IMPROVING CHP CYCLE WITH ONCE THROUGH STEAM GENERATORS AND ADVANCED MATERIAL SELECTION

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INTRODUCTION

An improvement in the cycle efficiency, or heat rate, has always been a target for CHP plant developers, owners and designers. Lately, we are observing considerable improvements in the efficiency of all major plant components. This has been achieved through the use of modern design tools, computer modeling, new and advanced multi censoring tools and implementation of improved and advanced materials. A heat recovery steam generator (HRSG) still provides an opportunity for improved efficiency by lowering the exhaust gas temperature exiting the system.

Condensate temperature for a moderately efficient plant would be too low for direct introduction into a conventional HRSG due to material restrictions. A Once Through Steam Generator (OTSG) with its alloy tubing allows the introduction of this cold feedwater. High nickel alloys have superior properties with respect to general corrosion and stress-corrosion cracking, which are the main limiting factors in HRSG cold end design and material selection, along with tube fin and liner material. SB423 NO8825, commercially known as Incoloy Alloy 825, offers unsurpassed properties and allows the acceptance of cold feedwater in the economizer section of an HRSG.

In addition to cold end recovery, this material allows dry running operation up to 538 °C and provided that all other boiler components are appropriately selected, allows a simplified boiler design with an increased efficiency.

The usage of advanced materials adds to the capital cost of an HRSG. However, an adequate and thorough evaluation proves that this investment pays for itself. The last decade has allowed IST to generate an impressive operational record in plants where cold feedwater, deaerated under vacuum, and advanced tubing material has been used. IST's experience confirms all advanced properties claimed by their manufacturers.

Refer to the following examples that will illustrate the impact of the exiting flue gas temperature on the HRSG efficiency. Note that the gas turbine and steam parameters used for this illustration have been arbitrarily selected. The gas turbine data that we used were not obtained from any gas turbine manufacturer, but each manufacturer can easily achieve the exhaust data that have been used. In order to secure the consistency, for each example we have used the same steam parameters. The flue gas pressure drop variation has been kept within 1 mbar to assure that the plant efficiency will not be affected. The HRSGs that were used in these examples were not entirely optimized in its design. One may argue that for the cases were hot feedwater was used, a small rearrangement of the heating surface would result in a higher HRSG efficiency. We have simulated a few different arrangements and the efficiency gain was negligible/minimal. The considered cases and designs will be sufficient to illustrate the point. In these exercises we have not considered supplementary firing, which would magnify the difference in the HRSG efficiency.

The HRSG efficiency has been calculated as per ASME PTC 4.4 using the input/output method. Therein, the input is defined as the total sensible heat supplied by the exhaust flow from the gas turbine. Output is defined as the heat absorbed by the working fluid. The main postulate of this method is that it takes into consideration the exhaust gas enthalpy at the reference temperature (5C these examples).

The following gas turbine data have been used:
Exhaust mass flow = 130 kg/s
Exhaust temperature = 530 °C
Exhaust composition: typical for today's gas turbines operating on natural gas

Steam data: as per the Table 1

Table 1	HP steam	LP steam
Steam pressure (bara)	60	6
Steam temperature (°C)	485	210

Feedwater (FW) temperature: 35°C for cold FW or 105°C for hot FW.

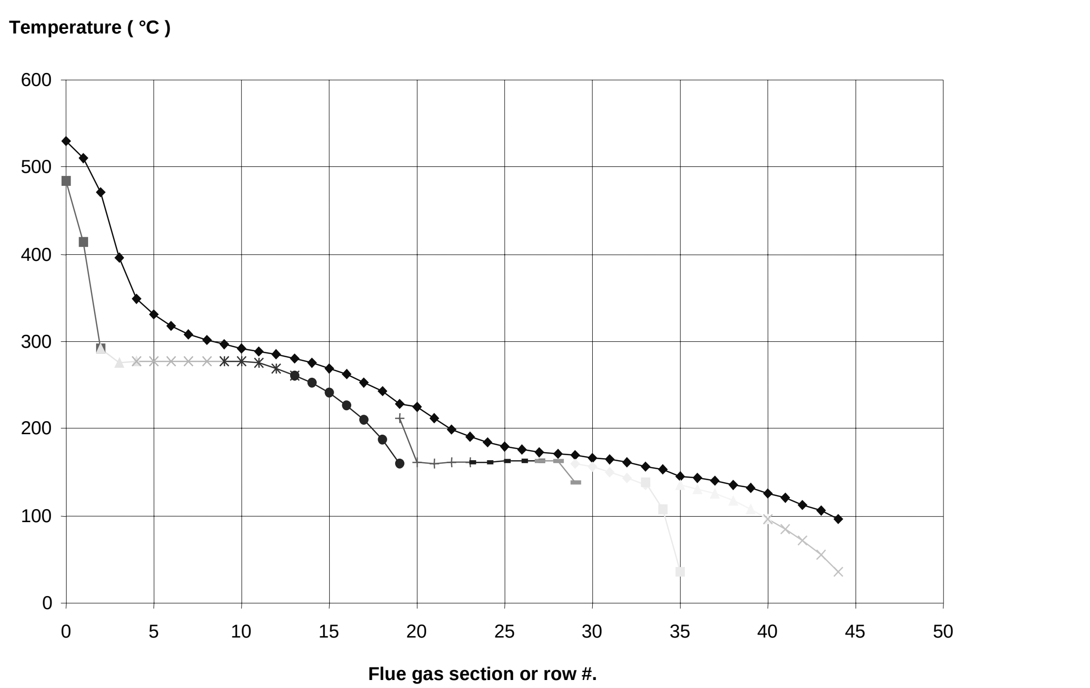
A short description of the OTSG that was used for this illustration/analysis:

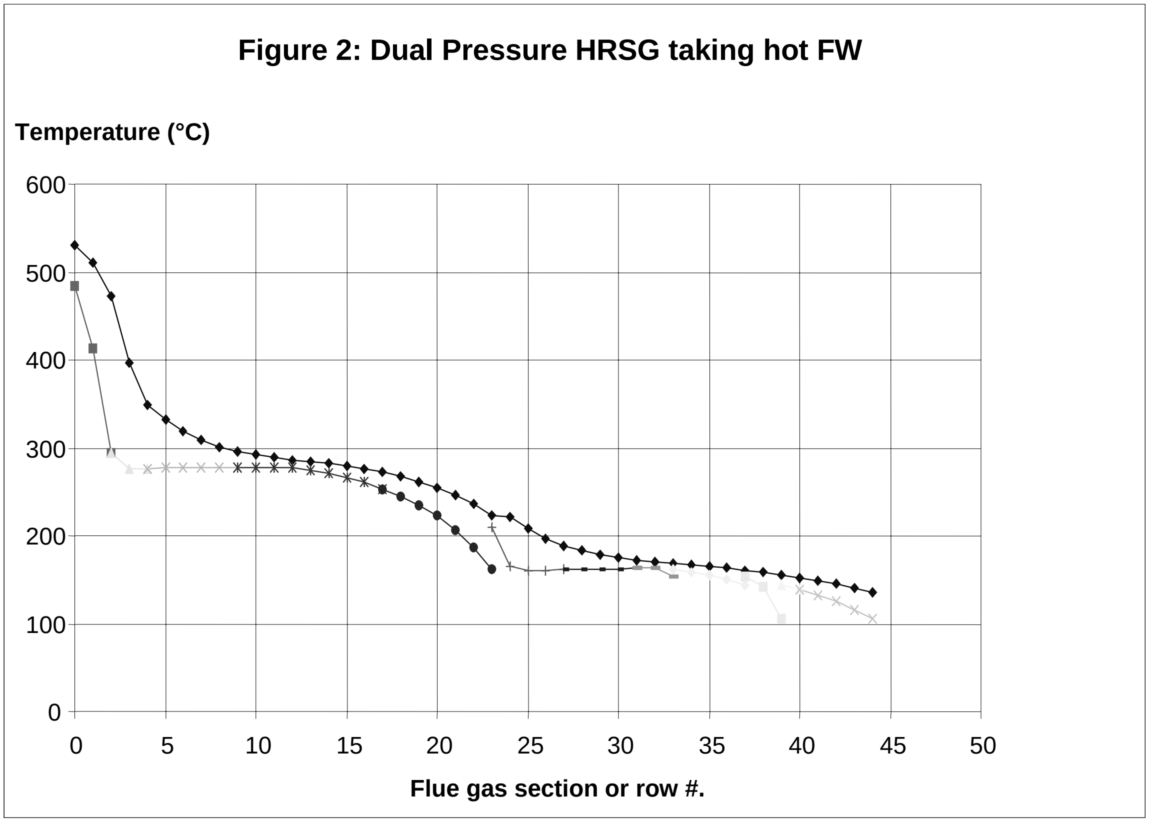
In an OTSG, preheating, evaporation and superheating consecutively take place in a series of long continuous finned tubes joined with u-bends forming a serpentine circuit. For a multiple pressure unit, like those considered in this illustration, the HP and LP heating surfaces have been divided in bundles and those bundles are intertwined or nested allowing different pressure level sections of the OTSG to be located in the optimum gas temperature zone for best performance.

Since an OTSG has no distinct heating surface division as a conventional drum type HRSG, all references to an economizer, evaporator or superheater have been used for an ease of the description. Different GT loads and steam demands will result in different size of OTSG sections. From the Figures it is clear that the OTSG's evaporator, economizer and superheater size fairly matches those seen in a conventional HRSG. During the start-up, transients, or off design operation, the OTSG's geometry will be self-adjusted. For example, at reduced loads or at startups, the entire heating surface can act as a superheater. This inherited feature offers a tremendous operational flexibility.

The material selection and its properties will be described in more details in the following section of this paper, but for now, let's just recognize that for each boiler section an appropriate material has been selected. The blue line in the temperature profile on each figure presents a flue gas and it has been provided for each heating surface row. Any change in water/steam line fonts or colors is reflective of some change in the heating surface adjustments like: tube diameter and or material, fin material and pitch and tubing pitch.

Figure 1: Dual Pressure HRSG taking cold FW





The same graphs for a single pressure HRSG are provided as well. The same trend in boiler efficiency in regards to the stack temperature will be observed. However, this option should illustrate the efficiency drop for a single versus dual pressure HRSG. Again, the same gas turbine and steam parameters have been kept. The single pressure unit has the same heating surface as the HP bundle of the dual pressure HRSG. The heating surface has been adjusted to have the same flue gas pressure drop as the dual pressure boiler. Stainless steel fins in the economizer section have been substituted with the carbon steel for a more efficient heat transfer.

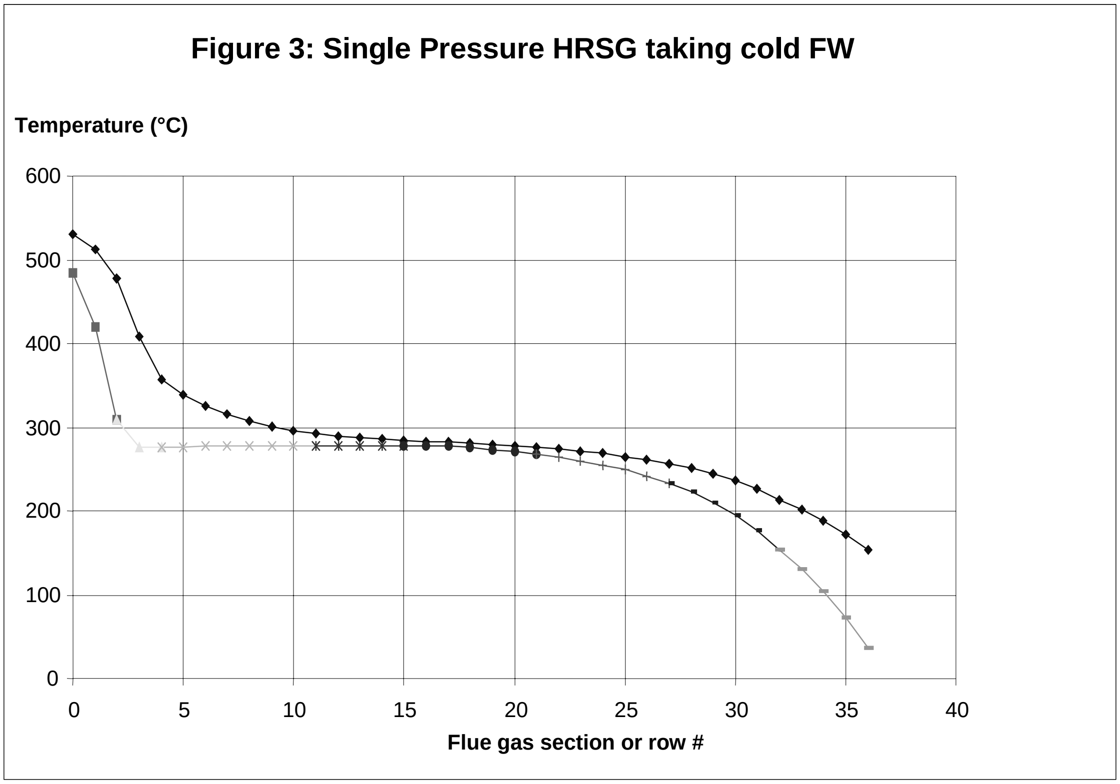


Figure 3: Single Pressure HRSG taking cold FW
Temperature (°C)
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
Flue gas section or row #

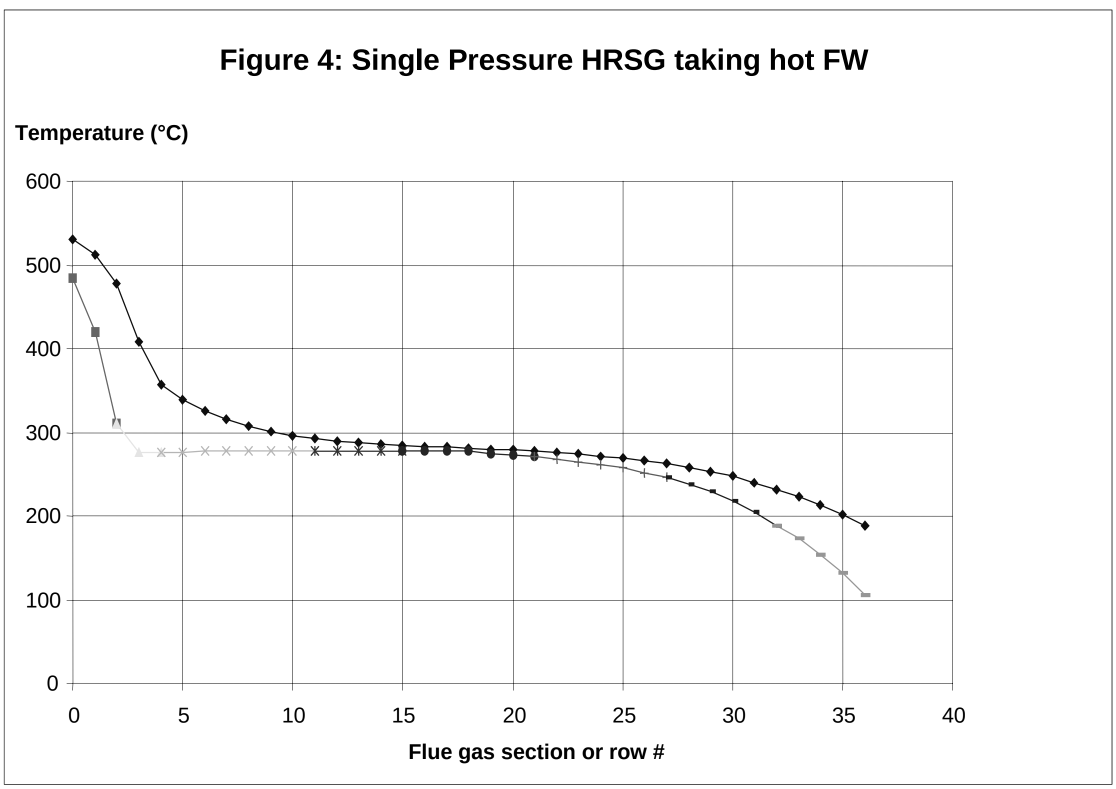


Figure 4: Single Pressure HRSG taking hot FW
Temperature (°C)
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
Flue gas section or row #

Table 2				
	HP steam mass flow (kg/s)	LP steam mass flow (kg/s)	Exit flue gas temperature (°C)	OTSG Efficiency (%)
Dual pressure OTSG with FW @ 35°C (as per Figure 1)	16.25	3.60	95	84.74
Dual pressure OTSG with FW @ 105°C (as per Figure 2)	16.27	3.80	134	79.06
Single pressure OTSG with FW @ 35°C (as per Figure 3)	16.81	0	154	73.74
Single pressure OTSG with FW @ 105°C (as per Figure 4)	16.84	0	188	67.21

The effect of the cold feedwater and corresponding OTSG efficiency is evident from Table 2. It should be noted that the flue gas temperature has been reduced simply by the introduction of cold feedwater directly into the OTSG. Other methods for a reduction of the stack temperature like: a separate condensate heater in the cold and of an HRSG, integral deaerator coil, and external heat exchanger are used in today's industry but each method increases complexity of the unit. It also brings the operational parameters to the point where a corrosion concern is legitimate and has to be carefully evaluated. Even for an HRSG coupled with a gas turbine burning only natural gas, corrosion problems have been observed with reduced flue gas temperature due to operation close to or below the water dew point with small traces of sulfur in the fuel. It appears that despite all design features and operational "tricks" corrosion problems are hardly unavoidable with conventional boiler material selection.

Today's market offers more advanced materials whose properties can handle a reduced temperature in the cold end of an HRSG eliminating all corrosion problems. Obviously the selection of these advanced materials will have an impact on the cost of the unit. It has been evaluated and proven by a multiple analyses that an increased cost that is coupled with increased efficiency may well be worth the effort. The same applies for an increased efficiency coupled with an increased reliability and availability due to reduction or elimination of the repair and/or replacement of some crucial boiler components.

IST's OTSG Tubing material selection

The 800 series of alloy was developed in the 1950's by Inco Alloys International. The alloys were developed to deliver high strength at elevated temperatures while maintaining good manufacturing characteristics and outstanding corrosion properties. Unlike many alloy materials, Incoloy is not difficult to weld, cold work or machine.

Incoloy is used in several industries where high temperatures are combined with the presence of corrosive or dangerous environments. Examples of applications that use Incoloy are chemical processing, radioactive waste handling and high temperature furnaces.

IST has used alloy 800 and 825 exclusively for pressure part tubing with outstanding results for more than 20 years. IST has amassed over 3,000,000 Incoloy operating hours on it's fleet of Once Through Steam Generators. The materials have been used in a wide range of HRSG environmental, exhaust and water/steam conditions. Incoloy has proven to be especially dependable and robust when factors such as sulphur containing liquid fuels, ammonia salts from SCRs or condensing environments are part of the HRSG design.

The Incoloy alloys are created using a unique metallurgical composition. The main component of the alloys is nickel. Nickel has a high corrosion resistance. According to the electrochemical series, nickel is more noble than iron which provides outstanding corrosion properties in a reducing environment. By adding chromium to the alloy, the corrosion resistance in an oxidizing environment is increased, resulting in an alloy that shows excellent resistance in a wide range of corrosive environments.

Table 3	Ni	Cr	Mo	Fe	Cu	C	Al	Ti
Incoloy 800	32.5	21	-	46	0.4	0.05	0.2	0.3
Incoloy 825	42	21.5	3	28	2	-	0.2	0.9

Table 3 - Nominal Chemical Compositions (% Weight)

For ease of recognition and some useful data of the mentioned alloys we have provided DIN names in Table 4.

ASME Material	SB407 NO8800 CW /Annealed	SB423 NO8825 CW /Annealed
Product Raw Form	Pipe and tube (seamless)	Pipe and tube (seamless)
DIN Material	X10NiCrAlTi3230	NiCr21Mo
Werstoff Nr.	1.4876	2.4858
Condition	CW	CW
Heat Treatment	Soft Annealed	Soft Annealed
Material Standard	VdTUV 412	VdTUV 432/2

Table 4 - DIN data

Alloy 825 has a higher percentage of Nickel than alloy 800. This increases the resistance to all forms of corrosion. Incoloy 825 also contains quantities of aluminum and titanium, which increase alloy 825's resistance to intergranular corrosion. Since the 825 grade alloy has superior corrosion properties than alloy 800, IST uses this tubing where the pressure parts will be below the acid-dew point or exposed to corrosive salts.

In an HRSG, the materials are particularly susceptible to two main forms of corrosion.

a) Stress Corrosion Cracking

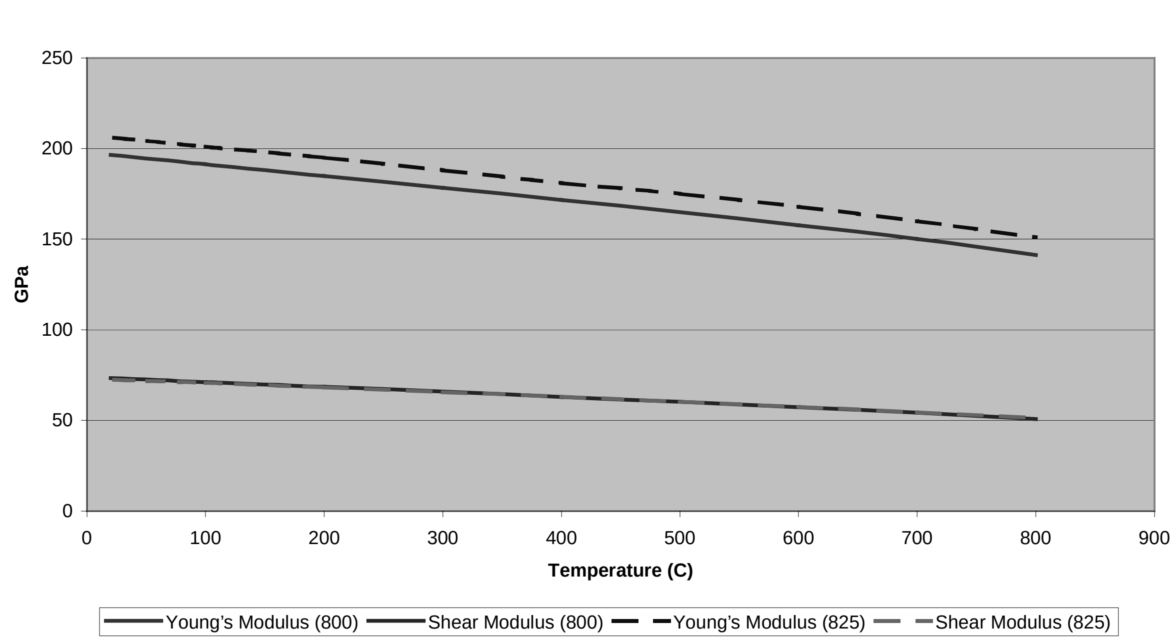
Stress corrosion cracking (SCC) is a concern because it can cause sudden, undetectable failures in materials. From a mechanical, operation or safety perspective, SCC is a serious concern. The failure occurs at a granular level when the material is subjected to combinations of material stress, corrosive environment and temperature ranges. The 825 grade of Incoloy is designed specifically to prevent SCC, and is used in condensing sections of the OTSG or in areas exposed to corrosive substances.

b) Flow Assisted Corrosion

Flow assisted corrosions (FAC) is corrosion that forms a general thinning of tubing surfaces. The thinning occurs due to erosion of the tubing due to corrosive attack. The effect of this corrosion is amplified because of the abrasive nature of fluid flowing through the tubing. Because of the excellent corrosion properties of the 800 series of alloys, there is very little concern of this corrosion mechanismTo Follow

Incoloy has superior mechanical properties to typical HRSG tubing materials. The alloys retain a large percentage of their strength at elevated temperatures, allowing the use of thin walled tubing, even in the hottest sections of the tube bundle. This not only helps ensure that the tubing is suitable for cycling applications, but also reduces the total weight of material required.

Figure 5 Alloy 800/825 Strength vs. Temperature



The alloy tubing allows a unique benefit for HRSGs built entirely out of 800 and 825 material known as dry running. The alloy tubes can have tube wall temperatures up to 538°C for alloy 825 and 816°C for alloy 800. This means that even during a shutdown of the steam system, as long as the gas turbine exhaust temperature does not exceed 538°C, the tubing can withstand being heated to this temperature. This eliminates the need for a bypass stack and diverter system for Incoloy based HRSGs.

IST's normal design practice have been to carefully examine the whole operational range and select an appropriate material for all boiler components. Stainless steel fins and liner are examples of material that should be used in the aggressive cold end environment.

From the previous section it is clear that alloy's 825/800 tubing properties will eliminate any corrosion concerns related to the introduction of the cold feedwater into an OTSG. It should be noted that an appropriate material shall also be selected for all boiler components located in a corrosive environment, like liner plates and tube fins. OTSG's tubing material also allows the aggressive gases level to be well above today's values practical for a conventional HRSG. However, the balance of the plant equipment is also sensitive on aggressive gases like oxygen and carbon monoxide and therefore they have to be removed or lowered to an acceptable level. From Henry's law it is obvious that thermal deaeration can be achieved either at low temperature and negative pressure or at high temperature and positive pressure. Pressurized deaerators have been universally used in CHP plants to expel dissolved aggressive gases and also to heat boiler feedwater to temperature ranging from 105 to 140 °C. One should not forget the previously demonstrated impact of the heated feedwater on the HRSG and, implicitly, the CHP efficiency. A considerable amount of steam has to be provided to a pressurized deaerator in order to allow deaeration and heating. It should be noted that that the opportunity cost of this option is that the same steam could have increased the steam turbine power output. Plant designers have developed a few ways to diminish the effects of this "opportunity cost". For example: the addition of a condensate preheater in the cold end of an HRSG which will considerably reduce the steam required for deaeration, or the addition of an external plate type heat exchanger, which is also used to preheat the condensate before it enters the deaerator and, at the same time, cools the deaerated feedwater. These options are somewhat effective but they add to the cost and complexity of the CHP, while reducing operational flexibility. The same deaerating effect can be achieved with deaerators operating below the atmospheric pressure, or as we call it, under vacuum conditions.

Before we turn to the vacuum deaeration let us focus on one crucial component of the CHP plant that might eliminate the need for either a pressurized or vacuum deaerator - the condenser. This device operates under vacuum conditions and a reduction in condenser's pressure will cause the end point steam enthalpy to get reduced, resulting in an increased generated power. Pulling and retaining vacuum means that a considerable amount of gases including aggressive non-condensables will be pulled out of the system. In the last decade the focus has been on a more thorough consideration of steam and air mixture dynamics in condensers. New plants and some recent retrofits are confirming a respected expert statement that the 21st century will have performance engineers pointing to equipment in power plants other than condensers as their biggest job related headache unlike what was the case for many for most of the 20th century. We should now rely increasingly on a condenser as the major deaerating device in CHP plants. Some condenser manufacturers are now challenging the assumption that a condenser's deaerated oxygen level cannot be maintained at startup and low loads. A lot of efforts have been completed on design criteria and features which would permit condensers to operate with a higher air ingress while reducing dissolved oxygen level even during a reduced loads and start ups. Our specifications for this equipment should now pay more attention to the deaerating segment requesting incorporation of advanced air removal lines and sections with enhanced venting system, trays, internal barriers, perforated baffles, steam distribution, more efficient heat and mass transfer, control system and so on. There are condenser designers/manufacturers who are able to meet all the above mentioned requirements.

The advanced condenser's design with properly selected associated accessory equipment have resulted in oxygen levels of up to 0.005 cc/l (7 ppb) when there is normal or low (up to 3%) makeup. Oxygen levels of less than 100 ppb can be achieved during startup and off design point. With the addition of scavengers this level can be further reduced, if required. The mentioned oxygen level is considered to be sufficiently low for combined cycles with an OTSG and carbon steel piping, provided that the remaining water chemistry is kept within the recommended values, especially pH and conductivity. Test results for plants with a deaerating condenser (without a conventional deaerator), even for those plants with larger quantities of make up water that is usually saturated with aggressive gases, show that oxygen level can be kept in a single digit range over the wide range of operation.

There are regions and plants where environmental thermal discharge or resources have left an air-cooled condenser (ACC) as the only option for the CHP plant. Today's design for this type of condensers reduces the possibilities for the mentioned design, venting and deaerationg performance enhancements. If the expected oxygen level in a plant with this type of condenser does not meet the specified values for the plant equipment excluding a OTSG, then a full flow vacuum deaerator can be placed downstream the condenser (see Figure 6). Therein, the condensate is being sprayed over a system of cascades inside a vertical dome. Make-up water is also brought into the same section of the deaerator. It should be noted that the OTSG does not need blow down, which considerably reduces the make-up flow. Since this device is on the same line as condenser, the vacuum is established together with that of the condenser. An enhancement in vacuum is achieved with a steam ejector (see Figure 5). Beneath the deaerating dome within the same apparatus is located a condensate storage tank. It is usually sized for the 10 minutes storage capacity. An oxygen scavenger is usually injected in this tank

Figure 6

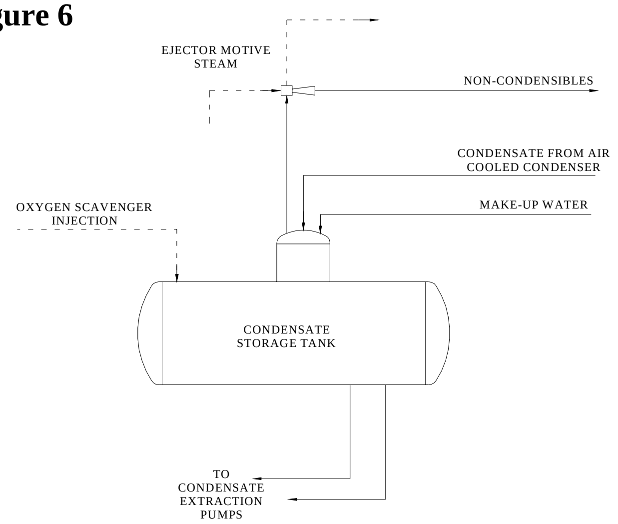


Figure 7

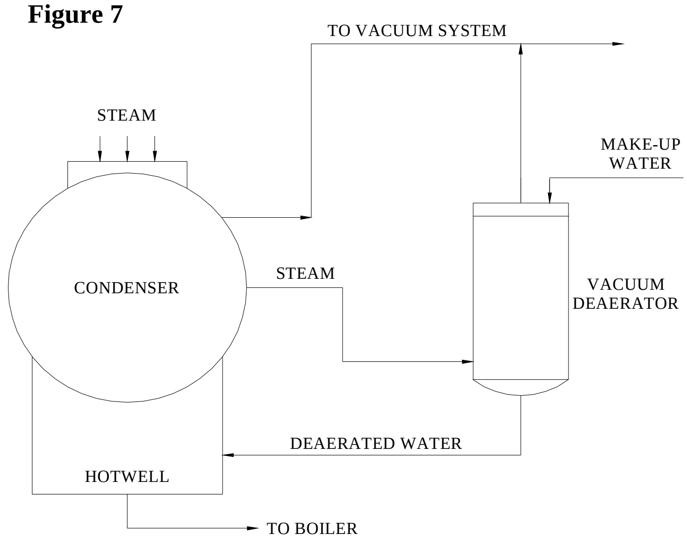


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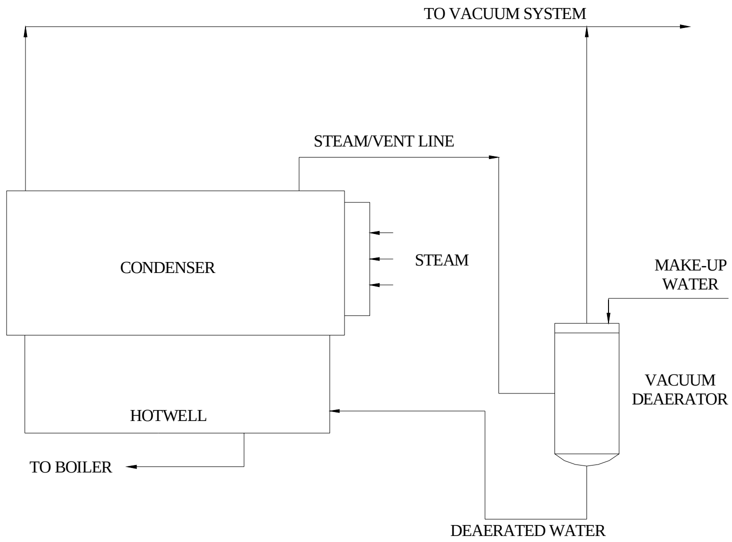
Figure7 and 8 are depicting another possibility for incorporation of a vacuum deaerator into a CHP. The whole make up water flow, which is saturated with aggressive gases, is brought into a small vessel that is at the same pressure as the condenser, which it is attached.

A few OTSGs installed in North America have been operating in plants with the arrangement as shown in the Figure 8. Steam turbines for the referenced plants are with an axial steam exhaust. It should be noted that the steam used for deaeration is actually the exhaust steam, which is intended to be condensed. Live steam is not used for deaeration, which results in increased plant efficiency.

A small make-up water vacuum deaerator performances, for a higher flowrates, can be enhanced with the packed column made of plastic pieces of varying sizes and shapes or a column of stainless steel packing. For combined cycles with OTSG were the make up flow rates are usually below 0.2% this packed column is not required.

Figure 8



It should be noted that vacuum deaeration offers the following benefits:

- A reduced amount of steam (energy) required for deaeration which would otherwise be wasted,
- the vacuum deaeration concept reduces and eliminates a considerable amount of piping, valves and instruments,
- positively impacts overall plant efficiency;
- adds to the plant design flexibility (equipment layout).

All the above mentioned benefits can only be achieved with the proper HRSG materials selection. IST's OTSG material selection has been proven as a right choice.

Operational experience:

IST's operational experience with Alloy 825 tubing has been excellent. This tubing has been used in the condensing section of the OTSG in presence of corrodant such as: sulfuric acid, hydrochloric acid, ammonium sulfate and/or bisulfate, nitric and carbonic acids. Alloy 825 does not suffer from sensitization as compared to Alloy 800. Alloy 800 is used in sections of the boiler not operating close to or below the dew point.
More than a decade in operation and over a three millions of operational hours have proven an appropriate material selection for all other boiler components.

Conclusion:

- Boiler and plant efficiency is greatly affected with the HRSG's flue gas exiting temperature.
- Due to material restrictions, cold feedwater imposes many constrains for a conventional HRSG. High nickel alloys, specifically alloy 825, with its superior corrosion properties, eliminates any corosion/errosion concern.
- Mechanical properties of alloy tubing have allowed a unique mode of operation where the GT stays in operation exhausting hot gases over the heating surfaces without any water/steam. This operation called dry running, means that costly diverter system and its bypass stack can entirely be eliminated from the plant. Elimination of this system remove thermal loses associated with flue gas leaks, increasing plant efficiency.
- Alloy 800 and 825 are high strength materials at elevated pressures and temperatures allowing reducing tube wall thickness that reduces the overall weight and size of the HRSG.
- Corrosive and aggressive gases still have to be removed from the water in order to protect other components within a CHP plant.
- Advanced condenser design features have resulted a product called deaerating condenser which nowadays meets stringent requirements for concentration of aggressive gases in a wide range of operational points.
- Additional deaeration, if required, can be accomplished under vacuum conditions. Condensate exiting vacuum dearator is at low temperature. Vacuum deaeration considerably reduces the steam demand and no live steam is taken from the cycle.
- Vacuum deaeration simplifies the whole cycle while increasing plant design flexibility.