Heat Recovery Steam Generators for large combined cycle plants (250 MWe GT output): experiences with different design options and promising improvements by once-through technology development

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Presented at

Power Gen Europe 2005, Milan, 28-30 June 2005

1. ABSTRACT

Ansaldo Caldaie has gained extensive experience in designing, manufacturing and installing HRSGs for gas turbine sizes ranging from 40 MWe to 250 MWe. The purpose of this paper is to focus on large size HRSG units suitable for Siemens GT V94.3A or GE 9FA with 250 MWe output. These HRSG units are designed under our proprietary technology based on two design options: horizontal gas flow with natural circulation and vertical gas flow with assisted circulation. Most of the units have been successfully tested and entered into commercial operation during the last five years. The most relevant projects of these types of units are herein presented and described along with their distinguishing features; specifically, the vertical HRSG design suitable for insertion into the existing steel structure of old fired boilers in re-powered power stations is described. A comparison between the horizontal and vertical design options is provided on the basis of functional, constructive and operating data collected from a combined cycle power plant where two units with the same operating characteristics and output, but with different configuration (horizontal and vertical), have been delivered.

Following a market trend towards extensive cycling operation and combined cycles of increasing size with gas turbines of improved technology having higher exhaust gas temperatures and flowrates, a new design option has become interesting in the recent years and has been taken into account as a possible advancement for the HRSG technology: once-through mode in the high pressure levels of the unit. For this design option, we, - as Siemens licensee for Benson Once Through HRSG technology – have developed our own standard project. This paper describes the main features of this project and highlights the most relevant advantages that HRSG units based on this concept offer compared to Drum Type units.

2. INTRODUCTION

The current trend in the power generation industry is of rising demand for combined cycles with improved efficiency and reduced delivery time. Improved efficiency reduces the fuel related cost and, at the same time, contributes to the resolution of the greenhouse effect. Heat Recovery Steam Generators are key components in the combined cycle. Starting from the early 90's, we began developing our proprietary HRSG design for:

- Horizontal gas path, natural circulation, cold casing and top supported HRSG.
- Vertical gas path and assisted circulation HRSG.

A standard design has been developed in order to meet the main requirements of modern combined cycles: short delivery time, high quality standards, fast site construction, proven performance, elevated operating flexibility and easy maintenance and repair.

In the last decade, the majority of horizontal and vertical HRSGs, has been mainly based on unfired triple pressure with reheater cycles downstream 250 MWe gas turbines. Also supplementary fired HRSGs with one or two post firing (up to 280 MWth) have been designed. Most of the units have been successfully tested and entered into commercial operation during the last five years.

In order to meet recent market requirements in terms of extensive cycling operation and fast start-up and to be ready for the next generation of high efficiency combined cycles based on high pressure and temperature steam requirements, we, as others did, acquired HRSG Benson Once Through technology from Siemens in 2003**.**

3. HORIZONTAL HRSG VS VERTICAL HRSG COMPARISON

4.1 Introduction

An intense HRSG re-powering of the old fired power stations units is currently underway in Italy starting from the second half of the last decade. Two different options are available: complete demolition of the existing boiler or insertion of the HRSG in the existing steel structure, like Ostiglia Power Station. This plant consists of three triple pressure levels with reheater HRSG's dowstream of a 250 MWe GE PG9351. Two are installed inside the existing steel structure of old 320 MWe Utility Boilers supplied by us in the Sixties. Because of stack height requirements for emission control, it was mandatory to install the third unit in horizontal configuration by applying a stack height of 150 m, higher than the maximum height sustainable from the existing structure. This uncommon plant configuration provides for a direct comparison of both vertical and horizontal HRSG having the same boundary conditions in terms of required HRSG design and performance.

4.2 Main HRSG characteristics comparison

Below Fig 1 shows the comparison of the two HRSG installed at the Ostiglia Power Station.

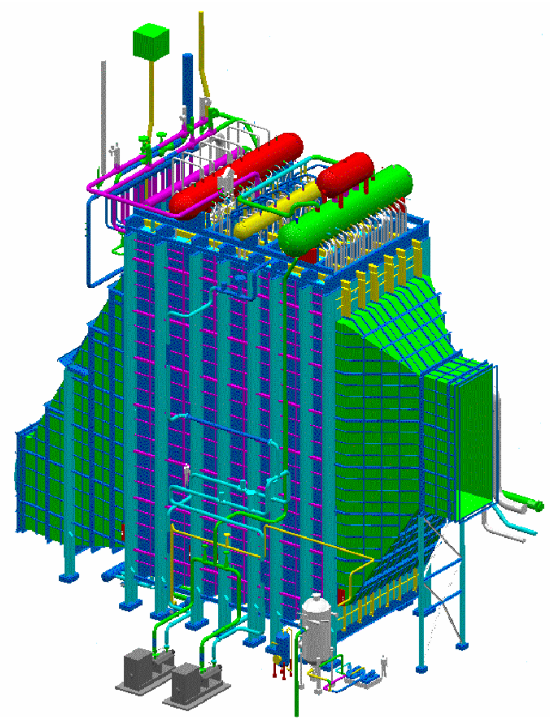

Fig. 1.1: Horizontal HRSG isometric view

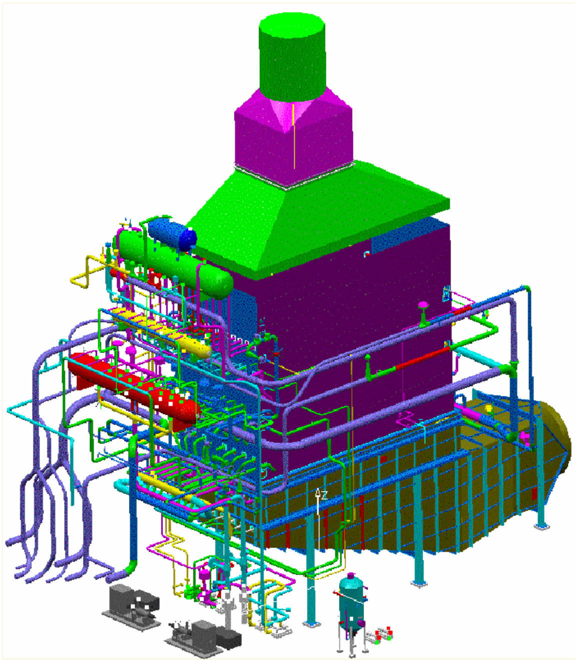

Fig. 1.2: Vertical HRSG isometric View

Common characteristics for both configurations are:

- Three pressure levels with reheater
- Intermediate desuperheating on high pressure superheater and reheater
- Integrated deareator on low pressure steam drum
- Drum level control valves downstream economisers to prevent steaming effect
- Serrated fin tubes in staggered arrangement.
- Standardised modular design to ease transportation and to reduce erection period at site.

Main characteristics of horizontal HRSG design are:

- Top supported tube elements to allow free downward thermal expansion
- Cold casing design
- Natural circulation evaporators with small diameter tubes to reduce drum level fluctuations.

Main characteristics of vertical HRSG design characteristics are:

- Top supported heating surfaces to the existing steel structure
- Cold casing (inner insulated) for the hot section and hot casing for the cold one
- Assisted circulation with 2x100% pumps for each pressure level.

From the geometrical point of view, Tab. 1 summarises the main vertical HRSG data differences compared to the horizontal ones. The difference in tube length is due to the geometrical constraints of the existing steel structures. The vertical HRSG has a higher number of tubes and, therefore, a smaller heating surface than the horizontal one due to the geometrical constraints of vertical HRSG design.

	Vert. vs. Horiz.
Tube Length	-9%
Max Parallel tubes Nr.	+9%
Transversal tubes Nr.	+5%
Total Tubes Nr.	+14%
Surface	-23%

Tab. 1: Main differences of Vertical HRSG geometrical data compared to the Horizontal HRSG ones

4.3 Performance and operational comparison

Both HRSGs have been successfully tested and was found that the vertical one had a larger over-performance in terms of power to the steam turbine. A detailed analysis of performance test results indicated that this was due to:

- the peculiar HRSG design adopted for this critical project since Ostiglia was one of our first application of vertical HRSG downstream large combined cycle plants
- a better overall performance of the vertical HRSG compared to the expected one; as an example Fig. 2 shows low pressure evaporators pinch diagrams comparison for the two configurations. It can be seen how multiple passage horizontal tube arrangement ensures a more uniform heat transfer along the evaporator.

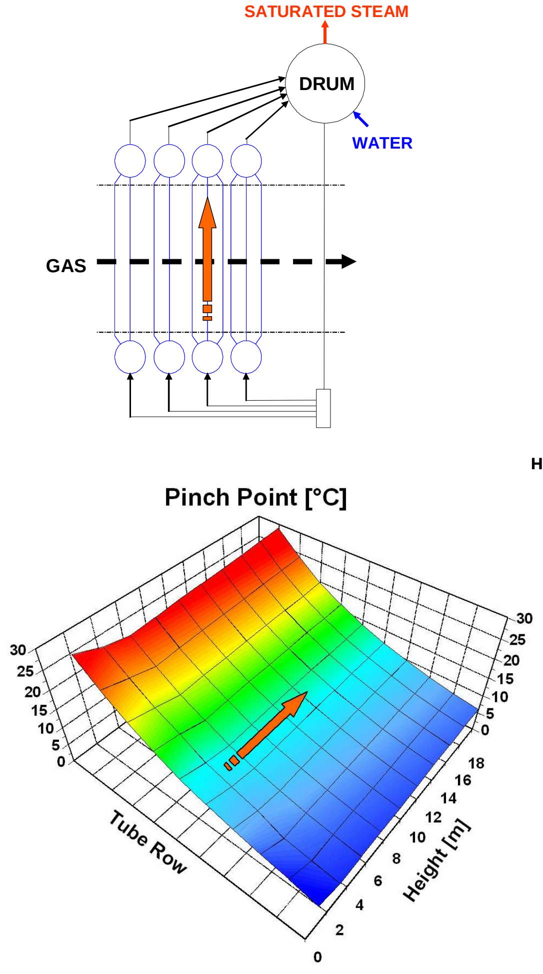

Fig. 2.1: Horizontal HRSG
LPEVA arrangement and
pinch diagram

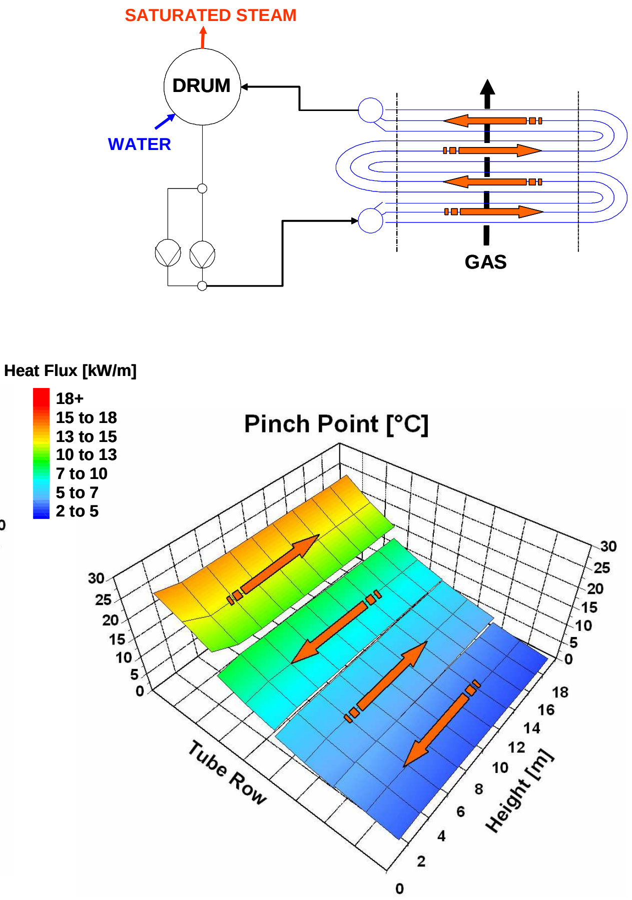

Fig. 2.2: Vertical HRSG
LPEVA arrangement and
pinch diagram

Another positive outcome of the vertical arrangement is the hot gas buoyancy effect, in the range of 8% credit of maximum guaranteed gas pressure loss value.

From the operational point of view the two plant configuration are equivalent even if vertical HRSG could be difficult drainable but has an easier heating surface accessibility.

As far as auxiliary power consumption is concerned, total consumption of vertical HRSG is about 4 times greater than the horizontal configuration, due to the three circulation pumps.

4.4 Weight comparison

Below Fig 3 shows the comparison of the total weight of the two different HRSG configurations as a percentage of the total horizontal HRSG weight.

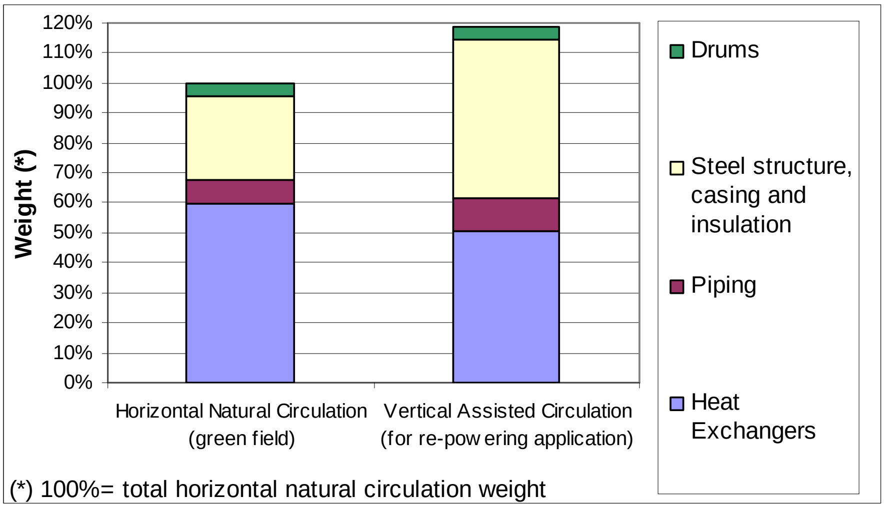

Fig. 3: HRSG Weight Comparison

Since Ostiglia vertical HRSG uses an existing steel structure, for the sake of comparison the weight of vertical HRSG steel structure has been estimated as a “new structure”, to eliminate any unwanted influence due to the re-utilization of the existing steel structure. A green field vertical HRSG should be optimised with regard to lay-out and general arrangement in order to minimise weights and costs.

It is possible to see how the vertical steel structure performs a huge effect on total weights. This is partly due to vertical HRSG design characteristics and partly to the non optimised lay-out imposed by the geometrical constraints of the existing steel structure, as shown on Fig. 4, where an example of Ostiglia intricate piping arrangement is presented. The weight of vertical HRSG heat exchangers is reduced compared to the horizontal one, due to a better evaporator performance of horizontal tube assisted circulation evaporators.

Fig. 4: Vertical HRSG intricate piping arrangement sample.

Since the high pressure evaporator is the main critical item in HRSGs, Fig. 5 below shows the comparison of the weight of the two different HRSG HP evaporators as a percentage of the total horizontal HRSG HP evaporator weight.

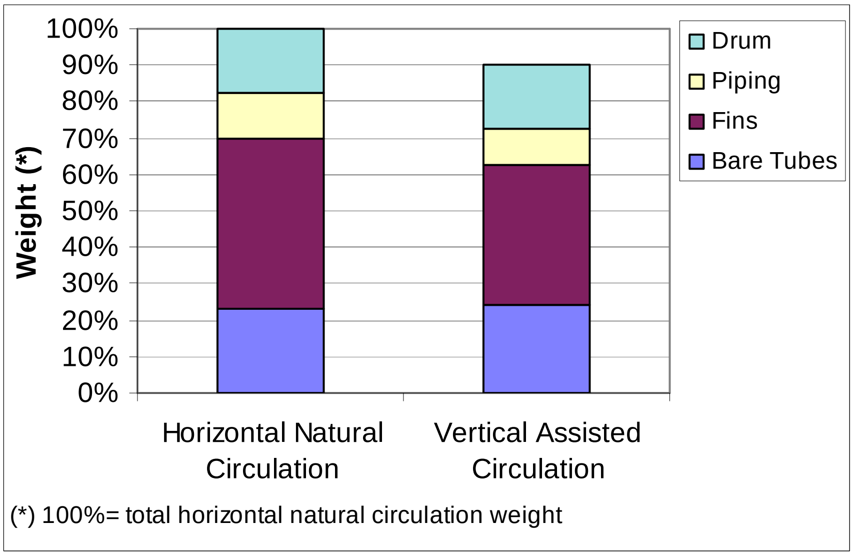

Fig. 5: High Pressure Evaporator Weight Comparison

4. NATURAL CIRCULATION HRSG VS BENSON ONCE THROUGH HRSG COMPARISON

4.1 Introduction

As a matter of information, we have been Siemens Benson licensee for Utility Boiler for a decade.

In order to meet recent market requirements in terms of:

- increased combined cycle performances (higher gas temperatures and higher steam pressures and temperatures)
- extensive cycling operation (increasing number of cycles and fast start-up)

we decided to acquire Siemens HRSG Benson license in year 2003.

Such technology has been successfully proven at Cottam power plant in England, (to a triple-pressure HRSG downstream Siemens V94.3A gas turbine), as described in Modern Power Systems, September 1999, pp.40-43 and Modern Power Systems, July 2000, pp 33-35.

We have recently undertaken an intense development activity with the purpose of best suiting the constructive and functional characteristics of our horizontal HRSGs to the functional requirements of Siemens Benson technology. At the end of last year such effort resulted in the acquisition of the Multiple Purchase Agreement (MPA) with Siemens. According to this agreement, the two companies intend to closely co-operate in the development, tendering, processing, standardization and total cost reduction for the delivery of both Benson type and drum type HRSGs for the next three years.

The main standard MPA HRSG characteristics are as follows:

GT: Siemens V94.3A4

HRSG design: Triple pressure with reheater. HP Benson Type (Drum type as an option) having the following main steam parameters

	Flow [kg/s]	Pressure [bar]	Temperature [°C]
HP Steam	77.3	129.9	566.5
RH Steam	91.1	30.7	565.1
LP Steam	10.6	4.4	234.6

Tab 2: Siemens Standard MPA SP3 main steam parameters

4.2 Main HRSG configuration comparison

At present the standard project of both Drum type and Benson type HRSG has reached completion. In order to reduce the differences between the two projects, the design of both HRSGs has been developed by applying a modification only to the HP evaporator module.

The main differences are:

- Drum in natural circulation HRSG and separator in Benson type one
- Different HP Evaporator internal and external piping
- Additional superheater in drum type HRSG design since Benson design steam temperature at evaporator outlet is 75 °C superheated, as described in the following paragraph.

4.3 Once Through Evaporator Arrangement

Below Fig. 6 shows HP Evaporator flow diagram and HP Evaporator arrangement developed for MPA Standard design.

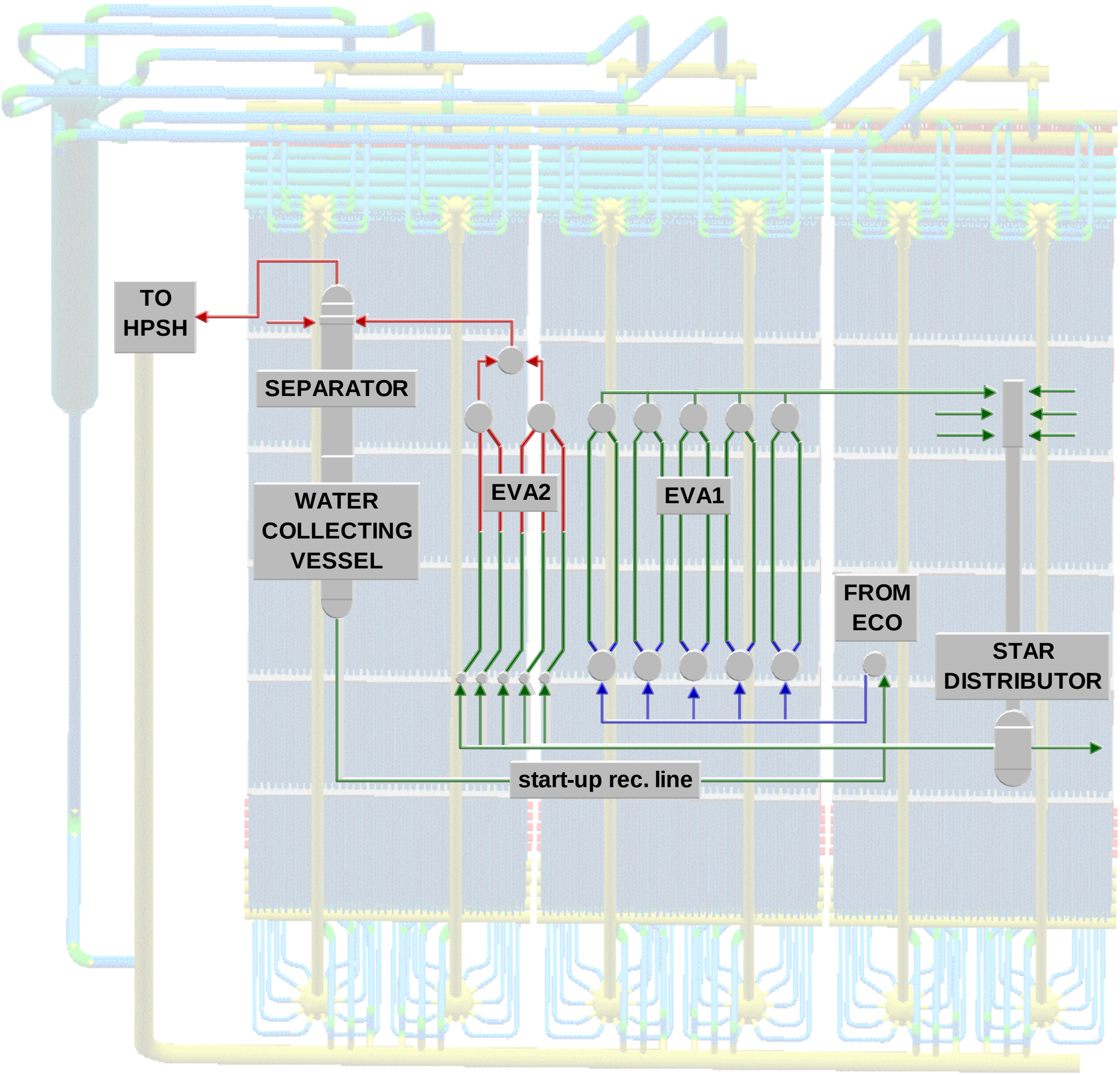

Fig. 6: Benson type evaporator: Top view and flow diagram

The HP evaporator consists of two partial sections (EVA1 and EVA2), connected in series on the exhaust gas side. Flow in each stage is in upward cross-flow arrangement. Wet steam flow leaving EVA1 is collected through risers and downcomers to the star distributors placed on the bottom of the evaporator, then it is distributed into the second evaporator stage EVA2. Flow at EVA2 outlet is about 75 °C superheated in order to have a sufficient range for a main steam temperature control by feedwater mass flow only during part loads and at varying ambient conditions. A piping system collects the steam to the separator and then to high pressure superheater. During start-up and at very low load condition flow at EVA2 outlet is wet steam and the separator splits steam from water which can be recirculated from the water collecting vessel to EVA1 through the start-up recirculation line.

Below Fig 7 shows the isometric view of MPA Benson type high pressure evaporator.

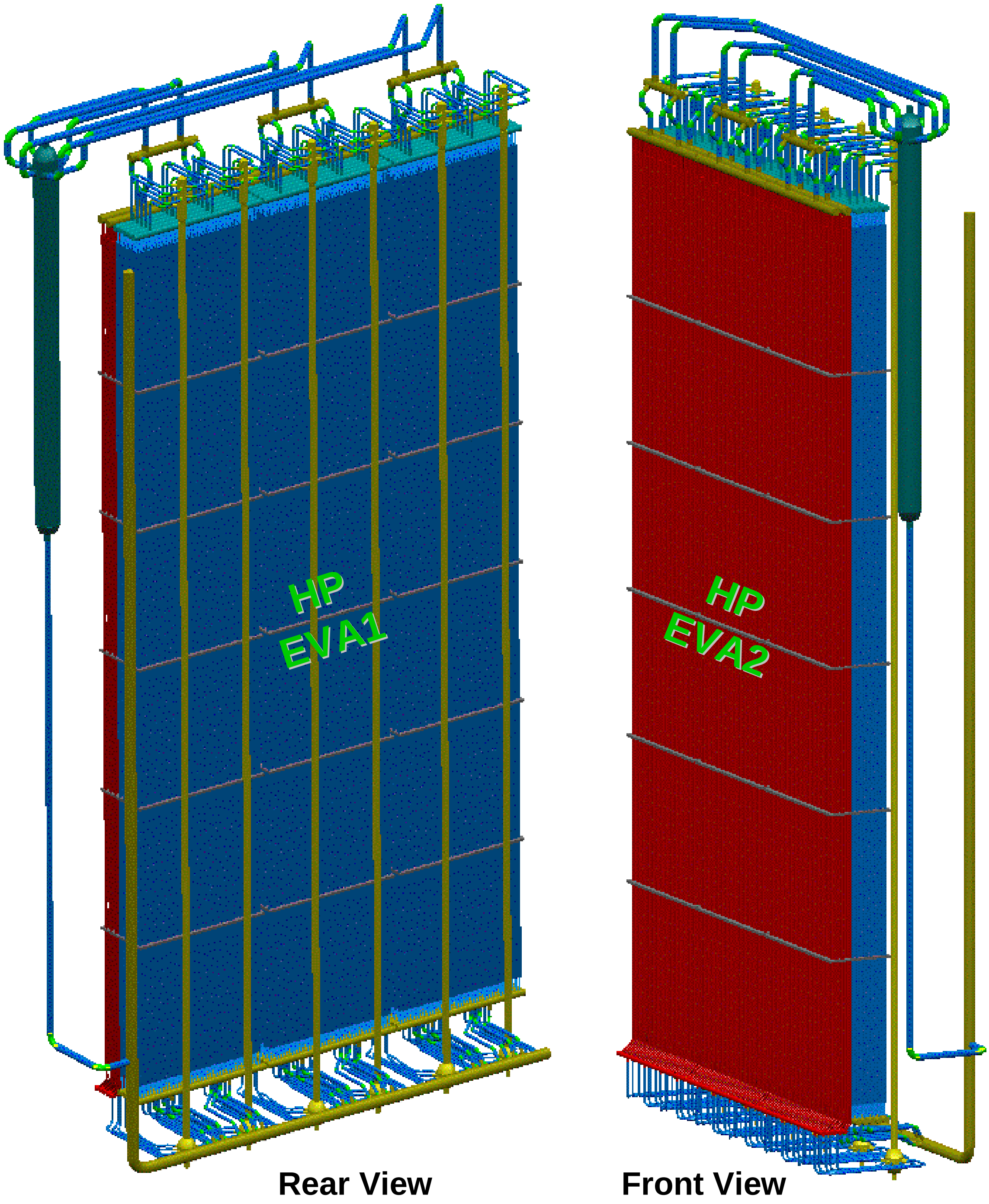

Fig. 7: Benson type evaporator isometric view

4.4 Thermal Performance comparison

Below Fig 8 shows drum type HP Evaporator main thermal performance data.

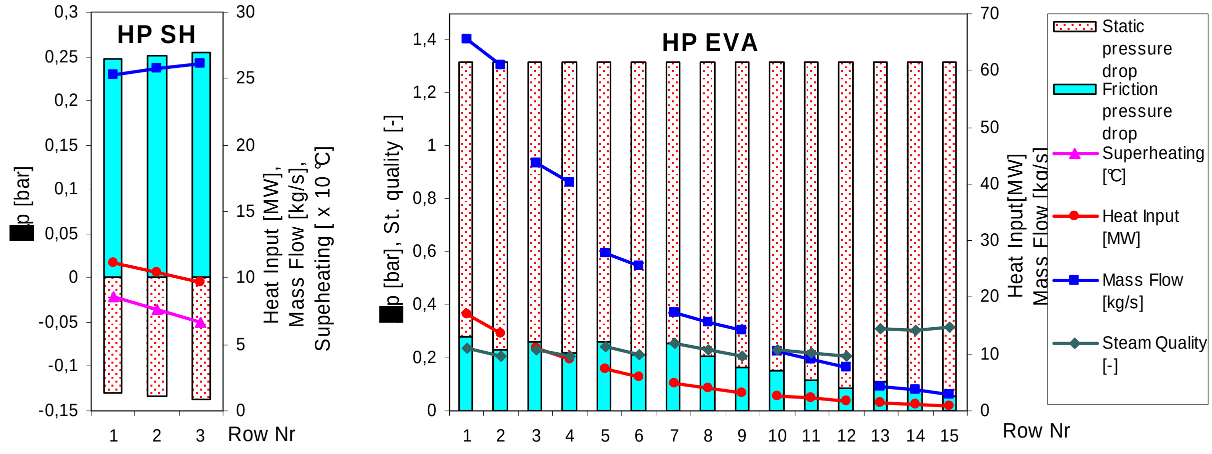

Fig. 8: Drum Type HP Evaporator Thermal Performance Diagram

Below Fig 9 shows Benson Type HP Evaporator main thermal performance data.

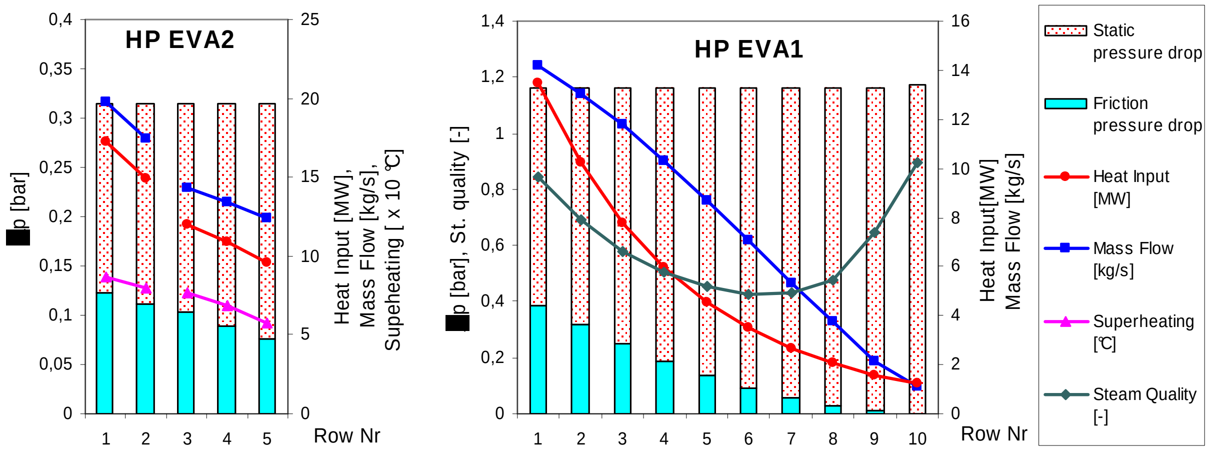

Fig. 9: Benson Type HP Evaporator Thermal Performance Diagram

EVA1 static head and friction loss bar chart shows how hydrostatic pressure drop decreases in the hottest tubes due to the increased steam fraction. In order to maintain the same overall pressure drop in all parallel circuits, steam water mixture flow increases in these tubes until frictional loss and static head sum is equal in all circuits. This is the basis of Siemens Benson technology, which ensures higher mass flow in the hottest tubes and lower mass flow in the coldest one and as a result steam quality at tube outlet is quite uniform along all parallel tubes. No individual orifice in the single tubes or tube rows is necessary.

Below Fig 10 shows high pressure evaporators pinch diagrams for both configurations.

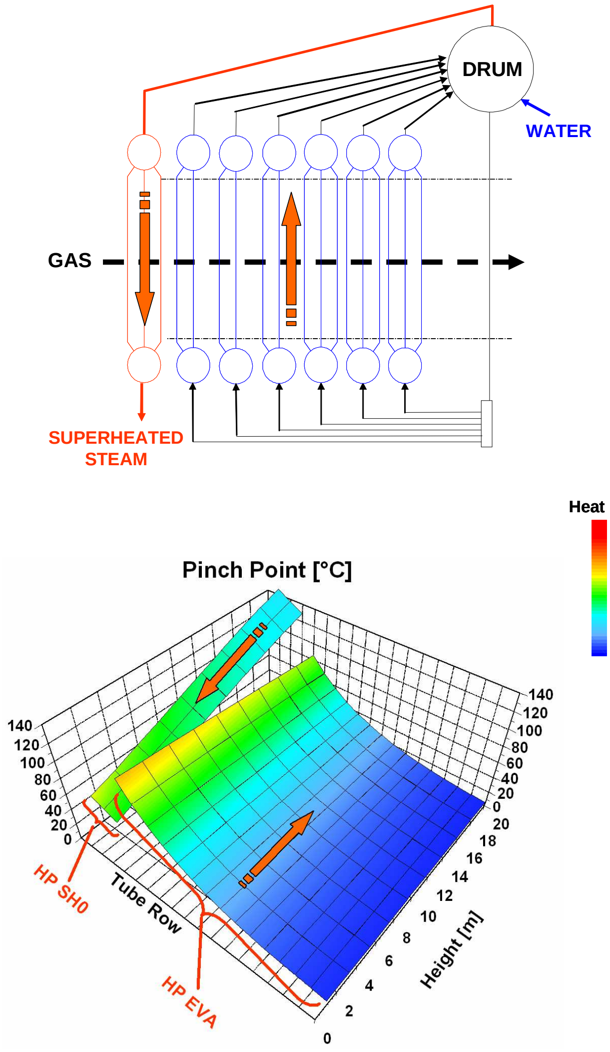

Fig. 10.1: Drum Type HRSG
HPEVA arrangement
ad pinch diagram

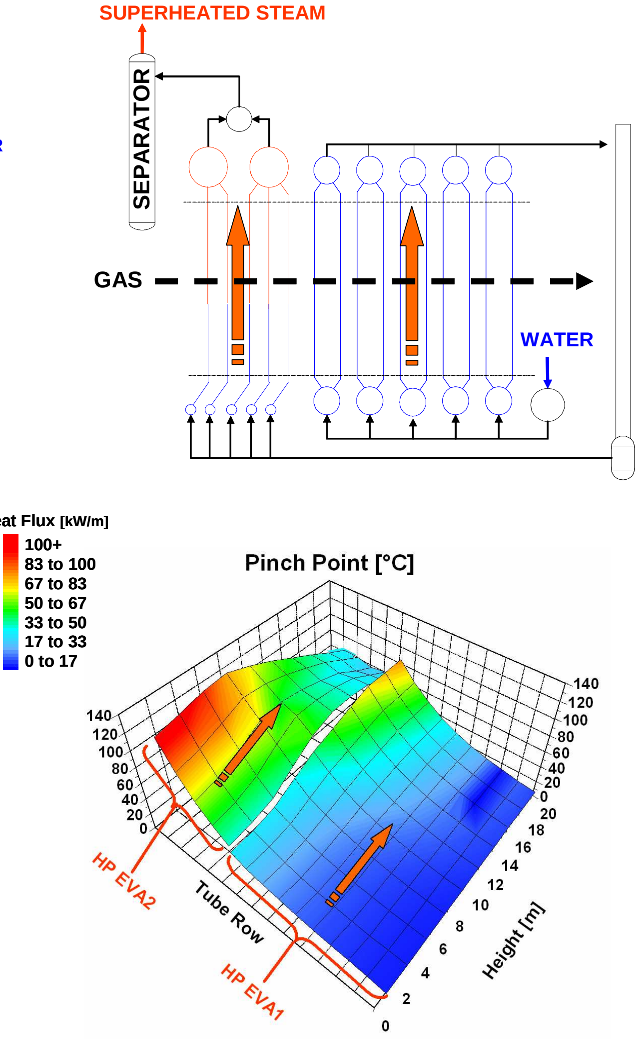

Fig. 10.2: Benson Type HRSG
HPEVA arrangement
and pinch diagram

4.5 Cycling behaviour comparison

The most interesting feature of Benson Once Through technology is surely the possibility to operate HRSG with elevated start-ups and the shutdowns gradients, which means fast start-up and short load variation time. This is due to the absence of high pressure drum that, because of the elevated wall thickness, strongly limits temperature gradients. The stresses induced by temperature gradients during start-up and shutdown cycles are in fact responsible of thick components fatigue life consumption.

A fatigue analysis has been carried out in order to optimise start-up time in consideration of the overall plant life consumption. To simplify the comparison only start-up and shutdown cycles has been taken into consideration without take into account load variations and abnormal cases like gas turbine trip.

The fatigue analysis and start-up optimisation has been carried out for three cases

- Drum type normal: typical start-up for drum type HRSG
- Drum type fast: drum type HRSG temperature gradient has been optimised during start-up in order to control fatigue life consumption.
- Benson type.

Fig. 11 shows the number of cycles taken into consideration, Fig. 12 shows the fatigue life consumption due to these cycles. Comparison of these figures shows how Benson type HRSG life consumption has been reduced up to more than 60% compared to drum type HRSG allowing higher number of cycles than those considered.

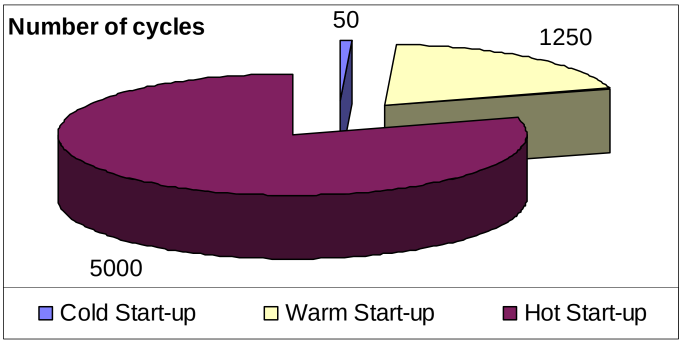

Fig. 11: Number of cycles considered

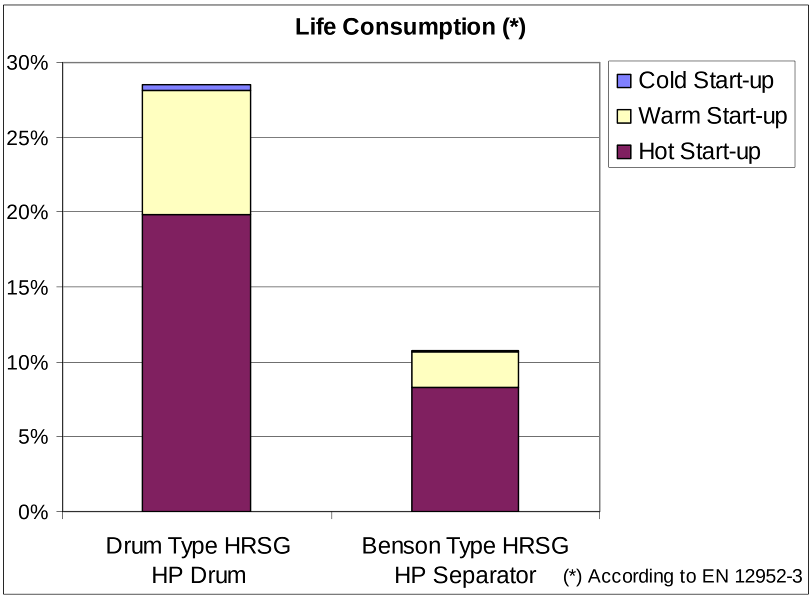

Fig. 12: Fatigue life consumption

Start-up curves of the above cases are presented in Fig. 13 (time for steam turbine warming has not been taken into consideration).

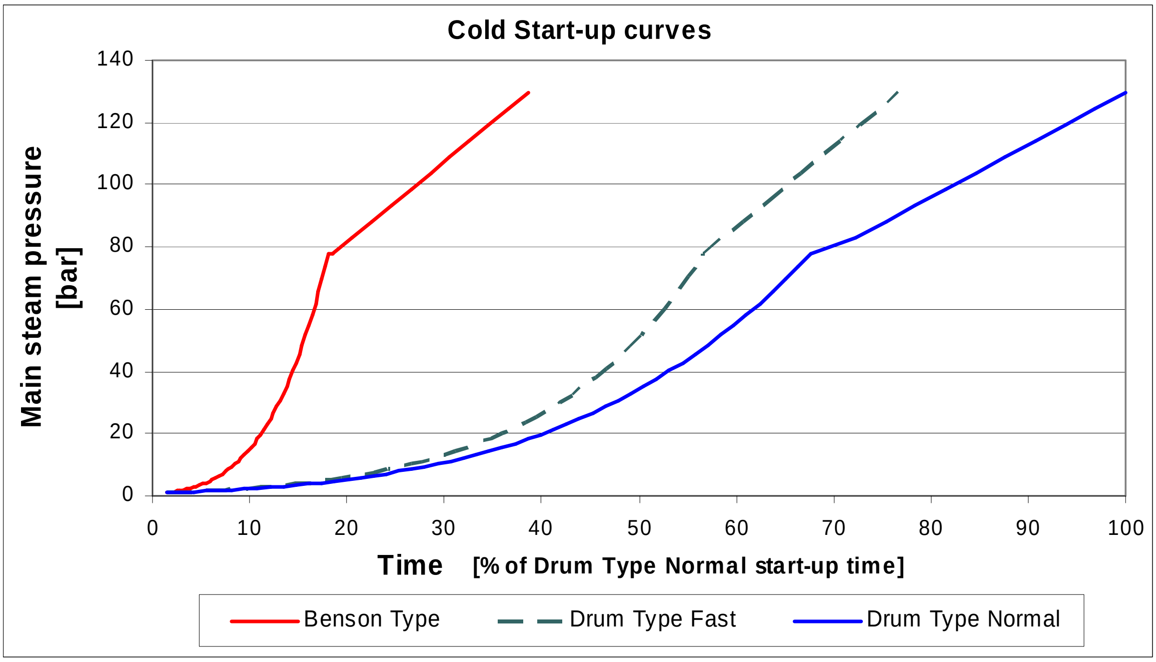

Fig. 13: Cold start-up curves comparison

It can be seen how the total start-up time has been reduced up to about 20% for drum type fast, and about 60% for Benson type.

4.6 Weight comparison

Below Fig 14 shows the comparison of drum type HP evaporator weights versus the Benson type one. This comparison is based on our standard design applied to Benson technology; other HRSG suppliers design could lead to different figures. It should be also pointed out that new Benson technology has not already been optimised as well known and consolidate drum type technology.

Main differences are:

- Absence of steam drum in Benson type HP evaporator system
- In Benson type, higher evaporator connecting piping weight due to the more complex internal piping.

- In Benson type, higher fin weight. Since mass flow in evaporators tubes is equal to steam production, our HP evaporator has been designed with the minimum number of parallel tubes in order to obtain the maximum flow. This involves the installation of maximum fin surface obtainable on a given number of tube rows.

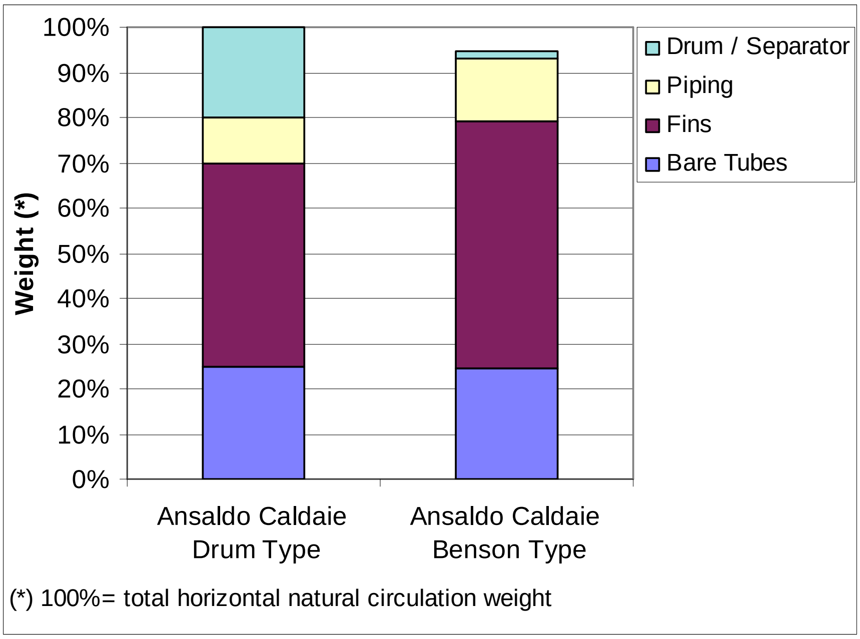

Fig. 14: High Pressure Evaporator Weight Comparison

5. CONCLUSION

An attempt to compare the Horizontal and Vertical HRSG designs has been carried out on the base of our experience. The vertical HRSG design presents some attractive advantages mainly connected with the possibility of inserting a HRSG in an existing utility boiler steel structure for re-powering. However, in case of green field applications, the overall weight of the vertical HRSG design remains well above the weight of the horizontal HRSG due to steel structure.

Natural circulation and Benson Once Through circulation have been compared on the base of the design activities up to now performed in the frame of the Siemens Benson technology. We have developed our own project for the OT HRSG and have dedicated special efforts to this design to meet important supply requests. The outcome of our Project confirms the features that are at the base of this technology allowing reduction of weights and optimum cycling performance.