

HOW GOOD WAS THE STEAM LOCOMOTIVE?

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The steam locomotive was the predominant form of motive power on Britain's railways for about 150 years. Thousands of books have been written recording the achievements or extolling the virtues of this or that class of locomotive. Very few books or articles make any attempt to consider the steam locomotive as a heat engine, and assess its efficiency at doing its job in engineering terms. The reason for this is probably that some arithmetic is involved, and access to Steam Tables is required. This article presents the results of some calculations applied to actual and 'might-have-been' locomotives, and considers the theoretical merit of a number of potential improvements to the basic design. Inevitably, I have had to make simplifying assumptions; I believe these do not affect the conclusions drawn. I have chosen to use pressure units of pounds per square inch (psi) and to quote temperatures in degrees Centigrade. However, as modern Steam Tables use 'bar' for pressure, Appendix 2 gives rounded equivalent pressures in bar for all psi values appearing in the text or tables.

A steam engine is a machine designed for converting the energy contained in hot steam into work. Strictly speaking the steam engine is only the cylinders and valve gear of a railway locomotive, but in common parlance 'steam engine' and 'railway locomotive' are used interchangeably. The railway locomotive has to be self-contained; in addition to its steam engine parts it has a boiler and carries its fuel and water. It has to be built to tight restrictions of size and weight; it must not fall to pieces when subjected to the shocks it receives when negotiating rail joints, points and crossings at speed. Small wonder, then, that the railway locomotive engine is not in the top league of steam engine efficiencies when compared with stationary plant, which is subject to none of these restrictions.

A word must be said about fuel. In the context of Great Britain, coke or coal has been the most usual fuel, but other fuels tried have included coal-dust briquettes, oil and in the case of Nellie at Esholt sewage works, wool grease recovered from Bradford's sewage!

The thermodynamicist talks of cycle efficiency, the proportion of the heat supplied which is turned into mechanical work. The text books (see for example ref. 1) invariably start by considering a reversible heat engine using a perfect gas as the working medium (or fluid), for which the Carnot cycle applies. For steam engines, the cycle is the Rankine cycle as water/steam is the working fluid; the appropriate efficiency measure is the Rankine efficiency. A formal definition is given in Appendix 1.

I have calculated the Rankine efficiency for some actual and hypothetical steam engines and presented the results in Table 1. The "Duchess" referred to is a member of the 4-6-2 "Princess Coronation" class designed in 1935 by the staff of Sir William A. Stanier for the London Midland and Scottish (LMS) railway, and represents the zenith of steam locomotive development in Britain. A member of this class, 46225 "Duchess of Gloucester" was subjected to scientific testing on the Rugby test plant in the mid 1950s. Although she was scrapped in 1964, fortunately another member of the class "Duchess of Hamilton" has been preserved, and will take to the rails again in 1990 following a major overhaul at the National Railway Museum, York.

When looking at Table 1, several qualifications must be borne in mind. Firstly, it has been assumed that full boiler pressure is attained at the cylinder - in practice there would be a drop of 10 to 15 psi between the boiler and the steam chest, and a further drop through the valve gear passages. Secondly, exhaust pressures as low as 2 psi above atmosphere have been recorded for modern steam locomotives, but these pressures represent the best possible, rather than the everyday performance. And, thirdly, it must be emphasised that the cycle efficiency as calculated is the theoretical figure, and that real engines only achieved typically half to three-quarters of this figure. A further note of caution: the boiler pressures given in the table are in psi 'gauge' which is in line with how they are invariably quoted in the railway books; add 14.7 to get psi 'absolute' before using your steam tables if you intend to check any of my efficiency calculations! What does Table 1 show? Row C is the "Duchess" as built, and shows a 40% improvement (i.e. 6% more efficiency) over a typical loco (row A) of 70 years previous. Some of the improvement is due to the increased boiler pressure combined with a lower exhaust pressure (compare rows A and B), and some to the use of superheating (rows B and C). Efficiency could be further increased by raising boiler pressure still further; however doubling the pressure to 500 psi improves efficiency by only one fifth (rows B and D). From mechanical engineering considerations, robust boilers for pressures above about 300 psi are very heavy, and the extra weight is itself a penalty for a mobile power plant to be offset against the improved efficiency. The highest boiler pressure used for any class of British steam locomotive was 280 psi in the Southern Railway 'Merchant Navy' and 'West Country' classes, and in the Great Western Railway 'County' class. So if we cannot improve on the boiler pressure, do we get a benefit by raising the superheat? Assuming we can get to a higher working temperature of $T_1 = 450^\circ$ corresponding to 242 degree of superheat, the efficiency achieved (row E) is not vastly better than row C. These temperatures are about equal to the highest achieved with pre-war stationary plant, and would be costly to achieve on a locomotive from metallurgical and cylinder lubrication considerations (oil carbonises at these temperatures).

A very significant efficiency improvement is made if the "Duchess" of row B could be made to work into a condenser (row F). The improvement is 46% (from 19.8% to 28%), and obviously well worth having. There is, however, a snag. The reason why steam locomotives did not have condensers was that there is no way of supplying the large amounts of cooling medium, either water or air, needed to maintain the condenser temperature low and hence maintain a good vacuum. I am aware of two circumstances only where substantial numbers of locomotives have had condensers fitted, one being steam underground railways where it reduced the amount of water vapour (though not smoke) emitted, the other being the Henschel locomotives for the South African railways where the objective was to cross a desert area where water is non-existent. In the latter case, the cooling medium was air, and four huge steam-driven fans were mounted on top of a massive tender. On the condensing underground railway locomotives, the limited amount of condenser cooling water which could be carried meant that its temperature rose rapidly, and the fireman would often take water from a water-crane, not because he was short of water, but to try and displace with cold water some of the hot water in the locomotive's tanks.

Having briefly explored the theoretical routes to higher efficiency, what practical steps can be taken to achieve an efficiency as close to the theoretical as possible? three will be discussed. Firstly, the use of compounding, secondly, the use of 'Uniflow' cylinders, and thirdly the use of a turbine instead of cylinders.

A compound engine is one where boiler steam is first admitted at full boiler pressure into a smaller cylinder, and after doing work there, is exhausted from this cylinder and admitted to a second, larger, cylinder at a lower pressure (but with a greater volume) where it does more work before being finally exhausted. In theory, compounding gives no efficiency gain whatsoever, and yet it was normal practice in mill engines and marine engines and has been applied to several classes of steam locomotive in Britain, and on the continent of Europe. A major disadvantage of the conventional cylinder is that the steam is admitted via a port into the cylinder when at its highest temperature i.e. straight from the boiler, and then does mechanical work on the piston, falling in temperature as it does so (the whole purpose of the engine being to convert heat into work) and then the cold steam is exhausted through the very same port it came in by, cooling the metalwork thereabouts as it departs. Thus the next charge of hot steam is immediately cooled when it has to warm the metal up. Superheating helps to stop condensation occurring, but does not overcome the fundamental inefficiency of the set-up. If compounding is used, the expansion, and therefore cooling, is spread over two cylinders, the range over which any piece of metal is taken is reduced, and so the thermodynamic losses associated with this heat transfer are reduced.

The second method of efficiency improvement was the fitting of Stumpf Uniflow cylinders, applied to only two locos in Britain, 4-6-0 No 825 of the S2 class and a Z class 4-4-2, both of the North Eastern Railway, By always admitting the steam through one port, and exhausting through another, towards the centre of the cylinder, not only is the alternate heating and cooling of the metal avoided, but the admission port can now be steam-jacketed to ensure the steam enters the cylinder at the highest possible temperature, giving in theory at least the most efficient engine. It is technically superior to compounding, and only requires the one cylinder, which has an even and steady temperature gradient along its length from the admission port to the exhaust port. However, though Stumpf Uniflow gained several applications on stationary engines it was not perpetuated in locomotives.

A steam turbine has rotating blades, rather than a reciprocating piston, and has the same beneficial feature of a steady temperature gradient as the uniflow engine. There were few steam turbine locomotives. The LMS gave facilities for testing a Ljungstrom/Beyer, Peacock condensing turbine locomotive in 1930. Three non-condensing turbine locomotives ran in Sweden pre Second World War, and in 1935, LMS 6201 4-6-2 "Princess" class, another non-condensing turbine locomotive was constructed at Crewe, the turbine design being in the charge of Metropolitan Vickers. 6201 was no worse a performer than her reciprocating sisters; she suffered the usual disadvantage of a one-off, and was converted back to being 'normal' in 1952. (Ref 2) The turbine's superiority is fully realised when it can work into a good vacuum, as shown by row H of the table. To maintain a good vacuum needs lots of cooling water. The condenser of the steam turbine at row H requires 2 tons per second of cooling water, though admittedly this is for a power output equal to 500 "Duchess".

After working through the figures quoted and tabulated, one is inclined to say 'so what'. Was the modest cycle efficiency of circa 20%, or even less the overall thermal efficiency of the locomotive, at best 7%, in any way responsible for the demise of the steam locomotive on British Railways? Before the second World War, labour and coal were plentiful and cheap, and the relative inefficiency of locomotives was of little import. Post war it was very different. Coal was in short supply, and as other, cleaner, employment opportunities grew (for example in the motor car industry) working with steam locomotives became less and less attractive. In October 1960, at Camden loco shed, the main passenger shed for Euston, out of the 32 engine cleaner posts on the establishment, 30 were unfilled.

Table 1 Rankine cycle Efficiencies

Row	Engine	Working Conditions	Cycle Efficiency
A	Loco with 140 psi boiler pressure	T1 = 183 deg C T2 = 109 deg C Exhausting at 5 psi above atmosphere	15.2%
B	"Duchess" if saturated at 250 psi boiler pressure	T1 = 208 deg C T2 = 104 deg C Exhausting at 2 psi	19.8%
C	"Duchess" at 250 psi with 150 deg of superheat	T1 = 358 deg C T2 = 104 deg C Exhausting at 2 psi above atmosphere	21.3%
D	"Duchess" if saturated at 500 psi boiler pressure	T1 = 243 deg C T2 = 104 deg C Exhausting at 2 psi above atmosphere	24.0%
E	"Duchess" at 250 psi with 242 deg of superheat	T1 = 450 deg C T2 = 104 deg C Exhausting at 2 psi above atmosphere	22.9%
F	"Duchess" if saturated at 250 psi boiler pressure and working into a condenser	T1 = 208 deg C T2 = 52 deg C Exhausting at 2 psi above an absolute vacuum	28.9%
G	A typical good mill enginee at 140 psi boiler pressure with 137 deg of superheat	T1 = 320 deg C T2 = 52 deg C Exhausting at 2 psi above an absolute vacuum	27.3%
H	Steam turbine at 159.6 bar pressure with 181 deg of superheat	T1 = 538 deg C T2 = 31 deg C Exhausting into a vacuum of 45 mbar	44.4%

References

- 1 "The Steam Engine and Other Heat Engines" by J.A. Ewing, Cambridge University Press 1926.
- 2 "LMS Turbine Locomotive 6202" by R.S. Carter, Peter Watts Publishing 1979.

APPENDIX 1 Definition of Rankine Cycle Efficiency, η_R

Formula for wet or saturated or superheated steam:

$$\eta_R = \frac{I_1 - I_2}{I_1 - I_{W2}}$$

where I_1 is the total heat of the steam at the upper working temperature, T_1

where I_2 is the total heat of the steam/water mixture at the lower working temperature, T_2

Where I_{W2} is the heat content of water at the lower temperature.

APPENDIX 2 Equivalent Pressures

psi	bar	
0.66	45	mbar
1	69	mbar
2	138	mbar
5	345	mbar
14.7	1.01	
140	9.66	
250	17.2	
280	19.3	
300	20.7	
500	34.5	
2314	159.6	