(1 - 1/N_T{}^*)$. The factor is 0.345/0.666 in the present instance, or 0.518, reducing the shaft power prediction to 0.482 hp, or 360 W.

The figure is corroborated by a forensic study (Organ 2007) based on experiments with a full-size replica (Figure 1.1) of furnace and displacer cylinder, backed up by computer simulation.

Chapter 1 of the 2007 text describes the construction of the replica furnace and flue, the stoking experiments and temperature measurements. At maximum stoking rate on coal, peak temperature measured at the rectangular exhaust outlet is 200 °C. It is possible to hold a hand against the upper inner surface of the expansion cylinder, suggesting that the internal temperature of the metal surface remains below 60 °C.

If the inevitable conclusion fails to convince, then it may help to recall the last time an egg was successfully boiled with the heat source some 10 feet (3 m) from the saucepan.

The simulation re-created the cyclic volume variations generated by the crank mechanism of the 1816 patent drawings. The start-point for exploratory simulation runs was the earlier estimate of flywheel-limiting speed of 27 *rpm* derived from considerations of hoop stress. Interpretation of the results erred in favour of best possible performance: Wire diameter d_w and winding pitch (essentially inverse of mesh number m_w) settled on for the regenerator were those which caused the simulation to indicate optimum balance between loss due to pumping and loss due to heat transfer deficit.

On this basis peak power occurred at 28 *rpm*. The simulation could coax no more than ½ hp (373 W) from the crankshaft.

Figure 1.1 Furnace, flue and upper displacer cylinder re-constructed full-size to the drawings and dimensions of the Edinburgh patent

Stirling's own hand-written description cites temperature *difference* (between upper and lower extremes of the cylinder) of 480 °F – or 297 °C. If ambient temperature were 30 °C this would require the hottest part of the cylinder to be at 337 °C. The quarry engine doubtless functioned – but not in the elegant configuration of the patent drawing.

A drawing of an engine which, by contrast, is readily reconciled with brother James Stirling's retrospective (1852) account is shown at Figure 1.2: flywheel, link mechanism, cylinder, piston, and displacer are re-used. However, the entire assembly now operates upside down relative to the patent illustrations, with cylinder head immediately above the furnace and the flame in direct contact.

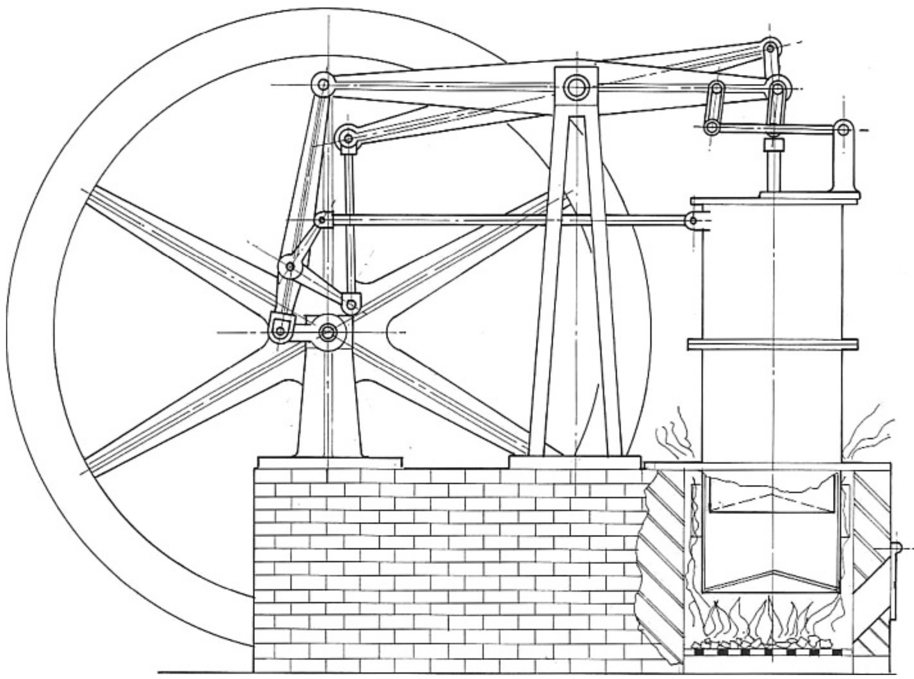

Figure 1.2 How the quarry engine might have appeared after inversion of the cylinder unit to allow heating to a viable operating temperature

Achieving ½ hp no longer requires Stirling to have optimized the thermal and flow design of the regenerator. Brother James' account of the eventual failure of the engine now makes sense: '*… the **bottom** of the air vessel became over-heated*.'

1.2.2 That the limiting efficiency of the stirling engine is that of the Carnot cycle

Nothing could be further from the truth! The Stirling engine functions by virtue of an irreversible process – that of of forced, convective heat transfer. It does so in spite of two further irreversibilities: thermal diffusion and viscous fluid flow. The *engine* – the hardware as distinct from the academic distraction – no more aspires to the Carnot efficiency than does the cement mixer.

The spurious comparison raises important matters which will need re-visiting at a later stage:

> The Carnot cycle appears to be imperfectly understood – not least by the man himself, Sadi Carnot.
> A part-understood criterion is not one which gets applied logically.

(There is something mildly fraudulent afoot when a principle hailed as an unsurpassed ideal on the blackboard promises dismal failure when converted to hardware. A Carnot 'engine' would be crippled by inadequate thermal diffusivity of the working gas, or by sealing problems – or by both. When *any* Stirling engine turns a crank, thermal efficiency and specific power surpass those of the hypothetical Carnot embodiment.)

Used appropriately, however, the ideal cycle has unexpected insight to offer: the element of net work W [J] when heat Q_E [J] is admitted to the cycle at T_E [K] is $Q_E(T_E - T_C)/T_E$ [J]. The value reflects the absence of losses of any kind. When the practical Stirling engine takes in Q_E per cycle at T_E, the resulting W is less than the Carnot value to the extent of net losses. For a given engine the numerical total of the loss per cycle varies with charge pressure, *rpm*, and so on. The point is, however, that the value of that net loss is given by simple numerical subtraction, and that a figure is available corresponding to each documented combination of charge pressure, *rpm* and working fluid.

Chapter 3 exploits this approach. The sheer magnitude of the loss relative to the useful work element will probably come as a revelation.

1.2.3 That the 1818 engine operated '… on a principle entirely new'

There is no doubting Stirling's integrity in making the claim, but it conflicts with a reality of some 22 years earlier. The patent granted in 1794 to Thomas Mead describes '*Certain methods … sufficient to put and continue in motion any kind of machinery to which they may be applied*.' Mead describes a pair of mating cylinders coaxial on a common vertical axis. The cylinder diameters overlap (cf. the telescope), so axial motion of one relative to the other changes the enclosed volume. In one of his several 'embodiments', the outer ends of both are closed, except for provision for a rod to pass through a gland in the lowermost closure and to actuate a cylindrical 'transferrer'. Heating the top of the uppermost cylinder from the outside and alternately raising and lowering the 'transferrer' promises a cyclic swing in pressure. Mead anticipated that this would cause the 'telescope' alternately to shorten and lengthen, affording reciprocating motion capable of being harnessed.

The Mead specification, eventually published in printed form in 1856, is illustrated by a line drawing ('scetch') devoid of crank mechanism and making no pretence at depicting engineering reality. Whether or not Robert Stirling was aware of the patent, here nevertheless, in 1794, had been the essence of the closed-cycle heat engine with displacer.

1.2.4 That the invention was catalyzed by Stirling's concern over steam boiler explosions

Authors promoting this version of Stirling's motivation have been contacted. Those who have replied have declared themselves unable to offer evidence from written record.

Flynn et al. note that statistics on steam boiler explosions for the early nineteenth century are lacking. Figures attributed to Hartford Boiler Insurance Co. suggest a heyday of explosions in England – 10 000-plus incidents – during the period between 1862 and 1879. This is half a century *after* the 1816 invention.

The comprehensively-researched account by 1995 by Robert Sier of the life and times of Robert Stirling gains much of its scholarly impact by offering a wealth of quotation from the historical record – and by withholding speculation about motives.

The United Kingdom considers Frank Whittle to be the inventor of the jet engine. As a Royal Air Force officer, Whittle would have been aware of the history of gruesome amputations by aircraft propellors. No one has (so far) had the bad taste to offer that awareness in explanation of his pioneering work.

1.2.5 That younger brother James was the true inventor

The younger sibling would have been 16 at the date of filing – and only 15 while Robert was incubating the invention. Robert was living in Kilmarnock, while the Stirling family home (home of the un-married James) was 115 km distant as the crow flies (70 miles) in Perthshire.

This does not deter Kolin from asserting: ‘… *invention of the Stirling engine is generally attributed to Robert Stirling, which may be attractive, but is rather doubtful.*’ … ‘*The only written sign that Robert was engaged on the Stirling engine is his name, together with his brother James* (!) *on the patent specifications.*’ (Kolin, 2000).

The statement is at odds with the meticulous attention to detail which distinguishes other work by Kolin. The patent description is in the name of Robert (alone), in his handwriting, and over his signature and seal. Evidence for a precocious contribution from James is, at the time of this writing, non-existent.

1.2.6 That 90 degrees and unity respectively are acceptable ‘default’ values for thermodynamic phase angle α and volume ratio κ

The false belief accompanies – and may stem from – a view that performance is more sensitive to changes in gas path specification (hydraulic radius, flow-passage length) than to changes in phase angle and volume ratio.

Systematic and long-overdue bench tests on a ‘Vari-Engine’ designed and built by Larque with input from Vaizey now convincingly indicate otherwise. If volume variation is simple-harmonic, $\alpha = 90$ degrees converts to $\beta = 45$ degrees and $\kappa = 1.0$ to $\lambda = 1.4$ of the ‘beta’ or coaxial configuration. (This is pure trigonometry – see Chapter 4 *Kinematics*. Thermodynamic considerations do not arise!) The ratio 1.4 is almost precisely the *inverse* of the value since demonstrated experimentally by Larque to give best operation of a small but ‘real’ engine of beta configuration (multi-channel exchangers, foil regenerator, modest pressurization on air).

Converting Larque’s optimum values to the kinematics of the ‘alpha’ (opposed-piston) configuration yields $\alpha = 132$ degrees. and $\kappa = 0.78$. Both figures are readily embodied into a one cylinder-pair unit, but only the latter can be achieved in the four-cylinder, double-acting ‘Rinia’ configuration. In any case a better choice for the Rinia would now appear to be three cylinders with $\alpha = 120$ degrees – or six cylinders with an inter-connection between alternate pairs.

1.2.7 That dead space (un-swept volume) is a necessary evil

At *rpm* and pressure giving viable operation, the gas processes in the variable-volume spaces are closer to adiabatic than to isothermal. Chapter 4 confirms, amplifies and argues that, one this basis the cycle of the regenerative gas turbine (Joule cycle – adiabatic, constant pressure)

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throws more useful light on the operation of the practical Stirling engine than does the Schmidt cycle with its assumption of isothermal processes.

Thermal efficiency of the regenerative gas turbine reaches a peak as pressure ratio increases to relatively modest values, and falls off thereafter. Dead space in the Stirling engine is linked to pressure ratio. Pressure ratio is implicated in mechanical friction and in seal blow-by (a phenomenon not to be under-estimated) and, crucially, in the adiabatic component of temperature swing. At any given combination of temperature ratio N_T, volume phase angle α and volume ratio κ, pressure ratio increases as dead space decreases, and vice versa. Finkelstein's generalization '… *harmful dead space to be minimized* …' may be the one and only over-simplification for which he can be criticized.

A related fallacy is that reduced charge pressure can be offset by increased pressure ratio. The adiabatic heating component is unaffected by the former, but strongly influenced by the latter. If pressure ratio were to increase in response to more effective separation of compression and expansion phases, then the net result might be performance improvement – but the matter appears not to have been explored.

1.3 … and some heresy

Items of myth addressed to this point are anodyne romantic notions compared to the real problem: perverse application of heat transfer and flow correlations acquired from steady, incompressible flow to flow which is essentially unsteady and compressible. The problem pervades computer simulation as well as some aspects of scaling.

The matter will warrant a dedicated chapter. Meanwhile it is sufficient to note that steady-flow correlations most widely applied to regenerator calculations were not acquired from tests on regenerators. Moreover, high Reynolds numbers were achieved by sleight of hand: not at high flow speeds through fine mesh, but by low speeds through crossed rods of massive diameter. The handy short-cut masked compressibility effects now suspected of limiting the *rpm* of engines charged with heavy gases – air or nitrogen.

Dealing satisfactorily with this chronic problem would require systematic experimental work. If it is undertaken at all it will doubtless take decades. The delay must not be allowed to get in the way of progress on other fronts. Where the algebra of these chapters would otherwise be unable to proceed for lack of appropriate data, formulation will be such that the offending correlations are incorporated as 'place-holders' pending eventual replacement by legitimate plug-ins.

1.4 Why this crusade?

Left uncontested, dis-information eventually subverts reality. Regrettably, the process has already built up a head of steam: The banner of web-site www.discoverthis.com is '***Educational Science***'. At 26 February 2012 the contribution by educationalist Kathy Bazan reads: '*that's exactly what the Stirling engine is; it's an engine created for compassionate reasons.*' In Ms. Bazan's fantasy world of 1816 '*steam engines powered everything from the smallest household device* (steam-powered blender?) *to the largest steam ships and trains. Yes, people were able to get from London to Cardiff quicker than ever before* …' (Cardiff station opened in 1850, Stephenson's *Rocket* not having run until 1829.)

Stirling's inventions (regenerator and engine) trump those of more celebrated names: While Watt, Whittle, and others built on pre-existing technology emanant in tangible, functioning hardware, the study of thermodynamics was not around to guide Stirling. As far as is known, no Mead 'engine' ever turned a crank. A precedent for the regenerator principle has yet to be suggested.

The un-sung genius of Robert Stirling merits the attention of scholarship rather than of creative journalism.