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HRSG SYSTEM DESCRIPTION AND WATER-STEAM ANALYSIS AT THE HRSG COLD START-UP

OPIS SISTEMA HRSG IN ANALIZA VODE-PARE PRI HLADNEM ZAGONU

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Keywords: boiler, duct, flue gas, heat recovery, stack, steam generator, superheater

Abstract

The basic purpose of this paper is to present the HRSG system description in detail and possibility analysis of preventing the HRSH water-steam generated release into the atmosphere through the sky valves during the HRSG cold start-up. The steam released into the atmosphere by the cross sky valve is not an adequate solution for the following reasons: Noise prevention, water losses, thermal heat release into the environment, etc. In this paper, the possibilities and solutions are investigated in order to avoid the HRSG start-up sky venting. For this purpose, the steam quality data at HRSG cold start-up is analysed, and the possibility is examined of discharging the HRSG generated steam at the start-up via a new start-up pipeline into the existing dump condenser, or into the start-up flash tank or into the blowdown tank. The results show that, at the first 3 minutes of cold start-up, the HRSG generated only water, and this water should not be discharged into the HP or IP pipeline headers. The HRSG generates a mixture of water and steam only after 4 minutes from the start-up. For that reason it is not recommended to drain the water-steam mixture at the HRSG start-up into the new start-up pipeline, but it is recommended to drain the water and steam mixture formed during the HRSG start-up into the new start-up flash tank, or into the blowdown tank. The flash tank, and also the blowdown tank, should be appropriately dimensioned.

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Povzetek

Osnovni namen prispevka je podrobna predstavitev HRSG-ja in analiza možnosti zmanjšanja izpusta generirane pare v atmosfero ob hladnem zagonu. Izpust zagonske pare v atmosfero ni najboljša možna rešitev, saj se s tem poveča zvočna obremenitev okolja, odvod kotlovske vode in toplotne energije v okolje itd. V tem prispevku so analizirane možne rešitve preprečitve odvoda zagonske pare v atmosfero, tako da se mešanica vode-pare ob hladnem zagonu HRSG-ja odvede v novi zagonski parovod, separatorsko posodo ali v posodo za odvodnjavanje. Analizirani pa so bili tudi podatki kvalitete pare ob zagonu HRSG-ja. Rezultati pokažejo, da prve 3 minute HRSG generira samo vodo, ki pa se ne sme odvesti v HP oziroma IP zbiralno kom parovoda. Šele po 4 minutah HRSG prične generirati mešanico vode-pare. Zato se pri hladnem zagonu ne priporoča odvod generirane pare v novi zagonski parovod, ampak da se navedena mešanica vode-pare, ki nastane pri hladnem zagonu HRSG-ja, odvede v separatorsko posodo oziroma v posodo za odvodnjavanje. Navedeni posodi morata biti temu primerno dimenzionirani.

1 INTRODUCTION

The electricity production using a gas turbine and an electric generator can be provided in an open cycle plant, where the hot flue gases from the gas turbine are released through the stack directly into the atmosphere. The disadvantage of this process is the relatively low efficiency of the open cycle plant, which, in practice, ranges from 30% to 40%. If the open cycle is upgraded with a Heat Recovery Steam Generator (HRSG) and with the steam turbine, the realistically achieved efficiencies of this process range up to 85%. Such a process is called a combined cycle gas turbine. The operation of this type of combined cycle gas turbine in energy systems is called a combined heat and power plant.

The purpose of the HRSG is to recover the maximum of the remaining energy contained in the flue gas at the outlet of the gas turbine. The recovered heat is transferred to feedwater in order to produce steam at the 2 different pressure levels required by the steam turbine. The HRSG feeds a steam turbine. The gas turbines are fired with natural gas as the main fuel and light fuel oil as a back-up fuel. There is no bypass stack. Therefore, the boiler runs in line with the gas turbine. The HRSG scope includes heat exchangers, a boiler casing, boiler inlet and outlet ducts, district heating recirculation pumps, a flash tank, a blowdown tank, boiler drums, piping, valves, instrumentation and air distribution, and nitrogen distribution. The most important components of an HRSG are shown in Figure 1. The HRSG is of the vertical boiler type with natural circulation; the exhaust gases have an upward path while crossing the different exchangers. The heat exchangers are made of finned tubes installed horizontally, with return bends, between an inlet and an outlet header. They are shop-assembled in 5 modules: 5 modules on the height and 1 module on the width of the HRSG. Each exchanger is inserted into the vertical gas flow. A casing is constructed around them to form a sealed unit. The casing is manufactured from steel sheets, without any refractory concrete or water tubes panel, and is insulated internally on the whole HRSG from the inlet duct to the stack. All exchangers are hung on horizontal hot beams, which are supported by the main boiler steel structure. The casing is also supported by the steel structure. This design allows free expansion, downward and laterally. The HRSG stack is supported by the steel structure penthouse. The natural circulation principle is used within the boiler evaporator drum loops, high pressure (HP), and intermediate pressure (IP) through the thermosyphon effect. Two pressure levels are installed in the HRSG: The two circuits produce the steam flows at two different required pressures and temperatures.

The work done thus far in the above-mentioned area is based on an optimal synthesis and design of the HRSG, for which Manassaldi et al. [1] presented the HRSG mathematical programming. Ahmed et al. [2] carried out modelling and practical studying of the HRSG drum dynamics and approached the point effect on the control valves. Wang et al. [3] conducted an experiment and optimisation analysis of a new kind of once-through heat HRSG based on exergy and economy. Using the calculation method, Naserabad et al. [4] optimised HRSG configurations on the steam power plant`s repowering specifications. Moreover, Beaujardiere et al. [5], Mokhtari et al. [6] and Zebian [7] analysed HRSG operational performance. However, we have not yet identified an HRSG system description in detail in the available literature .

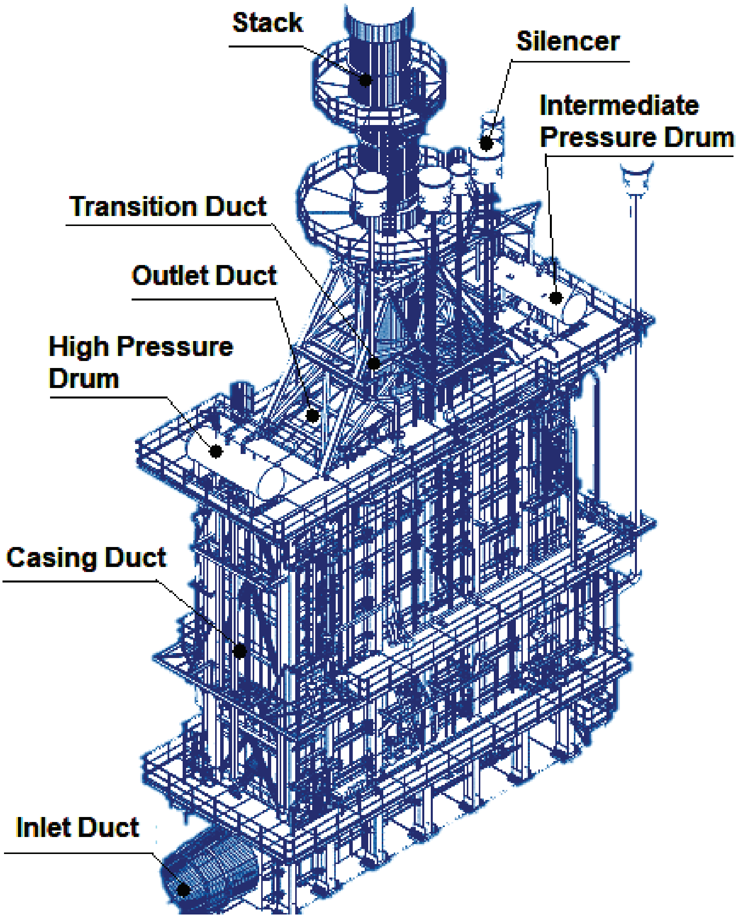

***Figure 1:** The most important components of an HRSG [8]*

A district heating system is installed to heat water coming from a district heating system and going to a district heating system. The district heater is recirculated with hot water in order to reach at its inlet at a minimum temperature above the acid dew point and a margin. This value is representative of the temperature at which sulphur may deposit on the tubes (flue gas acid, dew point temperature), and it is of prime importance to make sure that such a minimum water temperature (which depends on the sulphur content in the fuel) be matched, so as to avoid corrosion. A bypass line allows partial or complete bypassing of the district heater in order to control the final temperature of the water going to the DH system. The HP steam temperatures are controlled by water injection (through attemperators located on the HP superheaters line), ensuring adequate steam turbine inlet temperatures.

The structure of the paper is composed in such a way that the system description of the HRSG individual components, such as the HRSG pressure parts, HRSG non-pressure parts and steel structure are presented first. Then the system description of the auxiliary equipment is presented and the water-steam analysis at the HRSG cold start-up is carried out at the end.

2 SYSTEM DESCRIPTION

2.1 Pressure parts, description of the heat exchangers

Each heat exchanger is made up of horizontal finned tubes connected to each other by means of bare tube bends. The finned tubes are staggered in the tube bank. The fins are made of spiral steel strips. They are welded in a continuous way on the bare tubes. These fins are serrated. The tube quantity in a heat exchanger and the number of fins per metre are calculated in accordance with the required surface given by the heat balance of the boiler. The number of tubes in parallel depends on the water or steam flow. The fluid velocity in the tubes is selected according to the manufacturer`s experience. Appropriate material has been selected to avoid flow-assisted corrosion. The tube arrangement the width and length of the exchangers - is optimised in accordance with the gas velocity, the pressure drop, the water and steam pressure drop through the circuits and the shipment facilities. Each tube is simply supported on the tube sheets to allow free thermal expansion of the tubes. The touch points between tubes and tube sheets are the spiral fins: Wearing of the tubes themselves is, therefore, avoided. The heat exchanger modules are hung from the hot beams by means of prefabricated hangers. The HRSG cross-section with the 5 modules of heat exchangers is shown in Figure 2.

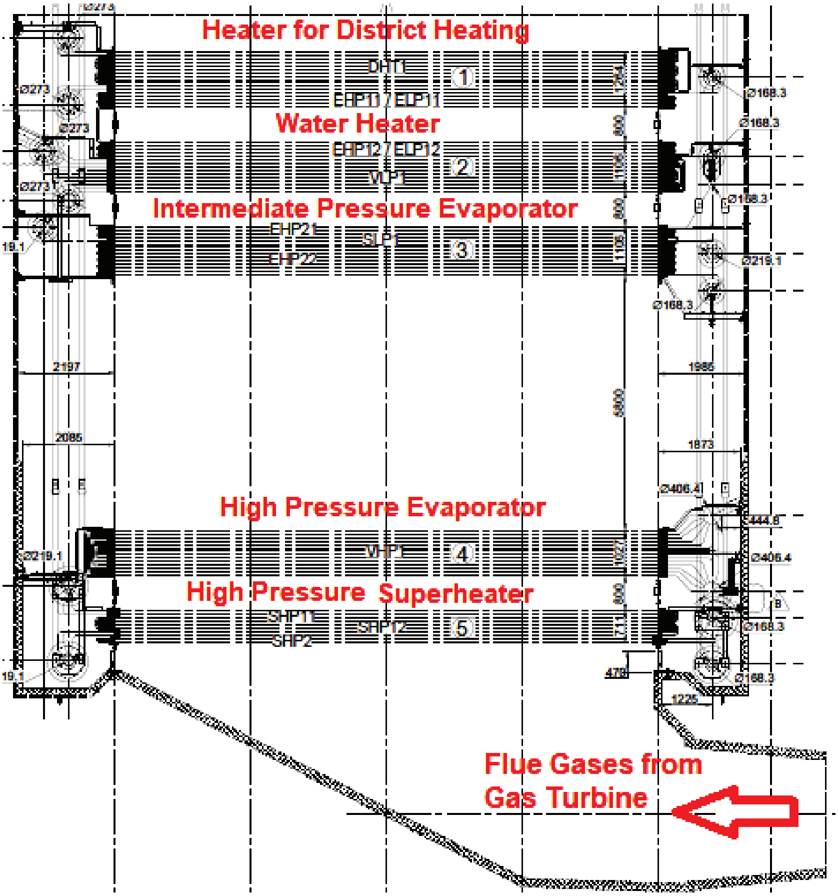

Figure 2: *The HRSG cross-section with the 5 modules of heat exchangers [8]*

The heat exchanger headers are enclosed in a box formed by the gas-tight boiler casing faces, the tube baffles and the closing plates, to avoid internal gas by-pass. The headers are provided with borescope holes in order to allow internal examination of each header. The heat exchangers are grouped in different sections to form an HP circuit, an IP circuit and a district heater circuit. In order to produce steam, the circuits comprise economisers, evaporators and superheaters. The functions of these heat exchangers are as follows:

- The economiser recovers the remaining heat contained in the flue gas at the evaporator outlet in order to heat up the water flow.
- The evaporator generates steam through a circulation loop to and from the HRSG drum.
- The superheater permits the saturated steam heating from the drum temperature up to the required value.
- The district heater circuit produces hot water for the district heating system by heating up the cold water coming from the district heating system. The water coming from the outlet of the district heater is recirculated in the district heater to increase the temperature at its inlet (the temperature depends on the actual sulphur content of the burnt gas in the gas turbine).

2.2 Pressure parts, natural circulation

The natural circulation through the HP / IP evaporators is ensured by the density difference between the water coming from the drum to the evaporator inlet header and the two-phase water/steam mixture between the outlet header and the return to the drum, as well as the transition phase that happens in the whole exchanger. During start-up, water flows naturally through the evaporator when the first bubbles of steam are generated. Natural circulation through the HRSG drum is shown in Figure 3.

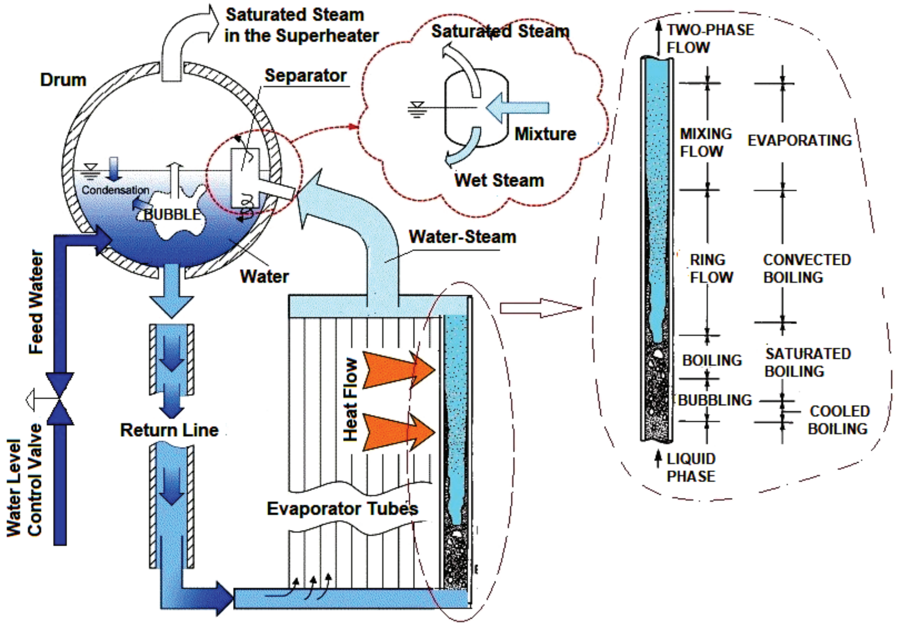

Figure 3: Natural circulation through the HRSG drum

2.3 Pressure parts, boiler drum description

The purposes of the boiler drums are multiple:

- To ensure a good mixing of the feedwater and boiler water;
- To constitute a water reserve in case of a feedwater pump trip (run-out-time);
- To allow water/steam expansion mainly during start-up, when the first steam produced in the evaporator sends back to the drum the water contained in the evaporator tubes (swelling effect), and
- To ensure the water and steam separation.

The steam and water separation is achieved by means of a mesh type separator installed in the upper part of the drum. The steam drums are equipped with all the required devices for their function:

- Mesh steam dryers;
- Steam distribution header;
- Water outlet (down comer) to the evaporator with an anti-vortex;

- Steam inlet nozzle from the evaporator, and
- Steam outlet nozzle to the superheater.

The HRSG drum is shown in Figure 4.

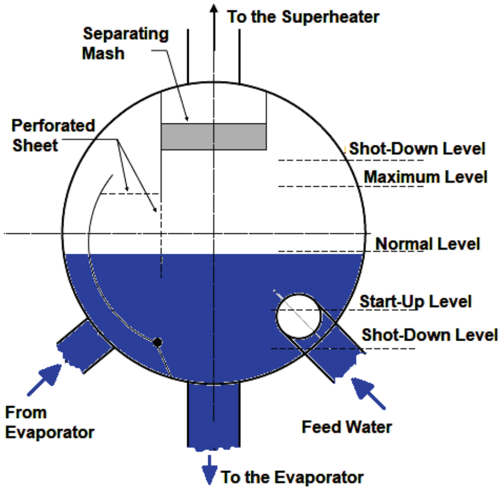

Figure 4: *The HRSG drum*

The HRSG equipment includes a manhole, nozzles for level measurement, pressure measurement, continuous and intermittent blowdown lines, nitrogen injection (on which the drum pressure gauges are connected, and skin temperature measurement for the drum. Connections between the drums and heat exchangers are realised by means of piping which is welded directly onto the drum nozzles, and, as such, all piping is free to expand without inducing any undue stress on the drum. In order to keep the drum level within the alarm limits during start-up (cold), it is necessary that the drum level is adjusted to the start-up level just above the low level. For the HP and IP circuits, the feedwater control valves are installed downstream of the economisers. Hence, the pressure inside the tubes is equal to the feedwater pump pressure, and is always higher than the pressure inside the drum (saturation pressure). Consequently, the risk of streaming is avoided.

2.4 Non-pressure parts, boiler casing

The complete heat exchangers with their headers and the tube sheets are within a gas-tight enclosure made of welded steel sheet panels, the boiler casing. Different to conventional boilers, the casing is made of steel sheets without any refractory concrete or water tube panels and is insulated internally and provided with a stainless steel liner. The casing is supported by the steel structure and is pressure resistant. Stiffeners are provided so that the enclosure can withstand the gas inner pressure. The boiler casing is equipped with access doors for internal inspection at each interblock level. The header boxes are equipped with closing plates to avoid flue gas circulation. The HRSG casing steel structure is shown in Figure 5 and the HRSG closing plates are shown in Figure 6.

Figure 5: *The HRSG casing steel structure*

Figure 6: *The HRSG closing plates*

2.5 Non-pressure parts, ductwork

The inlet ductwork and casing up to stack transition piece (outlet ductwork) are provided to convey the hot gases from the gas turbine exhaust to the boiler, then to the atmosphere. The ductwork is made of steel sheet panels internally insulated, provided with a stainless steel liner calculated to have a metal temperature of a maximum of 55°C. The inlet ductwork and casing to the stack transition up to the weather damper are insulated internally. No refractory concrete is installed in either the boiler nor in the ductwork; the thermal inertia is very low; the system allows rapid temperature changes without constraints, and the maintenance costs are minimal. As with the boiler casing, adequate stiffeners are installed on the ductwork to withstand the inner gas pressure. The whole exhaust system is designed for 0.05 design pressure. The inlet ductwork, i.e. the layout of the gas duct between the gas turbine and the boiler, is drawn in accordance with the site requirements, as indicated on the general arrangement drawing. The outlet ductwork is the boiler outlet duct, which is the transition piece between casing and stack. It has a gas exhaust function. The boiler sectional area is reduced through the outlet duct, in order to increase the gas velocity to the specified gas velocity.

2.6 Non-pressure parts, boiler stack

The HRSG main stack is a cylindrical section, and is constructed as follows: Carbon steel sheets which withstand all stresses due to the stack weight, wind and seismic loads. Outside this shell, heat insulation covers the stack. The thickness of this heat insulation is designed for personal protection, and aluminium cladding is provided to cover the heat insulation. The stack is equipped with aviation warning lights. Aircraft warning lights will conform to the Standard. The top elevation of the stack and its diameter are respectively 65 m and 2,66 m. Figure 7 shows the HRSG upper part stack lifting.

Figure 7: *The HRSG upper part stack lifting*

2.7 Non-pressure parts, inlet duct and elbow duct

The inlet duct casing and elbow duct casing are made of carbon steel material, insulated internally and covered in steel sheeting. The inlet duct panels are also insulated internally. The conception and the design of the inlet duct casing are shown in Figure 8.

Figure 8: *The HRSG inlet duct erection*

2.8 Auxiliary equipment

2.8.1 Pressure relief valves

The pressure relief valves are selected according to the codes and specifications for the material, quantity, set point and capacity. Valves are provided on the superheaters for the steam part, with a sensor line connection from the drum and on the economisers, and district heater lines for the water part. The steam pressure relief valves are controlled by a pneumatic control unit (fed by instrument air). A triple redundancy of pressure switches is present during the operation, 1 on the drum and 2 at the outlet of the superheater. All the steam pressure relief valves are welded. The steam pressure relief valves discharge to the atmosphere by means of a vertical exhaust pipe equipped with a silencer.

2.8.2 Blowdown tank

The Blowdown tank is a vertical tank whose function is to collect all drains from the boiler, and to allow the water expansion and flashing-up to the atmospheric pressure. The drains are connected to the horizontal inlet headers fitted tangentially to the tank, in order to permit the steam/water separation by centrifugation. Continuous, intermittent blowdown drains and steam drip leg drains are provided with motor operated valve control from the control system. Its shell is fitted with an internal shield to protect it against erosion. The resulting steam is simply blown into the atmosphere by means of a vertical exhaust pipe equipped with a silencer to limit noise, and water is discharged to the HRSG plant drain system by means of an extraction pumping system. The heat-insulated blowdown tank is equipped with two level transmitters to ensure water availability for the blowdown pumps. The blowdown tank is shown in Figure 9.

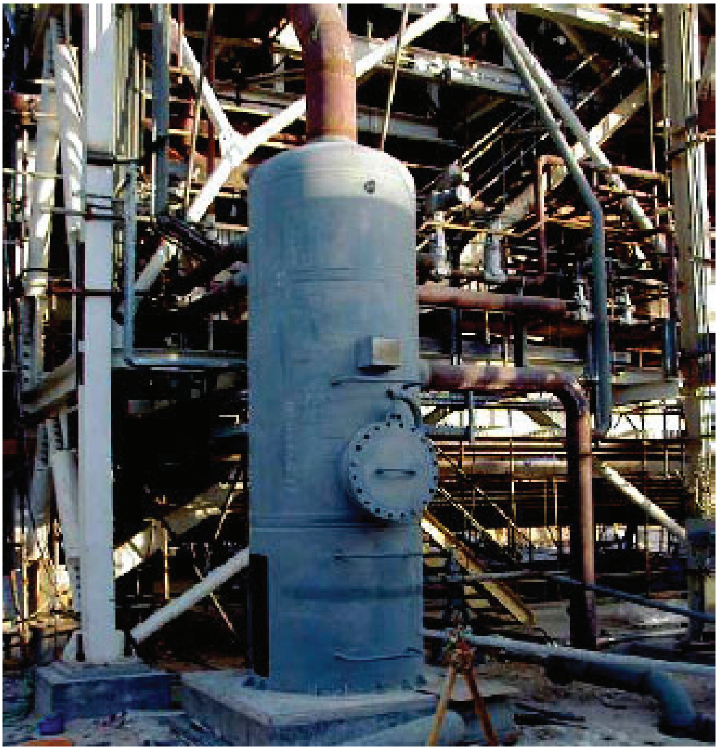

Figure 9: *The Blowdown tank*

2.8.3 Weather protection damper

A weather damper is provided at the top of the HRSG, within the stack. Its function is to prevent rain from falling inside the HRSG during a stoppage, and to break the natural draught during a stoppage in order to keep the HRSG as hot as possible. This damper, made mainly from carbon steel, is equipped with an electric actuator, with all the necessary devices to prevent the damper being closed during the operation, and also with a rainwater disposal system. Furthermore, this damper is self-opening when the gas pressure reaches approximately 10 mbar. The HRSG water dumper is shown in Figure 10.

Figure 10: *The HRSG water dumper drive*

2.8.4 Attemperators

The HP circuit is equipped with one inter-stage, spray type attemperator, located in the superheater's lines. The steam pipe will have a thermal liner. When the control loop requests a steam temperature reduction, a pneumatically operated control valve opens and water is sprayed into the main steam piping to control the steam temperature within from 3 °C to 5 °C during steady state operations. The HP attemperation water is a mixture of cold and hot water extracted from the HP economiser inlet and the HP economiser outlet.

2.8.5 Sparging

During short-term outages, it is preferable to maintain the pressurised HRSG sections in order to provide freezing protection, to avoid oxygen ingress, and to minimise the thermal stresses in the pressure part components during the next restart-up or cold start-up of the plant. An arrangement for injection of auxiliary steam has been provided on the HP side, which allows the drum pressure to remain above the atmospheric pressure while compensating for natural heat losses.

3 WATER-STEAM ANALYSIS AT THE HRSG COLD START-UP

The basic purpose of the analysis was to examine the possibility of preventing the release of steam into the atmosphere through the sky valve during the HRSG cold start-up. Steam emitted into the atmosphere through cross sky valves is not an adequate solution; heat is released into the environment, water is lost and unnecessary additional noise is caused. The possibility of finding a better solution is examined for that reason and the steam quality and possibility of discharging this steam via a new start-up pipeline into the dump condenser is analysed for that purpose.

3.1 HP water-steam quality analysis at the HRSG cold start-up

The HP water-steam analysis was based on a data set obtained from the supervisory control and data acquisition (SCADA) [9]. The data set of the HP water-steam mass flow during the HRSG cold start-up is shown in Figure 11 (a), the HP water-steam temperature during the HRSG cold start-up is shown in Figure 11 (b) and the HP water-steam pressure during the HRSG cold start-up is shown in Figure 11 (c).

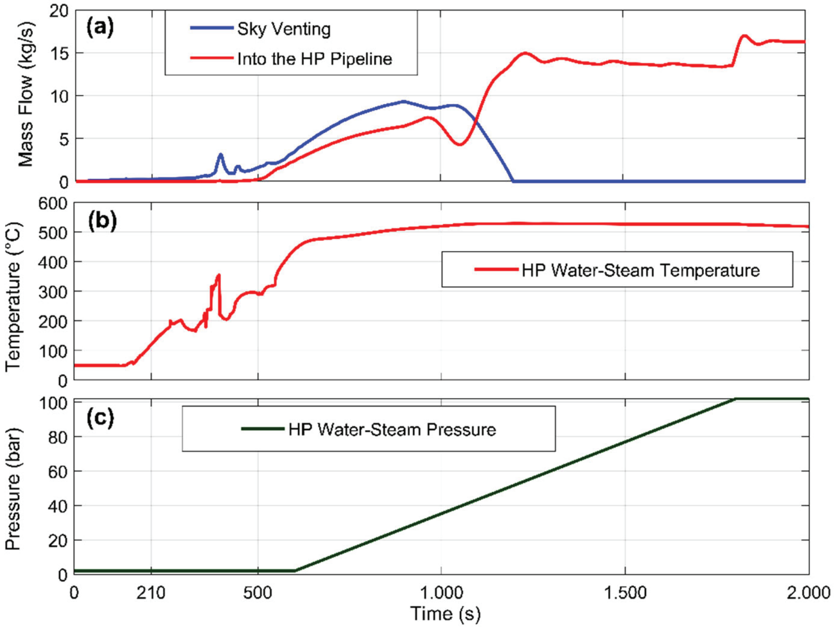

Figure 11: *The HP water-steam data set at the HRSG cold start-up; (a) The HP water-steam mass flow; (b) The HP water-steam temperature, and (c) The HP water-steam pressure*

The HP water-steam density during the HRSG cold start-up into the atmosphere is shown in Figure 12.

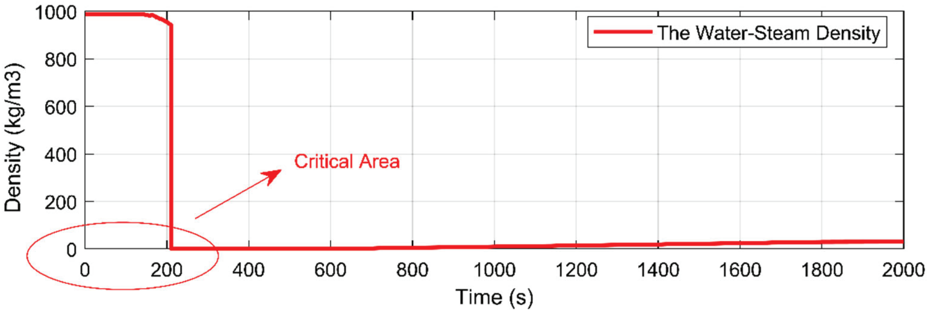

Figure 12: *The HP water-steam density during the HRSG cold start-up*

As shown in Figure 12, for the first 210 seconds from the HP part of HRSG, at the cold start-up, only the water is performed and released, the Critical Area. After 210 seconds the wet steam is generated and is flowing out from the HP part of the HRSG. The formed mixture at this time cannot be transferred either into the steam header or released through sky valves. For the first 210 seconds from the HRSG cold start-up, the HP water and water-steam mixture should be directed into the special blowdown tank, Figure 9. The water-steam density, depending on pressure and temperature, is shown in Figure 13.

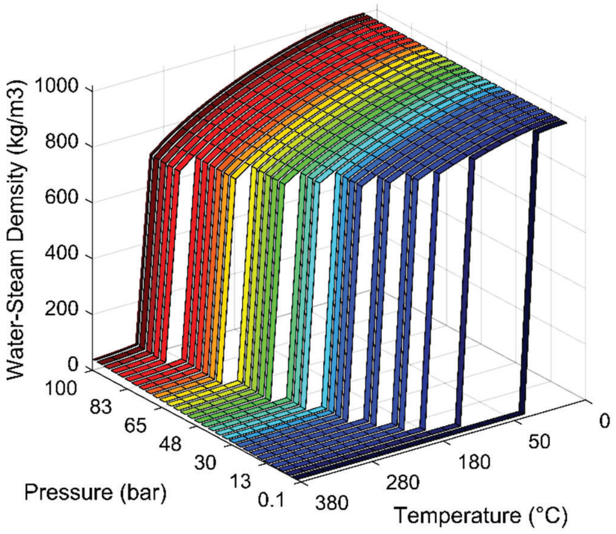

Figure 13: *The HP water-steam density depending on pressure and temperature*

3.2 HP water-steam velocity analysis at the HRSG cold start-up

In the case that the water-steam during the HRSG cold start-up would be discharged into the new start-up pipeline and not released into the atmosphere, the needed pipe diameter has to be calculated so that the steam velocity shall not exceed 50m/s. Several calculations of water-steam velocity were performed for this reason. The water-steam average velocity is dependent on the water-steam density, water steam mass flow, and the pipe`s inner diameter. The following equation was used for the water-steam average velocity calculation [10]:

$$v_a = \frac{4\cdot\dot{m}_{w-s}}{\pi\cdot\left(\frac{D_{ou}-2\cdot W_t}{1000}\right)^2\cdot\rho_{w-s}\cdot n_{pi}} \tag{3.1}$$

where v_a is the water-steam average velocity, $\dot{m}_{w-s}$ is the water-steam mass flow, π is a circular constant, D_{ou} is the pipe outer diameter, W_t is the pipe wall thickness, ρ_{w-s} is the water-steam density, and n_{pi} is the number of pipes. The water-steam density is a function of water-steam pressure and water-steam temperature, and is calculated by a special computer program, Matlab, X-Steam, which can calculate the remaining properties of the steam based on two known thermodynamic properties. The water-steam density is calculated as follows [11]:

$$\begin{matrix}\xrightarrow{p_{w-s}}\\ \xrightarrow{T_{w-s}}\end{matrix}\left[\text{XSteam}\right]\xrightarrow{\rho_{w-s}} \tag{3.2}$$

where p_{w-s} is the water-steam pressure and T_{w-s} is the water-steam temperature. The water-steam velocity in the new start-up pipeline at the different inner pipe's diameters is shown in Figure 14.

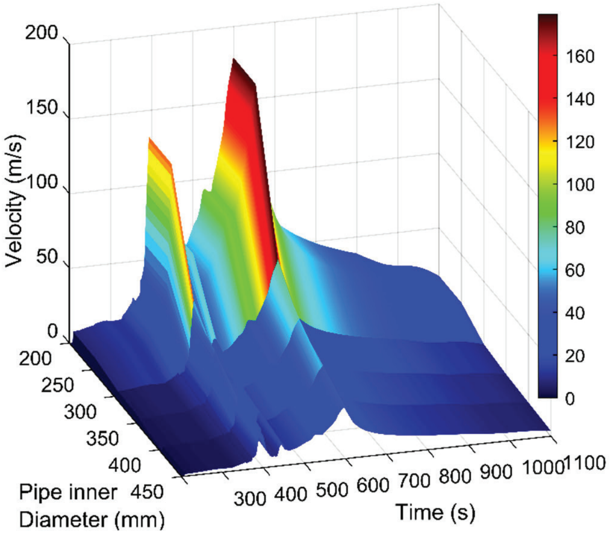

Figure 14: *The water-steam velocity in the new start-up pipeline at the different inner pipes` diameters*

The HP water-steam velocity analysis is based on the HP water-steam properties at the HRSG cold start-up, Figure 11. The HP water-steam analysis, Figure 14, shows that the maximum HP water-steam velocity when the 200 mm pipeline˙s inner diameter is 179 m/s, after 600 seconds from the HRSG cold start-up. At the pipe inner diameter of 250 mm, the maximum water-steam velocity was 117 m/s after 600 seconds from the HRSG cold start-up. The maximum velocity of the HP water-steam at the 300 mm pipe inner diameter was 79 m/s, the maximum velocity of the HP water-steam at the 400 mm pipe inner diameter was 45 m/s, and the maximum velocity of the water-steam at the 450 mm pipe inner diameter was 35 m/s after 600 seconds from the HRSG cold start-up.

The HP water-steam results analysis shows that the new start-up pipeline inner diameter should be at least 300 mm. The new start-up pipeline should be horizontal, very long, about 100 m long and, due to the flow of the water-steam mixture in the pipeline, this solution is not recommended. For that reason, it is recommended to integrate a new start-up flash tank into the HRSG system or existing blowdown tank, for which appropriate dimensions can be used. The HP water-steam at the HRSG cold start-up will be discharged into the new start-up flash tank or existing blowdown tank, where the HP water-steam mixture will be separated into the water and the steam. The water will be discharged across the existing blowdown tank into the water tank for district heating, and the steam will be discharged into the low-pressure steam pipe.

3.3 IP water-steam quality analysis at the HRSG cold start-up

The IP water-steam analysis was based on the data set obtained from SCADA. The data set of the IP water-steam mass flow during the HRSG cold start-up is shown in Figure 15 (a), the IP water-steam temperature during the HRSG cold start-up is shown in Figure 15 (b), and the IP water-steam pressure during the HRSG cold start-up is shown in Figure 15st (c).

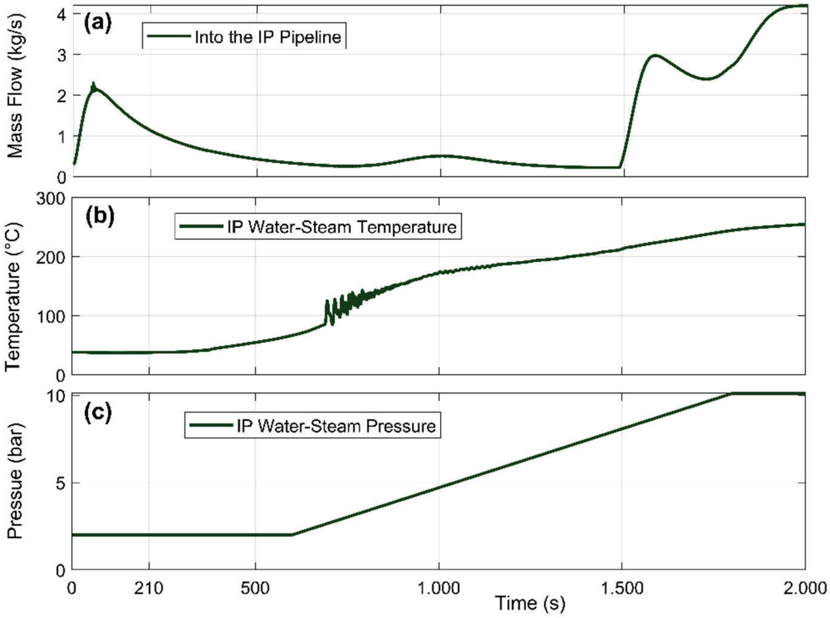

Figure 15: *The IP water-steam data set at the HRSG cold start-up; (a) The IP water-steam mass flow; (b) The IP water-steam temperature, and (c) The IP water-steam pressure*

The IP water-steam density during the HRSG cold start-up into the IP pipeline is shown in Figure 15.

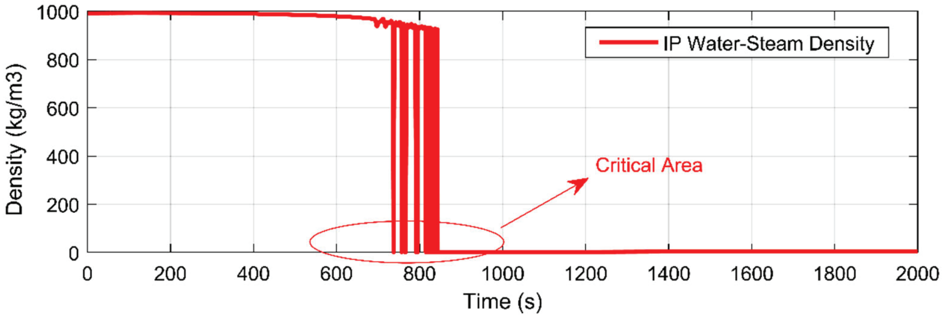

Figure 16: *The IP water-steam density during the HRSG cold start-up*

As shown in Figure 16, for the first 850 seconds, from the IP part of the HRSG, only the water is performed and released, the Critical Area. After 850 seconds from start-up the wet steam is generated and is flowing out from the IP part of the HRSG. The formed mixture at this time cannot be transferred into the IP steam header or into the IP pipeline. In the first 210 seconds from the HRSG cold start, the IP water and water steam mixture should also be directed into the special blowdown tank.

3.4 IP water-steam velocity analysis at the HRSG cold start

The IP water-steam velocity in the IP HRSG project-designed pipeline was analysed at the contractor predicted inner diameter of 204 mm. The IP steam velocity in the 204 mm designed IP pipeline inner diameter is shown in Figure 17.

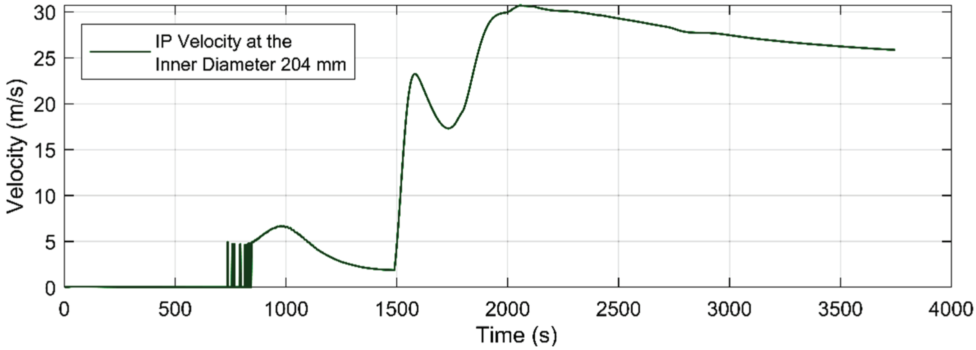

Figure 17: *The IP steam velocity in the 204 mm designed IP pipeline inner diameter*

The IP water-steam velocity analysis was based on the IP water-steam properties at the HRSG cold start-up, Figure 15. The IP water-steam analysis, Figure 17, shows that the maximum IP water-steam velocity at the 204 mm pipeline inner diameter was 31 m/s, after 2050 seconds from the HRSG cold start-up. The IP water-steam velocity analysis shows that the IP pipeline is properly dimensioned. In the first 700 seconds, Figure 16, the HRSG generated only the water; also, the IP pipeline was horizontal and very long, about 100 m, and this water should not be discharged directly into the IP pipeline. Also, at the HRSG start-up, the IP water should be discharged into the special blowdown tank.

4 CONCLUSIONS

The paper presents the HRSG system description in detail and the possibility of preventing the HRSH water-steam-generated release into the atmosphere through the sky valves during the HRSG cold start-up. The water-steam velocity, quality and mass flow from the HP and the IP HRSG parts are analysed during cold start-up. The results show that the first mixture of water and water-steam that is formed in the HP and IP HRSG parts should not be discharged into the HP or IP pipe header. The HP and IP pipelines are mounted horizontally at about 100 m. For that reason, it is recommended that a new start-up flash tank with appropriate dimensions can be integrated into the HRSG system or existing blowdown tank with appropriate dimensions . The water and water-steam can be separated from the water and the steam. The water can be discharged into the water tank for district heating purposes, and the steam can be discharged into the low-pressure steam pipeline.

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Abbreviations	(Symbol meaning)
HP	high pressure
HRSG	heat recovery steam generator
IP	intermediate pressure
SCADA	supervisory control and data acquisition

Parameters	(Symbol meaning)
D_{ou}	pipe outer diameter, mm
$\dot{m}_{w-s}$	water-steam mass flow, kg/s
n_{pi}	number of pipes
p_{w-s}	water-steam pressure, bar
T_{w-s}	Water-steam temperature, °C
v_a	water-steam average velocity, m/s
W_t	pipe wall thickness, mm
π	circular constant, 3,14
ρ_{w-s}	water-steam density, kg/m^3