Thermodynamic Analysis of Thermal Power Plant Cycle

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Abstract— The power sector is one of the sectors of the India's economy. The development of the country to a large extent is dependent on the growth of this sector. Through the progress of the power sector during the past four decades has been sustainable, the power industry has been unable to fulfill primary obligation of production quality power supply in required quantity. Our project was mainly concerned with the PowerPlant Operations &efficiency improvement. Initially, we calculated the performance and efficiency of the Boiler. The Computational Fluid Dynamics (CFD) approach is utilized for the creation of a two-dimensional model of the super heater or reheater coil. Using sanicro 25 material in the super heater or reheater part it gives better performance compared with the SA-213material (highly used at present). The fluid flow temperature, pressure is increase and velocity is decrease field of fluid flow within a super heater or reheater tube using the actual boundary conditions have been analyzed using CFD tool.

Key words: CFD, Thermal Power Plant Cycle

I. Introduction

A thermal power station is a power plant in which heat energy is converted to electric power. In most of the world the turbine is steam driven. Water is heated, turns into steam and spins a steam turbine which drives an electrical generator. After it passes through the turbine, the steam is condensed in a condenser and recycled to where it was heated; this is known as a Rankine cycle. The greatest variation in the design of thermal power stations is due to the different heat sources, fossil fuel dominates here, although nuclear heat energy and solar heat energy are also used. Some prefer to use the term energy centre because such facilities convert forms of heat energy into electrical energy. Certain thermal power plants also are designed to produce heat energy for industrial purposes of district heating, or desalination of water, in addition to generating electrical power. Globally, fossil-fuel power stations produce a large part of man-made CO2 emissions to the atmosphere, and efforts to reduce these are varied and widespread.

Sanicro 25 is an austenitic 22Cr25NiWCoCu stainless steel material with excellent high temperature properties, designed for use in advanced pulverized coal fired steam boilers.The energy efficiency of a conventional thermal power station, considered salable energy produced as a percent of the heating value of the fuel consumed, is typically 33% to 48%. As with all heat engines, their efficiency is limited, and governed by the laws of thermodynamics.

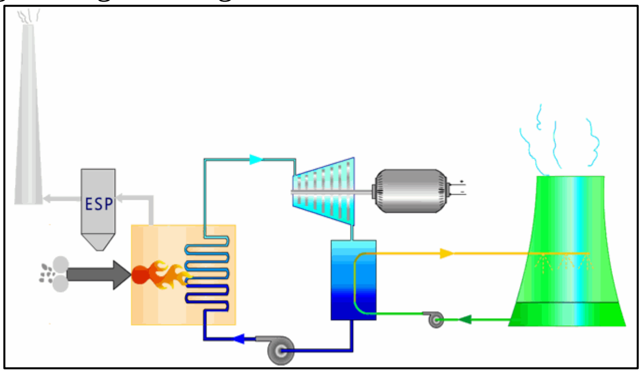

Fig. 1: Plant Layout

II. Working

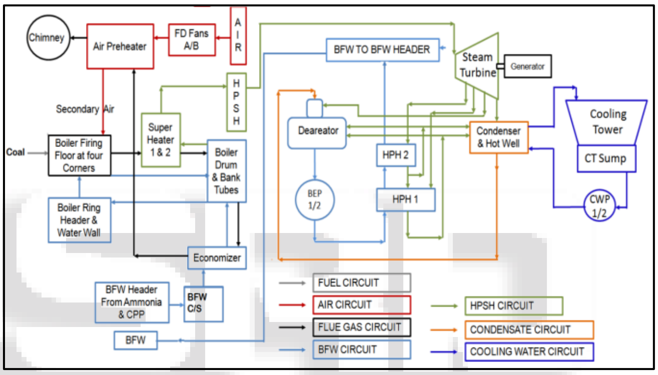

Fig. 2: Schematic diagram of a power plant

Thermal power plants use water as working fluid. Nuclear and coal based power plants fall under this category. The way energy from fuel gets transformed into electricity forms the working of a power plant. In a thermal power plant a steam turbine is rotated with help of high pressure and high temperature steam and this rotation is transferred to a generator to produce electricity. When turbine blades get rotated by high pressure high temperature steam, the steam loses its energy. This in turn will result in a low pressure and low temperature steam at the outlet of the turbine. Here steam is expanded till saturation point is reached. Since there is no heat addition or removal from the steam, ideally entropy of the steam remains same. This change is depicted in the following p-v and T-s diagrams. If we can bring this low pressure, low temperature steam back to its original state, then we can produce electricity continuously. Compressing a fluid which is in gaseous state requires a huge amount of energy, so before compressing the fluid it should be converted into liquid state. A condenser is used for this purpose, which rejects heat to the surrounding and converts steam into liquid. Ideally there will not be any pressure change during this heat rejection process, since the fluid is free to expand in a condenser. Changes in fluid are shown in the p-v and T-s diagram below. At exit of the condenser fluid is in liquid state, so we can use a pump to raise the pressure. During this process the volume and temperature (2-3 °C rise) of fluid hardly changes, since it is in liquid state. Now the fluid has regained its original pressure.

Here external heat is added to the fluid in order to bring fluid back to its original temperature. This heat is added through a heat exchanger called a boiler. Here the pressure of the fluid remains the same, since it is free to expand in heat exchanger tubes. Temperature rises and liquid gets transformed to vapor and regains its original temperature. This completes the thermodynamic cycle of a thermal power plant, called Rankine Cycle. This cycle can be repeated and continuous power production is possible. In order to reject heat from the condenser a colder liquid should make contact with it. In a thermal power plant continuous supply of cold liquid is produced with the help of a cooling tower. Cold fluid from the cooling tower absorbs heat from a condenser and gets heated, this heat is rejected to the atmosphere via natural convection with the help of a cooling tower.

Heat is added to the boiler with help of a boiler furnace. Here fuel reacts with air and produces heat. In a thermal power plant, the fuel can be either coal or nuclear. When coal is used as a fuel it produces a lot of pollutants which have to be removed before ejecting to the surroundings. This is done using a series of steps, the most important of them is an electro static precipitator (ESP) which removes ash particles from the exhaust. Now much cleaner exhaust is ejected into the atmosphere via a stack.

III. APPROACH TO INCREASE THE EFFICIENCY OF THE RANKINE CYCLE

The efficiency of Rankine cycle can be improved with considering following points:

A. Lowering the Condenser Pressure

Inside the condenser steam exists as a saturated mixture at the saturation temperature corresponding to the pressure inside the condenser. Therefore, lowering the operating pressure of the condenser automatically lowers the temperature of the steam. It increases the turbine output. It cannot be lower than the temperature of the cooling medium. Because, it increases the moisture content of the steam at the final stages of the turbine and it erodes the turbine blades. Finely decreases the turbine efficiency. Luckily, this problem can be solved by reheating of steam.

B. Superheating the Steam to High Temperatures

Superheat the steam to very high temperatures before it enters the turbine. This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency. However, it has the limitation to rise the steam temperature up to metallurgically safe levels.

C. Increasing the Boiler Pressure

Increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels.

D. Reheat Rankine Cycle

Increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to undesirable levels. Expand the steam in the turbine in two stages, and reheat it in between. It can decrease the excessive moisture problem in turbines. The reheat cycle was introduced in the mid1920s, but it was deserted in the 1930s. It was reintroduces single reheat in the late 1940s and double reheats in the early 1950s because of the operational complexities. The purpose of the reheat cycle is to reduce the moisture content of the steam at the final stages of the expansion process.

E. Regenerative Rankine Cycle

To transfer heat to the feedwater from the expanding steam in a counterflow heat exchanger built into the turbine, that is, to use regeneration. A practical regeneration process in steam power plants is accomplished by extracting/bleeding the steam from the turbine at various points. Regeneration not only improves cycle efficiency.

F. Superheating the Steam to High Temperatures

Superheat the steam to very high temperatures before it enters the turbine. This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency. However, it has the limitation to rise the steam temperature up to metallurgically safe levels. A super heater is used in this process.

IV. SUPER HEATER

Super heater tubes are surfaces for heat exchange, with the object of increasing the steam temperature, after it comes from the boiler drum, to a value higher than saturation. This has two basic purposes: to increase the thermodynamic efficiency of the turbine, in which the steam will be expanded and to make the steam free of humidity. In normal operation it produces steam that is superheated by approximately 200 °C at the inlet of the turbine. The steam flow has to be intense to permit the heat absorption from the tube, avoiding deformation because of high temperature. The super heater can be divided in two sections, primary and secondary, as in the boiler studied, where the super heater tubes are within the radiation zone.

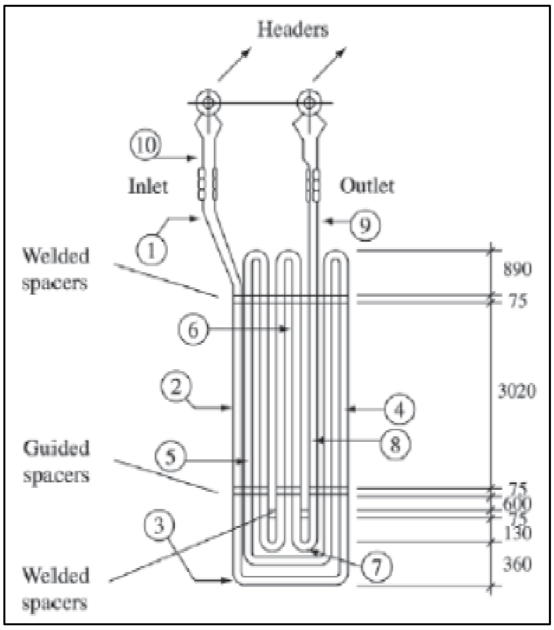

Fig. 3: Positions of the samples extracted from a primary super heater assembly

V. METHODOLOGY

A. We have considered an example to illustrate the change of efficiency with change in temperature

A boiler plant incorporates an economizer and super heater and generates steam at 40 bar and 300 °C with fuel heating value 33,000 KJ/kg burned at a rate of 50 kg/h. The temperature of feed water is raised from 40 °C to 125 °C in the economizer and the flue gases are cooled at the same time from 395 °C to 225 °C. The flue gases then enter the super heater in which the temperature of combustion air is raised by 75 °C. A forced draught fan delivers the air to the super heater at a pressure of 1.02 bar and a temperature of 16 °C with a pressure rise across the fan of 180 mm of water. The power input to the fan is 5 kW and it has a mechanical efficiency of 78%. Neglecting heat losses and taking C_p as 1.01 KJ/kg K for flue gases, Calculate:

- The mass flow rate of air,
- The temperature of flue gases leaving the plant,
- The mass flow rate of steam
- The efficiency of the boiler

1) Solution:

Power output to the FD fan,

$P = \frac{V * \Delta p}{\eta_{mech}}$

$V = \frac{P * \eta_{mech}}{\rho_w \, g \, h}$

$= \frac{5 * 10^3 * 0.78}{1000 * 9.81 * 0.180}$

$= 2.21 \ m^3/s$

Density of air, $\rho a = \frac{p}{R\,T}$

$= \frac{1.02 * 10^5}{287 * (273 + 16)}$

=1.23 kg/s

Mass flow rate of air, $m_a = \rho_a * V$

=1.23 * 2.21

=2.72kg/s

Assuming complete combustion of fuel, the mass flow rate of flue gases,

$$m_g = m_a + m_f$$

$= 2.72 + \frac{500}{3600}$

= 2.855 kg/s

Energy lost by flue gas = energy gained by air in super heater

$$2.855 * 1.01 * \Delta T = 2.72 * 1.005 * 75$$

ΔT = temperature drop of the flue gases = 71 °C

Temperature of flue gases leaving the plant,

= 225 – 71 = 154 °C

Making energy balance for he economizer,

$$m_w * c_w (125 - 40) = m_g * c_{pg} * (395 - 225)$$

$$m_w = \frac{2.2855 * 1.01 * 170}{4.182 * 85}$$

$$= 1.379 \ kg/s$$

Water enters the boiler as feed water at 40 °C

$$h_f = 167.4 \ kJ/kg$$

Steam leaves the boiler at 40 bar, 300 °C

$$h = 2962.3 \ kJ/kg$$

$$\text{Boiler efficiency} = \frac{(2962.3 - 167.4) * 1.379}{33000 * \frac{500}{3600}}$$

$$= \frac{3854.2}{4583.4}$$

$$= 0.84 \text{ or } 84\%$$

Now if we change the temperature leaving the super heater or boiler, from 300 °C to 350 °C, then the Steam leaves the boiler at 40 bar, 350 °C

$$h = 3090.94 \ kJ/kg$$

$\text{Boiler efficiency} = \frac{(3090.94 - 167.4) * 1.379}{33000 * \frac{500}{3600}}$

$= \frac{4031.6}{4583.4} = 0.8796 \text{ or } 87.96\% \approx 88\%$

From the illustration we can see that the small change in temperature leaving the super heater or boiler results in respective changes in boiler efficiency

B. Material considered in the project

Presently in India, SA-213 Gr.22 metal is being widely used for the production of super heaters. These kind of super heaters can only withstand temperatures up to 500 °C only. So we have considered a metal that can withstand temperatures up to 700°C and is being used for super heaters in few parts of the world

SANICRO 25-Sanicro 25 is an austenitic 22Cr25NiWCoCu stainless steel material with excellent high temperature properties, designed for use in advanced pulverized coal fired steam boilers. The grade is characterized by:

- Very – high creep strength
- High oxidation resistance
- High structural stability
- Good fabricability

Fig. 4: Boiler tubes for coal-fired power plants

C %	Si %	Mn %	P%	S%	Cr %	Ni %	W %	Co %	Cu %	Nb %	N %
≤ 0.1	0.2	0.5	≤0.025	≤0.015	22.5	25	3.6	1.5	3.0	0.5	0.2

Table 1: Chemical composition (nominal) % Mechanical properties

Proof strength MPa		Tensile Strength MPa	Elongation %		Hardness Vickers
$R_{p0.2}$[a]	$R_{p1.0}$[a]	R_m	A[b]	$A_{2"}$	
Approximate					
≥310	≥355	≥680	≥40	≥40	185

Table 2: Strength, Elongation and Hardness

At 20 C (68 F), annealed condition

- C-Carbon
- Mn - Manganese
- P - Phosphorus
- S - Sulfur
- Si - Silicon
- Cr - Chromium
- Ni – Nickel
- W – Tungsten
- Co – Cobalt
- Cu – Copper
- Nb – Niobium
- N – Nitrogen

Metal Temperature °C	Allowable Stress, MPa	Allowable Stress MPa[1]
40	184	184
65	184	184
100	174	184
125	184	167
150	161	181
175	156	179
200	152	176
225	149	174
250	146	173
275	143	172
300	141	171
325	139	170
350	138	170
375	136	169
400	134	168
425	133	168
450	131	167
475	129	166
500	128	164
525	126	163
550	125	160
575	123	158
600	122	154
625	120	140
650	111	111
675	85.1	85.1

Table 3: Max allowable stress values

The weldability of Sanicro 25 is also good and TIG welding method is recommended, and should be carried out with a low heat input, <1.0kJ/mm and an interpass temperature <100°C. The material has been specifically developed for use at material temperature upto around 700°C.

VI. Analysis of Super Heater

In order to perform a CFD analysis, a powerful tool like ANSYS is widely used presently. ANSYS Fluent, CFD, CFX, and related software are Computational Fluid Dynamics software tools used by engineers for design and analysis. These tools can simulate fluid flows in a virtual environment, for example gas turbine engines (including the compressors, combustion chamber, turbines and afterburners), pumps.

A. Creating the 3D Model

To create the 3d model of the super heater, CATIA V5 a cad based designing product was used. Then its been imported to the ANSYS 14.5 for further CFD analysis of the 3d model.

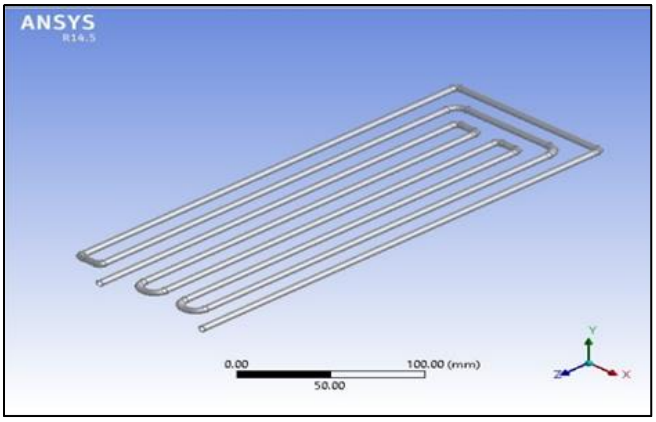

Fig. 5: 3d model created for analysis of super heater using ANSYS

B. Meshing the 3D Model

After importing the 3d model in the ANSYS workbench, the model is meshed with high smoothing and fine coursing. The sections like inlet, outlet, outer surface and inner surface of the tube are projected or named for the CFD analysis.

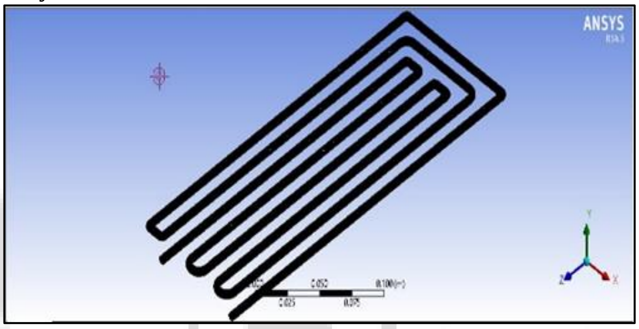

Fig. 6: Meshing of the model in ANSYS with high smoothing

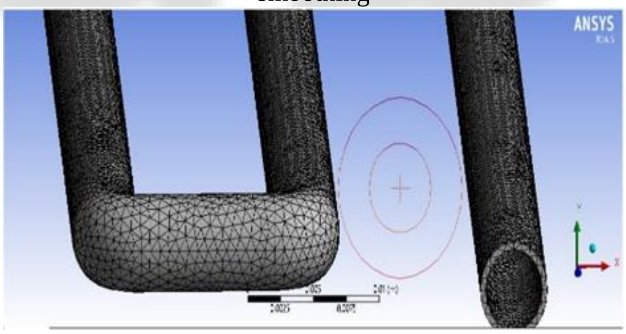

Fig. 7: Sectional view of the super heater tube after meshing

VII. Results

Considering the boundary conditions for a super heater tube, air is used as the fluid in the tube. CFD analysis has been carried out assuming the optimum surface conditions for the tube.

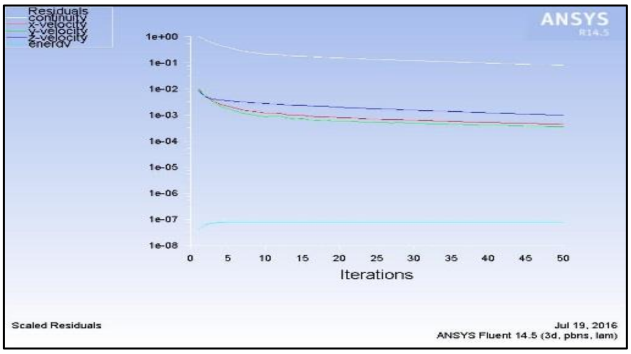

Fig. 8: Graph 1 Results taken for 50 iterations for temperature 350°C

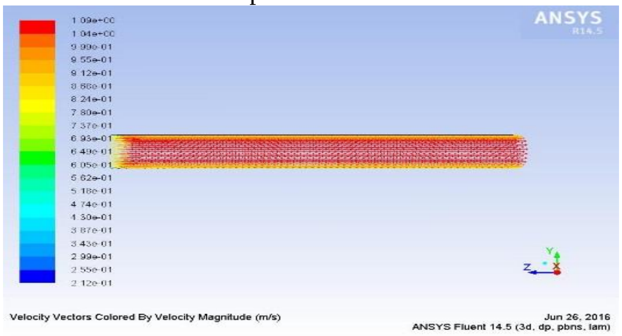

Fig. 9: Movement of atoms along the velocity vectors

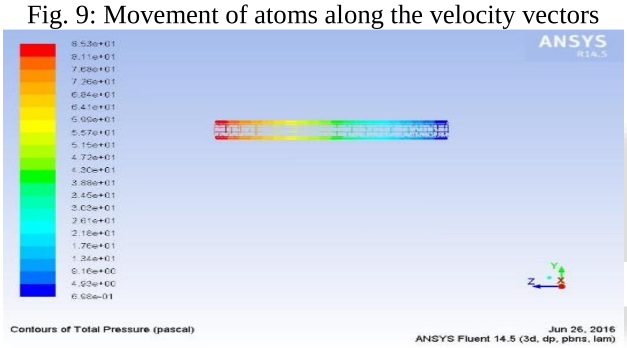

Fig. 10: Total pressure exerted on the inner surface of the super heater tube section

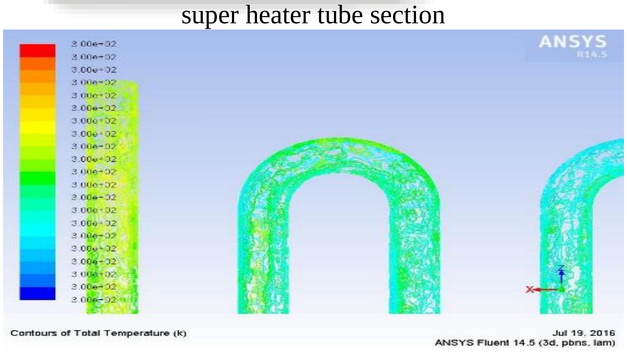

Fig. 11: Temperature countor through the super heater tube section

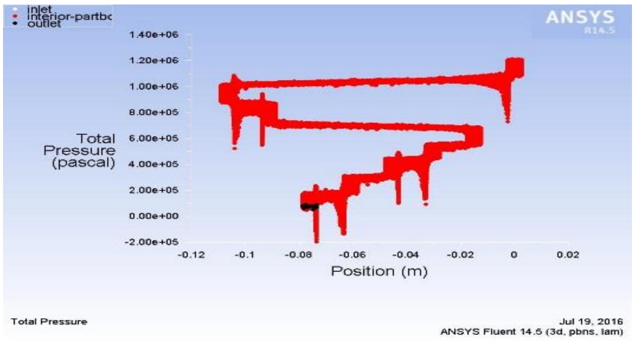

Fig. 12: Graph 3 The pressure variations throughout thetube

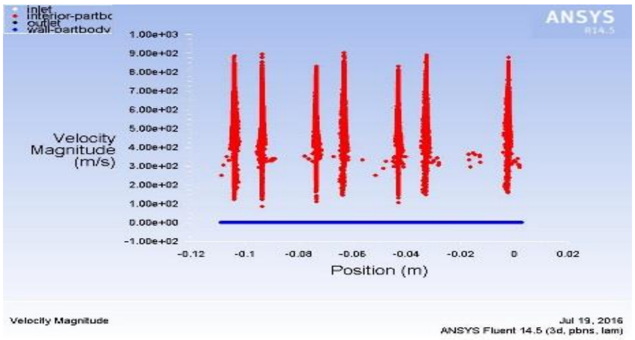

Fig. 13: Showing the velocity of the atoms throughout the tube

VIII. CONCLUSION

Increased efficiency in coal-fired power plant Our new material Sanicro 25 is engineered for the next generation of coal-fired power boilers, contributing to significantly greater efficiency and sharply lower CO_2 emissions. It is ideal for superheater and reheater tubes, allowing for material temperatures of up to 700ºC (1290ºF).

As per results obtained from the CFD analysis it is seen that the new material considered has low stress levels and high thermal values. The material has high strength, very good resistance to hot corrosion, very high oxidation resistance in a coal ash environment. The weldability of Sanicro 25 is also good and TIG welding method is recommended.

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REFERENCES

[1] I. H. Aljundi, "ExergyandExergy Analysis of a Steam Power Plant in Jordan," Applied Thermal Engineering, Vol. 29, No. 2-3, 2009, and pp. 324-328
[2] Hasan HE, Ali VA, Burhanettin, Ahmet D, Suleyman HS, Bahri S, Ismail T, Cengiz G, Selcuk A., Comparative energetic and exergetic performance analyses for coal-fired thermal power plants in Turkey. International Journal of Thermal Sciences 2009; 48:2179–86
[3] Rashad A., Maihy A. El, Energy and Energy Analysis of a Steam Power Plant in Egypt, ASAT- 13, May 26 – 28, 2009
[4] P. K. Nag, "Power Plant Engineering," Tata McGraw Hill, New Delhi.
[5] SANICRO 25, TUBE AND PIPE, Seamless. Datasheet from. www.smt.sandvik.com

