Bigger is <u>not</u> always Better

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Abstract

Some parts of the sugar industry – most notably India – have been pushing the boundaries of the HP steam conditions in their power stations with one of 12 MPa and 545 °C steam being planned. The wisdom and profitability of such selections are questioned in this paper. It makes use of some of the visual representations of the electrical export issues that were published in an early paper.

Introduction

Over the last 100 years the HP operating conditions of power stations have steadily climbed because the higher you go, the more efficient the station becomes. Today's thermal utility stations operate at supercritical or even ultra-supercritical [a nonsensical marketing term] conditions with pressures of 25 or even 30 MPa and temperatures up to 630 °C.

The sugar industry is doing the same thing, particularly in India where steam pressures are routinely exceeding 10 MPa and at least one owner is planning a 12 MPa station. This paper questions whether that is the correct solution for the industry when the design conditions of utility stations are dictated by totally different criteria than those for a sugar factory wishing to export electricity.

Thermodynamics

In a previous paper the basic principles of cogeneration and generation thermodynamics were set out in a visual way. It was shown that a temperature/entropy [T/s] diagram for water was the best way to visualise the thermodynamic cycle as the area bounded by the cycle is proportional to the work obtained [electricity generated] :

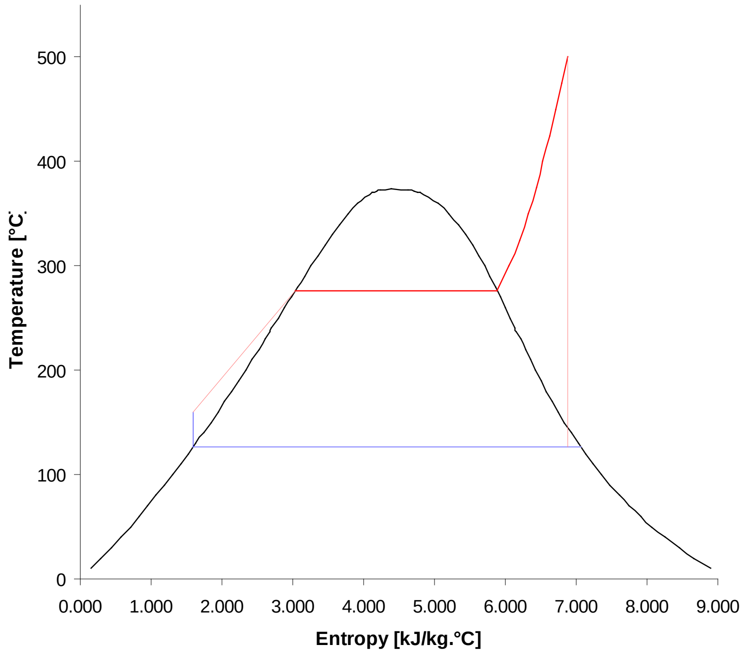

Figure 1 : Cycle with Superheat and BFW Pump

The same paper also discussed the difference between [low efficiency] generation and [high efficiency] cogeneration. Since then a new graphical presentation of the difference between the two has been developed using an enthalpy/entropy [H/s] axis : a Mollier diagram although you wouldn't recognise it as such.

Figure 2 shows the heating, evaporating [boiling] and superheating of the steam starting with boiler feed water at point ①. The original temperature axis is retained for comparison but the cycle is plotted on the right hand enthalpy axis. The steam then passes through a back-pressure turbine to point ② which is the exhaust condition for a typical factory. The drop in enthalpy is recovered as work. The steam is then used to drive the factory thermally so the drop in enthalpy as the system returns to point ① is also doing useful work :

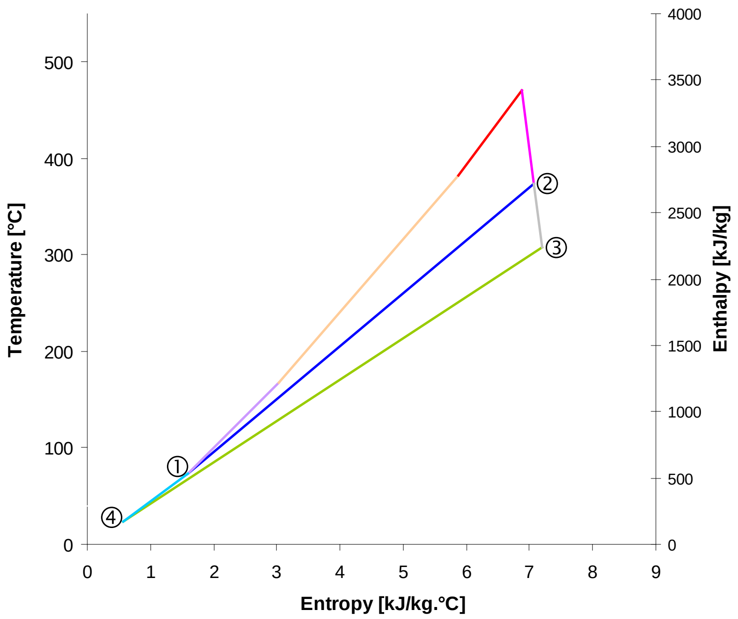

Figure 2 : Same Cycle on Enthalpy Axis

Compare that with a condensing turbine which starts from the same point, climbs to the same peak and then passes through the turbine but this time to point ③. The enthalpy drop is greater than with the back-pressure machine so more work is obtained. We get more electricity by using a condensing machine but the ‘steam’ [vapour] from the machine is too cool to do anything so it is condensed with cooling water, the operating line passing to point ④ from whence it must be reheated to point ① to complete the cycle.

In the cogeneration mode all of the enthalpy in the HP steam is used usefully. In generation, 65% of the enthalpy in HP steam [from point ③ at 2243 kJ/kg to point ④ at 167 kJ/kg] for this particular cycle is dumped to atmosphere.

Impact of HP Steam Conditions

The impact of increasing the HP steam conditions, whether in generation or cogeneration is easily seen on the T/s diagram, as shown by Figure 3 (over). Remember that fixing the HP steam pressure immediately sets the HP steam temperature for a particular turbine, all other temperatures being sub-economic in one way or another.

Increasing the steam pressure means that the saturation temperature is higher and a new superheating curve exists to match. The hatched area on the diagram represents the increased area bounded by the cycle and hence the additional work obtained.

There are several points to note however. The first is a result of the relationship between saturation temperature and pressure : for each unit increase in pressure there is a lesser increase in saturation temperature. Inverting that means that ever larger pressure increases are required to achieve a unit increase in temperature from one HP steam condition to the next.

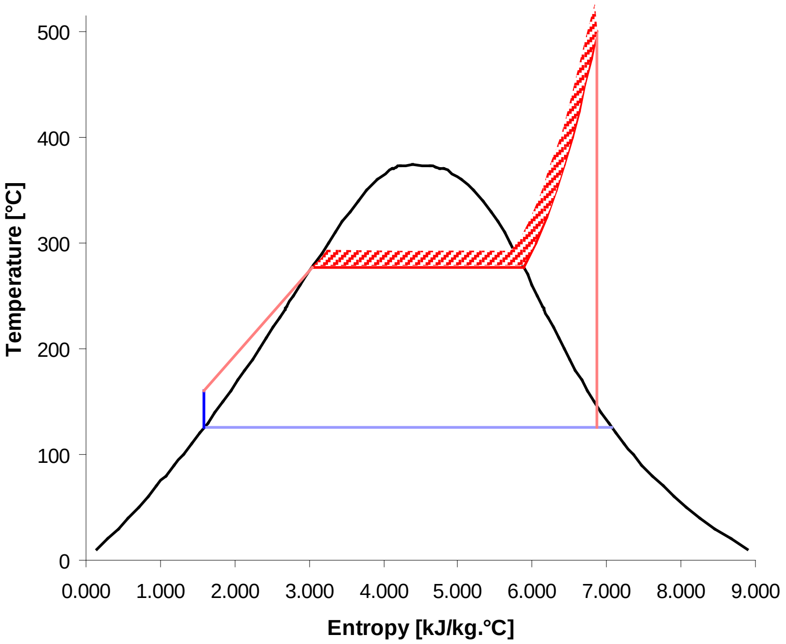

Figure 3 : Increased HP Steam Pressure

The second point is that as one increases the HP steam temperature the two halves of the bell curve draw closer together so the additional area bounded by a unit increase in saturation temperature decreases for this reason as well as for the first reason. In Thermal Energy Systems we call this the area of diminishing returns. Exactly how diminishing can be seen by plotting the work obtained for a particular amount of steam energy [rather than steam flow as that would not be a true comparison because the steam at each higher HP steam condition is more energetic so one obtains less per fixed amount of energy input] at each HP steam condition :

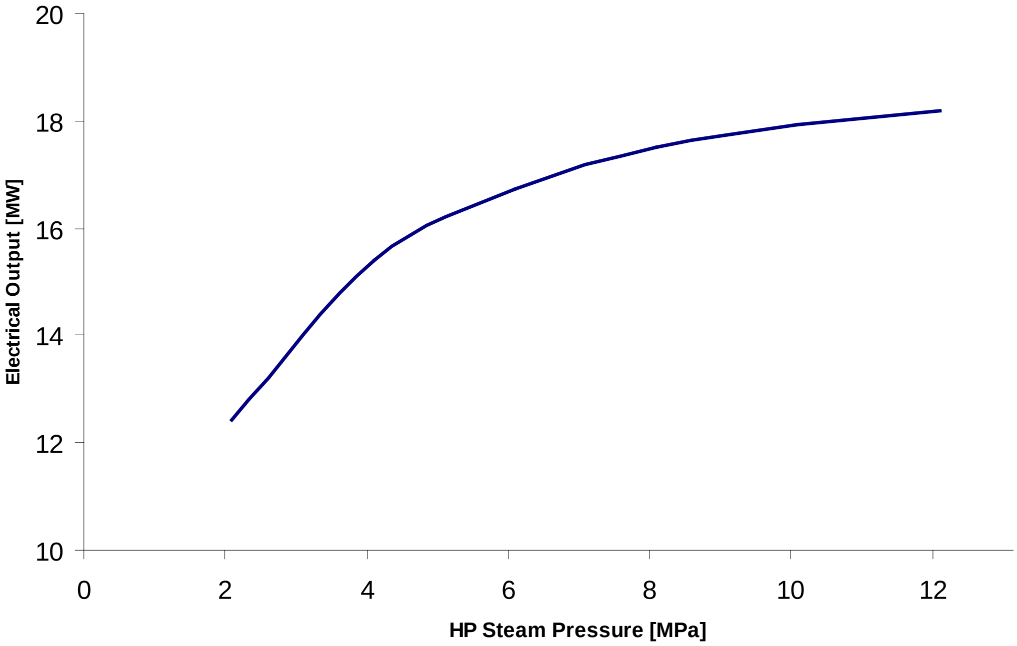

Figure 4 : Electrical Output at Different HP Conditions

Optimisation

As usual, the only way to really optimise the selection of the HP steam conditions is to resort to economics by calculating the return from increasing the HP steam conditions from one selection to the next. The problem is that while the physics in the previous section are definitive the capital cost of a power plant is much more a matter of opinion.

There are two logical progressions in the HP steam conditions, one set by the availability of steel in certain thicknesses and the other by the strength of steel at various temperatures which means that there is a need to move to ever more exotic materials as the temperature crosses certain thresholds. The traditional steps of 2 MPa each are used in this paper.

One point of note is that the HP steam pressure has an impact on the entire system – boiler, pipework and TA set but the HP steam temperature only has an impact from the superheater onwards as the rest of the boiler operates at saturation temperature.

Steel thickness might serve as an example of the different influences on the capital cost. Broadly speaking the steel thickness of pressure parts is almost directly proportional to the operating pressure and as perhaps 25% of the boiler cost is the pressure parts there is clearly a strong influence on the cost of the boiler. The steam pipe is almost completely influenced by such considerations and so is a good proportion of the steam turbine which is almost certainly the most expensive component of the TA set.

In the end a series of very thorough costing exercises is required, one for each possible HP steam condition. However, in order to limit the amount of work it is useful to have a 'scale-up' factor, in this case for increasing pressure, in the form of :

$$\mathrm{Pr}\,ice' = \mathrm{Pr}\,ice \times \left(\frac{P'}{P}\right)^{x}$$

The value of 'x', the power to which the pressure ratio is raised, seems to be in the range of 0.3 to 0.4 in the real world. Figure 5 uses a value of 0.35 to overlay the relative capital cost onto the curve of Figure 4 :

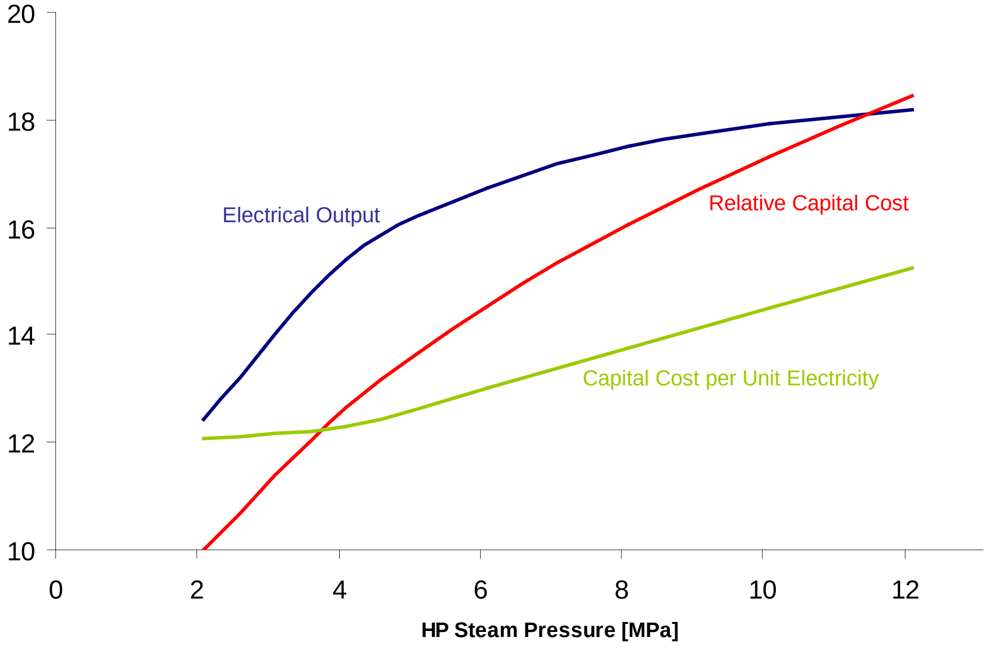

Figure 5 : Relative Cost and kW/$ Overlays

More importantly, Figure 5 plots the capital cost per unit of electricity. In this case it shows that even going to 3 MPa from 2 is less than optimum. As will be discussed shortly, that is almost certainly the wrong conclusion but, as discussed previously, the exercise is only to permit the selection of possible conditions to be examined – and costed – in detail.

Having stated that, it should be said that in two recent projects for a very well known cane sugar company it proved impossible to justify anything more than an HP steam condition of 3.1 MPa.

Practicalities

Having discussed the theoretical position, it is necessary to temper that with practicalities and comments relating to the real world.

The first point to note is that whilst the theory might predict that an extremely low HP steam condition is optimum, that ignores the key limitation of available 'free' fuel and/or energy. If the discussion is about a cane sugar factory then the minimum sensible HP steam condition is the one which ensures that no fossil fuel is required across the operating year. If the discussion is about a beet factory or a sugar refinery then the minimum is the condition which balances the site such that no electricity has to be purchased from outside.

In the later case, there is no doubt that the primary economic force should be to drive down the process steam consumption as that relates directly to fuel burn. However, the more one achieves that objective, the higher the minimum sensible HP steam condition is driven to deliver the electrical requirement of the site with the steam flow which is available.

The same thinking actually also applies to the cane sugar factory despite the potential abundance of bagasse. Reducing the exhaust steam consumption is a relatively 'soft' option as only low pressure heat transfer surfaces are required whereas increasing the HP steam conditions requires working with high pressure heat transfer surfaces.

History has shown that a typical cane factory has to have steam range of at least 3 MPa to be in balance and most modern, efficient refineries seem to require at least 4 MPa. A modern, efficient beet factory may well require even higher conditions as that part of the industry drives down its steam % beet below 25% and even below 20%.

It has to be admitted that this paper is probably biased by the best part of a lifetime in the cane sector where thinking, for the most part, pivots around the availability of bagasse. In some parts of the world that position is distorted, usually by the need to deliver firm power for 11 months a year and with penalties – either financial or political – attached to failing to do so. The stations on Reunion are classic examples of that as they are more utility power stations attached to sugar factories than anything else and the whole island relies on the electricity they generate.

It is clear that there is an element of that thinking in India where the stations are being design for a considerable amount of coal burning. Even then though, Reunion's stations operate at about 8 MPa and 520 °C so what allows India to justify higher conditions still? If going from 6MPa to 100 MPa yields an additional 7% of electricity to sell would it by wise to invest the additional 19% of capital cost to do so?

That is clearly a simplistic argument as the additional 7% is of the total electricity produced so in sales terms it is considerably more. At that point the question of sales price comes into play, something clearly beyond the scope of this technical paper.

Conclusions

A temperature/entropy [T/s] diagram for water helps visualise the impact of increasing the HP steam conditions in the power station of a sugar factory because the area bounded by the cycle is proportional to the work obtained [electricity generated]. However, it also clearly shows that each step increase gives a diminishing increase in work obtained. There are two factors at play : i) each step increase in pressure results in a smaller increase in saturation temperature and ii) the liquid phase and vapour phase curves are drawing together as the temperature increases.

Plotting the output against the HP steam pressure [with optimum HP steam temperature] clearly shows an asymptotic curve with increasing pressure, reflecting the diminishing returns.

Accordingly, unless the capital cost of achieving such higher conditions is similarly asymptotic with increasing pressure, there must be an optimum pressure for any one project. With today’s sophisticated models for cogeneration and generation in a sugar factory it is relatively easy to accurately predict the electrical output. What is much less easy is the derivation of the return on capital employed for a host of different reasons. It is certainly not possible to generalise.

Nonetheless a method is proposed of estimating the capital cost at different operating conditions using a ‘scale-up’ formula such that the cost per unit can be calculated as a first step to optimising the conditions. This seems to indicate that lower conditions are probably more profitable than higher ones, at least in the cane sugar sector where the base fuel is essentially free.