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Diffusion bonded heat exchangers (PCHEs) in Fuel Gas Heating to Improve efficiency of CCGTs

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ABSTRACT

The purpose of this paper is to show how compact heat exchanger technology can offer energy savings and hence cycle efficiency improvements on new and existing gas turbine installations by being utilised for fuel gas heating.

After a brief introduction to high temperature compact heat exchanger technology and comparison to traditional equipment, thermodynamic cycle analysis for a combined cycle gas turbine plant (CCGT) is used show the advantages of compact technology over conventional technology, analysing the fuel gas heating, to illustrate the overall savings. A case study is used to demonstrate an increase in net LHV electric efficiency in the range of 0.5 to 1.17 % achievable using high effectiveness compact diffusion bonded heat exchangers in fuel gas heating. Intermediate pressure and high pressure feed water heating is considered for increasing the fuel gas inlet temperature to the combustor. The model is built in Excel and is extended to a capital expenditure overview based on new or a retrofitting in existing plants.

INTRODUCTION

Heatric has been manufacturing compact Printed Circuit Heat Exchangers since 1985, when Heatric was first established in Australia. The term 'compact' is often confused with meaning small; however, individual heat exchangers can be in excess of 8 metres length and 100 tons weight; assemblies can comprise tens of exchangers, so compact heat exchangers can be of appreciable size. 'Compact' more accurately refers to the higher duties that are achieved in smaller sizes than (say) shell and tube heat exchangers. This compactness is achievable through higher surface densities (i.e. heat transfer surface area per unit volume of heat exchanger), and through enhancement of heat transfer coefficients by selection of heat transfer surface geometries.

The compact heat exchangers types that Heatric manufactures are Printed Circuit Heat Exchangers (PCHEs), Formed Plate Heat Exchangers (FPHEs), and Hybrid Heat Exchangers (H^2Xs). These are all formed from alternating layers (typically hot-cold, hot-cold etc., see fig. 1). For PCHEs, layers are etched plates (see fig. 2). For FPHEs, layers consist of fins (see fig. 3) which are bound by side bars and separated by flat parting sheets. H^2Xs are a combination of both, a typical sequence being etched-plate/parting sheet/fins/etched-plate/parting sheet etc. Figures 4, 5, and 6 show sections through a PCHE, an FPHE, and a H^2X respectively.

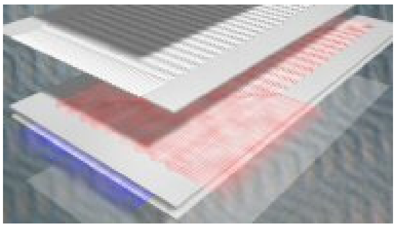

Fig. 1, stacked plates with the hot side shown in red and the cold side shown in blue.

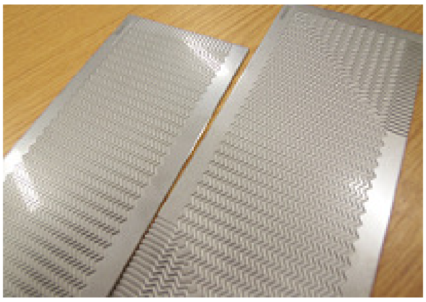

Fig. 2, etched plates (left plate is end-entry, right plate is side-entry).

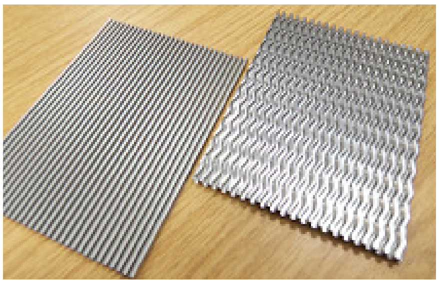

Fig. 3, fins (left side is plain-type, right side is herringbone-type).

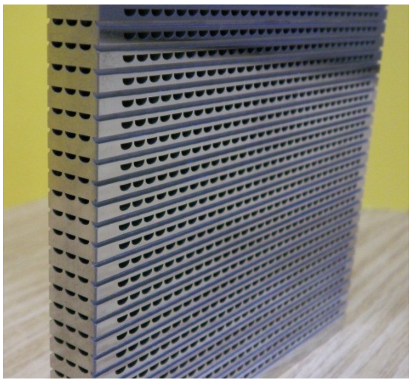

Fig. 4, section through a PCHE (cross-flow).

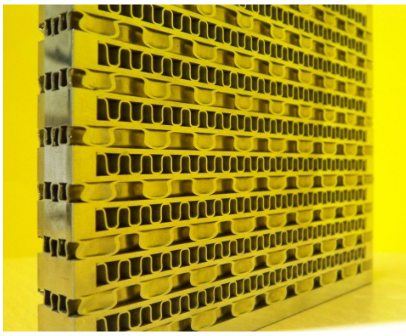

Fig. 5, section through a FPHE (cross-flow).

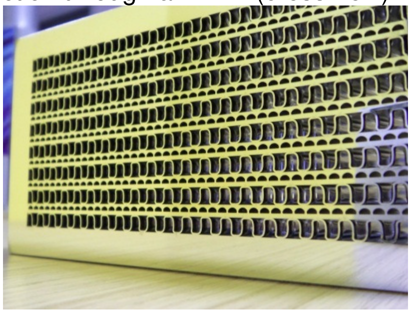

Fig. 6, section through a H^2X (counter-flow).

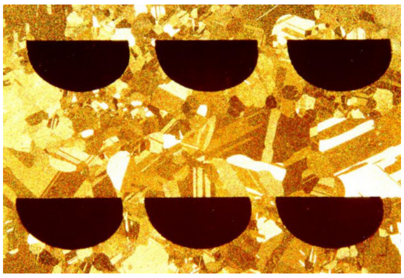

Fig. 7, micrograph of a PCHE section. Note that this is a crossflow PCHE, B side layers are not visible in this section.

The diffusion bonding process used by Heatric results in a return to the parent metal strength properties as listed in ASME. Allowable stresses for some of Heatric's bond-qualified materials are shown in fig. 8:

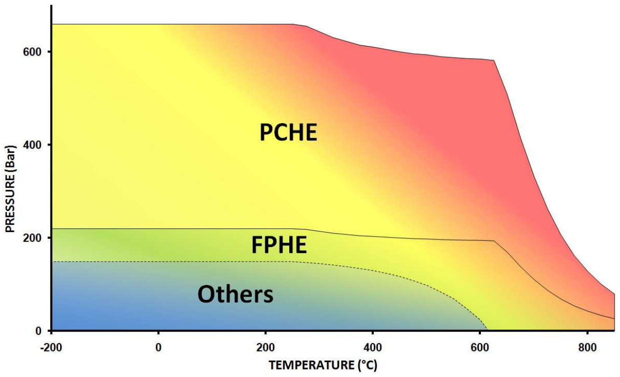

Fig. 8, allowable stresses for Heatric diffusion bonded heat exchangers.

Heatric diffusion bonded heat exchangers are very flexible and can be configured to have cocurrent, cross or countercurrent flow, essentially matching the thermal duty (NTU) with the pressure drop available. It is also possible to put multiple fluids (more than two) into one heat exchanger, which is beneficial when space is tight, such on modular skid mounted packages. This also eliminates some piping.

Below are some different configurations Heatric can utilise to best optimise the size of the heat exchanger:

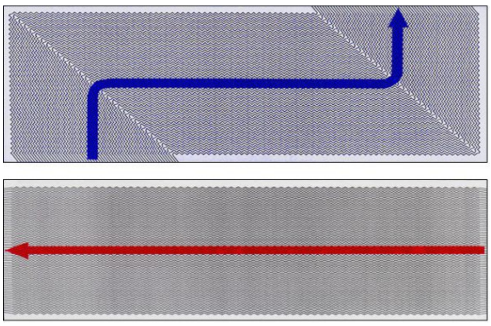

Fig. 9a, counterflow example with side-side and end-end flows.

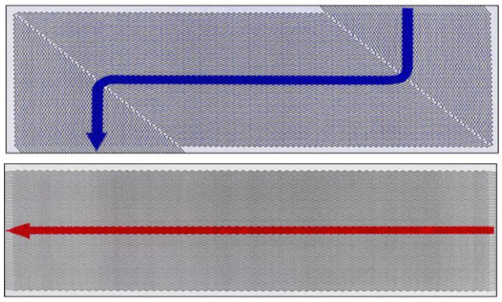

Fig. 9b, parallel flow example with side-side and end-end flows.

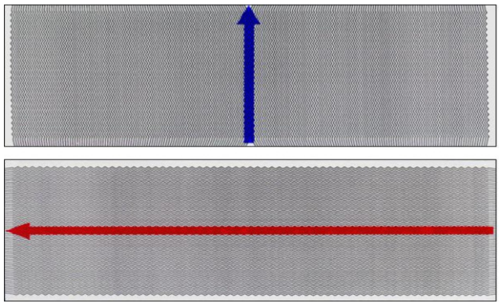

Fig. 9c, crossflow example.

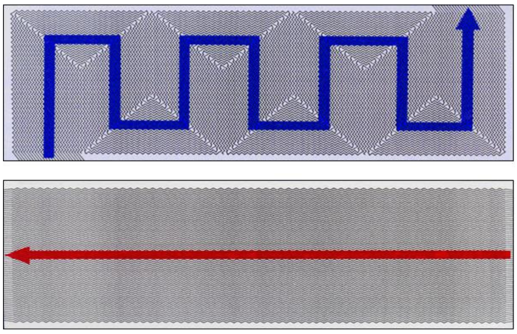

Fig. 9d, cross-counterflow example.

NOMENCLATURE

LP – Low Pressure
IP – Intermediate Pressure
HP – High Pressure
GT – Gas Turbine
ST – Steam Turbine
CCGT – Combined Cycle Gas Turbine
LHV – Lower Heating Value (kJ)
U – Overall Heat Transfer Coefficient (W/m².°C)
A – Effective Heat Transfer Area (m²)
Q – Thermal Load (kW)
TD – Temperature Difference (°C)
T_{hin} – Temperature hot side in (°C)
T_{hout} – Temperature hot side out (°C)

T_{cin} – Temperature cold side in (°C)
T_{cout} – Temperature cold side out (°C)

II. EFFICIENCY IMPROVEMENT OF FUEL GAS HEATING WITH PCHES

Heatric diffusion bonded heat exchangers can play a key role in achieving the goal of technology developers and power plant owners to improve plant efficiency and operational performance.

Increasing cost of running a power plant and a competitive energy market are forcing plant owners to target plant efficiency improvements that require less capital investments. The typical ways of achieving high plant efficiencies such as multiple pressure levels with HRSG, reheat systems, high steam temperature all require substantial investment. Among other ways to improve plant efficiency include steam injection, supplementary fired HRSG, inlet cooling, rotary air cooling steam generation and fuel gas heating [1].

Fuel gas heating is becoming a common focus for various turbine technology developers due to lower capital investment, while providing a moderate increase in efficiency. Fuel gas heating is the preheating of the inlet fuel gas using high temperature feed water from the economiser, before burning it in the combustor. Most often the Intermediate pressure (IP) feed water is used to increase the fuel gas temperature by about 185 to 200 ^{0}C. A further increase in fuel gas temperature to about 350 ^{0}C is achieved by using high pressure (HP) feed water line. The HP feed pressure can reach up to 255 barg favouring high integrity compact exchanger designs. In some cases a combination of Low pressure (LP) and intermediate Pressure feed water can be used in combination in which initial ~100 ^{0}C rise in temperature is achieved by LP feed water system.

Fuel cost being the major part of operating cost, minimising fuel consumption without compromising efficiency is an attractive plant performance enhancement option. The increase in efficiency using fuel gas heating is gained from the fact that less energy is required to bring the fuel to combustion temperature and hence reducing fuel consumption.

Gas turbine power plants are often used for peak power shaving. Higher energy prices during peak hours (particularly in summer) puts demand on the combined power plant operators to respond quickly and boost power on the basis of grid demand. The requirement of ability to reach peak power in a short period, whilst maintaining maximum plant availability, means that gas turbine developers look for reliable and robust solutions. Selection of the right technology to achieve fuel gas heating is critical to reliability of the power generation plant. To maximise plant availability the technology of choice needs to be robust, and able to respond to varied energy demands.

As failure in a fuel gas heating system directly affects plant availability, proper design and reliable operation of this system is critical. Heatric diffusion bonded technology has superior performance and minimum maintenance requirement assisting overall plant availability particularly in demanding peak hour operation modes.

Conventional heat exchangers are prone to tube failure due to vibration and have a slow thermal response time. Diffusion bonded heat exchangers are known for their high integrity and fast response time to temperature ramp rate. Their proven resilience to thermal stress caused by fast transient operation makes them ideal choice for gas turbine application. In this paper, analysis is made to demonstrate efficiency improvement using Heatric compact diffusion bonded exchangers, utilised in fuel gas heating of a combined cycle gas turbine plant with three pressure levels shown in Fig 10.

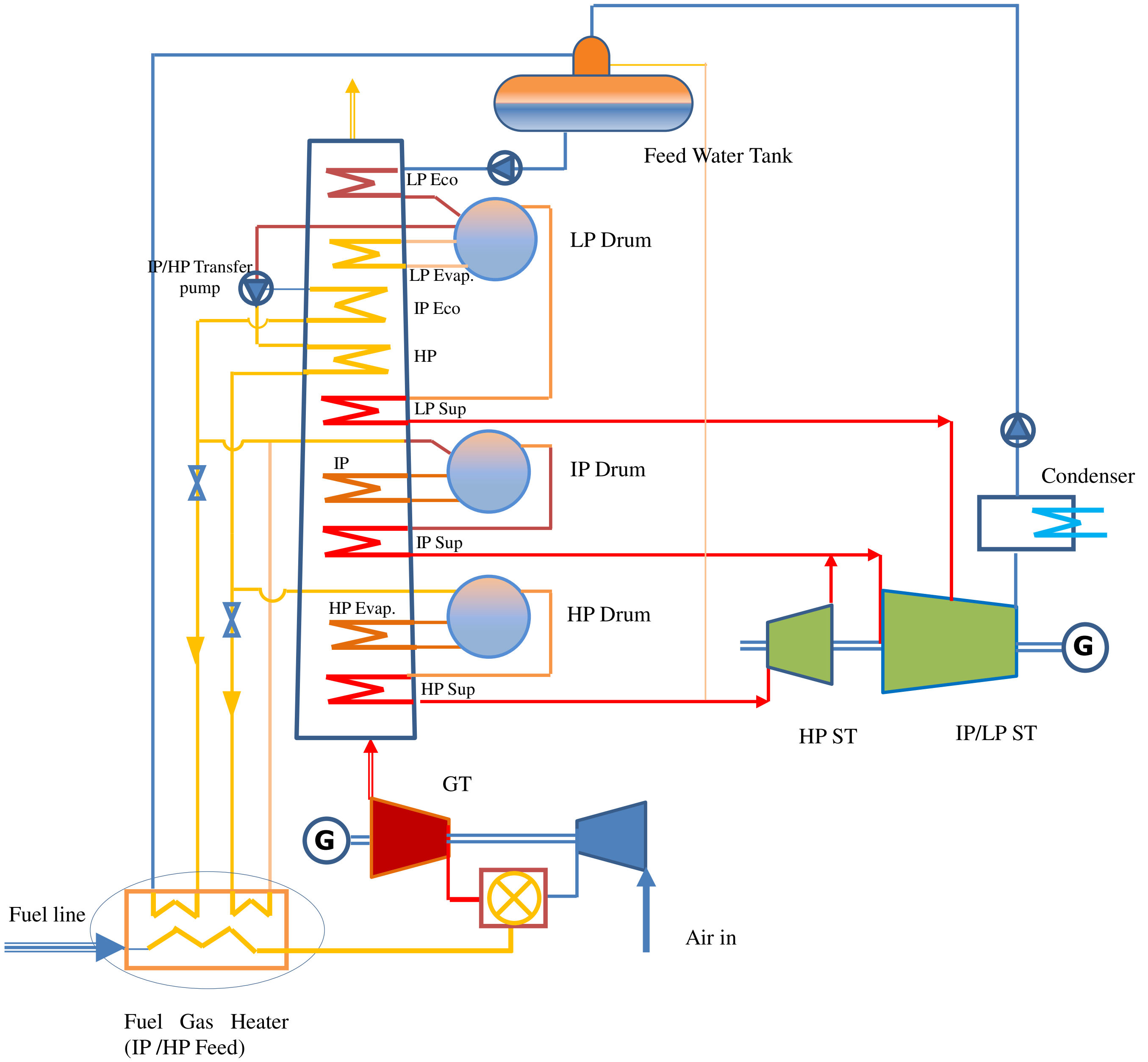

Fig. 10. Combined Cycle Gas Turbine Block Diagram with three pressure level.

A typical compact exchanger layout when a single pressure (mostly IP feed water) is used to preheat the fuel is shown in Fig 11. Such counter flow arrangements allow for a deep temperature cross heat release curves, i.e. closer temperature approach. The effectiveness of PCHE exchangers reaches 99 %, enabling a higher heat recovery.

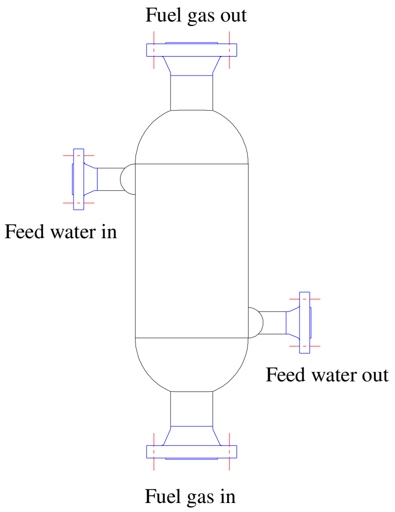

Fig 11. Typical Counter flow compact heat exchanger layout used in IP Feed water/ fuel gas heating

As shown above in Fig.8, the high pressure capability of diffusion bonded exchangers easily handles the HP feed water system. Although conventional heat exchangers such as Shell & Tube can reach the high pressure demands of HP feed water systems, the deep temperature cross means that they would require several shells in series, adding further piping complexity increasing capital and running cost, especially if skid mounted modular systems are desired. On the other hand, PCHEs are not only able to handle high pressure and tight temperature approaches, but can also be configured to handle multiple streams in a single block. Consequently, when there is a need for to use a combination of LP and IP feed water or IP and HP feed water system for fuel gas heating, both pressure systems can be incorporated in a single heat exchanger (Fig. 12). This would minimise pressure drop as well as the need for additional piping and easily modularised to a skid/package system.

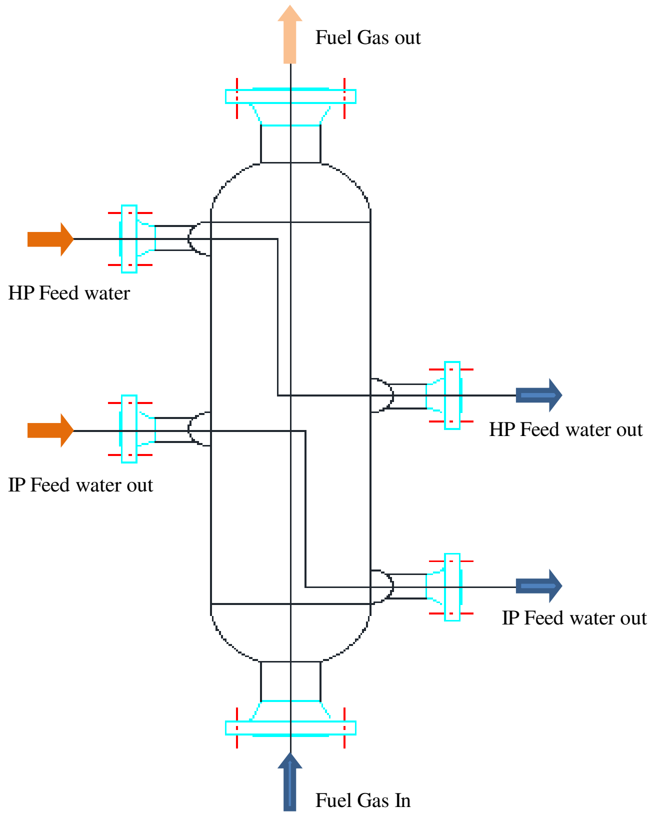

Fig. 12 Multi-stream counter flow compact exchanger combining different pressure level feed water systems

III. Efficiency Improvement Case Study

A case study on the use Heatric Diffusion Bonded Heat Exchangers in efficiency improvements as fuel gas heating with IP and HP feed water is discussed below.

An intermediate pressure feed water with 55 barg at 240 ^{o}C is used in the first section to increase the fuel gas temperature from 15 ^{o}C to 220 ^{o}C. Further increase in fuel gas temperature to 300 ^{o}C is then made utlising HP feed water (250 barg and 355 ^{0}C). The two pressure level operation allows for the flexibility required during part load operation in which the IP Feed water is not sometimes enough to keep the fuel gas temperature at a required constant value. For the purpose of analysing the effect of heat exchanger effectiveness (tighter temperature approach) on fuel gas heating duty, the fuel gas exit temperature is varied. The flow rate of the flow gas is considered as 15 kg/s and has a pressure of 50 bara.

For evaluating the increase in net LHV electric efficiency as a function of increase in heat exchanger effectiveness, it is assumed that the fuel gas has Lower Heating Value (LHV) of 50 MJ/kg, and the CCGT is estimated to have a net electric efficiency without fuel gas heating as 56 %. The net Power output of the plant is therefore estimated to be 420 MWe.

Figure 13. depicts the relationship of UA and heat added to fuel gas (Q) as a function of increase in effectiveness of IP feed water/fuel gas heat exchanger, where UA is calculated from

$$UA = \frac{Q}{corrected\ TD}$$

In its simplified form a heat exchanger effectiveness can be expressed as

$$Effectiveness = 1 - \frac{\Delta T_{approach}}{T_{hin} - T_{cin}}$$

Where minimum temperature approach is

$$\Delta T_{approach} = Min\left[(T_{hin} - T_{cout}), (T_{hout} - T_{cin})\right]$$

As can be seen from the curves, there is a steady increase in heat added to fuel gas as effectiveness of the heat exchanger increases. Whilst increasing effectiveness requires higher UA value and hence capital cost, the increase in UA gets greater as effectiveness of exchanger tends to unity. Conventional heat exchangers struggle to achieve effectiveness as high as counter flow compact heat exchangers, and therefore can only provide a limited increase in fuel gas temperature.

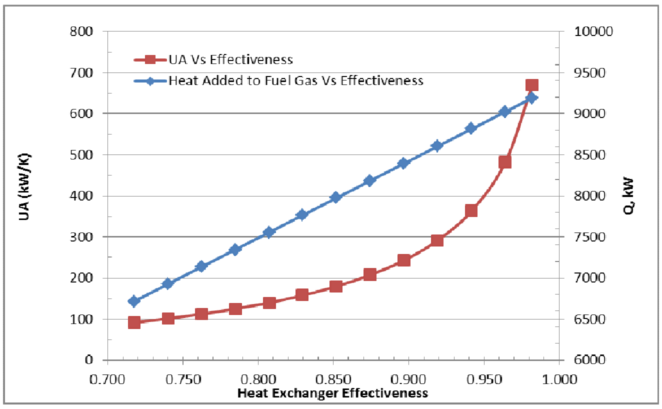

Fig. 13 UA and Q versus heat exchanger effectiveness for the IP feed water/fuel gas section

In Figure 14 the increase in fuel gas temperature by recovering heat from IP feed water system is translated to increase in net LHV electric efficiency.

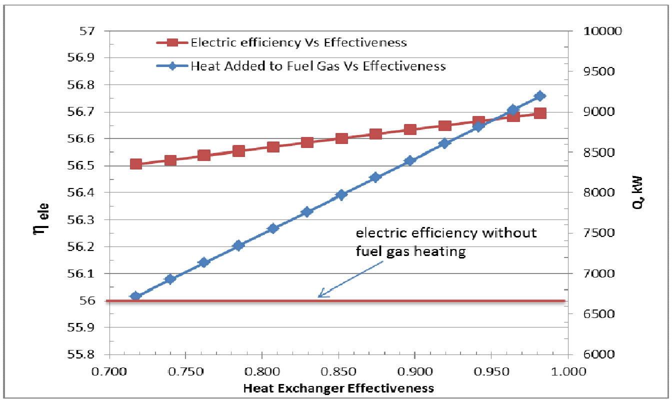

Fig. 14. Net electric efficiency and fuel gas heat recovery duty versus exchanger effectiveness IP Feed water / Fuel gas heating section

The increase in efficiency is due to less energy being spent on bringing the fuel to oxidation temperature, than the fuel required to heat the feed water. The analysis shows that there is an efficiency improvement ranging from 0.5% to 0.7 % as the fuel gas temperature is increased to 175 ^{0}C to 234 ^{0}C from 15 ^{0}C using only the IP feed water.

Figure 15 shows a relationship of heat duty and UA versus effectiveness based on a similar analysis made using HP feed water/fuel gas heat exchanger. The heat duty is only the additional heat added to increase the fuel gas temperature from the IP feed water/fuel gas section to a further high fuel gas outlet temperature. There is a steep rise in heat recovery as effectiveness increases with a significant rise in UA value at very high effectiveness

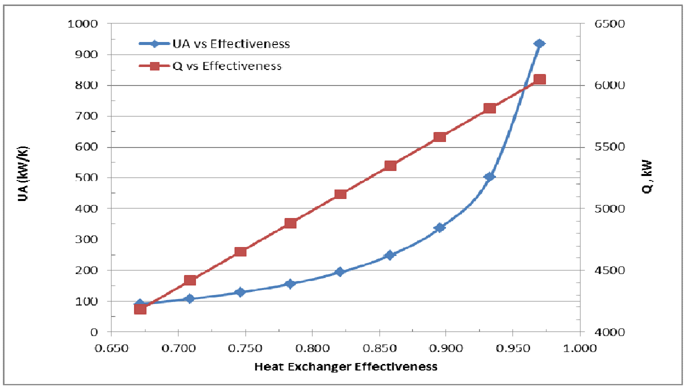

Fig. 15 UA and Q versus heat exchanger effectiveness for the HP feed water/fuel gas section

The corresponding additional increase in plant efficiency is shown in Fig 16. An additional increase in electric efficiency, from what is achieved by IP feed water/fuel gas exchanger, ranging between 0.27 to 0.47 % is calculated for a further increase in temperature from 60 ^{0}C to 115 ^{0}C.

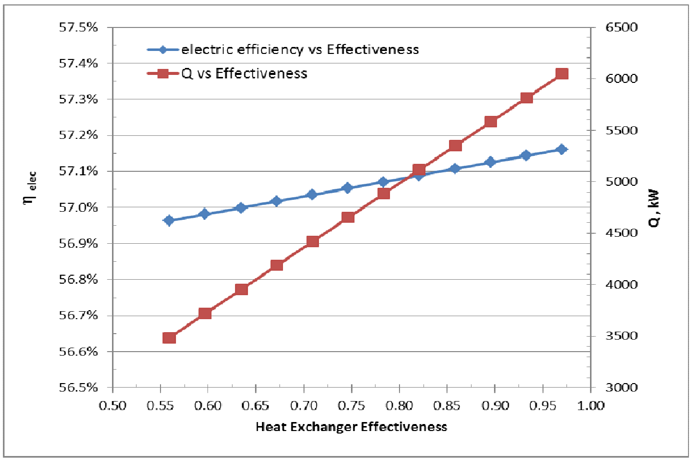

Figure 16. Net electric efficiency and fuel gas heat recovery duty versus exchanger effectiveness HP Feed water / Fuel gas heating section.

Overall fuel gas heating can achieve an increase in net electric efficiency between 0.7 % (for fuel gas exit temperature of 235 ^{0}C using IP feed water) to 1.17 % (fuel gas exit temperature of 350 ^{0}C using HP feed water).

Considering a fixed exchanger price per UA, and a fuel cost of \$2.5 per /MMBTU, the fuel saving due to improved efficiency is used to estimate plant operation hours required for a return in capital investment of the exchangers. This is evaluated at different exchanger effectiveness for both IP and HP feedwater/fuel gas systems, and is presented in figures 17 and Figure 18 respectively. Due to high pressure and hence mechanical strength requirement, the HP feed water /fuel gas exchanger has a relatively higher price per UA and hence a longer operation period to payback the investment.

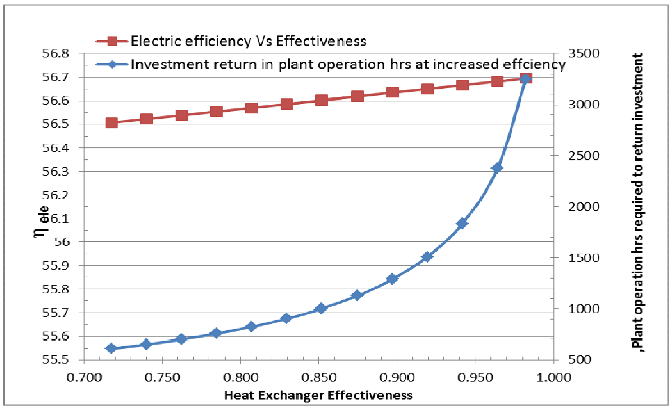

Fig.17, plant operation hours required to return in investment for IP feed/ fuel gas heating

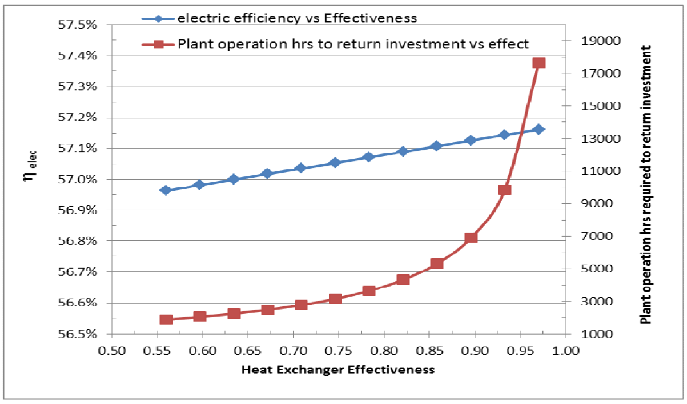

Fig 18. Plant operation hours for a return in investment for HP feed/ fuel gas heating

Summary

It is demonstrated that a moderate increase in plant efficiency is achieved by using high effective compact heat exchanger in fuel gas heating system. Among other things, the ability to handle high pressure and multi-streams is an attractive feature that can be utilised in minimising capital investment, whilst easily integrating them in skid mounted modular systems with gas turbines. Heat exchanger technology with high integrity and flexible performance demand is part of a solution to achieving low operating cost, increase plant availability, boost performance and minimise piping cost.

REFERENCES

1. Swanekamp, Robert. C. (2007). HRSG Users Handbook