Boiler design at Ultra Supercritical steam parameters (653ºC/672ºC - 303/60 bar)

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Abstract:

USC steam parameters allow lower fuel consumption and hence lower CO_2 emission due to higher steam parameters increase the overall power plant efficiency. The most common parameters occurring in the modern power plant units are: live steam temperature of **610°C**, pressure of **280 bar** and re-heated steam **620°C/55 bar**. The average efficiency of such power plant is about **45-46%**. The studies show that power plants with efficiency over **50%** and parameters of live steam temperature **720°C/350 bar** and re-heated steam **760°C/75 bar** are currently not feasible. RAFAKO proves that boiler construction and operation at following parameters: live steam **653°C/303 bar** re-heated steam **672°C/60 bar** is possible today. A power plant equipped with such a boiler will produce:

- **ca 2,250** tons of steam per hour with **≥94%** efficiency of the boiler,
- **ca 900 MW** output power with efficiency **≥48%** net,

and can prove to be the right response to low CO_2 emission demand.

This paper includes selection of the heating arrangement, thermo-mechanical arrangement, concept of the furnace arrangement and latest studies and analyses of materials used in construction of the boiler pressure elements. This article also presents the results of RAFAKO investigation on weldability of T24, T23 and other steels and alloys. Research of materials has been carried out jointly with the best centers and universities in Poland and Europe. The concept of RAFAKO boiler requires the application of 15% austenitic steel and **only** 5% nickel base alloy. Selected materials are designed in accordance with the applicable European Standards, approved for pressure elements, calculated at 200,000 hours lifetime and can be purchased from selected manufacturers. This boiler design is treated by RAFAKO as their fully commercial offer.

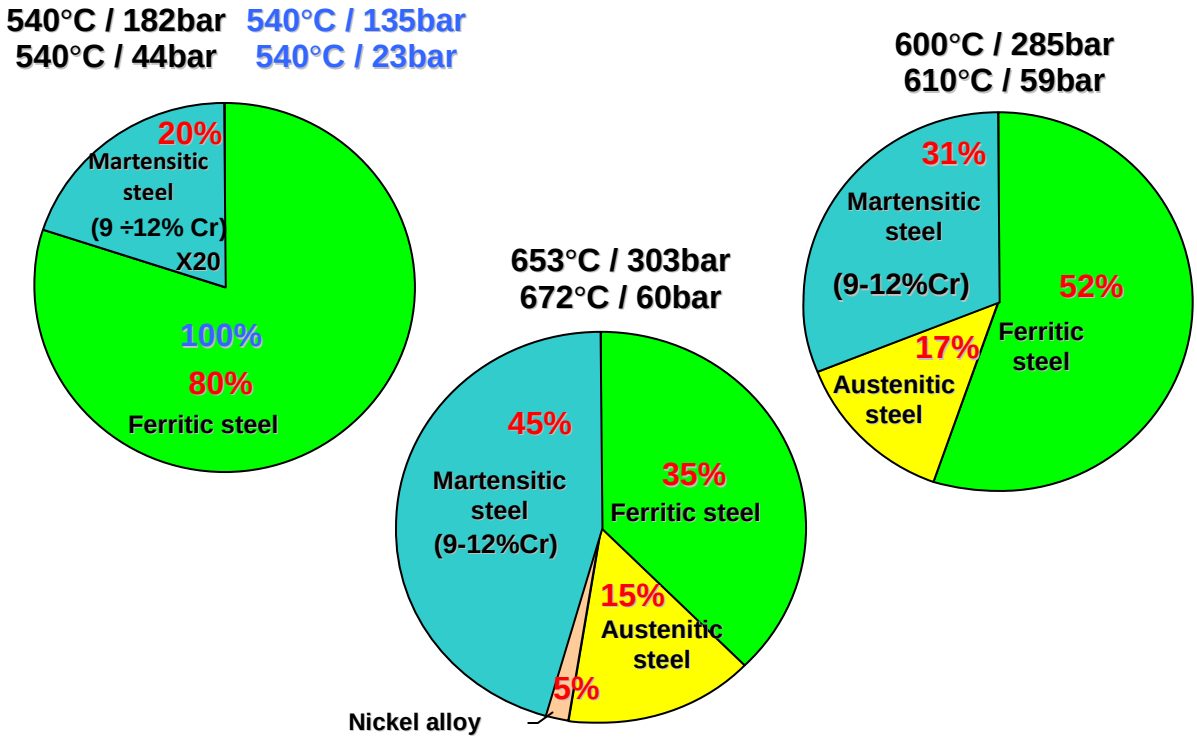
Introduction.

This paper is a part of a project carried out jointly with the National Centre of Research and Development and Universities from across Poland and Europe. The idea of the project was to develop a power plant unit with efficiencies above 50%. The designers of RAFAKO S.A. set themselves the goal to design a boiler to be manufactured using materials available on the industrial market. Realization of the tasks began by identifying the critical elements of the boiler. The next step was to analyze the world's steel market, selection of the materials and calculation of the maximum temperature at which the selected materials can operate. All

pressure elements of the boiler were calculated in accordance with the current European Standards. The project implementation of the boiler has been treated as ordered by the investor.

"Evolution of the materials"

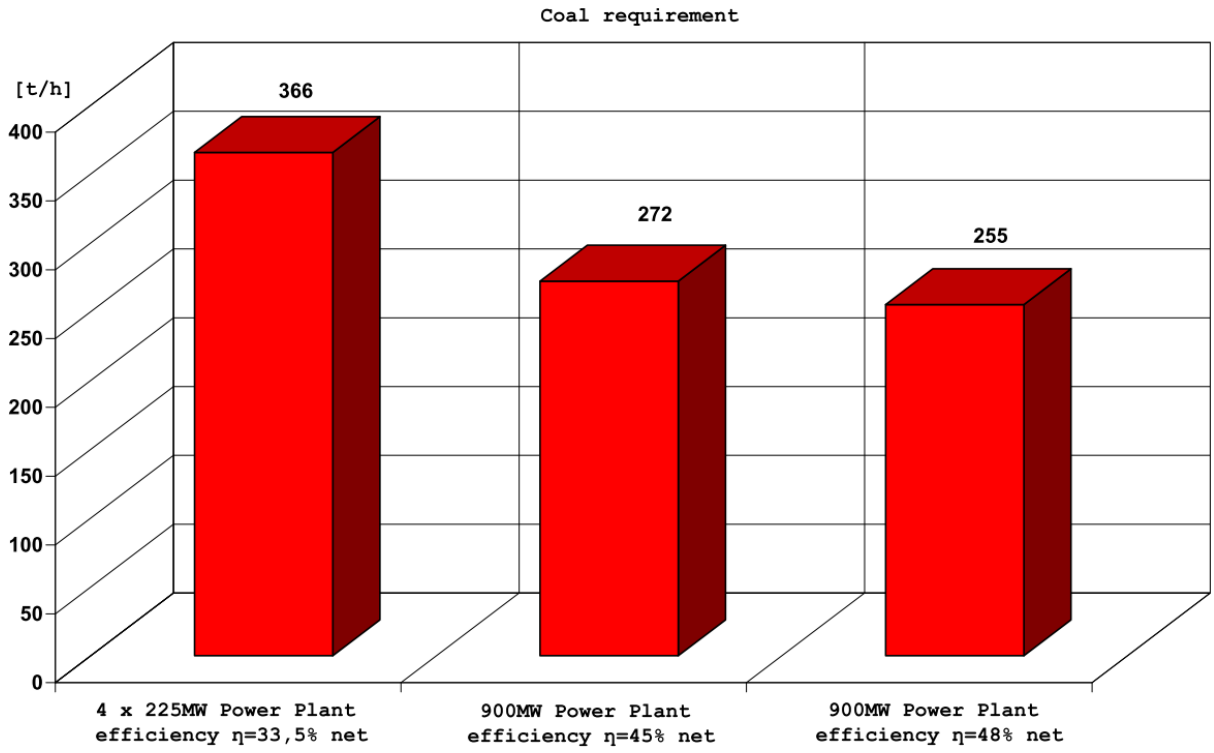
Using extensive experience in the construction of conventional boilers, RAFAKO developed a map of changes in materials. The changes are called "evolution of the materials". Below, there is an evolution scheme with changes in materials which have taken place in the construction of the boilers built by RAFAKO.



Scheme 1. "Evolution of the materials" in boilers over the years[1].

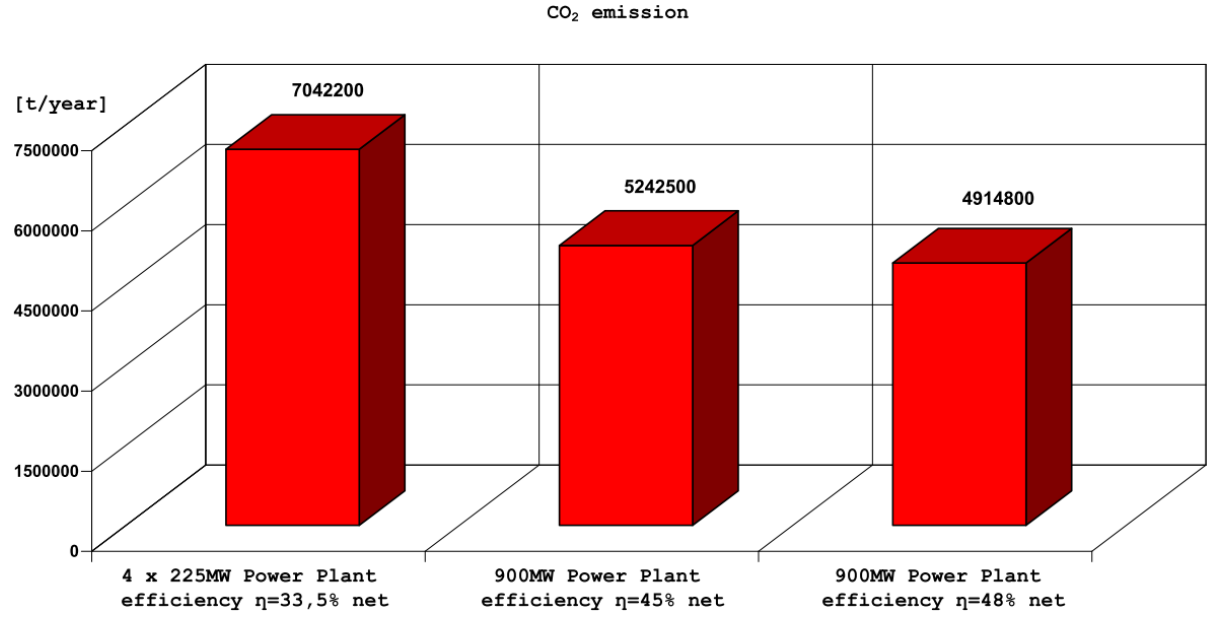
The graph illustrates how with the increase of outlet steam parameters materials have changed in the construction of the boiler. As you can see with increasing temperature and pressure for the construction of the boilers "new materials" appeared. For low steam parameters, the designer used conventional ferritic and martensitic steels. In boilers "600ºC" we used about 17% austenitic steels. For boilers with higher steam parameters it is necessary to apply nickel base alloy. Higher outlet steam temperature provides higher efficiency of the power plant, lower fuel consumption and hence lower CO_2 emissions. On schemes 2 and 3 we can see the dependency of coal consumption and CO_2 emission on the efficiency of the

power plant. Power plant operated with the efficiency 33.5% net consumes **ca 370** tons of coal per hour. It means that during one year this power plant will need **ca 3,000,000** tons of good quality coal and it will be **ca 900,000** tons more than power plant operated with the net efficiency of 48%.



Scheme 2. Hourly coal requirement for 900MW Power Plants.

If we look at scheme 3, we can see that the power plant operated with the efficiency of 33.5% net emits **ca 7,042,200** tons of CO_2 per year.



Scheme 3. Yearly CO_2 emissions for 900MW Power Plants.

If we compare this emission to the emission of the power plant operated with efficiency 48% net we have **ca 2,100,000** tons fewer of CO_2 emission per year. All these data were calculated for coal with the following specification:

- W_d = 24,6 [kJ/kg] (calorific value)
- A^r = 18% (ash content)
- W_r^r = 8% (moisture content)
- S^r = 0,6% (sulphur content)
- C_r^r = 64% (carbide element content)

Availability of the power plant will be not less than **8,200** hours per year.

Critical elements of the boiler

The critical elements of the boiler are the final elements of the live steam heater, reheater and pipelines connecting boiler with turbine. For these components materials of the highest strength properties for creep rapture, of superior resistance to high temperature corrosion at flue gas side and oxidation at steam side were selected. All pressure elements have been converted by TRD-EN program and some are additionally converted by the Finite Elements Method. As conditions of edge calculations the manufacturing possibilities of steal suppliers have been established. The results of these calculations are presented in two following tables.

The proposed materials and dimensions Superheated steam parameters: T_{medium}=653 [°C]; p_{medium}=303 [bar]						
Element	**Material**	**Overall dimensions**	**Oversize steel (C_1)**	**Operating oversize (C_2)**	**Calculation parameters t_{cal}**	**p_{cal}**
-	-	[mm]	%	[mm]	[^{O}C]	[MPa]
coils	X6CrNiNbN25-20 (20%)	Ø42.4x8	±12,5%	0.93	645	32
	NF709 (20%)			0.5	660	32
	HR6W (20%)	Ø42.4x8.8		0.61	674	32
	Sanicro 25(20%)			1,09	689	32
	NiCr23Co12Mo (20%) ..... DMV 617 mod (20%)			0,1 1,51	703	
Outlet header	HR6W	Ø220$_w$x75	+22	-	668	31.5
			-0			
			-0			

Table 1. Materials and dimensions for last part of superheater (SH4).

The proposed materials and dimensions Re-heated steam parameters: T_{medium}=672 [°C]; p_{medium}=60 [bar]						
Element	**Material**	**Overall dimensions**	**Oversize steel (C_1)**	**Operating oversize (C_2)**	**Calculation parameters t_{cal}**	**p_{cal}**
-	-	[mm]	%	[mm]	[^{O}C]	[MPa]
coils	X10CrNiCuNb18-9-3 (20%)	Ø60,3x5	±12.5	1	629	7,2
	NF709 (20%)				653	
	HR6W (20%)				665	
	Sanicro 25 (20%)	Ø60,3x5,6			686	
	NiCr23Co12Mo (20%)	Ø60,3x6,3			707	
	DMV 617 mod (20%)	Ø60,3x5				
Outlet header	HR6W	Ø410$_w$x43	+28	0	687	
			-0			
	NiCr23Co12Mo	Ø410$_w$x37	+28			
			-0			

Table 2. Materials and dimensions for last part of reheater (RH2).

The results from the above tables indicate that maximum parameters achievable by a boiler with application of the highest quality available materials are:

- Temperature of live steam of **653 ºC** at pressure of **303 bar**
- Temperature of reheated steam of **672 ºC** at pressure of **60 bar**

Materials for pressure elements of the boiler

Membrane walls

In the boilers designed with the above materials, membrane wall medium outlet parameters are **504 ºC** / 321 bar. For such parameters three types of steel have been selected. The furnace chamber will consist of the following materials:

- **13CrMo4-5** (the spiral part)
- **X10CrWMoVNb9-2** or **NiCr22Co12Mo9** (the vertical part)
- **RAF 01** (under investigation)

Problems with weld joints made from **7CrMoVTiB10-10** (T24) and **7CrWVMoNb9-6** (T23) steels were a reason to avoid using these steels as material for membrane walls in this case [2] [3] [4]. RAFAKO and many universities across Poland and Europe made many

investigations about **7CrMoVTiB10-10** (T24) weld joints. Weldability of T24 was carried out by [5]:

- Welding Institute (WI) in Gliwice (Poland)
- Institute for Ferrous Metallurgy (IFM) in Gliwice (Poland)
- Gdańsk Technical University (Poland)
- AGH University of Science and Technology in Kraków (Poland)
- UDT - CERT (Notified Body)
- PROSWECO Technical Consultant (Sweden)
- SGS Fresenius Institute GmbH (Germany)

Conclusions from the investigations are as follows [5] :

- Low plastic properties of weld joints
- Strength properties of welded joints made with submerged arc welding considerably (up to 48%) exceeding the properties of parent material
- High brittle point temperature of weld metal deposited using SAW method (ca 80-90°C)
- Tendency of weld joints made with SAW method to develop brittle cracking at ambient temperature
- Hot micro-cracking at root pass craters of butt welded joints made with TIG method
- and many others.

Materials selected for the membrane walls of the furnace chamber were the subject of thermo-mechanical analyses in operational conditions (established). As the result of these analyses was to ascertain that **X10CrWMoVNb9-2** (T92) steel has the adequate strength properties although it requires post weld heat treatment. Whereas the **NiCr22Co12Mo9** (DMV 617 mod.),a nickel based alloy, considerably exceeds the required properties of strength and does not require the heat treatment after welding. However, the price of this material is very high. Application of DMV 617mod. material is a very expensive solution. This year RAFAKO is going to start the investigation of steal named by us **RAF 01**. It is a ferritic steel with high mechanical properties and, what is very important, post weld heat treatment is not needed. This material can be the best solution for T23/T24 problems.

Coils

As it was earlier demonstrated in tables 1 and 2 to measure up the high steam parameters the innovative materials should be used in the industrial conditions. For the coils the following materials have been considered:

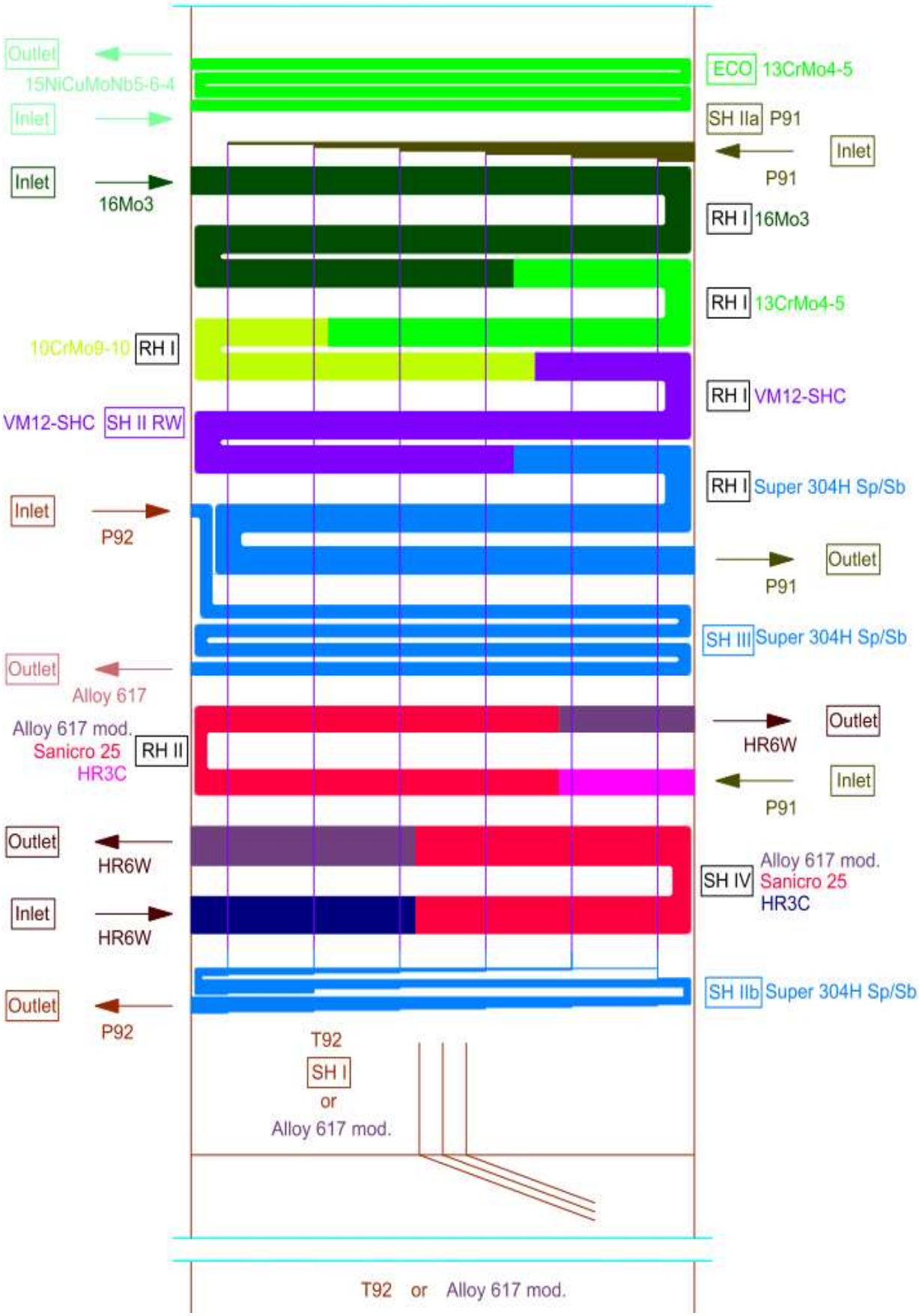
- **16Mo3**
- **13CrMo4-5**
- **X12CrCoWMoVNb12-2-2** (VM12-SHC)
- **X6CrNiNbN25-20** (HR3C, DMV 310N)
- **X10CrNiCuNb18-9-3** (Super 304H, DMV 304HCu)
- **Sanicro®25**
- **HR6W**
- **NiCr22Co12Mo9** (Alloy 617 mod., DMV 617 mod.)
- **NiCr23Co12Mo** (Alloy 617)

From the whole scale of classic materials, a few new generation materials are available as well. Let us pay attention to materials **Sanicro®25, HR6W** and **NiCr22Co12Mo9** in particular. These materials distinguish themselves by good properties of strength n high temperatures, resistance to high temperature corrosion and oxidation. Detailed examinations of **Sanicro®25** and **HR6W** are conducted at the International Centre of Electron Microscopy for Materials Science. For **Sanicro®25** the limit temperature of application is **700 ºC**. For **HR6W** this temperature is **685 ºC**. Precisely, thanks to the possibility of application of these materials in such high temperatures, very high parameters of outlet steam are achievable.

Headers and pipelines

As a basis for selection of headers and pipelines the maximum thickness of materials offered by manufacturers have been considered. The only suitable for the determined parameters are **HR6W** and **NiCr23Co12Mo** (Alloy 617) as shown in tables 1 and 2. The limiting elements of high parameters are live steam pipelines to the turbine. For the required parameters maximum produced thickness of **HR6W** that is **75 mm** should be accepted (Up to 2011. Now maximum thickness of HR6W is 90 mm).

All the aforementioned materials are showed on scheme No. 4. This scheme illustrates the heat exchange surfaces location and material inside the boiler.

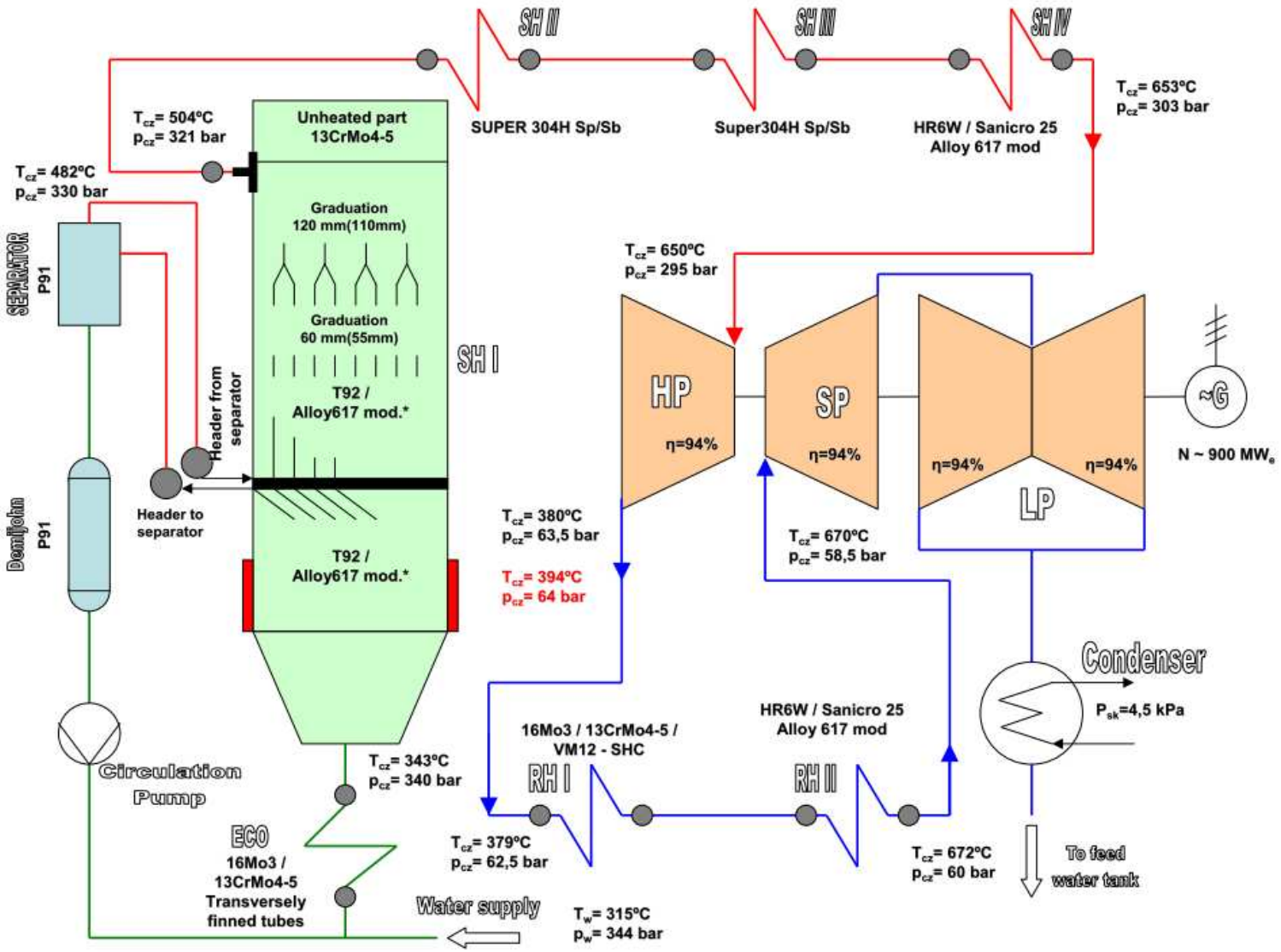


Scheme 4. Heat exchange arrangement.

Summary

The results of the undertaken research and analyses related to the topic of the article are presented on scheme No. 5. There is heat and material selection dedicated for the boiler. This diagram simultaneously presents the circulation of the medium inside the power plant unit. There are the temperature of the (T_{cz}) component, pressure value (p_{cz}) inside the selected parts of the boiler and material selected. The concept of the boiler design was to achieve the maximum parameters of steam using the market available materials. The result is a boiler design with the steam parameters of **653ºC/672ºC-303 bar**. These parameters allow us to achieve the following results for a power unit:

- **ca 2,250** tons of steam per hour with **≥94%** efficiency of the boiler,
- **ca 900 MW** output power with efficiency **≥48%** net,
- reduction of ca **900,000** tons (per annum) consumption of the coal regarding to power plants operated with efficiency **33.5%** net
- reduction of ca **2,100,000** tons of yearly CO_2 emission with regard to power plants operated with efficiency **33.5%** net.



Scheme 5. Water-steam cycle with material specification and steam parameters.

Acknowledgments:

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[1] K. Cieszyński, A. Sutowicz "Materiały dla kotłów na parametry Ultra Nadkrytyczne (USC)" - *Przegląd Energetyczny numer 1 (65) marzec 2012, ISSN 1641-7992*, p.37-38.

[2] Der Spiegel 15/2011 - *Risse im Kessel*, p.131.

[3] SpiegelOnLine 26. Juni 2011 - *Maroder Stahl verzoegert Start neuer Kohlekraftwerke*, http://www.spiegel.de/wissenschaft/technik

[4] Der Spiegel 26/2011 - *Die Not der Kesselflicker*, p.124-126.

[5] S. Fudali, J. Hajda, A. Kucybała "Assessment of base material, weld metal deposit and manufacturing process of gas-tight membrane walls made of 7CrMoVTiB10-10 steal grade " - *PowerPoint Presentation for VGB.*