

Steam Turbine Cogeneration

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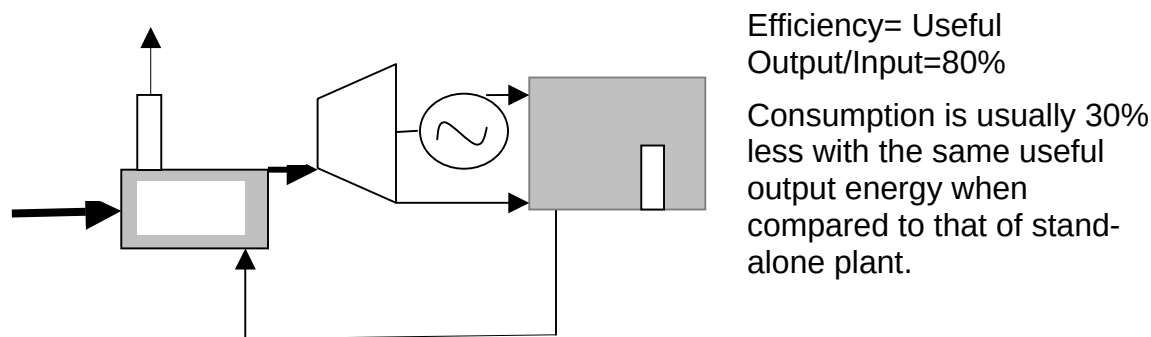
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ABSTRACT:

Steam turbines are widely used in most industrial facilities because steam is readily available and steam turbine is easy to operate and maintain. If designed properly, a steam turbine co-generation (producing heat and power simultaneously) system can increase energy efficiency, reduce air emissions and qualify the equipment for a Capital Cost tax Allowance. As a result, such a system benefits the stakeholders, the society and the environment. This paper describes briefly the types of steam turbine classified by their conditions of exhaust and review quickly the fundamentals related to steam and steam turbine. Then the authors will analyze a typical steam turbine co-generation system and give examples to illustrate the benefits of the System.

INTRODUCTION

Combined Heat and Power (CHP) or Cogeneration is primarily a thermal, technology neutral, energy efficient process. Input fuel could be biomass, coal, oil or natural/landfill gas. Technology could be steam turbine, gas turbine or reciprocating engine. The process allows us to simultaneously produce heat (steam) and electricity from a single fuel by making use of otherwise waste energy.



Combined Heat and Power

The benefits of CHP system are multi-fold. For example:

- CHP uses fossil fuels more efficiently, saving between 20% and 40% over stand-alone systems. In addition, CHP reduces energy costs by eliminating or deferring costly transmission and distribution infrastructure investments.
- CHP improves the reliability and security of energy supply by using local fuels and waste products as inputs. Many CHP facilities in Canada and in the US continued to supply power during the August 2003 blackout.
- CHP improves air quality, reduces the environmental impacts of energy use and produces less air pollutants than stand-alone alternatives.

CHP or cogeneration systems are classified according to the technology used to generate electricity. In this article, we will focus on steam turbine cogeneration because of our interest in its simplicity (the steam that drives the turbine is produced in a typical industrial boiler) and its flexibility (boilers are available that burn virtually any type of fuel). Furthermore, we would like to share with you the following:

- steam and steam turbine fundamentals;
- an example of a typical steam turbine cogeneration system to analyze steam turbine performance and the benefits that such system can bring; and
- another example to examine the conditions of eligibility for Canadian Capital Cost Allowance (CCA).

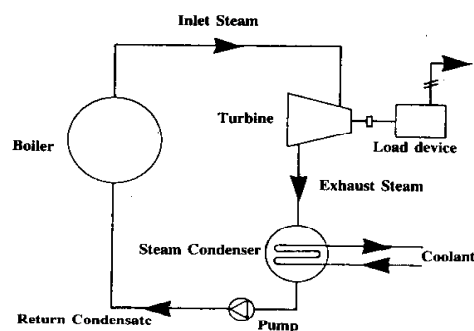
STEAM TURBINE TYPES

Steam turbines are classified by the conditions of the exhaust steam (see figures below).

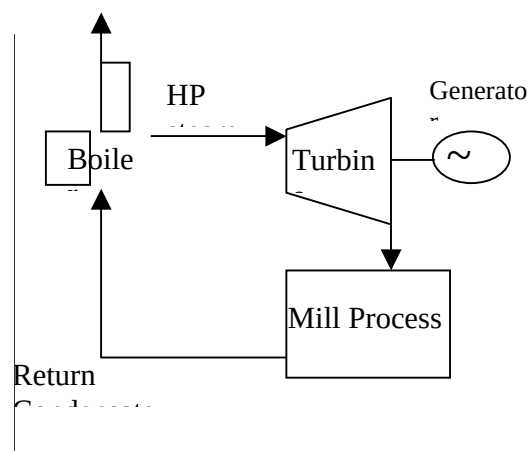
Condensing turbines usually utilize superheated inlet steam to minimize condensation within the turbine and operate the exhaust steam below atmospheric pressure.

Backpressure turbines operate with the exhaust steam at or above atmospheric pressure. They often utilize inlet steam at saturation pressure and temperature resulting in a mixture of steam and condensate at the exhaust.

Condensing



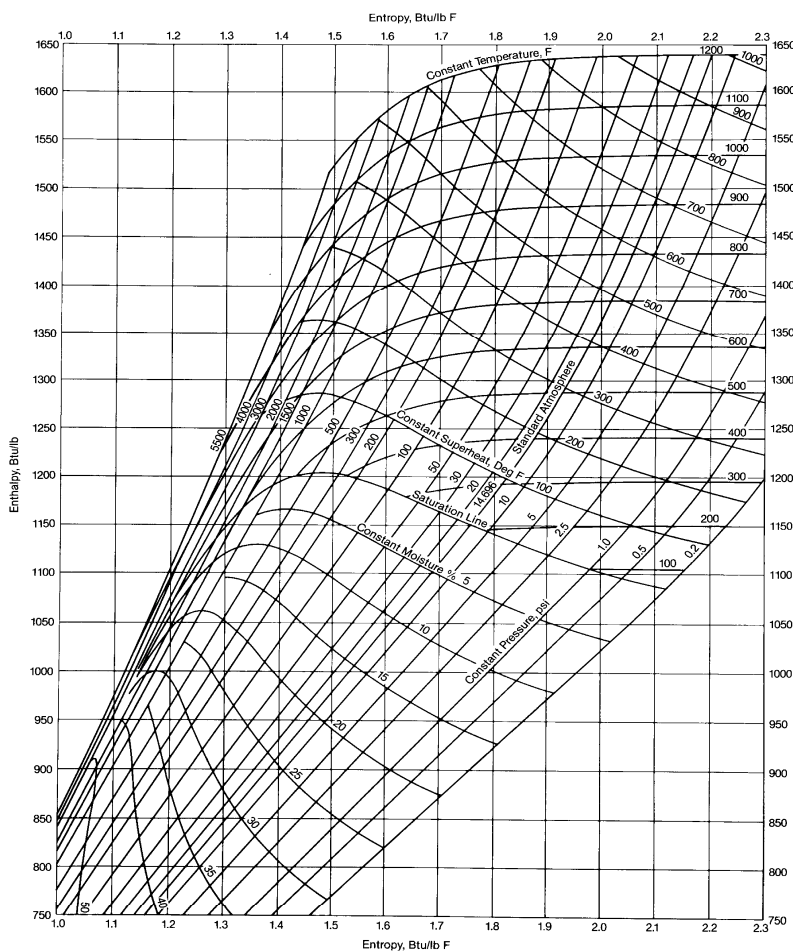
Non-condensing/backpressure



STEAM AND STEAM TURBINE FUNDAMENTALS

Here are some of the steam and steam turbine properties that are relevant in this article:

- Specific Enthalpy (h in Btu/lb of steam): is the amount of heat that a substance contains per unit mass.
- Entropy (s in Btu/lb F) is the rate of change of enthalpy per unit temperature change.
- Steam tables are tabulated listings of the following thermal properties of water and steam at various sustained temperatures and pressures.
 - The specific volume (ft^3/lb), for water at saturation temperature (v_f) and saturated steam (v_g).
 - The enthalpy for water at saturation temperature (h_f), evaporation or change of state (h_{fg}), and saturated steam (h_g).
 - The entropy for water at saturation temperature (s_f), evaporation or change of state (s_{fg}), and saturated steam (s_g).
- The values for saturated steam are for dry steam as pure vapour without entrained water droplets. The theoretical values can be used for most steam system calculations. Although most systems operate close to these theoretical values, some water is usually present. The amount of water is a measure of the steam “quality” and is expressed as “constant moisture per cent of weight”.



The Mollier Diagram (left) is a graphical representation of the steam table plotted with enthalpy on the vertical axis and entropy on the horizontal axis. Also included on the diagram are absolute pressures, temperatures, constant moistures percent and constant superheat temperatures. The major portions of the diagram are separated by the saturation line; below which, the steam contains some water droplets and above which, the steam is superheated and acts as a gas. (If superheating at constant pressure is continued the volume of the steam increases. Below the saturation line the temperature remains constant for a constant pressure.)

The Mollier diagram is used to determine characteristics of steam, usually from temperature and pressure information.

STEAM TURBINE PERFORMANCE

Manufacturers' performance information is the most reliable source of data for steam turbine operating characteristics. When the data is not available the energy consumption of a particular steam turbine can be estimated using measured data and the equations that are discussed here.

Ideal/Theoretical steam rate (ISR): It is the quantity of steam that will produce a unit of shaft energy output from an ideal steam turbine having no machinery or thermal loss.

$$\text{ISR (lb/kWh)} = 3413 / (h_i - h_o)$$

Where h_i : enthalpy of inlet steam (Btu/lb), h_o : enthalpy of outlet steam (Btu/lb), 3413: conversion of Btu to kWh

Actual steam rate (ASR): It is the flow of steam required to produce a particular shaft power output.

$$\text{ASR (lb/kWh)} = f_s / W_{to}$$

Where f_s : steam flow rate (lb/hr) and W_{to} : turbine shaft power output (kW)

Heat-to-Power Ratio: It is the ratio of the amount of useful thermal energy available to the amount of electricity generated and is usually expressed in Btu/kWh. For steam turbines, the Heat-to-Power ratios usually vary from 2:1 to 15:1.

Overall Steam Turbine Efficiency (Eff_t):

It is the ratio of the ideal steam rate to the actual steam rate, $\text{Eff}_t (\%) = \text{ISR}/\text{ASR} \times 100$

Energy extracted from steam to produce shaft energy

$$Q_e \text{ (Btu/hr)} = f_s \times (h_i - h_e)$$

h_i : enthalpy of inlet steam (Btu/lb), h_e : enthalpy of outlet steam and condensate at exhaust conditions (Btu/lb)

In many turbine applications the exhaust steam contains a significant amount of condensate. Sometimes, it is necessary to separately identify the energy content of the steam and the condensate in the equation for energy extraction.

$$\text{Thus, } Q_e = (f_s \times h_i) - (f_{co} \times h_{fo}) - ((f_s - f_{co}) \times h_{go})$$

f_{co} = exhaust condensate flow rate (lb/hr)

h_{fo} = enthalpy of outlet condensate (at the saturation temperature corresponding to exhaust steam pressure, h_f from steam table)

h_{go} = enthalpy of outlet steam (at the exhaust steam saturation pressure, h_g from the steam table)

Total energy required for a steam turbine system

$$Q_t \text{ (Btu/hr)} = f_s \times (h_i - h_r) \text{ where } Q_t: \text{ total steam system input, } h_r: \text{ enthalpy of return condensate (Btu/lb)}$$

Steam supply attributable to the operation of the turbine

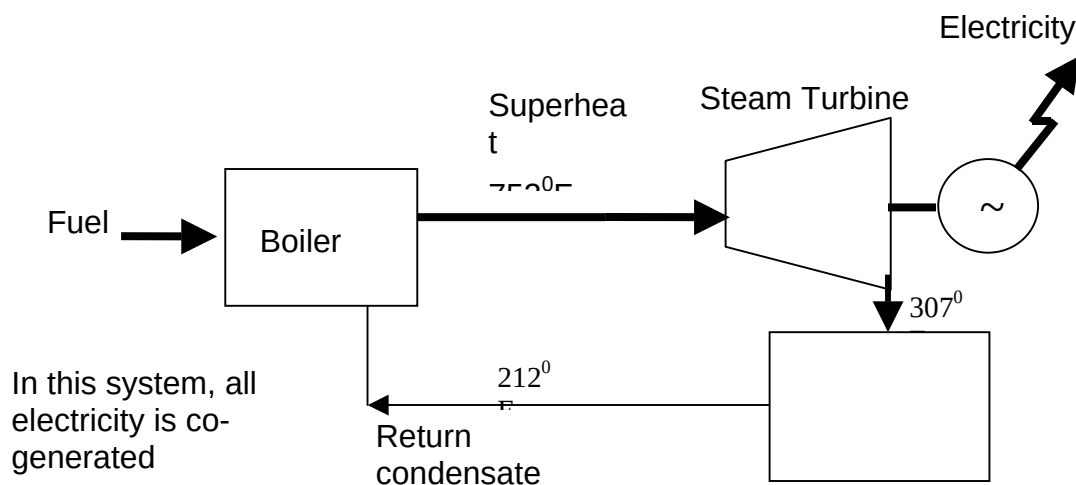
$$f_{st} = f_s \times Q_e / Q_t \text{ when all of the exhaust steam is condensed for other uses}$$

$$\text{Annual steam cost} = f_{st} \times t \times C_s$$

Where t = operation time (hr/yr) and C_s = unit steam cost (\$/lb)

STEAM TURBINE COGENERATION

An example is now carried out to illustrate the benefits of a typical steam turbine cogeneration. In it, a non-condensing turbine is used to drive a generator and reduces high pressure superheated steam to lower pressure saturated steam. The lower pressure steam is used for heating water and is condensed at 212°F. Please note that the lower pressure could be used for other purposes such as drying paper tissues.



Given:

Inlet steam pressure: 615 psi (absolute), inlet steam temperature: 752°F

Outlet steam pressure: 75 psi (absolute), outlet steam temperature: 307°F

Steam flow rate (measured): $f_s = 7289$ lb/hr, exhaust condensate flow rate (measured): $f_{co} = 218$ lb/hr

Unit steam cost, C_s : \$.01/lb, unit electrical cost, C_e : \$.08/kWh, operation time t : 8400 hr/yr

Turbine nameplate shaft power output, W_{ton} : 340 kW, turbine nameplate steam rate: 22 lb/kWh

Generator Efficiency, Eff_g : .92%, generator power output (measured): 309kW

Find:

Turbine efficiency, steam cost attributable to steam turbine, value of electricity generated and energy cost savings

Solution:

Shaft power input to generator: $309 \text{ kW} / .92 = 336 \text{ kW}$

Turbine connected to generator, drive loss negligible, turbine shaft power output, $W_{\text{to}} = 336 \text{ kW}$

To find ISR, use Mollier diagram/steam table/software, $h_i = 1378 \text{ Btu/lb}$, $h_o = 1182 \text{ Btu/lb}$

$\text{ISR} = 3413 / (1378 - 1182) = 3413 / 196 = 17.4 \text{ lb/kWh}$

$\text{ASR} = f_s / W_{\text{to}} = 7289 / 336 = 21.7 \text{ lb/kWh}$ (compared with the nameplate steam rate of 22 lb/kWh)

Overall steam turbine efficiency = $\text{ISR} / \text{ASR} = 17.4 / 21.7 \times 100 = 80\%$

$Q_t = f_s \times (h_i - h_r) = 7289 \times (1378 - 180) = 8.73 \times 10^6 \text{ Btu/hr}$ (h_r : the h_f column for 212°F condensate from steam table)

Energy extracted by the steam turbine

$Q_e = (f_s \times h_i) - (f_{\text{co}} \times h_{r,o}) - ((f_s - f_{\text{co}}) \times h_{g,o})$ (From steam table and the h_f and h_g column for 307°F steam)

$h_{r,o} = 277 \text{ Btu/lb}$, $h_{g,o} = 1182 \text{ Btu/lb}$

$Q_e = (7289 \times 1378) - (218 \times 277) - ((7289 - 218) \times 1182) = 1.63 \times 10^6 \text{ Btu/hr}$

Steam flow rate attributed to turbine: $f_{\text{st}} = f_s \times Q_e / Q_t = 7289 \times 1.63 / 8.73 = 1361 \text{ lb/hr}$

Annual steam cost of steam turbine = $f_{\text{st}} \times t \times C_s = 1361 \times 8400 \times 0.01 = \$114,324/\text{yr}$

Annual value of electricity = $W_{g,o} \times C_e \times t = 309 \times 0.08 \times 8400 = \$207,648/\text{yr}$

Annual energy cost savings = $\$207,648 - \$114,324 = \$93,324/\text{yr}$

CANADIAN CAPITAL COST ALLOWANCE (CCA) CLASS TAX 43.1

Under Class 43.1, eligible energy conservation property of qualifying systems can be written off at a 50% declining balance rate if the heat rate of the system is less than 6000 Btu/kWh. In general, qualifying systems are those that conserve energy by:

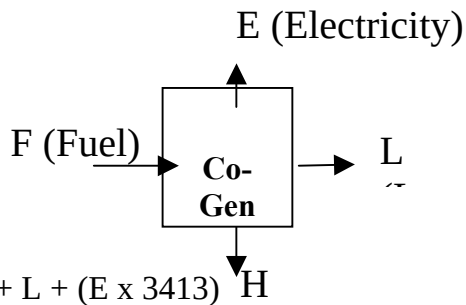
- Recovering and re-using thermal waste;
- Using specified-waste fuel;
- Using cogeneration; or
- Using renewable energy sources.

We will look at an example of natural gas fired steam turbine cogeneration, calculate the heat rate and determine the eligibility for CCA, tax class 43.1.

Doing an energy balance as illustrated below, we can determine the equations which can be used to calculate the heat rates:

Energy Balance, cont'd

Energy Balance

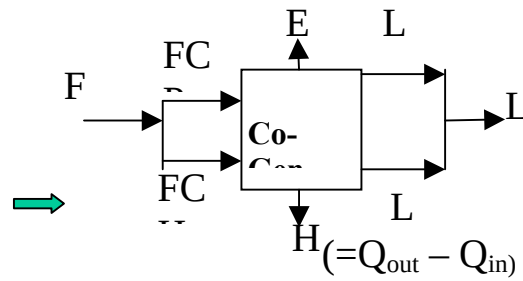


F: Fuel, BTU/yr

H: Heat

L: Loss

E: Electricity



FCP: Fuel chargeable to electricity

FCH: Fuel chargeable to heat

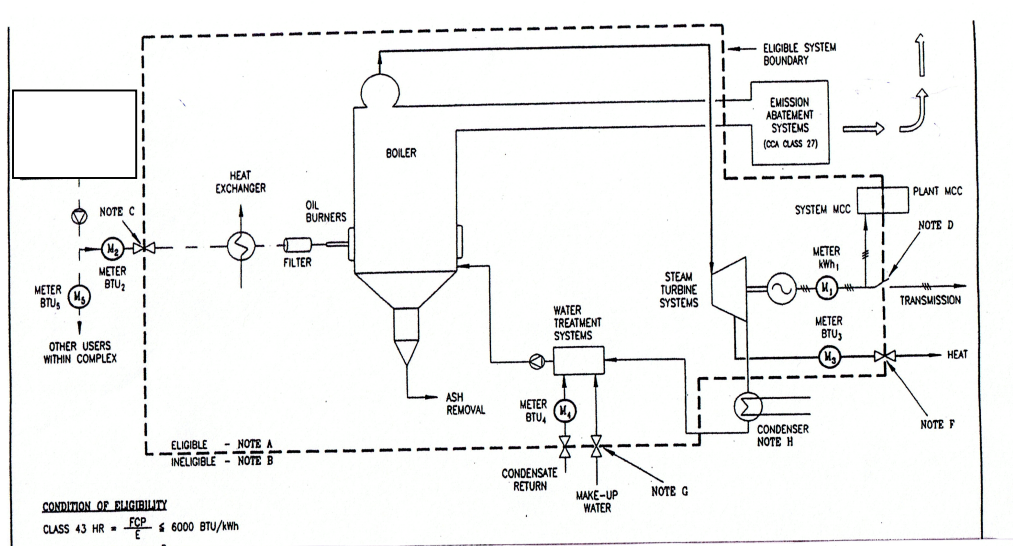
 L_E : Loss chargeable to electricity L_H : Loss chargeable to heat

UNV Basic

Therefore:

- $FCP = (E \times 3413) + L_E = F - H - L_H$, $L = F - (E \times 3413) - H = L_E + L_H$
- $L_E = L \times (E \times 3413) / (E \times 3413) + H$, $L_H = L \times H / (E \times 3413) + H$

Definition of Heat Rate = $FCP/E = F / (E + (H/3413))$ **If it is ≤ 6000 Btu/kWh then the system is eligible under 43.1****Example, gas fired, steam turbine cogeneration system**



Determine 43.1 Eligibility for the above co-gen system

Given: $M_1 = 543 \times 10^6$ kWh, $M_2 = 4740 \times 10^9$ Btu, $M_3 = 974 \times 10^9$ Btu, $M_4 = 68 \times 10^9$ Btu

Where M: meter

$E = 543 \times 10^6$ kWh (M_1), $H = M_3 - M_4 = 906 \times 10^9$ Btu, $F = 4740 \times 10^9$ Btu (M_2)

43.1 Eligibility = $F / (E + H/3413) = 4740 / .81 = 5852$ Btu/kWh (Yes)

Or

$L = F - (E \times 3413) - H = 1981 \times 10^9$ Btu, $L_H = L \times H / (E \times 3413) + H = 650 \times 10^9$ Btu, $FCP = F - H - L_H = 3184 \times 10^9$ Btu

43.1 Eligibility = $FCP/E = 3184/543 = 5860$ Btu/kWh (Agreed with the previous answer with round-off)

CONCLUSION

Steam turbines are the most common cogeneration system used in industrial applications, particularly in the pulp and paper sector (because there is a significant amount of wood residue and other biomass available as input fuel) and some in the oil sand sector with steam coming from boilers burning petroleum coke. Steam turbines are very flexible because the steam that drives the turbine is produced in a typical industrial boiler which is easily modified to burn virtually any type of fuel, including waste fuels such as pulping liquor, landfill gas, forest residue and other biomass. Steam turbine system is robust because there are very few moving parts and is easy to maintain. As we have seen previously, steam turbine performance analysis is straightforward to carry out with very simple tools.

Steam turbine cogeneration systems usually produce significantly more heat than electricity per unit of fuel consumed and therefore have high heat-to-power ratios. Steam turbines come in two types, back-pressure turbines and condensing turbines. Back-pressure turbine is used when the exhaust steam is needed for other processes such as drying papers or heating water and condensing turbine is employed when the operator wants to maximize the work done by the turbine such as producing more electricity. Therefore, when selecting the turbine type during the design stage, the operator needs to consider the future duty performed by the turbine carefully.

It is estimated that the existing CHP in Canada is responsible for a reduction of at least 15Mt of GHG emissions and significant reduction in other air pollutants as well if the electricity produced by cogeneration were produced by stand-alone plants. As mentioned earlier, CHP has other benefits including increasing electricity supply security and reducing energy

costs through increased efficiency. It is for these same benefits that the European Union (EU) has encouraged its member states to double the amount of CHP by 2010, from 9% of total electric capacity to 18% (EU Commission 1997). In the US, government agencies and industry groups have been trying to double CHP by the same year from 55 GW to 110 GW (US CHP Association 2001).

In its 2005 budget, the Canadian federal government signaled its intention to encourage more CHP by increasing the CCA tax deduction from 30% to 50% on a declining balance basis. In addition to the attractive CCA rate, the payback period for implementing a steam turbine cogeneration project might be as short as 3 years depending on the difference between the local steam and electricity price. As market penetration of CHP in Canada is much smaller compared to that of the EU and the price of fossil energy has stayed very high (US\$85-\$90/barrel of oil) in 2007-2008, there is a lot of opportunity to implement CHP in Canada. The more successful CHP projects we have, the more benefits everyone (stakeholder, the community, the government and the environment) will gain.

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