Optimize energy efficiency of HRSG

With a better understanding of temperature profiles, plant engineers can increase steam production and minimize losses

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When optimizing the efficiency of heat-recovery steam generators (HRSGS,) fully understanding the temperature profiles of these units is crucial. Gas turbine HRSGS are unique and pose peculiar problems as compared to conventional gas/oil-fired boilers when calculating efficiency or steam output. For conventional oil/gas-fired steam generators or boilers, one can do heat balances, efficiency calculations and fuel estimates by assuming an exit-gas temperature of 300°F to 340°F from the steam generator and assuming that the feedwater is at 220°F to 250°F irrespective of steam pressure. However, these assumptions are often not thermodynamically valid with HRSGS. Energy recovered in a HRSG or the exit-gas temperature from a HRSG is a function of several variables including:

- Gas inlet temperature to the HRSG
- Steam pressure
- Steam temperature
- How the heat recovery surfaces are arranged
- Number of steam pressure levels
- Pinch and approach points.

The reasons are:

- Low gas-inlet temperature to HRSGS (900°F-1,100°F in unfired mode compared to the adiabatic combustion temperature of around 3,300°F in oil/gas-fired steam generators)
- Large ratio of exhaust gas flow to steam generation in unfired mode (about 6 vs. 1.1 in conventional steam generators)
- How gas-to-steam flow ratios change with steam generation.

In conventional steam generators, the ratio of gas-to-steam flow does not change with steam generation. While in gas turbine HRSGS, the exhaust gas flow remains nearly constant irrespective of steam generation, which affects the gas/steam temperature profiles significantly. Several methods can be used to understand HRSG temperature profiles and offer ways to improve operating efficiency or energy recovery.

Pinch and approach points determine HRSG gas/steam temperature profiles. In a typical HRSG, the gas and steam temperature profiles are dictated by the design values for pinch and approach points. Fig 1 shows the gas/steam temperature profiles in a simple HRSG consisting of a superheater, evaporator and economizer.

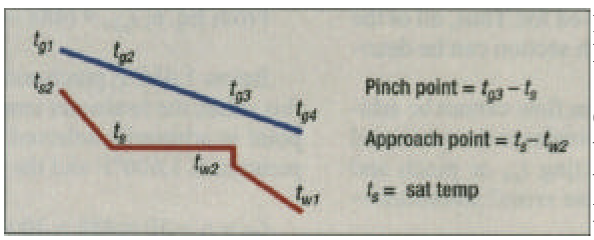

Fig. 1. Pinch and approach points in a simple HRSG.

Arbitrary selecting the exit-gas temperature or pinch and approach points to estimate steam generation can be faulty and cause "temperature cross."

For example, assume that the gas flow, inlet-gas temperature, desired steam temperature and feedwater temperature in the design case are known. Assuming a modest pressure drop in the superheater,then the drum pressure and saturated steam temperature can be derived steam tables. The pinch and approach points are set in the design mode. (For the off design case pinch/approach points and steam flow, an evaluation of the HRSG performance must be done using iterative procedures where: 1,2

Pinch point (PP) = gas temperature leaving evaporator-saturation temperature--(t_{g3}-ts)Approach point (AP) =saturation temperature-water temperature leaving economizer(ts - tw2).By assuming a nominal pinch point (10°F to 30°F in unfired mode) and a similar value for the approach point, the amount of steam generated in the HRSG may be calculated as:

t_{g3} = ts + PP tw_2 = ts -AP

The energy absorbed by superheater and evaporator, Q12, is given by:

Q12 = Wg xCpg x (tg1-tg3)xhl = Ws x (hs2 - hw2)

where: Wg = gas flow, lb/h

Cpg = gas specific heat at the average gas temperature, Btu/lb F

Tg1,tg2,tg3,tg4= gas temperature at various locations as shown, °F

W_S = steam flow, lb/h

hs2, hw2 = enthalpy of steam at superheater exit and water at economizer exit, Btu/lb°F hl= heat loss factor, typically 0.99 to 0.995. From Eq. 1, Q12 and then the steam flow, Ws, may be calculated. In Eq. 1, blow down was neglected.

If we consider the energy absorbed in the superheater,Q1

Q1=WgxCpgx(tg1-tg2)= Ws x (hs2 - hv) (2)

Fig. 2. O-type Fired HRSG with water-cooled furnace.

where hv = saturated steam enthalpy, Btu/lb

Since the right hand side of Eq. 2 is known, Q1 is known, then the only unknown is the gas temperature leaving the superheater, tg2,which may be solved for. Since Q12 is known from Eq. 1, then Q2 = energy absorbed in the evaporator-Q12-Q1.

Now from the economizer energy balance, the energy absorbed Q3 is given by:

$$Q3 = Wg \times Cpg \times (tg3\text{-}tg4)\, hl = Ws(hw2\text{-}hw1) \qquad (3)$$

where hw1 = enthalpy of feed water in, Btu/lb.

The unknown is tg4,which can be solved for. Thus, all of the gas/steam temperatures and duty in each section can be determined along with the steam generation.

The exit gas temperature, tg4 or steam flow cannot be arbitrarily assumed in a HRSG. An analysis similar to that presented should be performed. Arbitrarily selecting tg4 or pinch and approach points can lead to "temperature cross" situations an undesirable condition.

Never arbitrarily assume pinch and approach points. The overall energy transferred is:

$$Q13 = Wg \times Cpg \times (tg1\text{-}tg4) \times hl = W_S \times (hs2 - hw1) \qquad (4)$$

From Eqs. 1 and 4, we have

$$(tg1\text{-}tg3)/(tg1\text{-}tg4) = (hs2 - hw2/(hs2 - hw1) = K \qquad (5)$$

This equation neglects small variations in gas specific heats. K is a function of steam/water properties and is nearly a constant for given steam/water conditions. For steam generation to occur, two conditions must be met:

tg3>ts and tg4>tw1

If the pinch or the approach point is arbitrarily selected, then there is a high probability that tg4 can be lower than tw1 or tg3 is lower than ts. The lowest limit for tg3 is ts and for tg4 is tw1. Substituting these conditions into Eq. 5 and calling the tg1 as tg1c, we have:

$$(tglc\text{-}ts)/(tglc\text{-}twl)=K \text{ or } tglc=(ts\text{-}Ktwl)/(l\text{-}K) \qquad (6)$$

For gas-inlet temperatures greater than tglc, the feedwater temperature limits the temperature profile. For values below tglc, the pinch point governs the temperature profile. Now let us illustrate these issues using a few examples.

Table 1. Suggested pinch and approach points

Item	Pinch point, °F		Approach point, °F
Evaporator type	Bare	Finned	
Gas in: 1,200–1,800°F	130–150	30–60	40–70
750–1,200	80–130	10–30	10–40

Table 2. Effect of steam parameters on exit-gas temperature

Steam pr, psia	Steam temp, °F	Saturation temp, °F	K	Exit gas temp, °F
100	338	338	0.904	300
150	366	366	0.8754	313
250	406	406	0.8337	332
400	448	448	0.7895	353
400	600	450	0.8063	367
600	490	490	0.74	375
600	750	492	0.7728	398

[Pinch point = 20°F, approach = 15°F, feedwater = 230°F, gas inlet = 900°F]

Example 1. Assume the steam pressure in a HRSG = 585 psig; steam temperature = 700°F; feedwater temperature = 250°F. Let the approach temperature = 20°F, ts. = 488° F, tw2 = 468°F. From steam tables, hs2 = 1351.8, hw1 = 219.5 and hw2 = 450.7 Btu/lb.

From Eq. 5, K = (1351.8 -450.7)/(1351.8 - 219.5) = 0.796
From Eq. 6, tglc = (488 -.796 x 250)/(1 -.796) = 1,416°F.

Below 1,416°F, pinch point determines the profile and above this value, the feedwater temperature sets the profile. If a pinch point is arbitrarily selected, let us assume that gas-inlet temperature is 1,600°F and the pinch point is a 30°F:

Tg3=ts+30=488+30=518°F

From Eq. 5, then:
(1600 - 518)/(1600 – tg4) = 0.796 or tg4 = 240°F, which is below the 250°F feedwater temperature; thus, not a feasible profile. However, if we used a lower tw2 or higher K, it may work out. Assume tw2 = 400°F and K = 0.862, or tg4 = 345°F, which is feasible.

Example 2. Assume the exit-gas temperature = 290°F. From Eq. 5, then:
(1600 – tg3)/(1600 - 290) = 0.796 or tg3 = 557°F or pinch is (557 - 488) = 69°F, which is feasible.

Example 3. Assume tg1 = 900°F and pinch point = 20°F, then: (900 - 508)/(900 – tg4) = 0.796 or tg4 = 408°F, which is feasible.

Example 4. Assume an entry temperature of 900°F and an exit-gas temperature = 300°F. Is it feasible?
(900 – tg3)/(900 - 300) = 0.796 or tg3 = 422°F, which is below ts and thus, not feasible.

Arbitrarily fixing the exit gas temperature in a single-pressure HRSG to determine the possible steam generation is not a good idea. Table 1 suggests typical pinch and approach points to be used in waste-heat boilers. A detailed evaluation should be done to confirm these assumptions of pinch and approach points. Also, in off-design modes, the pinch and approach points must be determined through complex iterative calculations. Also, it is a good idea to select pinch and approach

Table 3. Effect of lower pinch and approach points on HRSG performance

Item	Unfired A	Fired A	Unfired B	Fired B
Gas flow, lb/h	150,000	150,000	150,000	150,000
Gas temp to evap, °F	900	1086	900	1,062
Gas temp to eco, °F	407	419	388	393
Stack temp, °F	332	329	309	302
Gas pr drop, in. WC	4.2	4.6	5.4	5.8
Steam flow, lb/h (150 psig)	22,107	30,000	22,985	30,000
Feedwater temp, °F	230	230	230	230
Wat temp to evap, °F	351	337	352	340
Boiler duty, MM Btu/h	22.1	30.0	22.99	30.0
Burner duty, MM btu/h	0	8.1	0	6.9
Surf area, evap, ft^2	13,227	13,227	16,534	16,534
Surf area, eco, ft^2	5,948	5,948	8,922	8,922
Pinch point, °F	41	53	22	27
Approach point, °F	15	29	14	26

Table 4. Inlet gas temperature vs steam generation

System	Gas inlet temp, °F	Gas/steam ratio
Unfired	800–1,000	5.5 to 7
Supplementary fired	1,000–1,700	2.5 to 5.5
Furnace fired	1,700–3,000	1.2 to 2.5

points for the HRSG evaporator in unfired mode since firing introduces uncertainty and possible temperature cross situations.

EFFECT OF STEAM PRESSURE AND TEMPERATURE

Steam pressure and temperature impacts the exit gas temperature, and hence, the steam generation.

Table 2 shows the effects of steam pressure and temperature on exit-gas temperature in an unfired gas turbine HRSG. Some observations are:

The higher the steam pressure, the higher the exit-gas temperature. The saturation temperature is greater at higher pressures; thus, the gas temperature, tg3, leaving the evaporator is higher with less steam generation as compared to lower steam pressure case. Steam generation is proportional to (tg1-tg3). With less steam generated, the water flow through the economizer is lower and the heat recovery potential is also reduced. From Eq. 3, tg3 is fixed by assuming a pinch point. Q3, the economizer duty, is smaller, but tg4 is higher as shown in Eq. 3.

Higher the steam temperature (for the same pressure), the higher the exit gas temperature. Less steam is generated in the evaporator as shown by Eq. 1. If the enthalpy absorbed by steam is higher (as with superheated steam), less is generated, which results in higher tg4. This is the reason for the lower exit gas temperature with saturated steam in Table 2. With less steam and less water flowing through the economizer, Q3 is smaller, which causes less heat recovery and higher exit-gas temperatures.

Exit-gas temperature cannot be arbitrarily assumed or determined. If someone had assumed a 300°F exit gas for the last case of 600 psig, 750°F steam, and determined the steam generation, the error would be very significant, about 17%. Also, it is not thermodynamically feasible. The author has seen inexperienced engineers still do this. HRSG simulation methods (as discussed previously for the design case) must be used to determine gas/steam profiles and steam generation. 1,2

Energy-recovery calculations for HRSGs should be done with the methods previously described since arbitrary assumptions can lead to errors.

Improving energy recovery by lowering pinch and approach points. With these procedures to evaluate HRSG temperature profiles, let us investigate how to improve a typical HRSG.

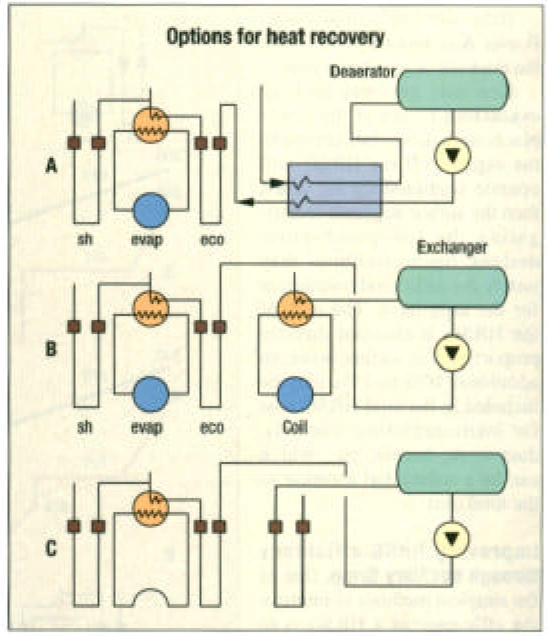

Fig. 3. Options for additional energy recovery in HRSGs.

Several methods are available. One method to optimize energy recovered or lower exit-gas temperature is reducing the design pinch and approach points when thermodynamically feasible. Lower pinch and approach point imply that the log-mean temperature difference in the evaporator and economizer would be reduced and hence more heating surfaces would be required; thus adding to the total cost of the HRSG. A techno-economic evaluation may be done based on operating hours to see if the lower pinch/approach point design is worth it.

Table 3 lists operating conditions of a HRSG for a 4500-Kw gas turbine generating 150-psig saturated steam. It was designed with a large pinch/approach point in the unfired mode (Case A) and with smaller pinch and approach points in Case B. For these two design basis, the performance is also verified in the fired mode, when 30,000-lb/h of steam is required. It is obvious that in Case A, the firing temperature will be higher; thus more fuel is consumed. Also due to the larger surface areas of evaporator and economizer in Case B, the gas pressure drop across the HRSG will also be higher than in Case A. In this example, assume:

Fuel cost = $5/MM Btu/ h Cost of steam = $4/1,000 lb
Electricity = 7c/kwh.

Also assume an additional 4 in. WC in the HRSG, which equals 1.1 % decrease in gas turbine power output of nominal 4500 Kw. Assume 8,000 hours of operation annually with 50% of the time in unfired and fired modes. The following simplistic evaluation may be done. Design B has an edge over design A in terms of operating costs:

Higher steam generation in unfired mode: (22,985 - 22,107) x 4 x 4,000/1,000 = $14,048 • Higher fuel consumption in fired mode:

(8.1 - 6.9) x 5 x 4,000 = $ 24,000 •

Higher gas per drop of 1.2 in WC:

1.2 x 4,500 x 0.07 x 8,000 x 1.1/(4 x 100) =-$8,316 The net benefit of design B over A = $(14,048 + 24,000 - 8,316)=$29,732/yr.

If the additional cost of Design B over A is about $30,000, then the payback is about one year.

One may perform such an evaluation to see if the lower pinch/approach points are worth the expense. If the HRSG will operate continuously for years, then the author suggests investigating the low-pinch-point designs. Such conditions may justify the additional investment for the long-term. The cost of the HRSG is also not directly proportional to surface areas; an additional 10% to 15% may be included in the total HRSG cost for instrumentation, controls, duct work, burner, etc., which can be a substantial increase to the total cost.

Improving HRSG efficiency through auxiliary firing. One of the simplest methods to improve the efficiency of a HRSG is to increase the steam output through supplementary firing. Unlike conventional steam generators where the ratio of gas-to-steam flow remains nearly constant at all loads, the ratio varies for a HRSG as shown in Table 4.

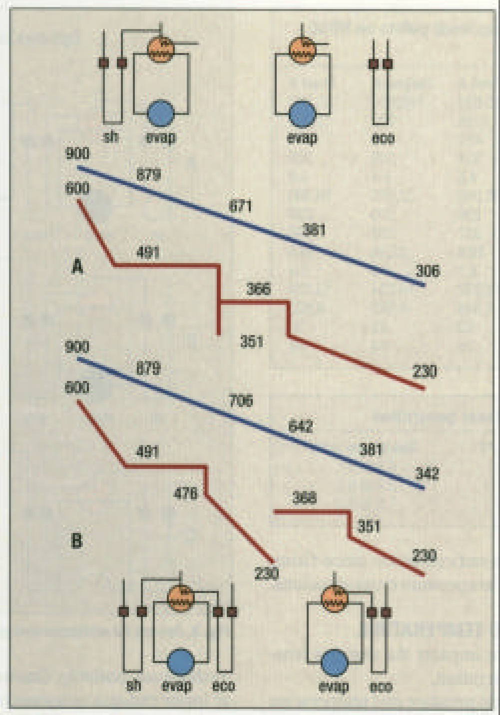

Fig. 4. Optimization of temperature profiles by rearranging surfaces.

The additional HRSG duty between unfired and fired case is 7 MM Btu/h in case B. We only used 6.9 MM Btu/ h (LHV) as fuel input. Thus, it is more than 100% efficient. Plant engineers should always think of increasing steam generation in cogeneration plants by auxiliary firing in HRSGs. The efficiency is much higher than in steam generators, which typically have an efficiency of 93% (LHV basis) for natural-gas firing. Thus, fuel utilization is improved by 6% to 7% when compared to regular steam generators.

• In conventional plant steam generators when excess air is increased, the losses increase and efficiency is reduced. In HRSGs, auxiliary firing cuts excess air requirements. The oxygen levels in the exhaust gas are lowered and the efficiency is improved.

Improve efficiency by adding secondary surfaces. By adding secondary surfaces such as condensate heater or deaerator coil or a feedwater exchanger, as shown

Auxiliary firing without additional air is feasible in HRSGs since the typical exhaust contains 13 to 15 vol% oxygen. The relation between oxygen content in exhaust gas and fuel consumption is shown in Eq. 7:[1,2]

$$Q = 58.4 \times 10^{-6} W_g O \quad (7)$$

where: Q = fuel input (oil/natural gas) in MMBtu/h on LHV basis (lower heating value) Wg = exhaust gas flow, lb/h

O = vol% oxygen consumed.

Example: If the exhaust gas is at 900°F and must be raised to 2,000°F, then the fuel input required = Wg x 0.31 x (2000 - 900) x 10^{-6} MMBtu/h. Equating with Eq. 7,we have:

O = 5.83 vol%. If we started with 15 vol% oxygen, we would end up with about 9 vol%; thus, there is excess oxygen in the exhaust gases.

Gas turbine HRSGs, which are free oxygen at 14 to 15 vol%, can easily fire up to about 3,000°E The HRSG design would require water-cooled membrane walls beyond 1,700°E Fig. 2 shows a HRSG firing to 2,300°E It consists of an 0-type boiler with water-cooled furnace section followed by a screen section, superheaters, convection bank and economizer.

Fired HRSGS are efficient because:

• When additional fuel is fired, air is not generally added. This reduces the exit gas losses and improves the HRSG efficiency. More steam is generated with less heat losses from exhaust gases.

• With a single-pressure HRSG, the steam flow is higher with firing; the economizer acts as a larger heat sink and lowers the exit-gas temperature as compared to unfired case (see Table 3).

in Fig 3 below, more energy can be recovered from the exhaust gases. These options reduce the amount of steam required for deaeration by preheating the makeup or generating low-pressure (LP) steam. Corrosion may occur in the economizer or condensate heater when fuel oils are fired and should be investigated.

Optimize efficiency through temperature profiles. With multiple pressure HRSGs, it is possible to relocate the heating surfaces and lower the exit-gas temperature and generate more steam. Fig 5 shows two options for generating high-pressure (HP) steam and LP steam in a HRSG. System conditions are: Gas flow = 500,000 lb/h

Exhaust-gas temperature = 900°F Gas analysis = vol%-CO_2 = 3, H_2O = 7, N_2 = 75, O_2 = 15 HP steam = 31,500 lb/h at 600 psig, 600°F

LP steam: maximum in unfired mode at 150-psig sat
Feedwater = 230°F
Assume heat loss = 1%.

Using HRSG simulation methods, two options were studied as shown in Fig. 4. In Case A, the HP stage is followed by the LP evaporator with a common economizer feeding both the evaporators.

In Case B, the HP stage is followed by the LP stage each with own individual economizer.

In Case A, the common economizer has a larger water flow (equal to the sum of the steam flows in HP and LP stages.) Result: A much larger heat sink and the gas temperature is 306°F and is much lower than Case B, which is 342°F. More steam is generated in case 6. The LP steam is 43,450 lb/h in Case A vs. 39,000 lb/h in Case B while the HP steam is 31,500 lb/h in both cases.

Rearranging the heating surfaces or relocating the surfaces can improve the gas/steam temperature profiles, particularly with multiple pressure steam generation. HRSG simulation-program developed by the author-can be used to study complex multiple pressure unfired or fired HRSGs.[1,2]

Overview. HRSG efficiency can be improved by several methods. One can use any or the entire presented methods on a HRSG project. Plant engineers must understand the significance of HRSG temperature profiles. One must also look at the cost implications and the period of operation to justify any additional expense. With HRSGs being used widely in cogeneration and combined cycle plants, a consideration for all of the presented methods will assist when optimizing the total plant efficiency.

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