STEAM ENGINES IN THE REAL WORLD

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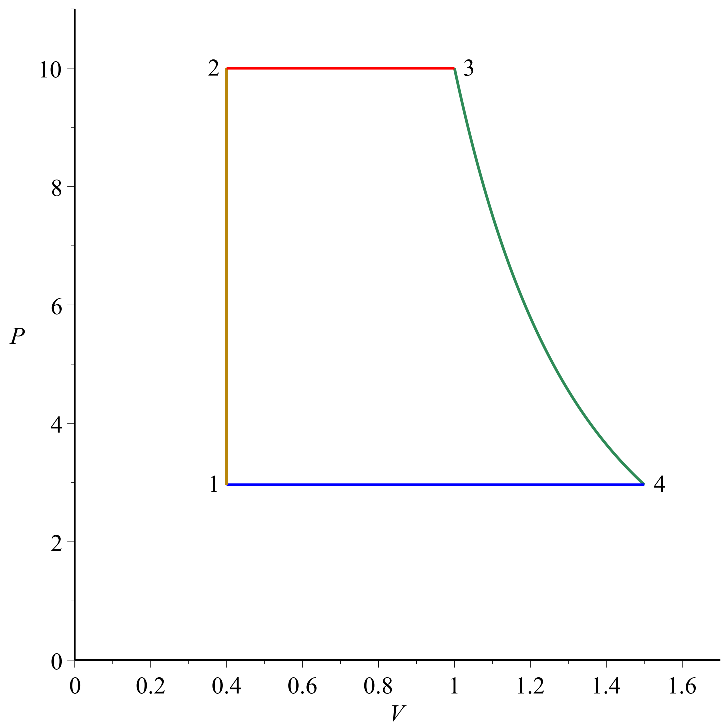
Reference: Daniel V. Schroeder, *An Introduction to Thermal Physics*, (Addison-Wesley, 2000) - Problems 4.25 - 4.26.

A steam engine follows the Rankine cycle, in which the work is done on the path in which superheated steam follows an adiabatic path from point 3 to 4 in the diagram, during which its pressure and temperature are reduced back to their lower values in the cycle.



To derive the efficiency, it is assumed that the path 1 to 2 is also adiabatic, so that all the absorbed heat Q_h occurs along edge 2 to 3, and all expelled heat Q_c along edge 4 to 1. Since both heat exchanges occur at constant pressure, the heat exchanged is equal to the enthalpy difference between the end points of the corresponding path. It is also assumed that the enthalpies of points 1 and 2 are roughly equal: $H_1 \approx H_2$. We then get an efficiency given by

$$e = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} \approx 1 - \frac{H_4 - H_1}{H_3 - H_1} \tag{0.1}$$

Calculating the enthalpies must be done using steam tables such as Tables 4.1 and 4.2 in Schroeder's book. H_3 is the enthalpy of superheated steam, and can be read from Table 4.2. H_4 is obtained by using the fact that, since path 3 to 4 is adiabatic, the entropies are equal: $S_3 = S_4$. We can read S_3 from Table 4.2 and, since point 4 is a mixture of water and steam at a given pressure and temperature, we can find the proportion x of water that gives the same entropy as S_3 by reading from Table 4.1. That is, we solve for x:

$$S_3 = xS_{water} + (1-x)\,S_{steam} \tag{0.2}$$

We can then find H_4 by using the same proportions:

$$H_4 = xH_{water} + (1-x)\,H_{steam} \tag{0.3}$$

However, suppose path 3 to 4 is *not* adiabatic; in fact in a real turbine, the entropy tends to increase along this edge, so that $S_4 > S_3$. If we know S_4, we can use the same procedure as above to find x:

$$S_4 = xS_{water} + (1-x)\,S_{steam} \tag{0.4}$$

Since (from Table 4.1) $S_{water} < S_{steam}$, we need a mixture with more steam and less water (that is, x is smaller than before) to get the increased entropy. In turn, since $H_{steam} > H_{water}$, this leads to a higher entropy H_4. Assuming H_1 and H_3 are the same as before, we see from 0.1 that the efficiency is lower than before.

[Of course, the cynics among you will say that this result is obvious from Murphy's law, in that the real world always makes things worse than they are in theory.]

As another example, suppose we have a real power plant in which the minimum pressure is 0.023 bar, the maximum pressure is 300 bar, and the superheated steam temperature is 300° C (these are the values used by Schroeder in his example). We can read $H_1 = 84$ kJ and $H_3 = 3444$ kJ from the tables, and calculate $H_4 = 1824$ kJ using the above procedure. If this power plant is to deliver 10^9 W of power then in one second we must produce 10^9 J $= 10^6$ kJ so the work done by 1 kg of steam is

$$W = Q_h - Q_c = H_3 - H_1 - (H_4 - H_1) = H_3 - H_4 = 1620 \text{ kJ} \tag{0.5}$$

The mass of steam required to produce 10^6 kJ is therefore

(0.6)
$$m = \frac{10^6}{1620} = 617 \text{ kg}$$

If we use the more accurate formula for $Q_h = H_3 - H_2$ that we calculated earlier, we found that $H_2 = 114$ kJ, so the work done by 1 kg of steam is

(0.7)
$$W = H_3 - H_2 - (H_4 - H_1) = 1590 \text{ kJ}$$

Thus we'd now need

(0.8)
$$m = \frac{10^6}{1590} = 629 \text{ kg}$$