TURBINE STEAM PATH

MECHANICAL DESIGN AND MANUFACTURE

Volume IIIa

William P. Sanders, P. Eng.

PennWell®

TABLE OF CONTENTS

PREFACE

As energy demands increase, utilities are faced with the responsibility of meeting them. To meet these demands, the providers of this energy are expected to make increased capacity available on their system or through purchases. The general consumers have little or no understanding of what effect increased demands have on those responsible for making power available. The providers of electric energy are not only responsible for making this power available but are also expected to provide this energy at a cost that is acceptable to the consumers. The power suppliers must be prepared to recognize and accommodate this.

The economic health of any community—country, district, or township—is directly related to its access to an adequate supply of electric energy at reasonable costs. The supply must be secure. This energy supply is essential for any industrial or commercial development.

Problems faced by electric utilities in meeting demand are many. First, and most difficult, is that they must be able to anticipate demand, which in a mature community is considerably easier than in a community that is developing and possibly trying to attract different forms of investment. The utility must plan to have adequate energy producing capacity available to support such development. This requirement can become an economic disaster for any community in the event capacity is provided and there is not sufficient demand for that energy.

Another problem is for utilities to determine how best to meet future demand. There are a number of options, each requiring some level of investigation. The alternates for increasing system capacity that need to be considered would include the following.

Installation of new generating capacity

This is ultimately the most expensive option, but it is also the most positive since it will make available on the system equipment that is new, and if selected properly, will comprise the latest technology and would therefore be expected to provide high efficiency and the best reliability available to the users at that time.

However, new capacity cannot be installed in the short term. The time to design, obtain licenses, let bids, and construct the plant will take many years. This is, therefore, the result of long-term planning based on a secure market demand once completed.

Addition of a gas topping unit

There are often a number of units on a system that can be converted to a combined-cycle application. This is an attractive and often cost-effective option for many steam turbine units that have operating life left in them but where other equipment such as the boiler or feed heaters have reached the end of their useful life.

Upgrade an existing base load unit

There are a number of large and mid range units that are currently operating and providing power to the system where unit capacity can be increased. There are two means of achieving this increase, such as redesigning portions of the unit with the installation of major components of improved design that will increase unit output.

It is also possible, if boiler capacity is or can be made available, to increase the amount of thermal energy supplied to the unit by increasing steam flow. This would produce a further increase in output. Unfortunately, such output increases will often result in decreased efficiency because the steam path was not optimized for the increased flow. Some design modifications could be made to improve efficiency; this is a matter of evaluation in terms of the cost of the modifications compared to the amount of increased output. It would also be necessary to evaluate the increase in stress levels of the components installed under the old rating.

Secure a purchase agreement with a neighboring utility

The advantage of this option is that it does not involve any significant and immediate expenditure. However, it is also possible that the costs paid for this energy will be the generating costs of the oldest and most inefficient generators on the system from which the power is being purchased. This could in the long-term result in excessive costs.

This could however, be a suitable solution while a new modern plan is being constructed.

Development of alternate sources of renewable power

The possible development of alternate fuel sources can be considered, such as wind, incineration, hydro, or solar energy. However, several of these concepts are in their infancy of development, and total economics are at this time far from established.

Another problem the utility must address is the need to finance new capacity. This often proves to be the most difficult matter involved in adding capacity. Fortunately, this is beyond the scope of this book, because it would require the wisdom of Solomon to address in any meaningful form. Of the power producing systems available, steam turbines are the most abundant producers in the world today; they are also important motive units in both industrial and marine applications. However, their installation requires the inclusion of considerably more peripheral equipment than the gas turbine or many other possible options. Therefore, their selection may prove to be a more expensive option to providing required power. They can, however, be installed as very large generating units.

A steam turbine generating plant is expensive as a new installation. However, it can be particularly attractive if older units can be upgraded and used in conjunction with a gas turbine in a combined-cycle application.

The development of steam turbines has taken place in a little more than a century. The initial units were built as a consequence of the foresight and pioneer work of engineers such as Parsons, Curtis, and Ljumstrom working independently and each producing a unit that was able to convert thermal potential to rotational kinetic energy. Rotational energy was preferable to reciprocating, which to that time was the most commonly used. Rotational units offered certain advantages. The units are considerably more compact and able to be balanced with a greater accuracy than a reciprocating motion. Although the steam turbine units of these pioneers performed the same function, details of their designs were quite unique. These early efforts laid the groundwork for the preparation of a unit that has now been able to produce outputs up to 900,000 kilowatts (kW) in a tandem compound arrangement and up to 1,300,000 kW in a cross compound configuration.

Many of the units currently in service are contained in power generating plants or industrial installations and continue to operate for years without being shut down for inspection or maintenance. These extended operating periods do not represent negligence on the part of operators. Designers designed units to be opened only every 4 or 5 years for inspection and maintenance. Now, there is a growing tendency within industries to increase this operating period to 8 to 10 years. These extended operating periods are a conscious decision made possible due to advancing technology, particularly in terms of improved materials and the ability of designers to more accurately predict stress levels and the remaining life of components whose failure could force a unit from service.

These extended operating periods have a number of important implications for the operating engineer, including the need to make an exhaustive examination when the unit does become available. To examine these units in greater detail requires they be removed from service and opened for inspection. Reparative actions may have to be undertaken that could have been delayed for a 4-year operating cycle, but cannot for 8 to 10. The cost of opening a unit is high and, more importantly, while these units are open, they are not producing power. Therefore, at those planned outages when units are open it is a responsibility of the plant engineers to ensure all actions identified and required to make the unit suited for another extended operating period are taken.

The extended operating period between maintenance outages provides certain advantages to the owners. They do not require as much reserve capacity, and the cost of opening and taking maintenance activities has in the short-term been reduced. At this time in the evolution of the industry, it is not clear whether, in the long-term, any additional degradation in efficiency during this extended period of operation will cover the cost of the one outage that has been missed. Much of this gain or loss will depend upon the manner in which the plant is operated.

Therefore, the operating staff at any plant is now charged with the additional responsibility of operating the unit to maximize its efficiency and minimize any operating regime that could diminish its reliability or force it from service. Unfortunately, there are limited actions operators can take to achieve these performance goals once the unit has been returned to service. Those positive actions that operators can take include careful monitoring and maintenance of water quality, and helping ensure that the unit does not experience any unjustified or avoidable transients. Many such transients of speed or thermal conditions have the potential to cause deterioration in efficiency and to compromise structural reliability.

Though these difficulties and complexities in generating power exist, the general public has no idea of the difficulties involved in securing an adequate supply of electrical power. Similarly, they cannot comprehend what the possible consequences would be if the engineers responsible for the maintenance and care of power plants were to fail to keep these units running efficiently, reliably, and safely.

There are today many facilities generating with units that were installed more than 40 years ago and that have exceeded their design life. These units are still generating power as required, and this power is fed into the distribution system. Many of these older units are still required to meet peak demands, and this type of duty places a heavy burden on them because the start/stop-type of operation is more destructive as the units are continually cycled. Therefore, while the operating hours may be relatively low, the requirements of maintenance can be high.

In many instances, there may have been significant advances in design methods, manufacturing, and installation since the units being considered were designed. If replacement components are to be purchased, there are often alternate designs or design features available that can either increase efficiency or improve reliability or both. These manufacturing changes can either increase or decrease manufacturing costs. In such instances, it is for the plant engineer to evaluate the advantages of incorporating new components since they always seem to have a higher purchase price. However, the return on investment could well pay for the additional cost within a very short period of operation.

W.P.S.

Chapter

1

The Basic Considerations of Thermodynamic Design

INTRODUCTION

The purpose of this chapter is to outline the thermal considerations responsible for preparing a thermal design specification sufficient that selection and mechanical design can be completed. The object is not, therefore, to prepare a detailed description of the thermal design process. Such description is available in a number of excellent texts, to which the reader should refer. However, it is necessary to provide a brief explanation of some of the more important aspects of design and design choice, so that any differences between the decisions made by turbine builders can be appreciated. It is hoped this allows a more informed evaluation of alternate offerings that are made to the buyer at those times he is evaluating a number of bids and having to choose between them to award contracts.

The expansion line end point (ELEP) defines the enthalpy of the steam at exhaust from the low-pressure turbine sections. However, in the exhaust from the low-pressure section, energy is lost due to the velocity of the steam entering the condenser. This lost energy is deducted from the total exhaust energy, and the ELEP defines the used energy end point (UEEP) as seen in chapter 3.

From the heat balance, other information can also be determined, relating to both the output of the various sections and the cycle configuration. As an example of the output determination, consider the high-pressure section:

- The basic high-pressure section is shown in Figure 1–3, and the expansion line for this same section in Figure 1–4. This expansion line shows the effect of the 3% pressure drop at constant enthalpy through the inlet valve system. This pressure drop increases the steam entropy from 1.5324 to 1.5352 ft-lb/lb/°F. Associated with this pressure drop there is also a reduction in steam temperature from 1000 to 996°F.

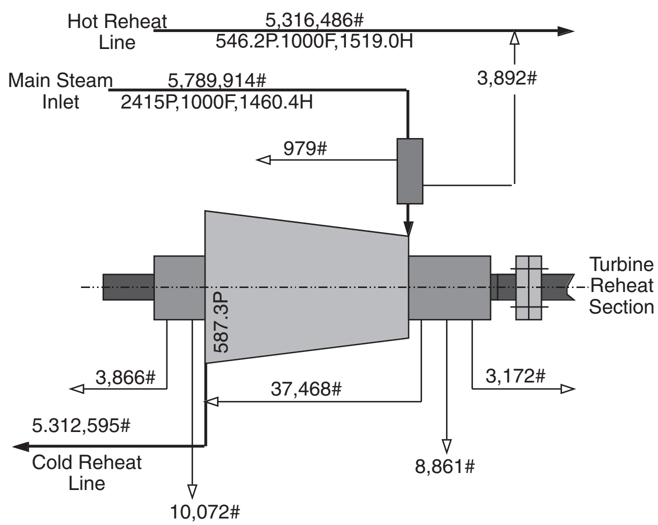

Fig. 1–3 Details of the High-Pressure Section for the Unit Shown

From this expansion diagram, it can be seen that the steam that leaks across the seals carries with it energy that degrades the output of the high-pressure section, bypassing the entire rotating blade rows, but that can be utilized to produce power in the reheat section.

The net effect of this leakage is to degrade the high-pressure section efficiency and output and to increase the output and efficiency of the reheat section. However, the overall effect on the unit is a degradation of output, since the leakage quantity bypasses the high-pressure section, and while it does generate output in the reheat section it would have passed through this section of the turbine and produced the same level of power anyway.

SECTION AND STAGE ENERGY

Before beginning the detailed design process for the individual stages, it is necessary for the design engineer to first establish the energy ranges of the individual sections and then the details of the stages. There are various considerations related to the selection of the high-pressure extraction pressure, including the possible requirements of removing steam at a pressure that will provide heating steam to achieve the final temperature of the feed water.

It is necessary to consider the general process of selecting the energy ranges of the various turbine sections and where steam should be removed from the unit and returned to the boiler for reheating. At this point in the design, no effort has been made to define the optimum arrangement of the stages, number of stages, or diameters. These requirements are considered in the next section.

However, from the Mollier diagram in Figure 1–11, it can be seen that assuming the high-pressure extraction pressure has no impact upon state-line efficiency, then the extraction pressure will have an impact on the total unit design. Note the following specific effects.

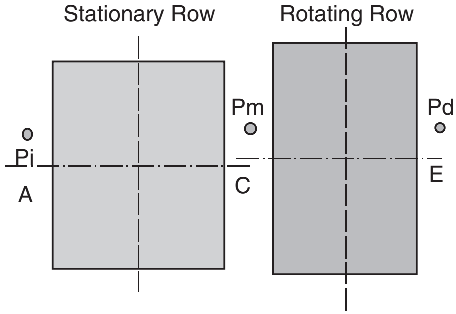

Fig. 1–17 A Stage Showing the Condition at One Radial Location

The preceding analysis of Figure 1–16 has assumed the efficiencies in the stationary and rotating blade rows are the same, and the locus *A-E* represents the change in steam conditions throughout the stage. In fact, the true efficiency of the two rows may be somewhat different because it is often possible to achieve a higher efficiency in one row of elements than the other. Under these circumstances, the true condition might be more correctly represented by the locus *A-X-C*, as shown in Figure 1–18. In this case, *A-X* represents the expansion in the stationary blades, and *X-E* the expansion in the rotating blade row. This, for most purposes, is a small effect and can be neglected. However, in an operating unit where one row of elements has sustained damage, this effect could be quite significant and has the potential to modify the steam conditions through the remainder of the section or even the entire unit. However, this cascading effect becomes less evident with continued expansion down the steam path.

In Figure 1–18, the energy available to the rotating blade row is shown as *ΔHar*, coming from conditions *B-F*. In fact, the energy to be expended over this row is from *X-D*, assuming the inlet conditions are represented by those at condition *X*. However, the energy range *X-D* is greater than *B-C* due to a phenomenon known as the reheat effect. The reheat effect takes account of the frictional

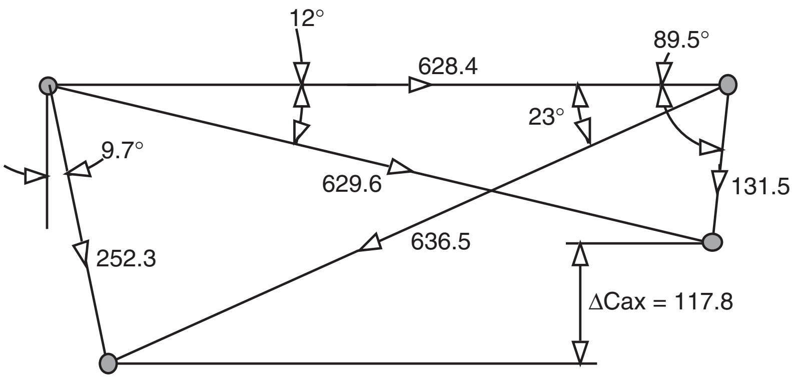

Fig. 1–23 The Velocity Diagram for the Reaction Stage

A comparison of the major parameters of these two stages is shown in Table 1–3. From this comparison, several interesting observation can be made regarding the resultant design of the impulse and reactions stages. Among these are

- The steam velocities in the reaction stage are lower than those in the impulse. One advantage of this is that the row Reynolds Numbers will be lower, and therefore it can be anticipated that the surface frictional losses will be less for any level of surface roughening.
- Both designs produce relative discharge velocities from the rotating row, which is close to axial, meaning that as much of the kinetic energy as possible will have been extracted from the steam.
- The difference in differential axial velocities produces a significantly higher reaction axial thrust in the rotating blade row. This requires a larger thrust bearing to balance the stage, if the section design is not double flowed.

Table 1–5 shows the thermodynamic requirements in terms of flow and thermal characteristics of the steam around the heaters. In terms of the requirements this places on the steam turbine, this steam must be removed first from the steam path and then through an outer and possibly an inner casing or between blade carriers. In the case of multiple flows, there are often requirements for symmetrical extractions from both ends to maintain even axial thrusts, and when more than one double-flow section in the low-pressure sections is used, there is often a requirement of balancing the flows through the last stage blades to maintain blade loading at acceptable levels.

Heater:	G	Mixing	F	E	D	C	BFP	B	A
Temperature at Inlet:	79.0	140.2	141.1	188.9	237.1	285.0	333.0	340.1	385.1
Temperature at Discharge:	140.2	141.1	188.9	237.1	285.0	333.0	340.1*	385.1	470.0
ΔT though equipment:	61.2	0.9	47.8	48.2	47.9	48.0	7.1	45.0	84.9
Enthalpy at Inlet:	47.1	108.1	109.0	156.8	205.4	254.0	303.9	316.0	362.7
Enthalpy at Discharge:	108.1	109.0	156.8	205.4	254.0	303.9	316.0	362.7	453.8
ΔH through equipment:	61.0	0.9	47.8	48.6	48.6	49.9	12.1	46.7	91.1
Feed Water Flow 1,000lb:	1,250.6	-	1,528.4	1,528.4	1,528.4	1,846.9	-	1,846.9	1,846.9
Heater Flow 1,000lb:	76.7	-	64.4	67.3	69.3	68.9	-	70.4	179.3
Drains Flow 1,000lb:	277.8	-	201.1	136.7	69.3	1,846.9	-	249.7	179.3
Drains Temperature:	145.1	-	151.1	198.9	247.1	333.0	-	350.1	395.1

Notes: Pressure in psia, temperature in °F, and enthalpy in BTU/lb.

Table 1–5 Thermal Conditions in the Heater Train

As the steam expands, the specific volume increases, until at the low-pressure end the volumetric flows can become particularly large requiring a number of pipes to remove the steam and maintain acceptable velocities in the pipes. It is normal for the architect engineer to specify the maximum pressure drop allowable in the extraction lines, and therefore the turbine designer must calculate the number and size of the extraction pipes so as not to exceed this pressure drop.

Table 1–6 shows factors that influence the sizing of the extraction lines which are to be used in any configuration. Consider the extraction

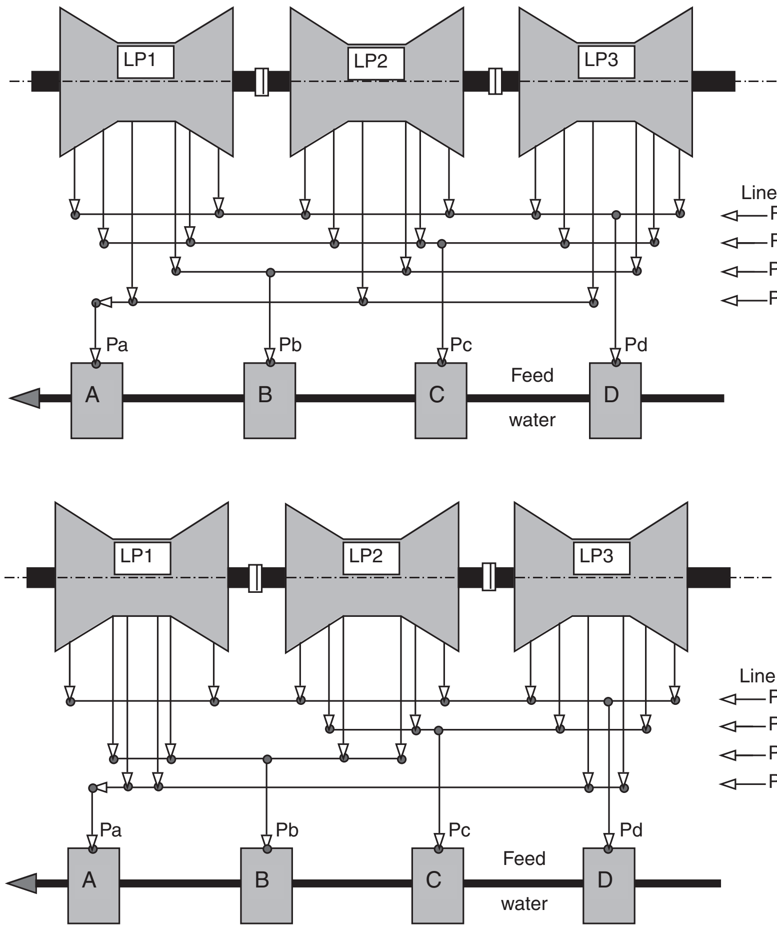

Fig. 1–44 Alternate Steam Extractions Patterns from a 6-Flow Low-Pressure Design

These three low-pressure rotors of Figure 1–44a can be interchangeable if the axial clearances between the blade rows are retained at the same values in all three. Alternately axial clearance differences can be minimized by adjustment of the stationary blade row axial position setting. Under these circumstances, only one rotor design and one spare would be required for all three sections. The