STEAM TURBINE OPERATIONAL ASPECTS

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Contents

Summary

Steam turbines generally operate very reliably and for lengthy periods between

shutdowns for major maintenance. During these periods however there may be slow degradation of performance due to wear, erosion or fouling of critical components. This has a slight detrimental effect on the overall plant efficiency but this translates in a very significant increase in fuel costs due to the high rate of energy conversion in a modern plant. To optimize plant efficiency, the losses in performance need to be categorized and monitored with a view to correcting deviations where possible.

Moisture in the steam in the turbine has a detrimental effect but it tends to decrease as load is decreased. At very low loads the exhaust steam may actually become superheated which is even worse. Thus slightly wet steam in the exhaust provides some flexibility of operation without changes in exhaust steam temperature.

Turbine back pressure as determined by the condenser conditions is also critical to turbine operation. Deviations in back pressure affect the steam flow through the last stage blades of the turbine resulting in various undesirable effects. The turbine must therefore operate within prescribed limits of back pressure and the condenser must be capable of maintaining these limits.

Power plants are also subject to thermal transients, which result in thermal stress and differential expansion. These require monitoring to ensure that they do not exceed prescribed limits and endanger the integrity of the turbine.

Another critical aspect of turbine operation is governing to maintain speed and load. The turbine is the link between the energy input by the steam and the energy output in the electricity. Any mismatch between these will cause the turbine to accelerate or decelerate. Uncontrolled acceleration is very dangerous and precautions must be taken to ensure rapid closure of the steam valves in the event of a disconnection of the electrical generation.

1. Turbine Losses

1.1. Categorization of Losses

Fluid friction is the most significant of all turbine losses. The high velocity steam suffers friction in passing through the nozzles or fixed blades as well as the moving blades. There is also friction between the steam and the rotor discs. Turbulence within the fluid stream itself results in frictional loss. Fluid friction losses amount to about 10 percent of the total energy input to the turbine. This is a major factor in the loss which is ultimately reflected as turbine internal efficiency.

Supersaturation causes a loss as will be described below. This is also a factor included in the overall definition of turbine internal efficiency as is the moisture loss.

Moisture loss occurs when the condensed moisture passes through the turbine blades and the moisture drops impinge upon the moving blades. As mentioned in an earlier section the condensed droplets collect in a film on the larger fixed blades. When the film is swept off by the steam the more slowly moving entrained drops are hit by the moving blades. This retards the moving blades reducing turbine output and efficiency.

There is a loss in stage efficiency at the rate of about 1% for each 1% moisture content of the steam at that point in the machine.

The residual kinetic energy in the steam leaving each stage is usually recovered in the following stages. At the last stage however the specific volume of the steam is very large and, to obtain manageable flow areas at the turbine exit, high velocities must be tolerated. This results in a high residual kinetic energy and a significant leaving loss. This is in the order of 2 percent to 3 percent of the total energy input.

Heat losses occur directly from the turbine. Most of this comes from the high pressure and intermediate pressure cylinders which are lagged with heat insulation to minimize leakage. Nevertheless there is an overall small loss due to convection and radiation to the surrounding atmosphere. Small steam leaks also account for some loss particularly on older machines.

Bearing losses arise due to oil friction in the bearings. Some auxiliaries such as the main oil pump are usually directly driven from the turbine shaft and add to these losses.

Windage loss occurs in the generator where fans mounted directly on the generator rotor circulate the hydrogen coolant within the generator housing.

Some electrical losses occur within the generator windings but are quite small.

2. Supersaturation

2.1. Metastable Conditions

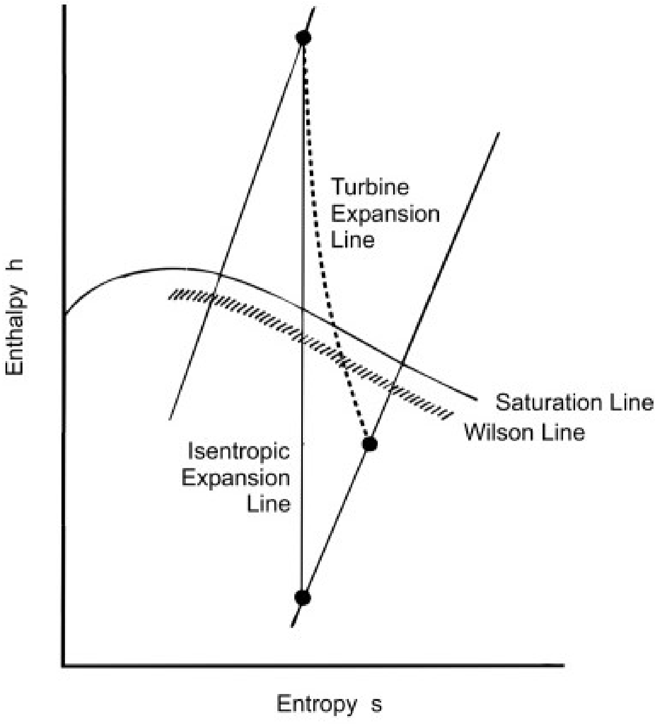

Figure 1: Wilson line relative to saturation line

Steam expanding in a turbine invariably goes from a superheated state to a saturated mixture state. When crossing the saturated vapour line rapidly, the steam does not condense immediately but remains briefly in a state of metastable equilibrium. In this state it follows the laws governing superheated steam until a lower pressure is reached.

At some point condensation suddenly takes place and the fluid is once again in thermal equilibrium and subject to the laws of a saturated mixture. The points at which this condensation occurs vary depending upon conditions and are scattered in a band somewhat below the saturation line as shown in Figure 1. This band is known as the Wilson Line.

The phenomenon of metastable equilibrium is associated with the surface effects on very small drops and bubbles. Both small drops in a vapor near saturation and small bubbles in a liquid near saturation are subject to the same effects as illustrated in Figure 2. If a vapor is suddenly cooled below saturation, it initially becomes supersaturated or undercooled while in metastable equilibrium.

Similarly, if a liquid is suddenly heated above saturation, it initially becomes supercooled and is also in metastable equilibrium. This transient state is one in which drops or bubbles grow from very small diameters with highly curved surfaces to larger sizes.

Very small drops and bubbles can exist at temperatures different from those of the surroundings and this inhibits their growth. Figure 2 shows, for condensing conditions, an extended free surface made up of an infinite number of molecules and a very small drop consisting of only a few molecules.

Molecular attraction holds the molecules within the liquid but those with sufficient excess energy leave the free surface through which there is a general interchange of molecules. In a small drop the attractive force on a single molecule by the surrounding molecules is less due to their being fewer molecules in contact with the surface molecules in question.

This molecule can therefore leave the surface of the drop at a lower energy and hence temperature than would have been the case from a free surface. In equilibrium therefore the drop is at a temperature less than the normal saturation temperature.

This metastable condition persists only while the drops are small. A similar phenomenon occurs in boiling. Figure 6 shows, for boiling conditions, an extended free surface and a very small bubble.

Since surface molecules surrounding the bubble are attracted by more molecules than those in an infinite free surface they require a greater energy to escape from the surface. Thus the temperature must be higher than the normal saturation temperature before the vapour bubbles will begin to grow resulting in metastable equilibrium.

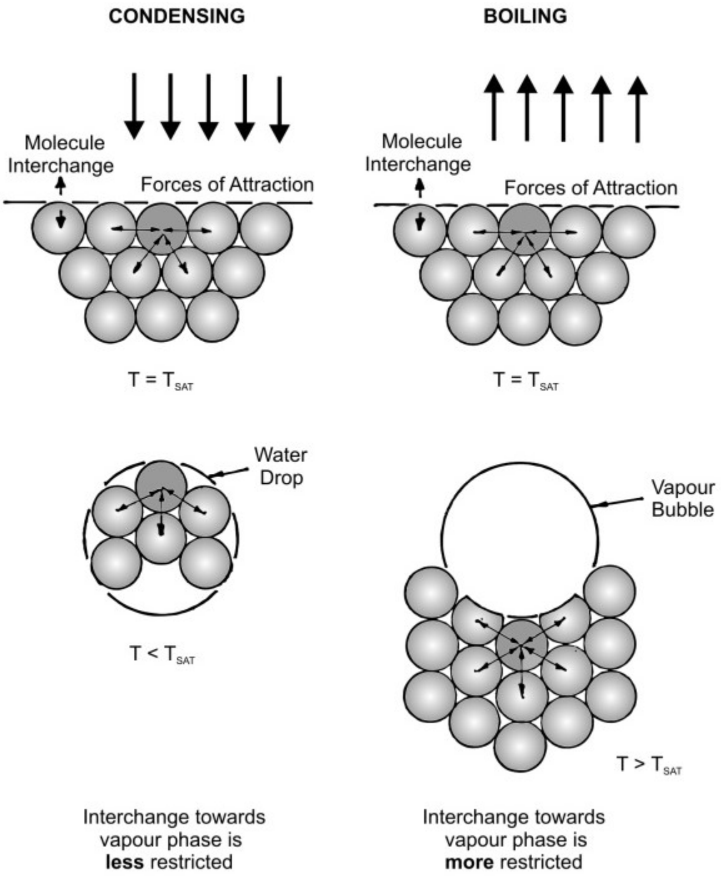

Figure 2: Effect of surface tension on small drops and bubbles

The phenomenon of metastable equilibrium occurs during transients from one phase to another when large extended surfaces are not available for normal molecular interchange across the surface. Once these larger surfaces have been created the fluid reverts rapidly to normal thermodynamic equilibrium. In a steam turbine where steam tends to condense during expansion across the saturation line this change from metastable equilibrium to thermodynamic equilibrium takes place irreversibly and therefore with a loss in availability. This is known as condensation shock. It represents one of the losses in efficiency suffered by steam turbines.

Calculation of this loss may be done by assuming superheated steam conditions below the saturation line, as shown in Figure 3 where dotted lines represent the temperature of the undercooled steam. Isentropic expansion occurs from Point A to Point B as if the vapor was still superheated. At Point B sudden condensation occurs and the vapor becomes a wet vapor at Point C. Ideally the transition occurs at constant pressure but with an increase in entropy. From Point C the steam again expands isentropically to Point D. The loss in work is represented by the difference in the enthalpy between Point B and Point C. Remember that the enthalpy at Point B is not that indicated on the Mollier chart. It must be obtained from metastable superheated steam tables or by using the gas laws. Had the expansion been slow enough for normal thermodynamic equilibrium the expansion line would have gone from Point A to Point B and directly on to Point E.

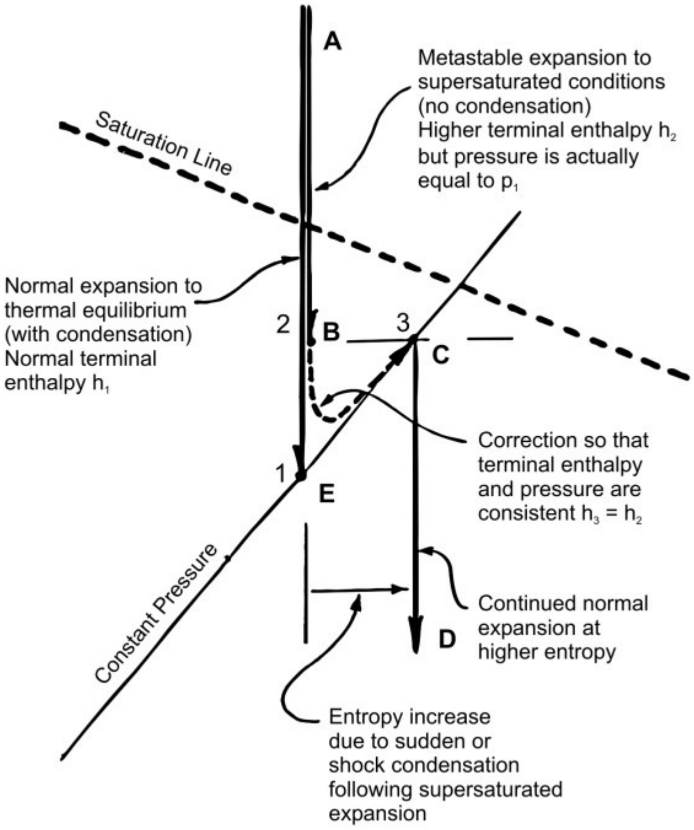

Figure 3 Supersaturated expansion of steam into wet region

3. Turbine expansion line

3.1. Steam Conditions

The turbine expansion line or condition curve represents steam conditions prevailing in sequential stages of the steam turbine. Plotted on a Mollier Diagram it provides a useful visual image of these conditions. Both stage efficiency and internal efficiency may be defined with reference to the expansion line. Stage efficiency and internal efficiency are of course related to one another by definition of the reheat factor. The turbine expansion line can illustrate other characteristics of the turbine.

The condensation shock may be shown as a small step in the curve just below the saturation line. Once moisture begins to condense in significant quantities it must be removed by various means as described in a following section. Each time some moisture is removed the expansion line takes a step along a constant pressure line towards the region of less moisture. A number of these steps may be apparent in an actual condition curves such as the one illustrated in Figure 4 which shows just one at about 10 percent moisture. The leaving loss may also be included at the end of the expansion line as a step along the constant pressure line towards a higher enthalpy since the leaving loss results in a smaller actual enthalpy drop in the turbine. Sometimes these various steps are approximated by a curve in the expansion line within the saturated region as shown in Figure 5. Note that there is an inherent curvature of the expansion line in this region due to the divergence of the constant pressure lines. This additional approximation may make the curvature quite significant. Such approximations are useful in the application of computer codes for assessing steam cycle performance and efficiency.

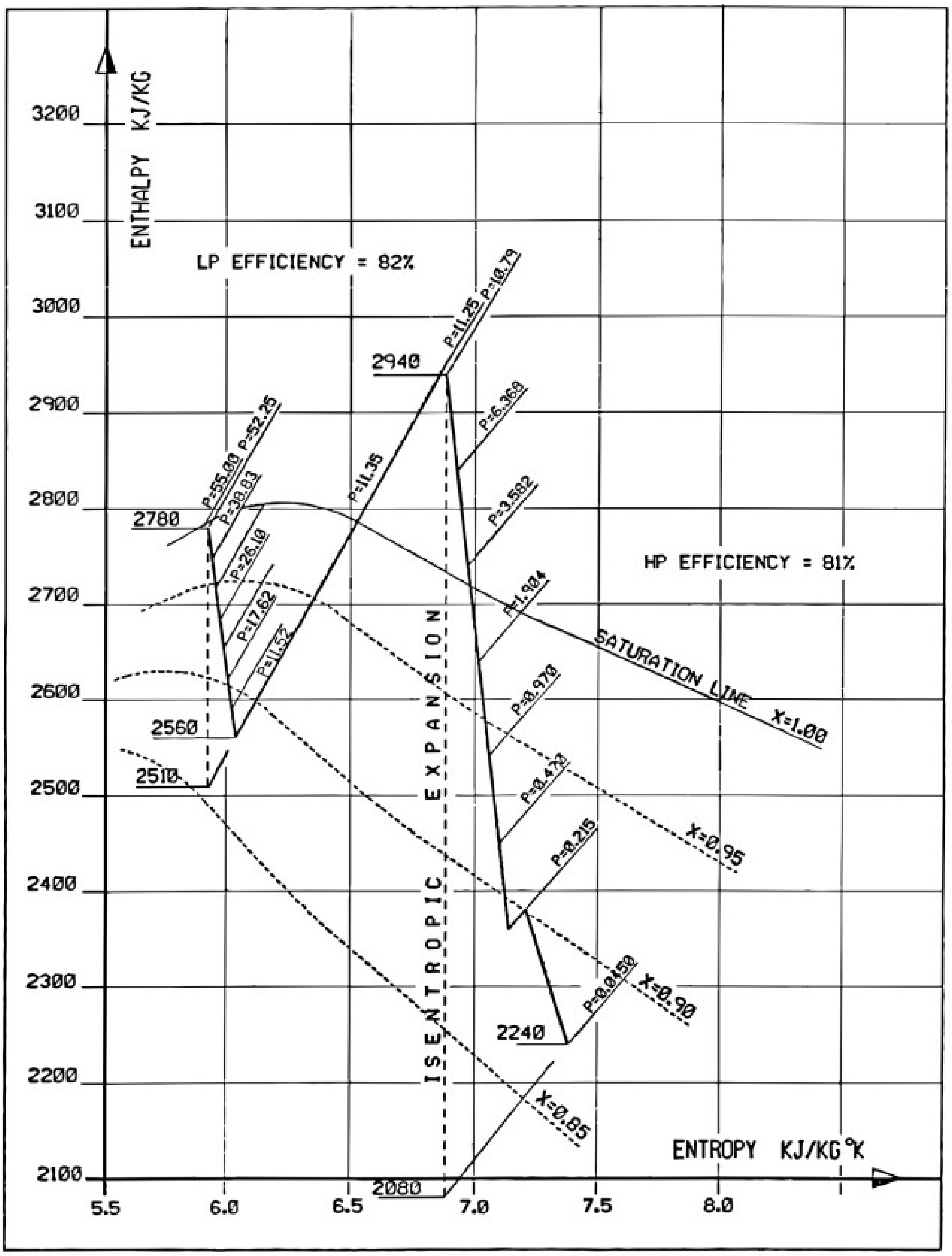

Figure 4: Turbine expansion line showing moisture removal
(adapted courtesy of Eskom)

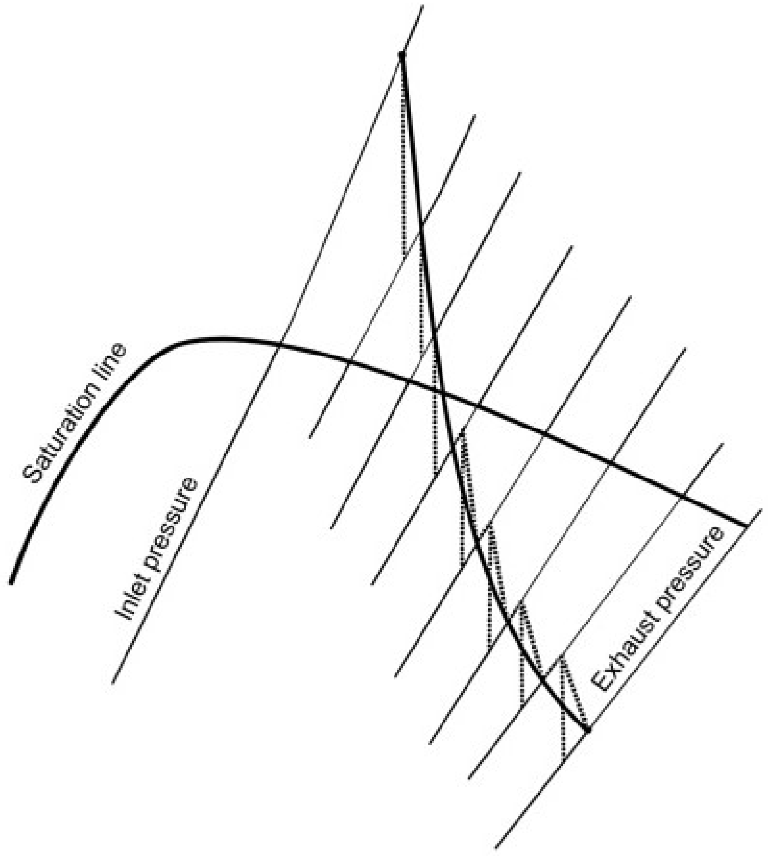

Figure 5: Effect of moisture extraction on turbine expansion line

The turbine condition curve changes its position on the Mollier Diagram with changes in turbine load due to changing inlet steam conditions. It is important to understand how these changes affect the turbine performance. These changes will be explained in a later section.

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.