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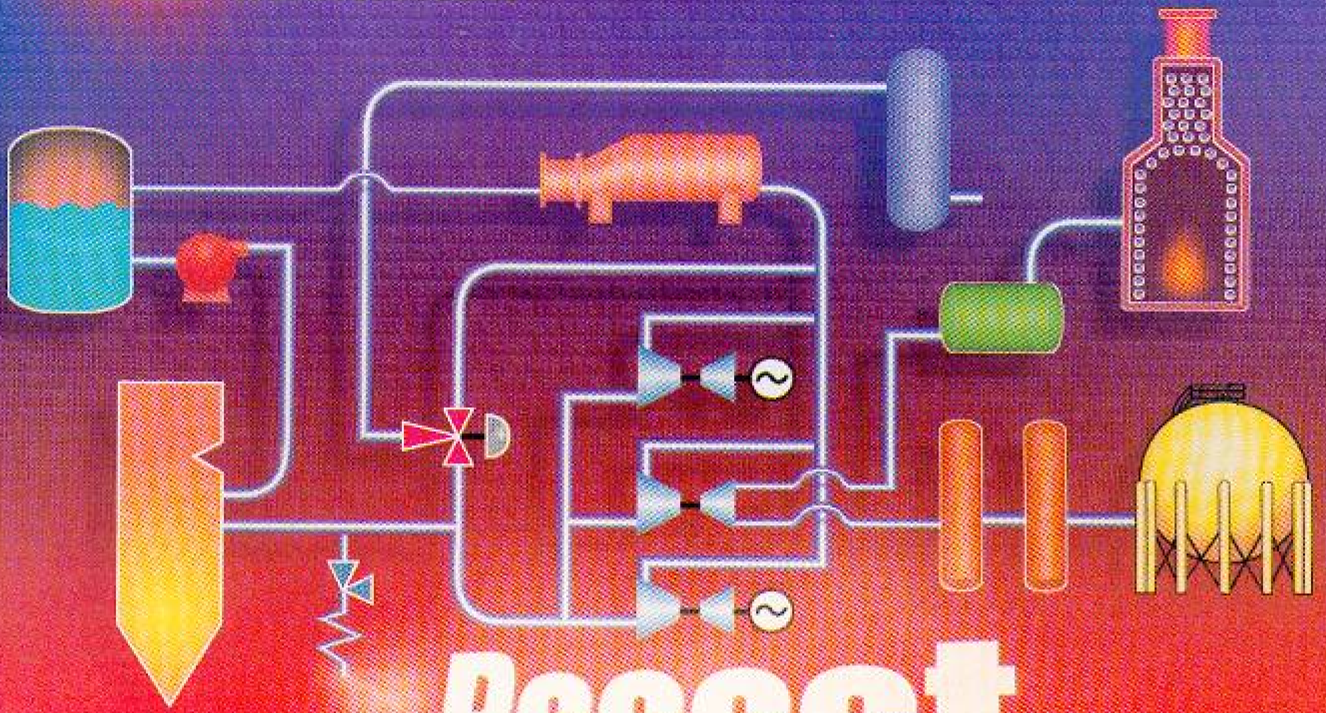
Page 101



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Page 70

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Benefit from Steam-balance Optimization Strategies

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Replace control valves with thermocompressors to prevent steam venting and gain overall efficiency

The improvements to the steam engine that James Watt registered as a patent in 1769 lies at the origin of the industrial revolution [*1*]. His "invented method of lessening the consumption of steam and fuel" [2] is mirrored in today's quest for optimized steam systems. Such optimization in modern refineries and chemical plants is still not a simple or intuitive task. This is especially true when considering the complexity of multiple steam subsystems (steam mains), each maintained at its own pressure, and the presence of steam turbines, waste-energy and ancillary steam generators, pressure-reducing valves and vents to the atmosphere.

However, innovative technology can be used to optimize existing steam systems and to design new systems for optimal performance. For the sake of brevity and generality, most of the key ideas in this work are explained by simple concepts, such as pressure and temperature. The discussion excludes advanced thermodynamic calculations, in a bid to make this article accessible to engineers who lack a specialized background in utilities management.

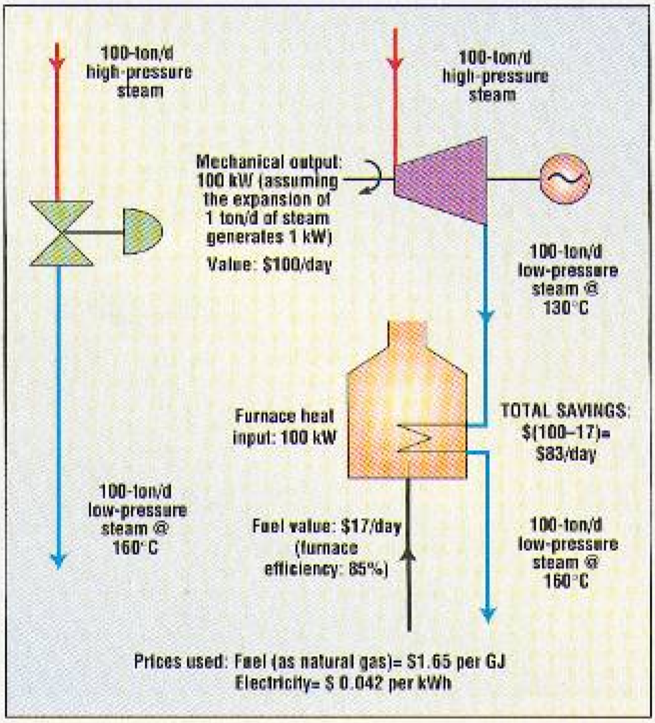

FIGURE 1. Replace a throttle valve with a turbine to recover mechanical work

Steam-balance operation

Each steam main in a petroleum refinery or chemical plant may possess either an abundance of steam (excess-steam mode) or a shortage of steam (deficit-steam mode) at a given moment, thus existing in an unbalanced mode. Steam systems often include an ancillary steam generator to supply make-up steam. The pressure in the steam mains is maintained and the balance restored by the additional steam produced by this generator. A steam main is balanced when all users drawing steam from the main are supplied with sufficient steam at all times, and when there is no need to vent any excess steam to the atmosphere.

Excess steam, detected by an increase in the steam-main pressure, is commonly vented to the atmosphere by a pressure-controlled valve to maintain a balance in the steam main. In an extreme case of excess steam, pressure-relief valves protecting the mains will be actuated, venting steam to the atmosphere and preventing overpressure and physical damage to the steam system.

A steam deficit is indicated by a decrease in the steam-main pressure. To achieve a balanced steam main in the absence of an ancillary steam generator, it is necessary to inject steam from another available source of steam. The most common source is another main at a pressure immediately higher than that of the one in a deficit condition. The pressure in the unbalanced main is frequently restored by injecting steam from the higher-pressure mains through a throttle valve. Although this strategy addresses the immediate steam-deficit, it is not the optimal way to operate the steam system, for reasons discussed below.

The steam enthalpy at a throttle-valve inlet can be assumed equal to that downstream of the valve, so no energy is lost across the valve. However, throttling degrades the quality of energy.

During the throttling of high-pressure (HP) steam to low-pressure (LP) steam over a valve, energy is converted from mechanically useful steam pressure to thermal energy, resulting

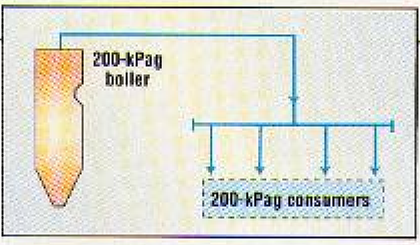

FIGURE 2. Example of a single, low-pressure steam system

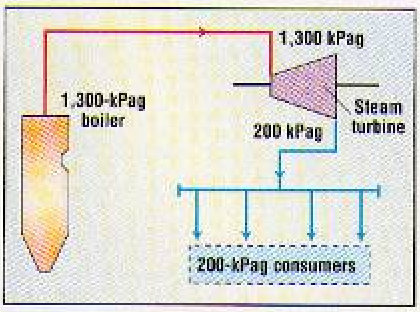

FIGURE 3. Example of a high-pressure boiler with steam expanded over a turbine

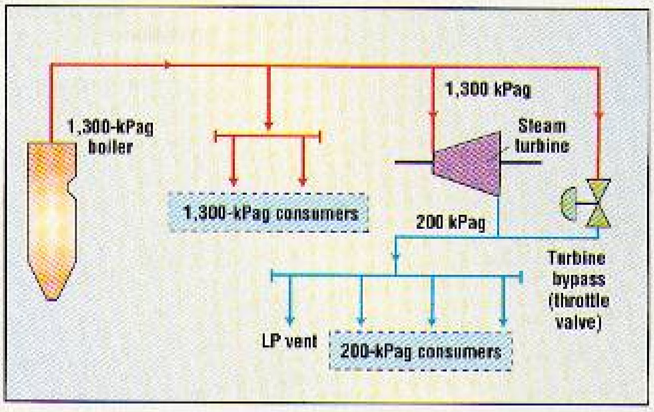

FIGURE 4. Complex steam system with one boiler and two steam-main pressures

in steam superheating at the valve outlet. This ability of HP steam to be a source of more mechanical energy than LP steam may, of course, be put to greater use by powering a turbine, which, in turn, can be used to drive pumps or compressors normally driven by electric motors. Therefore, when a steam turbine is used to expand steam, part of the HP-steam energy is applied toward a decrease of electricity consumption in the plant. This well-established practice has more economic benefit than the steam superheating that results from using a throttle valve, as shown below.

The saturated exhaust steam from a turbine will have a lower temperature than the superheated steam in a throttle-valve outlet and may need to be reheated to match the outlet condition of the throttle valve replaced by the steam turbine. Considering that electricity is energy of a higher quality than thermal energy, and is consequently more expensive, the cost of the electricity saved by operating a turbine instead of a electric motor to drive a pump or a compressor is much higher than the cost of the fuel that would be required to superheat the turbine-steam exhaust to the same temperature as the throttle-valve outlet.

This idea is expressed in the theoretical comparison depicted in Figure 1. In the case of the throttle valve, no mechanical work is recovered and all the energy of the expansion is used to superheat the 100 tons/d of LP steam to 160°C. In case of the turbine-superheater combination, 100 kW of mechanical energy is recovered in the turbine. This is based on the assumption that 1 ton/day of HP steam generates 1 kW of electricity, at an electricity price of \$0.042/kWh. The electricity generated by the turbine is therefore able to replace \$100/d of electricity otherwise procured from more-expensive sources.

After the turbine expansion, however, the LP steam is 30°C colder than the steam expanded through a throttle valve. Passing this LP steam at 130°C through a furnace to raise its temperature to 160°C costs \$17/d in a furnace that is 85% efficient with fuel available at \$1.65/GJ. Therefore, the total savings incurred by replacing a throttle valve with a steam turbine and superheating step is \$83/d, given the assumed electricity and fuel prices. Note that the furnace is not necessarily required in real applications and that waste heat may be used to superheat the turbine exhaust.

When a refinery is in an excess-steam scenario in one of the steam mains, it is usually uneconomic (depending on steam and electricity prices) to expand HP steam through a turbine to the lower-pressure, excess-steam mains while simultaneously venting steam from the latter to maintain its balance. In this case of excess-LP steam, it would be economically beneficial to shut down some turbines. The continuous monitoring of turbine operation, throttling, venting and system losses is crucial for an optimal steam balance and economical steam-system operation (further discussion on this in the next session accompanies Figure 4). To further ensure good economy and optimize overall thermal efficiency, the operation of a waste-heat steam generator should be maximized compared to that of an ancillary steam generator that consumes valuable fuels.

Steam balance and design

The traditional approach to designing a steam system is to install ancillary steam generators that are able to generate steam at the maximum pressure and temperature required by the process. Consider a simplistic case where the steam pressure requirement is only 200 kPag maximum. The flowsheet emanating from the traditional approach to steam-system design is depicted in Figure 2.

When a new steam system is installed, the extra investment associated with choosing steam generators rated at a higher pressure is relatively small compared to the overall investment. LP steam required by the process can then be supplied by expanding HP steam from the high-pressure boiler over a noncondensing, backpressure steam turbine, thereby obtaining mechanical energy from the HP steam to run pumps and compressors or to generate electricity (Figure 3).

Figure 4 shows a steam system where some of the consumers require 1,300-kPag steam and others require only 200-kPag steam. The throttle valve shown in the drawing is also considered a turbine bypass valve. One of the ways to optimize the steam balance is to maximize the ratio of steam passing through the turbine (or turbines) to the steam being throttled across the valve. This strategy maximizes the mechanical energy generated in the steam turbine. However, if more 1,300-kPag steam is expanded than required by the 200-kPag steam consumers, the system will vent 200-kPag steam to the atmosphere. This situation is usually uneconomical (depending on steam and electricity prices) and the flowrate of steam ex-

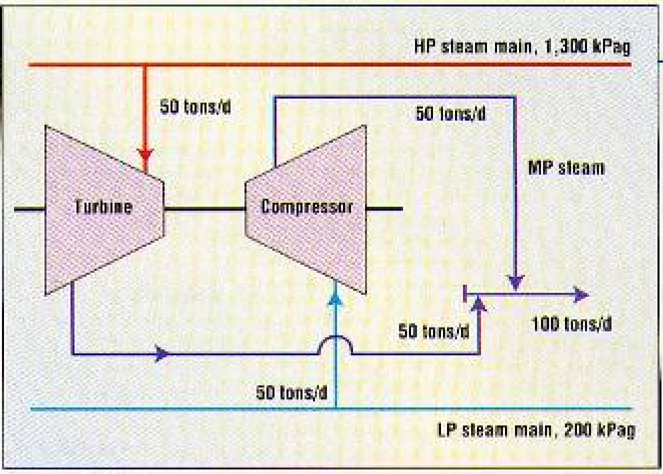

FIGURE 6. Traditional energy-recovery during steam expansion

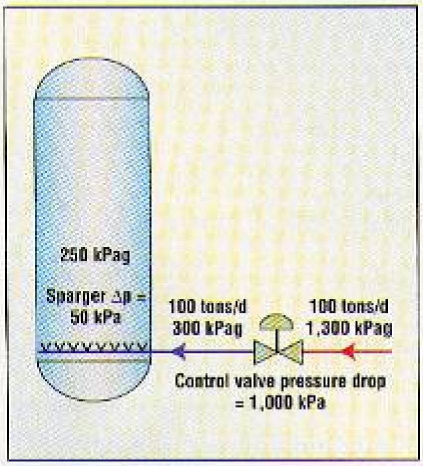

FIGURE 5. Operation of a traditional steam-stripping column

> 'When we pass through the colliery or iron districts we often see clouds of steam blowing off to waste, but there is much less than was formerly the case, because low-pressure turbines worked by the exhaust steam from other engines are coming into extended use for utilizing what was formerly a waste product.' [3]

panded in the turbine should be reduced to avoid venting.

Capital expenditure is an important consideration when considering a new steam system. As alluded to earlier, steam generators rated at higher pressure are somewhat more expensive than LP-steam generators. However, due to the fact that saturated HP steam is at a higher temperature than saturated LP steam, the heat-exchange surface area required in heat exchangers and reboilers is lower when using HP steam. Furthermore, HP steam has higher density than LP steam and therefore requires smaller-diameter steam mains. This represents further savings in capital expenditure.

Although this design philosophy leads to minimum initial capital investment, it can fail in its ability to ensure the lowest longterm operating cost. This is because it is usually more economically efficient to use LP steam than HP steam. Furthermore, by maximizing the ratio of LP-steam consumers to HP-steam consumers, the amount of steam that can be expanded through turbines to drive pumps or compressors or to generate electricity is maximized as well. In summary, the following rules should be followed:

1. Produce steam at the highest possible temperature and pressure.
2. Expand steam from a higher pressure to a lower pressure by the most-efficient means possible.
3. Apply steam to process applications at the lowest economically attractive pressure and temperature. For instance, reboilers and steam preheaters should be designed using tubes with high surface-area and lower tower operating pressures, to use the lowest steam pressure available.

However, to apply these rules fully, a refinery would have to be designed with as many steam-main pressures as there are steam consumers requiring different pressures, using turbines to expand steam from the maximum pressure to each mains' pressure to meet each consumer's steam demand. This is not feasible with the number of different steam consumers in a typical modern refinery. Accordingly, a compromise is often made, and refineries are designed typically with two or three steam pressures.

The optimal steam pressure required by a consumer often lies between two steam-main pressures. In this case, the steam is supplied from the immediately higher-pressure steam main and the consumer's control valve actuates, serving as a sort of throttle valve.

Consider, for example, a steam-stripping column in which the internal pressure exceeds the LP-steam-main pressure. Since LP steam cannot be used, the immediately higher-pressure main will supply the steam. The stripping-steam control valve, usually set as a flow controller, will work as a throttle valve, effectively letting down the steam from the steam-main pressure to the pressure in the column (Figure 5).

This represents a lost opportunity to generate mechanical energy. Complicated arrangements could be developed using traditional technology to meet the required intermediate pressure, using a mixture of LP and HP steam while generating useable mechanical energy (Figure 6). However, while these flowsheet arrangements are certainly technically feasible, they often are economically unacceptable because of the high capital investment required.

This dilemma introduces the alternative technology of static mixing-devices called thermocompressors (Figure 7). They are often economically feasible, due to low initial and operating cost compared to turbines and compressors.

Thermocompressors

A thermocompressor (or controlled ejector) is a device, without moving parts, that is capable of compressing a fluid from a low pressure (P2) up to a greater pressure (P3) using a stream with an even higher pressure (P1) as the driving force (Figure 8). The thermocompressor uses the energy of this motive stream, expanding it from from P1 to P3, to compress a fluid from P2 to P3 (where P1 > P3 > P2). Table 1 contains a brief description of the three streams associated with a thermocompressor.

The flowrate ratio of Stream 1 to Stream 2 is a function of the pressures utilized. A thermocompressor is a type of control valve, by virtue of the fact that it can control pressures, flowrates and other variables, like a normal control valve. Thercompressors achieve this by changing the internal nozzle-pass section, thereby

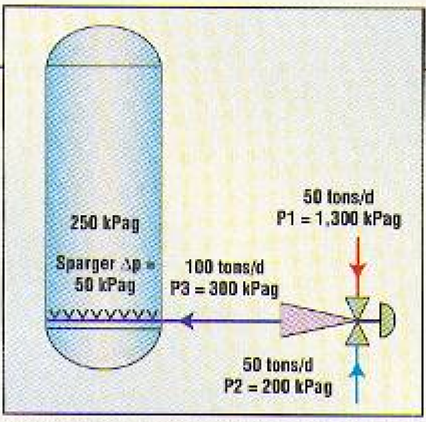

FIGURE 7. Using a thermocompressor for medium-pressure steam

TABLE 1. THERMOCOMPRESSOR STREAM DESCRIPTION

Stream #	Pressure	Description
1	High	Motive stream
2	Low	Suction
3	Medium	Discharge

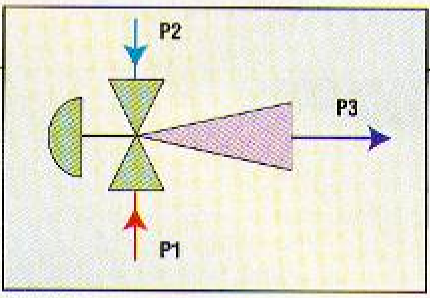

FIGURE 8. Basic operation of a thermocompressor

> 'In short, I expect almost totally to prevent waste of steam'[4]
>
> 'A reducing valve is, from a thermodynamic point of view, an invention of the devil' [5]

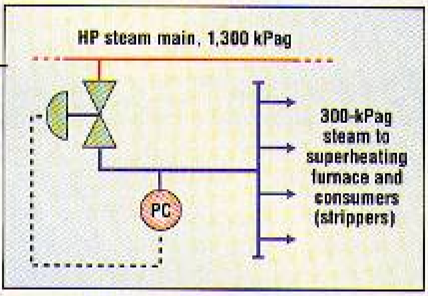

FIGURE 9. Using a control valve to generate 300-kPa steam

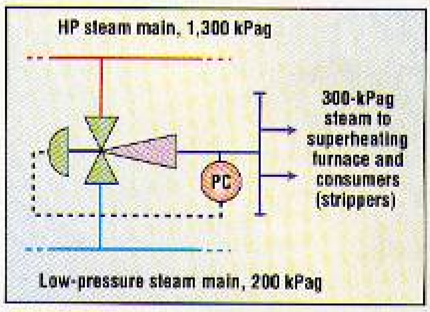

FIGURE 10. Using a thermocompressor to generate 300-kPa steam

changing the motive-stream flowrate and, consequently, the suction-stream flowrate. The flow ratio varies for different valve positions.

An example of this technology being applied is described next. Consider a crude-oil distillation unit in a refinery that needs approximately 250 tons/d of steam with a minimum pressure of 300 kPag. This required minimum pressure is approximately 100 kPa higher than the refinery's LP steam mains (200 kPag). Because LP steam cannot be directly used for this duty, the steam-pressure requirement for these consumers is currently met by throttling 1,300-kPag steam (Figure 9). As an alternative to this approach, a thermocompressor can be used to withdraw some LP steam to supply the consumers of 300 kPag medium-pressure (MP) steam (Figure 10). The motive stream for the thermocompressor will be 1,300-kPag steam, resulting in a decrease in HP-steam demand compared to the traditional setup shown in Figure 5.

Consider furthermore that the steam demand for these consumers can oscillate from 170 to 250 tons/d, and that the thermocompressor will be operated by controlling the discharge-pressure to 300 kPag. The expected flowrate ratio for this set of pressures is approximately 1.0, implying that for each ton of LP steam used, one ton of HP steam will be needed as a motive force. Therefore, the steam demand for this duty can change from the current 250 tons/d of HP steam to 125 tons/d of withdrawn LP-steam plus 125 tons/d of motive HP-steam. The extra 125 tons/d LP-steam demand created by the thermocompressor, met by expanding an extra 125 ton/d of HP-steam through the refinery's HP-LP steam turbines, also results in the recovery of additional mechanical energy.

As discussed earlier, the MP-steam originating from the thermocompressor will be less superheated than that currently obtained from the throttle valve. However, this is not an issue in this case because the MP steam is currently superheated in the crude furnace before being used as stripping steam. After a thermocompressor is installed, the MP steam will absorb the additional thermal energy required to match the previous throttle-valve-derived level of superheat, from the furnace fluegas waste-heat. In the process, the furnace fluegas will be cooled down slightly more and no extra fuel consumption will be required in the furnace. The existing throttle valve can be left onsite, available in case of a thermocompressor malfunction or during maintenance.

Conclusions

Any steam-control valve with a significant pressure drop could be replaced by a thermocompressor that controls pressure, flow or temperature in a manner similar to that of a normal control valve, while meeting the consumer steam demand by mixing steam with two different pressures. The additional LP-steam demand created by the thermocompressor is obtained by expanding HP steam in a turbine, thereby extracting mechanical energy from the turbine and providing some of the refinery's electricity demand.

Spare steam-turbine capacity is required to make use of this opportunity, however, to prevent the additional LP steam demand created by the thermocompressor from being met by the senseless expansion of HP steam through a throttle valve. If there is no spare turbine-capacity available, the decision to install a new turbine to drive a spare pump or compressor rather than using another electric motor should be based on the electricity savings obtained by running the turbine. However, the higher maintenance costs associated with turbines should also be evaluated.

Another, more-flexible, option is to use a turbine to generate electricity. The operational flexibility associated with this option comes at the cost of a higher investment in the electricity generator connected to the turbine.

As a general rule, the replacement of steam control valves with thermocompressors is more likely to be economically viable in new projects than in existing steam systems. The fact that the price of a thermocompressor is not much higher than that of a normal control valve makes it an attractive option.

The replacement of throttle valves by turbines to throttle steam is desirable regardless of the efficiency of the turbines installed. Inefficient turbines produce less mechanical energy and hence yield higher-temperature exhaust steam than more-efficient turbines. Considering the overall energy balance, it will therefore always be more beneficial to operate a turbine than a throttle valve. In the extreme case, a turbine with zero efficiency would not produce any mechanical energy, thereby becoming, in effect, a throttle valve.

Consequently the marginal price per mass unit of LP steam (used to evaluate projects saving LP steam, utilities cost profiles, and so on) should be quantified as follows:

a) If the refinery has spare steam turbine availability:
   LP steam price = Price of one unit of HP steam minus the electricity cost saved by expanding one extra unit of HP steam through a theoretical turbine (with the refinery's average turbine efficiency).

b) If the refinery has no spare steam-turbine capacity:
   LP steam price = HP steam price.

c) If the refinery is venting LP steam to atmosphere:
   LP steam price = 0 (there would no point in saving LP steam if the refinery were already venting it).

In some refineries or chemical plants, the venting of LP steam to atmosphere cannot be avoided by conventional flowsheet or operational modifications. In such a case, all LP steam consumed as a result of a thermocompressor installation is steam that would otherwise have been vented to atmosphere and subsequently have been made up by generating more HP steam. Since HP-steam demand is usually met by operating ancillary boilers that consume valuable fuel and feedwater, the cost savings associated with cutting back HP-steam demand in this fashion may be substantial, resulting in the payback time of a new thermocompressor being in the order of only few months. ■

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