Vapor Recompression

In many industrial processes, large quantities of steam are either vented to the atmosphere or condensed in a cooling tower, wasting energy. This steam can be compressed back to a usable pressure using only 5-10 percent of the energy required to generate the steam in a boiler, thereby conserving the energy in the waste steam. This Technology Update discusses how this is accomplished and outlines the methodology for calculating the energy and financial savings generated.

Background

Vapor (or steam) recompression is the technique of compressing a vapor from a pressure too low for application use to a higher, usable pressure. Vapor recompression is analogous to the operation of a heat pump where mechanical work is used to upgrade energy from a lower temperature level to a higher temperature level.

Energy is supplied to the compressor to raise the steam pressure. However, this operation typically requires only 5-10 percent of the energy necessary to generate the same steam in a boiler. This unique aspect of vapor recompression is a result of the major fraction of the energy in the steam being available to the compressor inlet as latent heat. As a result, only a small fraction of additional energy is required to raise the pressure and temperature to a useful level.

In practice, vapor recompression is limited to compression ratios of less than about 2:1 per stage. The compressor may be driven by an electric motor, gas engine, or gas turbine.

The graph in Figure 1 indicates the energy required to compress steam as a function of the compression ratio and inlet pressure. The curves are based on adiabatic compression with a compressor efficiency of 70 percent. Because the steam leaving the compressor is superheated, it is also assumed that water at 82.4°F is sprayed into the steam to eliminate the superheat. Figure 1 can be used in conjunction with standard steam tables to estimate the energy savings possible by employing vapor recompression. (Note: For a more accurate estimate, steam tables and/or a Mollier Chart should be used, together with efficiency data relating to a specific make of compressor. Also, when desuperheating is not necessary, the calculation should be adjusted accordingly.)
The nature of the industry or plant, the amount of higher pressure steam needed, the compression ratio, and the source of low-pressure steam vary widely; thus a complete review must precede each installation decision.

**Applications**

Two common applications using vapor recompression are steam quality upgrading and waste-steam heat recovery, which are discussed in the following sections.

**Steam Quality Upgrading**

A processing plant that has been using steam at a relatively low pressure (say, 50 psig) may have an unexpected requirement for steam at a higher pressure (say, 100 psig). If the new steam demand is large, the need for new boiler capacity may be unavoidable. However, lesser steam requirements could possibly be met by mechanical compression of existing low-pressure steam.

Operations in which steam quality may be upgraded by recompression include food processing, vulcanizing, and clothes laundering. Steam recompression can also be used in distribution piping systems to boost steam pressures that have dropped to an unacceptably low level.

The benefits of steam quality upgrading, compared with alternatives, may include lower capital cost, a lower requirement for floor space, reduced installation time and cost, and sometimes a reduction in air pollution problems. If cheap exhaust steam is available, the operating costs may be very favorable.

**Waste-Steam Heat Recovery**

In many industrial processes, large quantities of waste energy are often liberated in the form of low-pressure waste steam. Examples of such waste energy sources are the following:

- Steam turbine exhaust
- Evaporators (pulp and paper manufacturing, chemical manufacturing, food processing)
- Refiner waste steam (thermo-mechanical pulping)
- Flash steam
- Steam cooking

It is common practice to vent such waste steam at pressures below, say, 20 psig.

In many such instances there is, at the same time, a plant application, such as the drying or heating and/or evaporation of liquids, in which steam at a pressure higher than the exhaust pressure is required. Under such a circumstance, it may well be possible to reuse the low-pressure vapor (steam) by compressing it to a higher pressure (vapor recompression). Vapor recompression can, therefore, result in energy savings by reducing the amount of steam required to be generated from a boiler.

An example of a system in which steam is generated in a boiler to provide the heat needed to run an evaporator is shown in Figure 2a. Vapor from the evaporator is driven off under atmospheric pressure at 212°F. There is no vapor recompression, the evaporator vapor being sent to a cooling tower where it is condensed, giving up heat which is wasted energy.

Much of the heat in the evaporation can be recovered by recompression (Figure 2b). By adding a relatively small amount of thermal energy to the vapor, the compressor raises the pressure of the vapor to about 5 psig, which corresponds to a saturated steam temperature of about 228°F. The steam is then returned to the steam chest in the evaporator to continue to drive the operation.

![Figure 2a. Single effect evaporator system—no vapor recompression](image)
The economics of waste-steam heat recovery by vapor recompression depends mainly on the cost of owning and operating the compressor. Although the capital costs for a compressor installation may be high, the reduced boiler steam requirements can result in sufficient energy savings to pay for the compressor installation and running costs in an acceptable time.

**Savings**

The dollar savings per year ($S$) available by using the vapor recompression process for heat recovery is calculated by the formula:

$$S = (t \times f) \times (C_{bs} - C_{vr})$$

where:
- $t$ = operating time (hr./yr.)
- $f$ = steam flow (lb./hr.)
- $C_{bs}$ = cost of boiler steam production ($/lb.)
- $C_{vr}$ = cost of vapor recompression ($/lb.)$

Sensitivity analysis shows that the factor $C_{bs}$ is the most significant in achieving savings and the cost of compression $C_{vr}$ is about $\frac{1}{12}$th of $C_{bs}$ as shown in the example calculation in the next section. The savings can be calculated from the formula:

$$S = (t \times f) \times \left[ \frac{h_g - h_f \times C_o}{n \times O_e} - (E_c \times A \times C_e) \right]$$

where:
- $h_g$ = enthalpy of steam (Btu/lb.)
- $h_f$ = enthalpy of water (Btu/lb.)
- $C_o$ = cost of oil ($/gal.)
- $n$ = efficiency of boiler
- $O_e$ = energy content of oil (Btu/gal.)
- $E_c$ = energy required to compress steam (Btu/lb.) (see Figure 1)
- $A$ = factor to convert Btu to kWh (0.000293 kWh/Btu)
- $C_e$ = average electricity cost ($/kWh$)
The Electric Ideas Clearinghouse is a comprehensive information source for commercial and industrial energy users. It is operated by the Washington State Energy Office and is part of the Electric Ideas technology transfer program sponsored by participating utilities and the Bonneville Power Administration.

Example Calculation of Energy and Cost Savings

A plant vents 14.9 psig steam to the atmosphere. Concurrently, in another application, there is a requirement for 4,960 lb./hr. of 39.9 psig steam from the boiler.

The following calculations provide an estimate of energy and cost savings to be realized by compressing the 14.9 psig steam to 39.9 psig, using an electrically driven compressor rather than generating the 39.9 psig steam from a boiler. Calculations are based on the following (assumed) data.

- Boiler feed water temperature = 82.4°F
- Boiler efficiency = 80%
- Annual operating time = 5,200 hr.
- Fuel = #6 oil
- Fuel heating value = 181,840 Btu/gal.
- Fuel cost = $1.364/gal.
- Electricity cost = $0.04/kWh
- From steam tables:
  - $h_f = 50.4$ Btu/lb. for 82.4°F water
  - $h_g = 1175.7$ Btu/lb. for 39.9 psig steam

**Annual Energy Requirement of Boiler Fuel**

$$\frac{4960\text{ lb/yr.} \times (1175.7 - 50.4)\text{ Btu/lb.} \times 5200\text{ hr/yr.}}{0.8} = 36280 \times 10^6\text{ Btu}$$

**Annual Cost for Raising Boiler Steam**

$$\frac{36280 \times 10^6\text{ Btu}}{181840\text{ Btu/gal.}} \times \$1.364/\text{gal.} = \$272,100$$

**Compressor Work**

$$\frac{39.9\text{ psig} + 14.7\text{ psia}}{14.9\text{ psig} + 14.7\text{ psia}} = 1.84$$

(From Figure 1, the compressor requires 67 Btu/lb. of steam delivered.)

**Annual Energy Required for Driving Compressor**

$$67\text{ Btu/lb.} \times 4960\text{ lb/yr.} \times 5200\text{ hr/yr.} = 1730 \times 10^6\text{ Btu}$$

**Annual Cost for Compressor Energy**

$$1730 \times 10^6\text{ Btu} \times 0.000293\text{ kW/h/Btu} \times $0.04/\text{kWh} = $20,300$$

**Annual Savings**

- Energy: $34,550 \times 10^6\text{ Btu}$
- Cost: $272,100 - $20,300 = $251,800

**Return on Investment**

The cost for a compressor package to handle the installation in this example would be in the order of $250,000. On this basis, the simple payback would be approximately 1 year:

$$\frac{$250,000}{251,800\text{ yr.}} = 0.99\text{ yr.}$$

Note: The above estimate is for illustrative purposes only, and numbers have been rounded off for simplicity.