The Practical, or Sawn-off Rankine Cycle

The Classical Rankine cycle

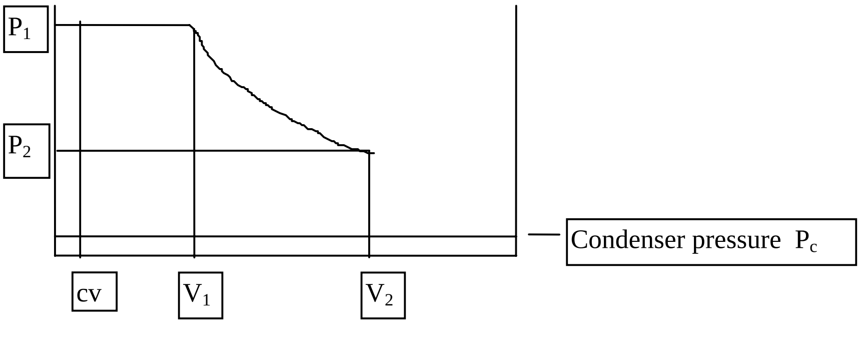
Reversible, adiabatic expansion takes place between ***specified pressure*** limits, i.e between the steamchest pressure and the condenser or exhaust pressure. The enthalpies (h_1 and h_2) of the steam can be evaluated at these pressures (they are at the same entropy) and the work output is then $(h_1 - h_2)$ per unit mass of steam used. Clearance volume is neglected, as is the work required to pump the condensate back into the boiler. The energy supplied in the boiler is $(h_1 - h_f)$ where h_f is the enthalpy of the boiler feed water. Thus the efficiency is $(h_1 - h_2)/(h_1 - h_f)$, and can be evaluated either by use of a Mollier chart or by accessing the steam property tables, preferably using a computer!

In a practical engine there is a finite clearance volume, and unless exhaust steam is compressed precisely to the steamchest pressure there will be an irreversible pressure change involved in filling the clearance volume. It is also usually uneconomic to expand right down to the exhaust pressure.

The Practical cycle

In this case expansion takes place between specified ***volume*** limits, i.e. between the volume of steam in the cylinder at cut-off, v_1, and that at release, v_2, the pressure at the latter point being somewhat above the condenser or exhaust pressure. The ratio of the final to the initial volume (the Expansion Ratio) is equal to the volume at cut-off divided by the volume at the release point (when the exhaust port opens) - in each case the clearance volume is included. Locating the state of the steam at the final volume is a fiddly business when using steam tables or a Mollier chart, but is relatively easy with a computer and a decent steam library. Again, we ignore the business of filling the clearance volume, although we take it into account when determining the Expansion Ratio.

Notice that the release process from P_2 to P_c is ***not*** one of constant enthalpy (as it would be if the expansion were unresisted) because work is done on pushing steam into the condenser. We cannot therefore equate the work done to the overall change in enthalpy of the steam. But we can equate the work done in expanding from v_1 to v_2 to the change in internal energy of the steam, $(u_1 - u_2)$. Thus the work output W is given by:



$$W = p_1v_1 + (u_1 - u_2) - p_cv_2 = (u_1 + p_1v_1) - (u_2 + p_2v_2) + v_2(p_2 - p_c)$$
$$= (h_1 - h_2) + v_2(p_2 - p_c)$$

and Efficiency = $W/(h_1 - h_f)$ -- where h_f is the enthalpy of the feed.

The Computer Solution

The basis of the solution is a library of water properties (WTHLIB) written by Dr H-P Wolf.[1]. Having found the initial entropy at the given initial pressure and temperature the programme searches the library for a state having the same entropy, and a specific volume defined by the initial specific volume multiplied by the Expansion Ratio. The search is conducted by following a constant entropy line and using a bisection root-finder to locate the pressure corresponding to the required specific volume. The Efficiency is then calculated using the above equation.

Results

The cycle Efficiency as a function of Expansion Ratio for a range of initial pressures and temperatures is shown in Figs. 1 and 2. It is perhaps worth noting that even for a locomotive notched up to 15% cut-off, with 10% clearance volume and with release at 70% stroke, the Expansion ratio would be no larger than 3.2. In normal operation it would therefore normally be around 2 to 3. The classical Rankine Efficiency, which assumes expansion down to the exhaust pressure therefore seriously overestimates the efficiency. In the light of this, a measured cylinder efficiency of around 10% to 12% is a good performance.

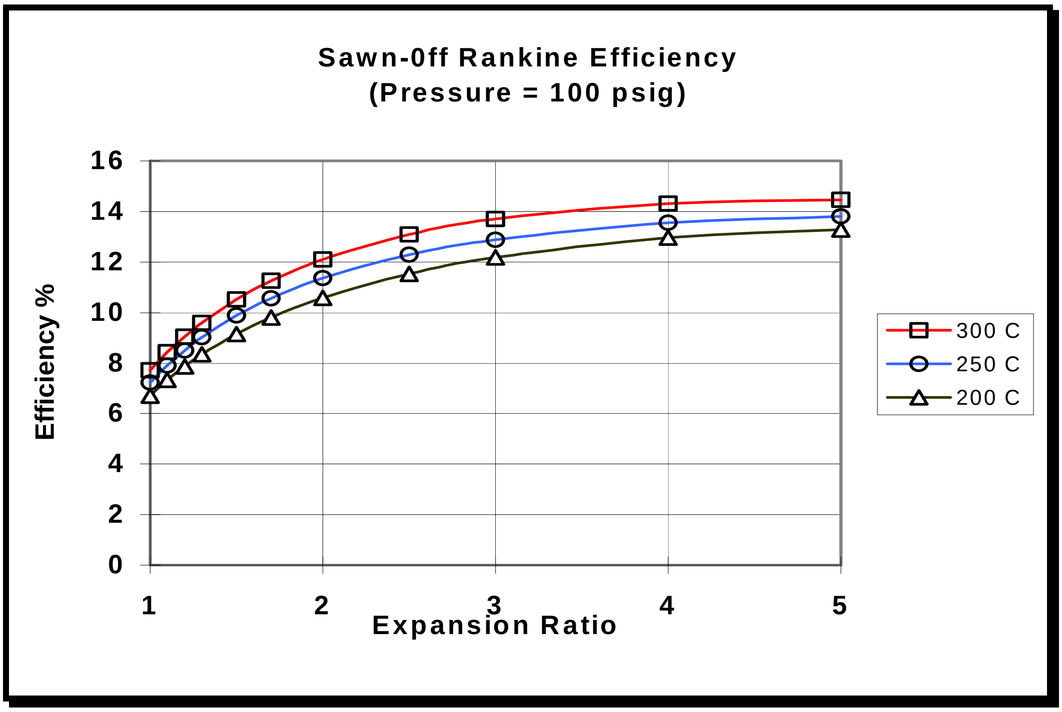
The shortfall between actual indicated efficiency and theoretical efficiency is sometimes attributed to wiredrawing, and no doubt there is some loss caused by irreversible pressure drops as the steam flows through the inlet ports. Certainly the IHP is often quite drastically reduced, but the efficiency is less seriously affected because wiredrawing also reduces steam consumption. A point that is often missed is the ***beneficial*** effect of the slower release of steam following the opening of the exhaust port; this means that some steam is retained longer in the cylinder and continues to contribute to the work produced.

As a matter of interest I append values of the classical Rankine Efficiency corresponding to the initial steam conditions used in Figs. 1 and 2.

Pressure (psig)		100	150	200	250
Temp (deg.C)	200	13.35	15.48	17.01	----
	250	13.81	15.88	17.30	18.53
	300	14.47	16.49	17.95	19.08
	350	----	-----	-----	19.77

These figures, and those in Figs. 1 and 2 were calculated on the assumption that the feed water temperature to the boiler was 30 deg.C

W B Hall, 1999


Sawn-0ff Rankine Efficiency
(Pressure = 100 psig)
Efficiency %
16
14
12
10
8
6
4
2
0
1
2
3
4
5
Expansion Ratio
300 C
250 C
200 C

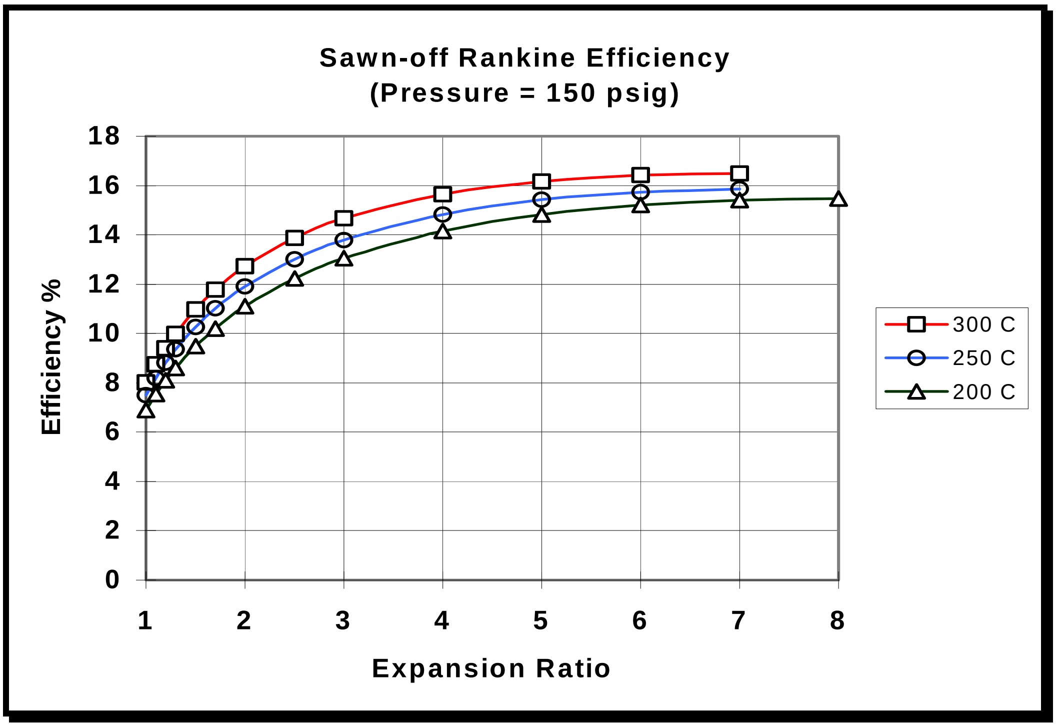
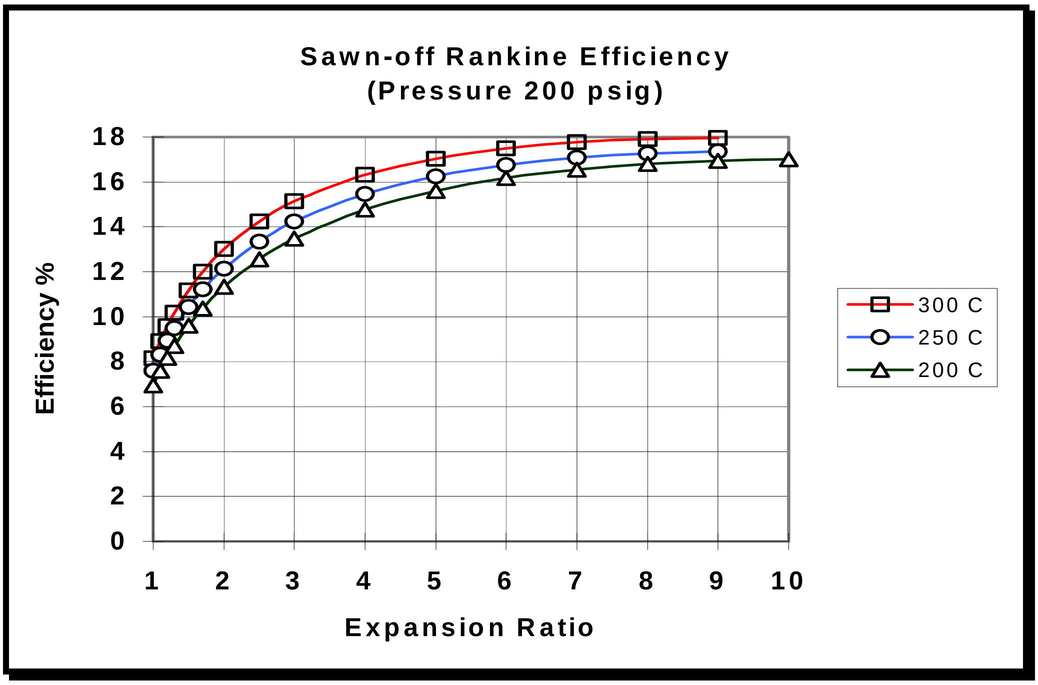

Sawn-off Rankine Efficiency
(Pressure = 150 psig)
Efficiency %
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
Expansion Ratio
300 C
250 C
200 C

Figure 1


Sawn-off Rankine Efficiency
(Pressure 200 psig)
Efficiency %
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
Expansion Ratio
300 C
250 C
200 C

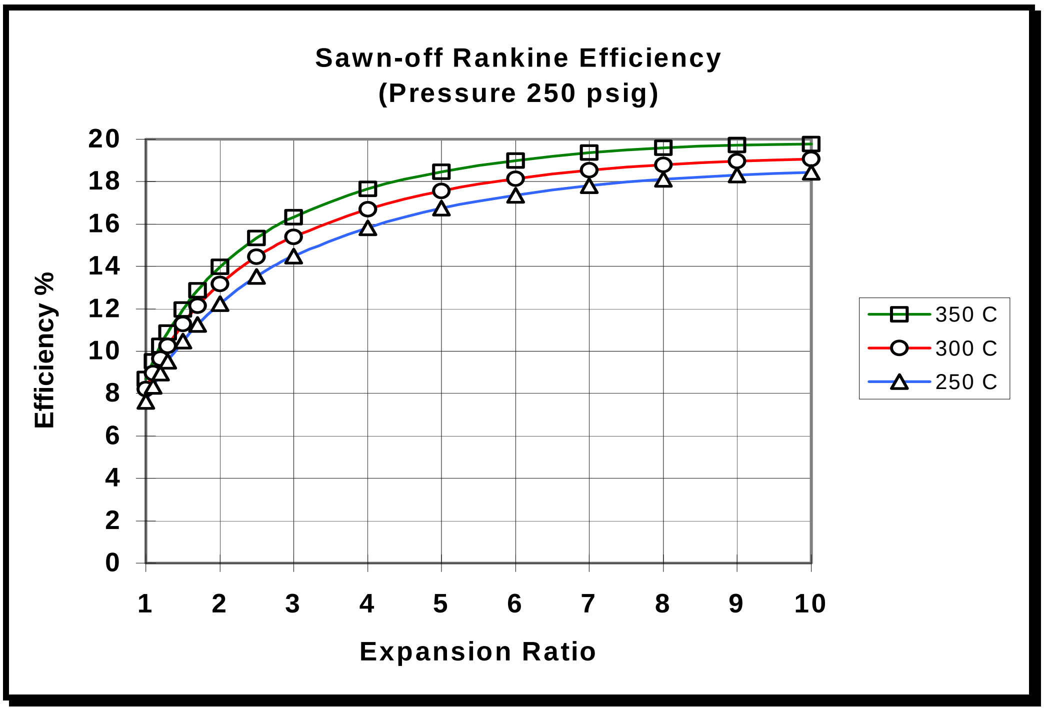

Sawn-off Rankine Efficiency
(Pressure 250 psig)
Efficiency %
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
Expansion Ratio
350 C
300 C
250 C

Figure 2

Comparison of Classical Rankine Efficiency with Practical Rankine Efficiency

Assume an expansion ratio of 3.3 for the practical cycle, on the basis that with conventional minimum cut-off , release and clearance volume it is difficult to achieve more. The Table at the end of the document "The Practical, or Sawn-off Rankine Cycle" is extended below to include the expansion ratio (R) that would be required to achieve the classical Rankine efficiency, and the practical Rankine efficiency for R=3.3. Feed temperature 30deg.C and exhaust at atmospheric pressure.

Pressure (psig)		100	150	200	250
Temperature (Sat)	R	6.1	8.4	10.6	12.8
	classical efficiency %	13.22	15.42	17.01	18.23
	practical efficiency %	12.19	13.29	13.90	14.29
Temperature 200deg.C	R	5.8	8.1	10.5	
	classical efficiency %	13.36	15.84	17.02	
	practical	12.49	13.45	13.93	
Temperature 250 deg.C	R	5.3	7.5	9.7	11.9
	classical efficiency %	13.82	15.89	17.38	18.53
	practical efficiency %	13.16	14.17	14.67	14.95
Temperature 300 deg.C	R	5.0	7.0	9.0	11.0
	classical efficiency %	14.47	16.49	17.95	19.08
	practical efficiency %	13.97	15.02	15.55	15.84

Based on UK Steam Tables, 1970

W B H 02/2001