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THE RESUME OF THE DOCTORAL THESIS

THE THERMAL REGIME INFLUENCE OF A ROTATING- PLATE REGENERATIVE AIR PRE-HEATER ON ITS ACID CORROSION

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R.A.P.H.[1]- rotating- plate air pre-heater

ABSTRACT

The rotating- plate regenerative air preheaters, of Ljungstrom or Rothemuhler types, belong to the category of preheaters that equip modern steam generators. They are heat exchangers used to transfer heat between the flue gases and the incoming combustion air that enters the furnance across an inert material called metal filler. A disadvantage of these preheaters is the acid dew phenomenon that appears inside the preheater , leading to a decrease in the operating efficiency. This paper treats many case studies on a rotating- plate regenerative air preheater, among which: the points and zones of occurrence of the corrosion phenomenon of the metal filler; heat exchanger according to the preheater rotation speed; its operation at partial loads; the influence of the combustion air temperature of the heat exchanger inlet on its acid corrosion; the acid dew phenomenon was presented; there were presented two ideas for future concerns/ research on the corrosion phenomenon. A numerical calculation model (mathematical model) has been developed that simulates the preheater operation and which highlights the temperatures inside it: the temperatures of the metal filler, the gases and the air at significant points of the metal comb, depending of the height h and the center angle formed by its rotation φ. The model is used to optimize the operation of the heat exchanger in a manner that the apparition of the acid corrosion phenomenon does not occur or is kept under control. The mathematical model was applied to a real rotary air preheater, Rothemuhle type, belonging to a steam generator which works with coal (lignite). Applying the mathematical model to the actual preheater case leds to the calculation of the point on the preheater height where sulfuric acid appear (which destroys the metal filler material) and then to determined the optimal height of the cold zone, in order to replace the filler from this zone during repairs or to refurbish the steam generator.

The paper provides the specialists in this domain a new approach in thermal processes analysis of a rotating- plate regenerative air preheater.

Keywords: rotating-plate regenerative air preheather, acid corrosion, flue gases, combustion air, metal filler, temperature points.

CHAPTER 1

1. INTRODUCTION. THE THERMAL CALCULATION OF A R.A.P.H.

1.1. The construction and functioning of a R.A.P.H

Some of the society's concerns are non-renewable energy sources and the energy generated by the burning of fossil fuels, such as combustible gases, liquid fuels (eg . fuel oil) and coal, which will continue to play an important role as a sources of energy for a long time.

An application of combustion of the fossil fuels is represented by their use as fuels for the operation of steam generators, which are usually equipped with rotating-plate regenerative air pre-heaters- R.A.P.H. (Ljunstrom, Rothemuhle types etc.) [2].

The pre-heater’s rotor consists in cylindrical structure made of profiled iron (cornier) shaped as a cage divided by metal sheet walls, radial in sectors, with center angle of 15° or 20° . The whole structure is fixed rigidly on the rotor axis that can be vertical or horizontal. Within the structure modules of inert filler are layered, usually metallic, that transport the heat between two thermic agents, flue gases and combustion air, by means of heating and then of cooling. The metal filler is made of shaped metal sheet, usually corrugated, characterized by its specific large mass (the quantity of material within a rotor cubic meter), *kg/m^3*.

For idea fixation the physical model of the R.A.P.H. with mobile rotor, **Fig. 1.1.a**.

The superior and inferior parts of the carcass are prevised with flue gases and combustion air guidance and admittance channels at the rotor entry, respectively exit, they belonging to the gas and combustion air generator’s circuits. If the entry and exit of the gases and air have rectangular forms, in continuing the respective channel enlarges in the way that becomes AOA’ (for gases) and BOB’ (for air) **Fig.1.1.c.**

With the help of an electric engine, the metal comb rotates counter clockwise. In its movement, the rotor enters in the cold combustion air ceasing towards it the filler accumulated heat, the cooling-heating process is returned.The flue gases with the temperature from exiting the previous generator exchanger penetrate through the free section of the AOA’ circular sector in the filler mass transfering heat to it.

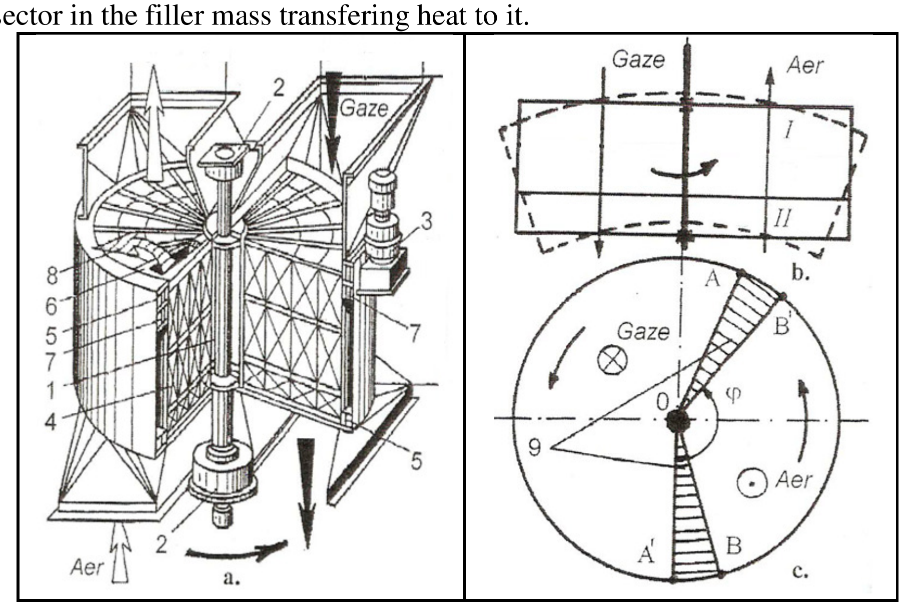


Fig.1.1 Sketches of the R.A.P.H. with mobile rotor (Ljungstrom): a- through the pre-heater view and section, b. bending of the vertical axis rotor and descendant gas flow; c- horizontal section through the rotor: 1- rotor axis; 2- support shaft; 3- training electric engine; 4- metal filler (inert mass); 5-external carcass; 6,7 - radial and peripheral sealing; 8- air infiltration by sealing; 9- sealing sectors

1.2 SUBJECT OF THE WORK INTEGRATED IN THE SPECIALTY MATERIALS

The rotating-plate regenerative air pre-heaters have a great contribution in the thermal- power plants efficiency. The usage of such thermal equipment is recommended for the case of steam generators that use fuel containing Sulphur in its chemical composition.

This thesis main subject is represented by the optimization of the rotating-plate regenerative air pre-heaters in a manner in which the output of the thermal- power plant reaches a mostly high value. The efficiency of this thermal equipment has been internationally treated, by specialists in the field, in many works in which the problems that these types of equipment are confronted with have been analyzed. Like any other industrial equipment, the air pre-heater, when functioning, presents some undesired effects, and a main disadvantage is represented by the acid dew that appears in its inner part, which conducts to a decrease in the functioning efficiency. This research presents a mathematical model that simulates the rotating-plate regenerative air pre-heaters' functioning. The model allows the operator to find the significant temperature points in the pre-heater and represents a justified by the experimental data in the field approach.

The model is used at optimizing the heat exchanger in such way that the acid corrosion phenomena is prevented, controlled or does not happen and it has been validated by measurements performed at a real thermal power plant from our country. Different tests were performed, with diverse functioning regimes for the steam generator, on different loads, and, moreover, some case studies regarding the thermal transfer of the pre-heater in function of its rotation speed, of the increase in temperature of the combustion air at the exchanger entrance and of the acid dew phenomena apparition.

Nowadays, this Sulphur acid apparition phenomena has been studied by the producer of such rotating-plate regenerative air pre-heaters of Ljungstrom type, a multinational company, world leader in the industrial equipment production [30]. They found a solution by which means they eliminate the Sulphur acid form the flue gases by injecting of absorbing substances, in a injection procedure called SBS. For this injection procedure that they declared reduces the SO_3 level from the flue gases that enter to the pre-heater, at less than 5 ppm. It may be used but implies supplementary costs, not at least unneglectable, corresponding to the injected substances and injecting equipment. The procedures used in the present work represent an alternative to this method.

1.3 CLASSIC STEAM GENERATOR, WITH NATURAL CIRCULATION CALCULATION

In the introduction the calculation for obtaining the necessary parameters for subsequent determinations presented in this work were realized by means of a classical steam generator, with natural air circuit that has been projected after the general example of a steam generator[1].

It is to be considered the steam generator with the following parameters:

Nominal flow $D_n = 287.5$ kg/s;

Nominal temperature $t_n = 540\ ^oC$;

Nominal pressure $p_n = 192$ bar;

Supply water temperature $t_e' = 240\ ^oC$;

Ambiental temperature $t_o = 25\ ^oC$;

Preheating fuel oil temperature $t_c = 120\ ^oC$;

Reference temperature $t_{ref} = 0\ ^oC$;

Air absolute humidity $x = 10\ g/kg_{aer}$;

The used fuel is fuel oil with elementary analysis:

$C_i = 81.2\ \%$; $S_i = 4.5\ \%$; $H_i = 8.2\ \%$; $N_i = 1.4\ \%$; $W_{ti} = 1.5\ \%$; $O_i = 2.8\ \%$; $A_i = 0.4\ \%$;

1.3.1. Calculation of the calorific value

1.3.2. Air volume calculation

1.3.3. Fuel combustion calculation

1.3.4. Establishing of the air excess coefficient in the flue gas channels

1.3.5. Flue gas temperature determining on evacuation, $t_{ev,}$ of the air heating preliminary temperature, t_a', and of the acid dew temperature t_{ra}

The flue gases temperature decreases during their flowing through the pre-heaters filler and implicitly, the Sulphur acid that condenses or acid dew temperature also decreases.

The acid dew temperature t_{ra}, ^oC is calculated using the following relation[4]:

$$p_{ra} = \exp[(\frac{1}{0.22 + 1.02 \cdot 10^{-5} \cdot p_{va}} - 9.563)(\frac{596.19}{50.206 + t_{ra}} - 1.7958) + 9.5364]$$

The enthalpy of the air and flue theoretical humidity gases were calculated in **Table 1.3.**

1.3.6. Indirect efficiency determining

1.3.7. Determining of the useful heat and of the fuel consumption

1.3.7.1. Determining of the work fluid pressure within a steam generator

1.3.7.2. Determining of the working fluid work temperature

1.3.7.3. Determining of the useful changed heat in the steam generator

1.3.8. Determining of the *B*, kg/s fuel consumption of the steam generator

1.3.9. Determining of the flue gases temperature between the two zones (hot and cold) on evacuation, t_{gi}

1.3.9.1. Temperature of the metallic wall of the pre-heater, t_{pm}, ^oC

1.4. CALCULATION OF THE ROTATING- PLATE REGENERATIVE AIR PRE-HEATER

1.4.1. Determining of the constructive parameters of the rotating regenerative air- preheater

There are shown the constructive parameters used on project[4].

The first layer (hot) of the metal filler is made of thin metal sheet (δ_s mm) and the cold layer that may function in acid corrosion regime is made of thicker metal sheet (δ_g mm), or specially treated one. The thermal calculation is made separately for each layer.

The number and the angle of the pre-heater are distinguished: air sectors, flue gases sectors and sealing sectors.

1.4.2 Calculation of the R.A.P.H. hot zone

The metal sheet load for the R.A.P.H is chosen from distance corrugated metal sheet for the pre-heaters hot zone.

Angle at the center of the cooling sector φ_{rt}, grd :

$$\varphi_{rt} = \frac{\varphi_{rt}(grd.) \cdot 2 \cdot \pi}{360} = 2.094 \; rad. \qquad (1.103)$$

Angle at the center of the heating sector φ_{it}, grd :

$$\varphi_{it} = \frac{\varphi_{it}(grd) \cdot 2\pi}{360} = 3.491 \; rad. \qquad (1.105)$$

1.4.2.1. Gases and combustion air speed at flowing through the filler

1.4.2.2. Determining of the heat exchange global coefficient, k, $W/m^2 \cdot k$

1.4.2.3. Heat changed in the P.A.R.R. hot zone

1.4.3. Calculation of the cold P.A.R.R. zone

In order to calculate all the parameters of the pre-heater's cold air zone the calculation methodology used is the one from its hot zone, from the relation (1.109) until (1.132), precising that the calculated parameters get a "1" index.

In **Fig. 1.5** the physical model of the studied pre-heater is presented.

In the end of each chapter there are shown the calculated numeric values of the presented parameters.

Fig. 1.5 P.A.R.R.- presented functional scheme

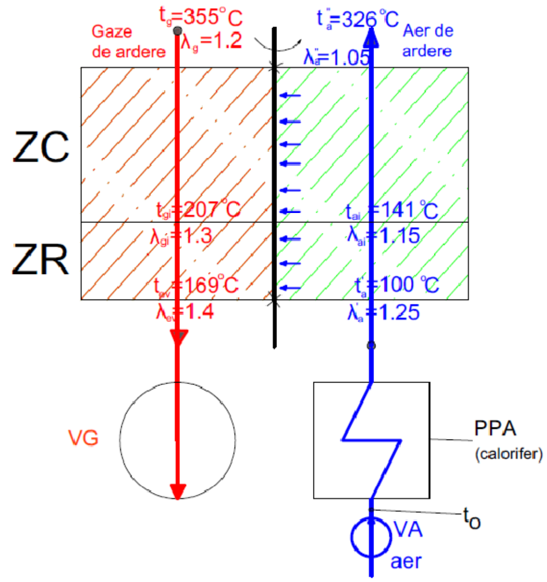


Fig. 1.5 P.A.R.R.- schemă funcțională

1.5 NUMERIC VALUES RESULTED FROM CHAPTER 1

In this subchapter the numerical values of the calculated or used parameters are presented, in a table, obtained using the formulas presented from relation (1.1) to the relation (1.138).

In Chapter 1, a steam generator that functions with fuel oil has been presented, together with the corresponding air pre-heaters. The acid dew temperature in function of the used fuel was calculated, then the usage of a special filler for the last exchanger step was taken into consideration (its cold zone). In the first chapter the necessary parameters were found for future determinations.

CHAPTER 2

THERMAL CALCULATION IN THE COLD ZONE OF THE STUDIED PRE-HEATER

This chapter has been destined to the thermal calculation of the last step of the pre-heater Ljungstrom[3] type, calculation that implies determining of the temperatures from the inner cold zone of the heat exchanger, after an analysis that variates linear, for the purpose of finding out the filler, flue gases and combustion air temperatures that afterwards are necessary in the acid dew phenomena specific analysis.

The rotating-plate regenerative air pre-heaters (R.A.P.H.) physical model is presented in **Fig. 2.1** and **Fig. 2.2.** In this chapter, the thermal calculation of the last pre-heater's Ljungstrom[3] type step is calculated.

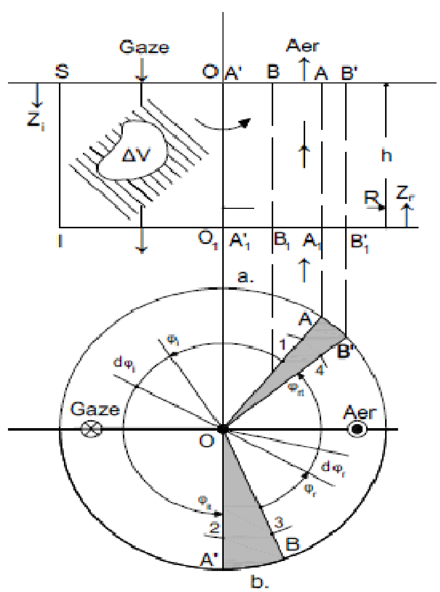


Fig.2.1 The physical model necessary in order to determine the thermal regime of a R.A.P.H.: a-vertical section through the rotor; b-horizontal section; SI- superior section, respectively inferior through the rotor; OO_1- rotor vertical axis

2.1 CALCULATION METHOD BASED ON A LINEAR HYPOTHESIS

In order to reach the treatment and deduction of variation laws (heating or cooling) of the thermal agent's temperatures, that normally imply a thorough analysis, difficult and that does not vary by a linear math function, these temperatures were calculated, before, after a math analysis based on the linear variation [3].

These are the reasons why a simplifying in the math analysis is being admitted, meaning, the filler and flue gases temperatures (in the heating period) are linear decreasing with z_i increase and linear increase by φ_i; analog, in the air preheating period, its temperature and the filler one linear increases when z_i increases and linear decreases when φ_i increases.

The notations $z_{i,r}$ represents the rotor's height at a certain moment and $\varphi_{i,r}$ is the center angle of the pre-heater sectors at a certain moment.

For the filler warming duration, the t_g and t_u parameters receive each an index "i" (heating) and in the period of filler cooling, respectively t_u and t_a the "r"index (cooling). With help of the presented expressions, the numeric values of the thermic agents in the significant points of the R.A.P.H. rotor (for heating-cooling filler, for flue gases and combustion air), please see **Fig. 2.2.**

2.2 CALCULATION OF THE FILLING TEMPERATURE t_{ui} *(h,0)*

The filling temperature in the heating period $t_{ui}(h,0)$, at $z_i = 0$ and $\varphi_i = 0$, ^oC:

$$t_{ui}(h,0) = \frac{N(t_g)}{N(t_{ui})} t_{gi} + \frac{N(t_a')}{N(t_{ui})} t_a' \tag{2.30}$$

The temperatures expression $t_{ui}(h,0)$ is necessary in the filler corrosion process analysis, if this point's corrosion is avoided, then the whole R.A.P.H. rotor is taken from under its influence.

If $t_{ui}(h,0) > t_{ra}$, then the acid corrosion phenomena does not appear on the whole pre-heater's surface.

Underlining of the thermic agent's temperature is shown in the following lines:

For the flue gases, ^oC:

$$t_{gi}(0,\varphi_i) = t_{gi}(0,0) = t_{gi}(0,\varphi_{it});\ t_{gi}(h,0);\ t_{gi}(h,\varphi_{it});\ t_{gi}(h_m,0);$$

For the metal filler of the pre-heater, ^oC:

$$t_{ui}(0,0);\ t_{ur}(h,\varphi_{rt}) = t_{ui}(0,0);\ t_{ui}(0,\varphi_{it});\ t_{ur}(h,0) = t_{ui}(0,\varphi_{it});\ t_{ui}(h,0);$$
$$t_{ur}(0,\varphi_{rt}) = t_{ui}(h,0);\ t_{ui}(h,\varphi_{it});\ t_{ur}(0,0) = t_{ui}(h,\varphi_{it});\ t_{ui}(h_m,0);$$
$$t_{ur}(h_m,\varphi_{rt}) = t_{ui}(h_m,0);\ t_{ui}(h_m,\varphi_{it});\ t_{ur}(h_m,0) = t_{ui}(h_m,\varphi_{it});$$

For the combustion air, ^oC:

$$t_{ar}(0,0) = t_a';\ t_{ar}(0,\varphi_{rt}) = t_{ar}(0,0);\ t_{ar}(h,0);$$
$$t_{ar}(h,\varphi_{rt});\ t_{ar}(h_m,0);\ t_{ar}(h_m,\varphi_{rt});$$

2.3 NUMERIC APPLICATIONS CALCULATED IN CHAPTER 2

Within this subchapter, the numerical values of the calculated parameters are shown in a table using the formulas presented (from relation (2.1) to the relation (2.93)).

The following figures underline the flue gases behavior, the filler and the combustion air in the pre-heater studied model.

In **Fig. 2.2** is shown the physical model of a rotating-plate regenerative air pre-heater together with the numeric values of the thermal agents (°*C*) calculated in this chapter.

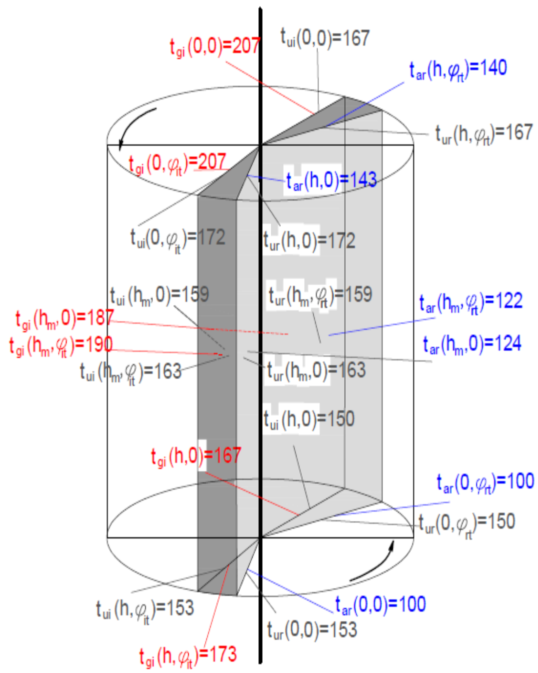


Fig. 2.2 Presentation of the physical model and numeric values of the thermal agents (°*C)* in the significant points of the projected R.A.P.H. rotor (for heating- cooling filler, for flue gases and combustion air)

The significant temperature points from inside the metal comb of the pre-heater were calculated when they vary on a linear function, taking into consideration the height *h* and the angle that the heat exchanger is forming in its spinning φ, temperatures found both on the gas cooling part, on the pre-heating of the combustion air part as well as on the heating, respectively inner filler cooling.

CHAPTER 3
INFLUENCE OF THE PARTIAL LOADS ON THE ACID CORROSION OF THE R.A.P.H

3.1 THERMIAL REGIME OF THE PARTIAL LOAD R.A.P.H. IN FUNCTION

For the punctual analysis it is admitted that the un-nominal generator functioning is due only to the variation of its load, *D*= variable. This means the calculation of the numeric values of the thermal agents in the significant points of the heat exchanger, with help from the semi-empiric formulaes and their measurements.

In order to elaborate these calculations, we call for the empirical dependencies taken from specialty works, the partial load *Dsp* (these dependencies are valid for the given generator, they must not be generalized).

This part of the work represents a continuing of the Chapters 1 and 2 from which methods, formulae and calculated data are taken.

The “sp” index is used to designate a given parameter when the steam generator works on partial loads.

In **Fig. 3.1** a steam generator is presented together with the two identical pre-heaters. In this chapter’s calculation only one pre-heater from the two has been used.

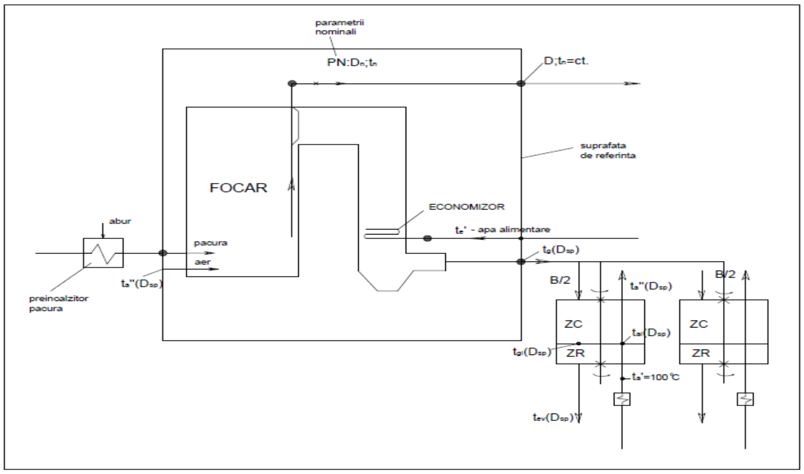


Fig. 3.1 –Steam generator constructive scheme

The important air temperatures of the air pre-heater on steam generator partial loads, were calculated and are shown in the following rows.

$t_{g.sp}\ {}^oC$	$t_{a.sp}''\ {}^oC$
$t_{gi.sp}\ {}^oC$	$t_{ai.sp}\ {}^oC$
$t_{ev.sp}\ {}^oC$	$t_{a.sp}'\ {}^oC$

3.2 THE ACID DEW PHENOMENA

The main heat loss of the steam generators consists in the sensible enthalpy of the evacuated flue gases. The making of equipment with high efficiency is limited, in the case of the high leveled in Sulphur fuel, due to the corrosion phenomena apparition in the last step of the air pre-heater [3].

In the process of fuel oil burning that contains Sulphur in their chemical structure S_c^i, % Sulphurous anhydride is forming SO_2. Then, a series of factors: the excessive oxygen in the flue gas, their temperature, the catalytic effect of the metal walls, cinder and soot, determines the transformation of a part 1… 3 % of the SO_2 in Sulphur anhydride SO_3, the rest 97… 99 % of the SO_2 is found in the flue gases that circulate towards the pre-heater exit.

The theoretic and experimental researches show that between 400 °*C* and 200 °*C* (in the sense of the flue gases through R.A.P.H.) the Sulphur anhydride is combined with water vapors from the gases forming in this way Sulphur acid values in overheated state, phenomena that takes place almost in its entirety in the pre-heater rotor volume under the formulae:

$$SO_3 + H_2O \leftrightarrow H_2SO_4 + \Delta Q, \quad (3.33)$$

cu cât scade volumul de SO_3 cu atât crește volumul de acid H_2SO_4.
as much as the SO_3 volume decreases, the volume of the H_2SO_4 acid increases.

In the process of cooling the flue gases, the water vapors condense is produced at a proper temperature corresponding to their partial pressure [4]. When using the fuel oil the simultaneous water vapor and SO_3 condensationis produced in the form of a Sulphur acid thin layer. The condense temperature of the acid vapors in the filler channel, at the wall is called acid dew temperature t_{ra}, ^oC; it depends mainly on the partial pressure of the acid vapors p_{va}, Pa; between t_{ra} and p_{va} there is a biunivoc relation. The continuing cooling of the flue gases in contact with the terminal surfaces of the generators amplifies the process of condensing and the thin layer becomes more and more aggressive as the Sulphur acid fades. In this way, an increase of the meal corrosion is produced to the maximum value.

3.3 NUMERICAL CALCULATED APPLICATIONS

In **Fig. 3.2** are presented, at nominal and partial load of 80% the value of the temperatures in the pre-heater's significant points.

In **Table 3.2** are presented the numerical values calculated with help of the presented formulae, from 3.1 relation until 3.68 relation.

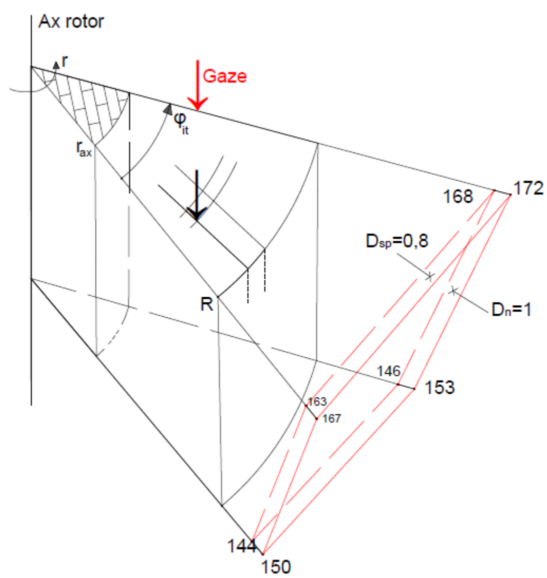


Fig. 3.2 Significant temperatures of the filler in the heating period for the generator's loads $D_{sp} = 1$ and $D_{sp} = 0{,}8$ $D_{sp} = 0.8$

3.4 ANALYSIS OF THE POSSIBILITIES FOR CONTROLLING THE ACID DEW PHENOMENA

In this subchapter a case study is made, on the studied pre-heater example in which the influence of the rotor on the acid dew phenomena is shown. The study implies also another method of stopping the Sulphur acid apparition inside the heat exchanger by means of increasing the combustion air at the pre-heater entry.

These methods become work instruments for optimizing this type of pre-heater.

3.4.1 Rotor spinning influence on the acid dew phenomena

In this subchapter the heat exchanger rotor engine spinning influence on its thermic regime is analyzed, at normal load as well as at partial load (the treated partial load is of 80%). It is shown, among others, as how varying the rotor spinning the apparition of the acid corrosion on the R.A.P.H. refill may be prevented or influenced.

For the nominal load $D_n = 1$ and variable spinning the Table 3.2 is made; the elements presented in the table are known, the calculation method being presented in chapter 2 of the work, the relations used are from (2.30) to (2.33).
The metal filler temperature $t_{ui}(h,0)$ found in function of the calculated parameters obtained on the pre-heater functioning at nominal load D_n= 1in function of its spinning.

Table 3.2 The metal filler temperature $t_{ui}(h,0)$ found in function of the calculated parameters obtained on the pre-heater functioning at nominal load $D_n = 1$ in function of its spinning.

	n, *rot/s*			
	0.05	0.1	0.25	0.50
$m_i = \exp(-4.008 \cdot 10^{-3} / n)$	0.9230	0.9607	0.9841	0.9920
$n_i = \exp(-6.8720 \cdot 10^{-3} / n)$	0.8716	0.9336	0.9729	0.9864
$m_r = \exp(-3.088 \cdot 10^{-3} / n)$	0.9401	0.9696	0.9877	0.9938
$n_r = \exp(-2.2997 \cdot 10^{-3} / n)$	0.9550	0.9773	0.9908	0.9954
$N(t_a')$	0.0124	0.0032	0.0005	0.0001
$N(t_g)$	0.0108	0.0029	0.0005	0.0001
$p(t_a')$	0.4527	0.4439	0.4387	0.4369
$t_{ui}(h,0)$	149.9	150.5	150.9	151.0

The air pre-heater that equipages the steam generator has been projected for the $n = 0.05 \ rot/s$ rotation and the previous air preheating temperature $t_a' = 100 \ ^oC$. In this conditions (see Table 3.2) and from the relation (2.30) results the value of the metal filler temperature $t_{ui}(h,0) = 150 \ ^oC$. Due to the fact that the acid dew temperature is of $t_{ra} = 149 \ ^oC$, there is no danger of Sulphur acid condense, the corrosion being therefore avoided. From **Table 3.2** is observed that the influence of the spinning may prevent the acid dew phenomena only up to some point, only when the acid dew temperature is close to the filler temperature at pre-heater's end. Using the same calculation methodology as in the making of table 3.2, in the case of partial load $D_{sp} = 0.8$, **Table 3.3** and **figure 3.2** are made.

It is seen that major influences that the rotation may have on the acid dew phenomena might be obtained only on higher speed rotation of the heat exchanger rotor.

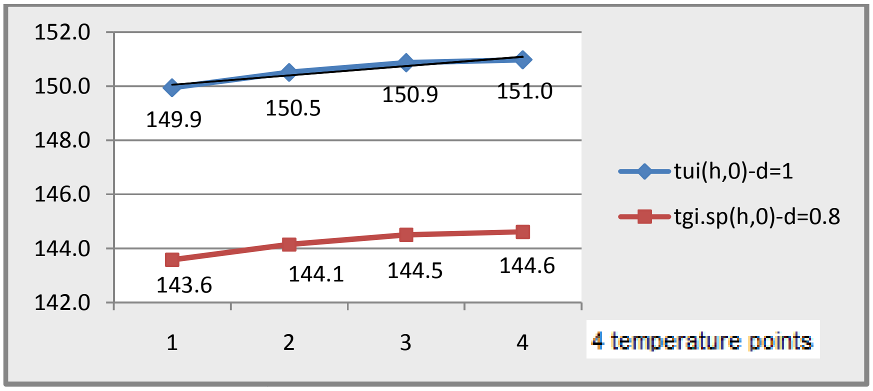


Fig. 3.3 Chart representation of the temperature points of the metal filler $t_{ui}(h,0)$ and $t_{ui.sp}(h,0)$ obtained in **Tables 3.2** and **3.3.**

3.4.2 The influence of the increasing combustion air temperature at the inlet of the air pre-heater on its acid corrosion

Another method of avoiding the acid corrosion is represented by the temperature increase of the combustion air at admittance in the air pre-heater t_a' at an optimum value, value obtained by calculation means and displayed on **Tables 3.4** and **3.5.**

In the above mentioned tables an oscillation of the temperature point of the metal filler is represented at the end of the pre-heater, in the flue gases flow direction, in function of the combustion air temperature at pre-heater entry t_a' and its rotor rotations.

Table 3.5 Filler temperature $t_{ui}(h,0)$, in function of temperature increase t_a' and functioning at nominal load $D_n = 1$

	$t_{ui}(h,0) = N(t_g)/N(t_{ui}) \cdot t_{gi} + N(t_a')/N(t_{ui}) \cdot t_a',\ ^oC$			
	$n,\ rot/\sec$			
	0.05	0.1	0.25	0.50
$t_a' = 90^oC$	144.6	145.2	145.6	145.7
$t_a' = 100^oC$	149.9	150.5	150.9	151.0
$t_a' = 110^oC$	155.3	155.8	156.1	156.2
$t_a' = 120^oC$	160.6	161.1	161.4	161.5

For the pre-heater case presented when functioning at nominal load, the rotor rotation $n = 0.05\ rot/s$ and the acid dew temperature of $t_{ra} = 149\ ^oC$, from **Table 3.4,** it is observed that: for a pre-heating air temperature $t_a'=149\ ^oC$, the temperature value $t_{ui}(h,0)=144.6\ ^oC$, that is being under the acid dew temperature conducts to the apparition of the Sulphur acid inside the heat exchanger. For the other three values of the temperature t_a', of 100 ^oC, 110 ^oC and 120 ^oC, from the mentioned table is observed that the temperature value $t_{ui}(h,0)$ constantly increases in report with the entry combustion air temperature, from the value of 149.9 ^oC up to the value of 160.6 ^oC. For these three values, because $t_{ui}(h,0)>t_{ra}$ the acid dew phenomena does not appear on the whole pre-heater surface. For the second case, at partial load functioning of 80 % of the steam generator, the results are presented in table 3.6 and interpreted in the same way as at the steam generator's nominal load functioning.

At a normal air pre-heater whose two areas hot and cold, are distinct, their thermal calculations are made separately, because each one's filler has different geometrical characteristics. During the steam generator's functioning usually in variable regime, with partial loads, acid corrosion conditions are being created, the phenomena comprising the ZR cold area. The two areas can be constructively separated in a way such that the rotor to be made in two steps (like the carcasses), see **fig. 3.4.** At such construction it is allowed to adopt variable speed rotation for the second part corresponding to the cold zone of the heat exchanger. In this way, the rotor speed rotation may be optimized that the acid dew phenomena does not take place or is held better under control. The training of the R.A.P.H. two steps may be done with separated electromotor.

With this system the last pre-heater's step being considerably lighter (as in mass) than the standard one may be easily replaced if needed and this zone's rotation speed might be considerably increased. All these modifications impose technical and economic calculations in order to find an optimum solution.

Another control possibility of the acid dew phenomena is to know the air pre-heater's thermal regime by mounting some very small temperature sensors (maximum 1 mm diameter) in the metallic filler. The sensors should function by wireless and transmit the signal to a command unit from outside the pre-heater, in this way the thermal regime of the heat exchanger being monitored in real time. For now, about these small but powerful sensors, with great autonomy and transmitting the signal throught the pre-heater material, unknown until nowadays here was no knowledge but future technology may progress a lot in this direction also. These last two ideas need a future research.

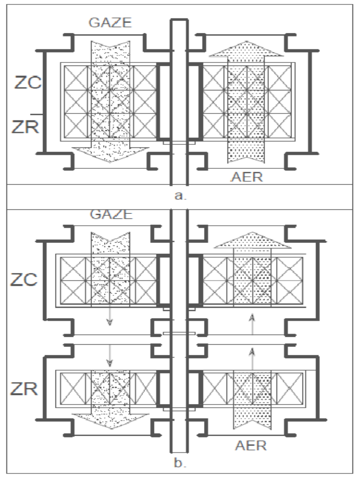


Fig 3.4 Constructive R.A.P.H systems: a- in one step, b- in two steps (second step with variable speed rotation)

It found that the speed rotation, in case of this pre-heater type, has been a small influence on the heat exchanger thermal regime. it was shown that the filler temperature on the end of the pre-heater, in the sense of flue gases flow, at the height h and the angle $\varphi = 0$, $t_{ui}(h,0)$, ^oC, did not considerably differed by increasing the rotation speed. The calculation was made also for the steam generator load of 80 %, the results were presented in table 3.4.

The second Sulphur acid apparition stopping method inside the heat exchanger, presented in subchapter 3.4 consisted in rising the air temperature at preheater admittance from t_a', from 90 ^oC to 120 ^oC (see **tables 3.5** and **3.6**) for different pre-heater rotations. By increasing of this temperature the acid dew phenomena is diminished or even disappears, obviously with disadvantages connected to the corresponding consumed energy.

The two stopping or controlling methods of the acid dew apparition presented need an additional analysis regarding a thermic and economic calculation: what is more convenient, to increase the rotation speed, to increase t_a', to increase both or to use another method for treating the corrosion phenomena.

CHAPTER 4

NUMERICAL SOLVING OF THE EQUATION SYSTEM THAT MODELS THE R.A.P.H. FUNCTIONING

4.1 SOLVING OF THE EQUATION SYSTEM RESULTED ON THE FLUE GASES PART

4.1.1 Metal filler heating

The space variations of the flue gases heat content from a volume element of the filler (during the cooling period of flue gases and filler heating), takes us to the next differential equation system, that mathematically model the thermal regime of the analyzed system.

For heating the filler the equation system formed by the relations (4.1) and (4.2) is to be used [8].

$$w_g \frac{\partial t_{gi}(z_i,\varphi_i)}{\partial z_i} + \omega \frac{\partial t_{gi}(z_i,\varphi_i)}{\partial \varphi_i} = -a \cdot \left[t_{gi}(z_i,\varphi_i) - t_{ui}(z_i,\varphi_i) \right] \quad (4.1)$$

$$\omega \frac{\partial t_{ui}(z_i,\varphi_i)}{\partial \varphi_i} = b \cdot \left[t_{gi}(z_i,\varphi_i) - t_{ui}(z_i,\varphi_i) \right] \quad (4.2)$$

It then gets approximated by the neat partial derivate of second order from the system formed by the equations presented at the (4.10 and (4.2) [8].

By solving the equation system formed by the relations 4.1 and 4.2 the unknowns are found, the temperature of the preheater at z_i height and center angle formed by its rotation φ_i:

From the relation (4.19) results the temperature $t_{ui}(z_i,\varphi_i)$, ^oC:

$$t_{ui}(z_i,\varphi_i) = \frac{E \cdot C \cdot t_{gi}(z_{i-1},\varphi_{i-1}) - A \cdot \omega \cdot t_{ui}(z_{i-1},\varphi_{i-1})}{E \cdot B - A \cdot G} \quad (4.20)$$

Calculation of the temperature $t_{gi}(z_i,\varphi_i)$, ^oC:

$$t_{gi}(z_i,\varphi_i) = \frac{A \cdot B \cdot \omega \cdot t_{ui}(z_{i-1},\varphi_{i-1}) - t_{gi}(z_{i-1},\varphi_{i-1}) \cdot (B \cdot C \cdot E - F \cdot C)}{A \cdot F} \quad (4.22)$$

The step with which the pre-heater's height increases for each calculated temperature point p, m:

$$p = h / i_{\max} \quad (4.23)$$

The step with which the pre-heater's angle increases for each calculated temperature point pp, rad:

$$pp = \varphi_{it} / i_{\max} \quad (4.24)$$

For $i = 1$, with help of the notations (4.10),(4,11),(4.12),(4.16),(4,21), the relations (4,20) and (4.22) become ^oC:

$$t_{ui}(1,1) = \frac{E \cdot C \cdot t_{gi}(0,0) - A \cdot \omega \cdot t_{ui}(0,0)}{E \cdot B - A \cdot G} \quad (4.29)$$

$$t_{gi}(1,1) = \frac{A \cdot B \cdot \omega \cdot t_{ui}(0,0) - t_{gi}(0,0) \cdot (B \cdot E \cdot C - F \cdot C)}{A \cdot F} \quad (4.30)$$

Variables " i " and " j ", on the filler heating part are chosen function of how many temperature points are to be calculated inside the air pre-heater. All temperature are defined with the help of the two variables z_i and φ_i, presented on (4.25) and (4.26). 12 temperature points are being analyzed ($j = 1...12$), in function of the height and the angle formed by the pre-heater when spinning. For each temperature the calculation mode presented in the relations (4.29) and (4.30) are to be used.

4.1.2 Presentation of the numerical values calculated on the heating of the filling part

4.2 SOLVING OF THE EQUATION SYSTEM RESULTED ON THE COMBUSTION AIR PART

4.2.1 Cooling of the metal filler

For cooling the filler the equation system formed by the relations (4.31) and (4.32) is to be used [8].

$$w_a \cdot \frac{\partial t_{ar}(z_r,\varphi_r)}{\partial z_r} + \omega \cdot \frac{\partial t_{ar}(z_r,\varphi_r)}{\partial \varphi_r} = a_r \cdot [t_{ur}(z_r,\varphi_r) - t_{ar}(z_r,\varphi_r)] \tag{4.31}$$

$$\omega \cdot \frac{\partial t_{ur}(z_r,\varphi_r)}{\partial \varphi_r} = -b_r \cdot [t_{ur}(z_r,\varphi_r) - t_{ar}(z_r,\varphi_r)] \tag{4.32}$$

It then gets approximated by the neat partial derivate of second order from the system formed by the equations presented at the (4.31) and (4.32) [8] .

The step with which the pre-heater's height increases for each calculated temperature point p, m:

$$p = h / j_{\max} \tag{4.52}$$

The step with which the pre-heater's angle increases for each calculated temperature point pp_r, rad:

$$pp_r = \varphi_{rt} / j_{\max} \tag{4.53}$$

For $j = 1$:

With help of the notations (4.39),(4,41),(4.44),(4.45),(4,50), the relations (4,48) and (4.51) become ^oC:

$$t_{ur}(1,1) = \frac{T \cdot R \cdot t_{ar}(0,0) - M \cdot \omega \cdot t_{ur}(0,0)}{T \cdot N - M \cdot S} \tag{4.56}$$

$$t_{ar}(1,1) = \frac{K \cdot \omega \cdot t_{ur}(0,0) - S \cdot T \cdot R \cdot t_{ar}(0,0) + S \cdot M \cdot \omega \cdot t_{ur}(0,0)}{K \cdot T} \tag{4.57}$$

In a manner identical with the heating one, the "*j*" variable on the filler heating part is chosen function of how many temperature points are to be calculated inside the pre-heater. All temperatures are defined with the help of the two variables z_r and φ_r, presented on (4.54) and (4.55). 12 temperature points are being analyzed ($j = 1...12$) identically with the heating part.

With this mathematical model presented in Chapter 4 it can be calculated, on the heating or cooling part of the pre-heater as many temperature points are to be desired depending only the step chosen for the rotor height (z) and the step of the rotation angle (φ) of the pre-heater.

4.2.2 Presentation of the numerical values calculated on the cooling metal filler part

The **Figures 4.1** and **4.2** represent in a chart the temperature points of the filler, gases and combustion air obtained.

The solving of the equation system from the relations (4.1),(4.2) on the filler heating part, respective (4.31), (4.32) with the unknown $t_{ui}(z_i,\varphi_i)$ and $t_{gi}(z_i,\varphi_i)$, respectively $t_{ur}(z_i,\varphi_i)$, $t_{ar}(z_i,\varphi_i)$, allows finding the practical possibilities of avoiding the acid corrosion of the R.A.P.H. rotor metal sheet.

The point mostly exposed to corrosion is the one (zone) with the temperature $t_{ui}(h,0)$; if the acid corrosion in this zone is avoided, the whole rotor shall be protected. This happens when când $t_{ui}(h,0) > t_{ra}$, °C (the acid dew temperature value is presented in the previous chapters).

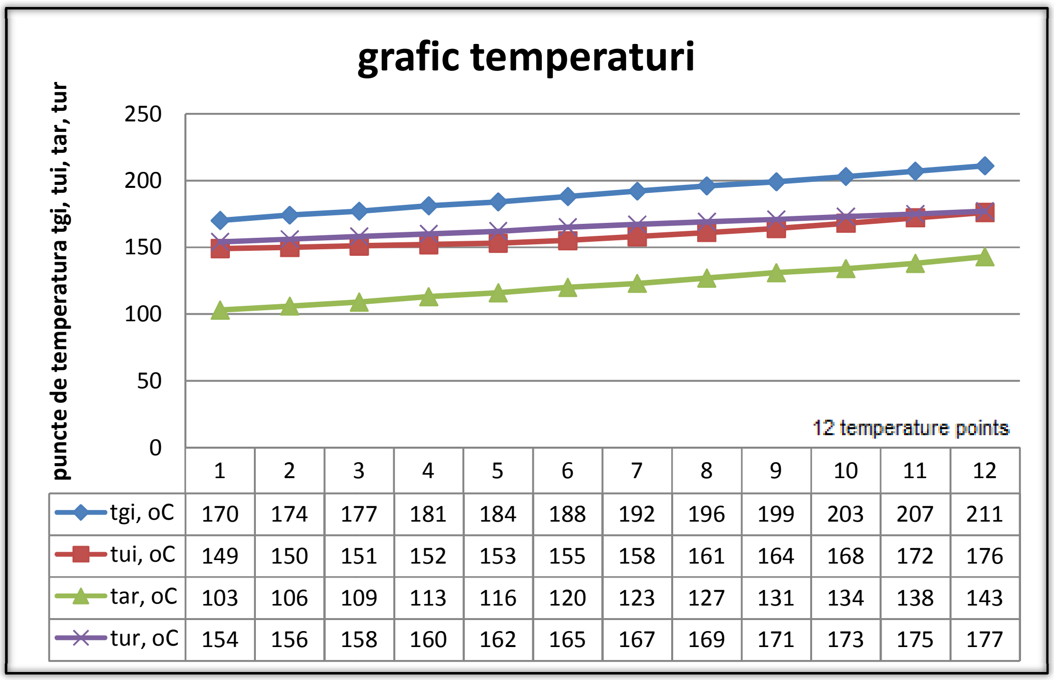


Fig. 4.1 Temperatures chart, t_{gi} - flue gases temperature, °C; t_{ui} - heating part filler temperature °C; t_{ar} - combustion air temperature, °C; t_{ur} - cooling part filler temperature, °C

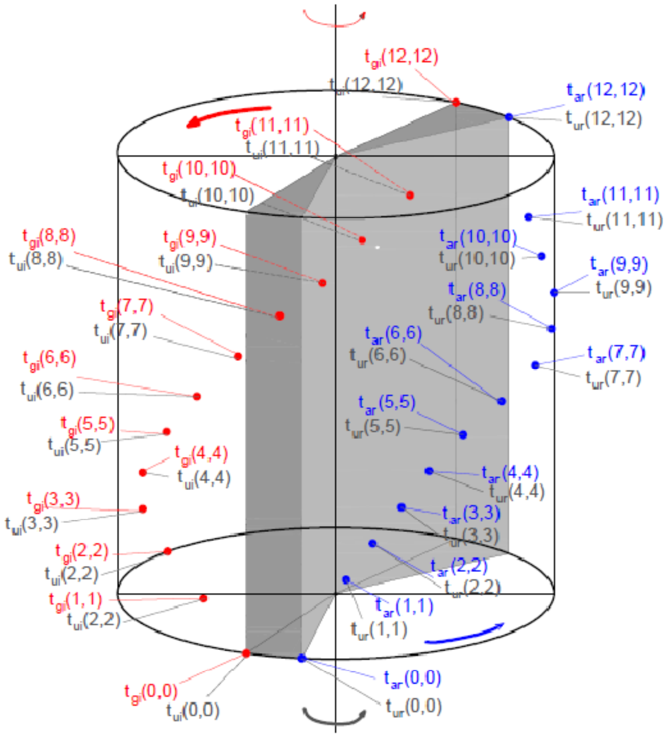


Fig. 4.2 Spatial view of the R.A.P.H. rotor, t_{gi} - flue gastemperature , °C; t_{ui} - heating part filler temperature °C; t_{ar} - combustion air temperature, °C; t_{ur} - cooling part filler temperature, °C

CHAPTER 5
APPLICATION OF THE EQUATION SYSTEM FOR A REAL MODEL OF REGENERATIVE AIR PRE-HEATER

5.1 THE ACID CORROSION PHENOMENA ON A REAL ROTATING-PLATE REGENERATIVE AIR PRE-HEATER

5.1.1 Constructive and functional characteristics of the real rotating plate air pre-heater

The mathematical model developed in chapter 5 has been validated on a real rotating-plate regenerative air pre-heater, Rothemuhle type, that equips a steam generator of 510 t/h from CET Isalnita. In the first experimental part phase, the thermoelectrical plant was in revision (may be observed in **Fig. 5.4**) and one of the interventions refers to the rehabilitation of the steam pre-heaters in order to change the rotor (the active zone) and reduce the fake air infiltrations. With a fix rotor (Rothemuhle type) or mobile (Ljungstrom type), the results may be validated, because the rotation speed of the pre-heater influences very little the variation in the flue gases and air temperature, affirmation demonstrated on Chapter 3. Together with these, both rotating pre-heaters use metallic filler, which leads to similar heat exchanges.

In **fig.5**.1.a and **5.1.b** the new filler metal combs to be assembled inside the carcass are presented and in **fig.5.2** an overview of the active zone that was unassembled in order to be replaced is presented.

Fig. 5.1.a- New metal filler for the rotating-plate regenerative air pre-heater from CET Isalnita, formed by metal undulated sheet metal comb-overview

Fig. 5.1.b- Metal filler, from emanel sheet, for the cold zone of the studied air pre-heater

The main parameters of the 7B steam generator from CET Isalnita, are:
Nominal flow $D_n = 510 \quad t/h$; $D_n = 141.667 \quad kg/s$;
Nominal temperature $t_n = 540 \ ^oC$;
Nominal pressure $p_n = 196$ bar;
Supply water temperature $t_e' = 240 \ ^oC$;
Ambiental temperature $t_o = 25 \ ^oC$;
The used fuel is fuel oil with elementary analysis:
$C_i = 22.8$ %; $S_i = 0.74$ %; $H_i = 2.08$ %; $N_i = 0.51$%;
$W_{ti} = 41.86$ %; $O_i = 9.78$ %; $A_i = 22.23$ %;

The characteristics of the air pre-heater, Rotermuhle type are:

Rotor diameter 8.5 *m*;

Active zone height 1.35 *m* (0.55 *m* hot zone, 0.55 *m* intermediary zone, 0.25 *m* cold zone). In this work the hot and intermediary zone are regarded as a sole hot zone of the pre-heater.

Filler type: undulated metal sheet of 0.5 *mm*

A presentation of the metal filler is shown in **fig. 5.3.a** and **fig. 5.3.b.**

Fig. 5.3.a- Used metal filler 1- overview

Fig 5.4 Revision of the R.A.P.H, Rotermuhle type- CET Isalnita.

The scope of the calculation was the determination of the acid dew and of the cold zone air pre-heater height. It is desired that on this height the active zone shall be made of emaliate undulated metal sheet. In **fig. 5.5** a part of the active corroded zone to be changed is presented and in **fig. 5.1** a part of the new active zone. The calculation was made for 4 functioning regimes of the steam generator as it follows: nominal load of 100 %, partial load of 72 % and partial load of 85 %.

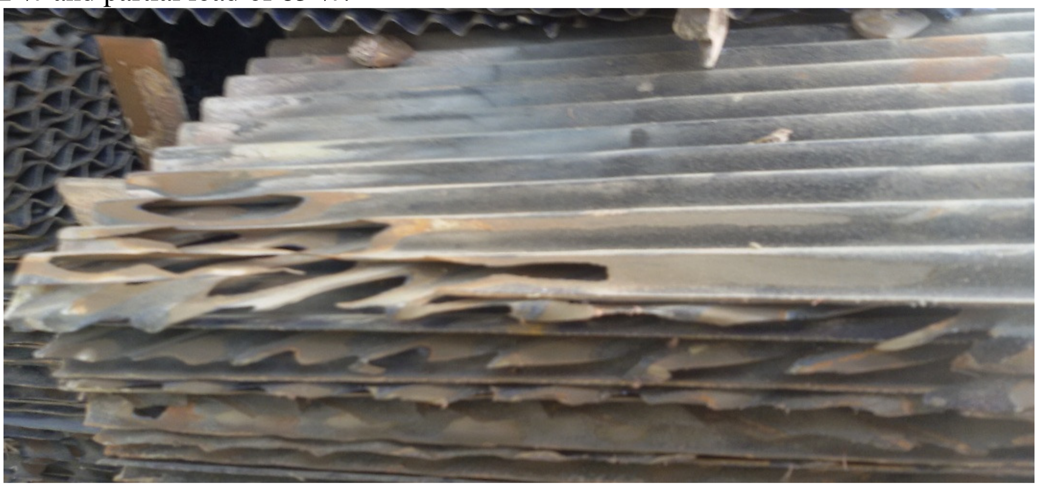


Fig 5.5 Metal filler corroded of the used pre-heater, formed by metal undulated sheet metal comb

In the beginning, the calculation has been made for the normal parameters for the thermal plant.

5.1.2 Determining of the acid dew point for the real case

The acid dew temperature is being calculated with the relation (1.35):

$$t_{ra} = 152\ ^{o}C$$

In function of the in and out flue gases and combustion air temperatures, the temperatures between the two zones were calculated, hot and cold of the working fluids t_{gi} and t_{ai} with the values displayed above.

$t_g = 310^{o}C;$ $t_a'' = 282^{o}C;$

$t_{gi} = 205^{o}C;$ $t_{ai} = 124^{o}C;$

$t_{ev} = 147^{o}C;$ $t_a' = 50^{o}C;$

5.2 CALCULATION OF THE HOT AND COLD ZONE OF THE ROTATING-PLATE REGENERATIVE AIR PRE-HEATER

5.2.1 Calculation of the hot zone of the real rotating-plate regenerative air pre-heater

5.2.2 Calculation of the cold zone of the real rotating-plate regenerative air pre-heater

For the cold zone (ZR) the filler with the following characteristics is chosen:

It is desired that on this height the active zone has to be made of emaliate undulated metal sheet, with a email layer of 0.2 *mm* on each side, resulting in a final thickness of 0.9 *mm* on the cold zone.

5.2.3 Determining of the significant temperature points of the studied air pre-heater

The loads presented in **Table 5.1** were taken, from the functioning history of the C7B steam generator from Isalnita Power Plant: maximum possible, intermediary and minimal for the following necessary determining.

Table 5.1 Presentation of the tests taken from CET Isalnita, on C7B generator at different functioning loads of functioning for the steam generator

PROBE	C7B Steam Generator
PROBE NR. 0	510.0 (100 % ·Dn) t/h
PROBE NR. 1	440.8 (aprox. 86 % · Dn) t/h
PROBE NR. 2	369.1 (aprox. 72 % · Dn) t/h
PROBE NR.3	295.6 (aprox. 58 % ·Dn) t/h

Indexes 0, 1, 2, 3 are used for tests no. 0, respectively no. 1, no. 2, no. 3.

The following temperature value sets are obtained for different functioning loads of the steam generator and are presented in tables 5.3, 5.4, 5.5, 5.6:

The results obtained in **Tables 5.3- 5.6** shown the influence of the partial loads on the thermal regimes of the pre-heater. The flue gases temperature on entry (t_g) are shown, on exit (t_{ev}) and between the two zones hot and cold of the pre-heater (t_{gi}). On the combustion air part the temperatures on the same zone (t_a', t_a'', t_{ai}) are shown. In function of decreasing the partial loads of the pre-heater the entry flue gases temperature t_g decreases from 310 ^oC to 269 ^oC, the evacuation gases temperature t_{ev} decreases from 147 ^oC to 132 ^oC and the temperature between the two zones, hot and cold of the pre-heater t_{gi} decreases from 205 ^oC to 189 ^oC. In function of the decrease of the partial loads of the pre-heater the air temperature on exit t_a'' decreases from 282 ^oC to 250 ^oC, the temperature between the two zones, hot and cold of the pre-heater t_{ai} increases from 124 °*C* to 131 °*C* and the entry air temperature t_a' is constant, 50 ^oC.

5.3 DETERMINING OF THE TEMPERATURE SPECIFIC POINTS FOR THE R.A.P.H. FILLER

5.3.1 Heating of the corresponding filler for the nominal steam generator functioning regime

From this point on, all calculations refer only to the cold zone of the pre-heater.

The specific resulted system on the cooling part of the flue gases calculation and heating of the pre-heater filling, respectively heating of the combustion air part and cooling of the pre-heater's filler is made in conformity with the calculation methodology presented in Chapter 4.

The numeric value of the metal filler temperature on the heating part, in the limit point of the pre-heater, at $z_i = 0$, $\varphi_i = 0$, in its nominal functioning is calculated with the (2.30) relation.

$$t_{gi0}(0,0) = 147 \ ^{o}C; \qquad t_{ui0}(0,0) = 124 \ ^{o}C;$$

Some of the elements calculated at the beginning of Chapter 5 are taken:

The step with which the pre-heater's height increases for every temperature point calculated $p = 0.063 \ m$, for $j_{\max} = 4$ is to be calculated with the (4.23) relation.

The step with which the pre-heater's angle increases for every temperature point calculated $pp = 0.851 \ rad$, is to be calculated with the (4.24) relation.

For $j = 1$:

The corresponding height to each calculated temperature point is determined with the (4.25) relation:

$$z_1 = 0.063 \ m$$

The corresponding angle to each calculated temperature point is determined with the (4.26) relation.

$$\varphi_1 = 0.851 \ rad.$$

With the help of (4.29) and (4.30) relations the filler and flue gases temperature are calculated at z_1, ^{o}C, and φ_{i1}, rad:

$$t_{ui0}(1,1) = 132 \ ^{o}C; \qquad t_{gi0}(1,1) = 160 \ ^{o}C.$$

For the other points until $j = 4$, the filler and flue gases temperatures on generator's functioning are calculated in the same way, on the flue gases flowing part, at nominal load as well as on $j = 1$ and the values from **Table 5.7** and **Table 5.15** are obtained.

5.3.2 Cooling of the corresponding filler for the nominal steam generator functioning regime

The numeric value of the metal filler temperature on the cooling part, in the limit point of the pre-heater, for $z_r = 0$, $\varphi_r = 0$, in its nominal functioning is calculated with the (2.49) relation.

$$t_{ar0}(0,0) = 50 \ ^{o}C; \qquad t_{ur0}(0,0) = 124 \ ^{o}C;$$

The total angle of the cooling zone on which the heater is rotating $\varphi_{rt} = 2.356 \ rad$, is found with help of the (1.103) relation.

The step with which the pre-heater's height increases for every temperature point calculated $p = 0.063 \; m$, for $j_{\max} = 4$ is to be calculated with the (4.52) relation.

The step with which the pre-heater's angle increases for every temperature point calculated $pp_r = 0.589 \; rad$, is to be calculated with the (4.53) relation.

For $j = 1$:

The corresponding height to each calculated temperature point on the cooling part is determined with the (4.54) relation:

$$z_1 = 0.063 \; m$$

The corresponding angle to each calculated temperature point on the cooling part is determined with the (4.55) relation.

$$\varphi_{r1} = 0.589 \; rad;$$

With the help of (4.56) and (4.57) relations the filler and flue gases temperature are calculated at z_1, ^oC, and φ_{r1}, rad:

$$t_{ur0}(1,1) = 134 \; ^oC; \qquad t_{ar0}(1,1) = 64 \; ^oC.$$

For the other points until la $j = 4$, the filler and flue gases temperatures on generator's functioning are calculated in the same way, on the flue gases flowing part, at nominal load as well as on $j = 1$ and the values from **Table 5.8** and **Table 5.15** are obtained.

5.3.3 Temperatures obtained for the 4 analyzed functioning regimes

In **Table 5.9**, **Table 5.10** and **Table 5.15** are presented the numerical values calculated on the heating part, respectively cooling part of the filler corresponding to test no. 1 of steam generator in nominal functioning regime.

The calculations specific to the filler's heating for tests no.1, no.2, no.3 are made in conformity with the calculation methodology presented on test no. 0, of generator's nominal functioning regime.

In **Table 5.11**, **Table 5.12** and **Table 5.15** are presented the numerical values calculated on the heating part, respectively cooling part of the filler corresponding to test no.2 of steam generator in nominal functioning regime.

In **Table 5.13**, **Table 5.14** and **Table 5.15** are presented the numerical values calculated on the heating part, respectively cooling part of the filler corresponding to test no.3 of steam generator in nominal functioning regime.

The calculation results corresponding to Chapter 5 are written in **table 5.15** and represented as chart in **fig. 5.6.**

Table 5.15 The temperature points corresponding to chapter. 5, obtained at steam generator functioning on different loads

Temp. points obt. at z_i and φ_i	t_{gi0}, ^oC	t_{ui0}, ^oC	t_{ar0}, ^oC	t_{ur0}, ^oC	t_{gi1}, ^oC	t_{ui1}, ^oC	t_{ar1}, ^oC	t_{ur1}, ^oC
(1,1)	160	132	64	134	155	128	63	129
(2,2)	175	142	80	144	169	137	79	139
(3,3)	190	153	100	155	184	148	99	150
(4,4)	206	167	126	168	200	161	124	162
Temp. points obt. at z_i and φ_i	t_{gi2}, ^oC	t_{ui2}, ^oC	t_{ar2}, ^oC	t_{ur2}, ^oC	t_{gi3}, ^oC	t_{ui3}, ^oC	t_{ar3}, ^oC	t_{ur3}, ^oC
(1,1)	147	122	62	124	144	117	61	119
(2,2)	160	131	78	134	157	126	76	128
(3,3)	175	142	98	144	171	136	94	138
(4,4)	190	154	122	156	186	149	116	149

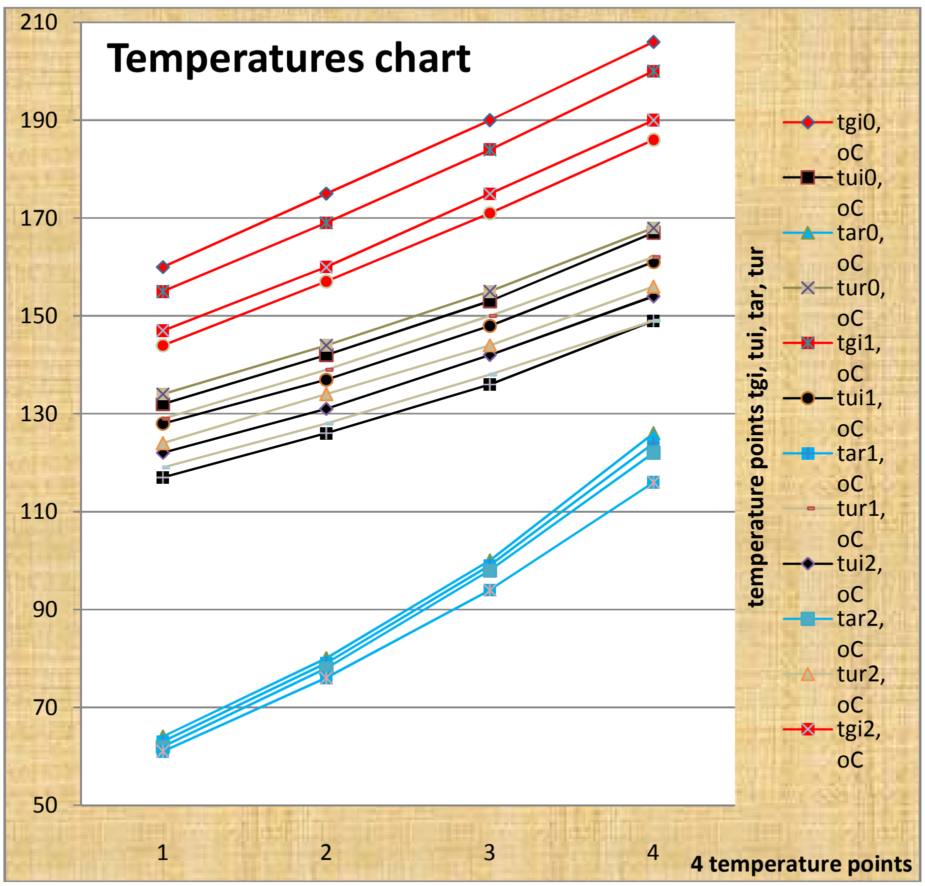


Fig. 5.6- Chart representation of the air pre-heater's functioning, represented by specific temperature points, function of the steam generator load.

Acid dew temperature for the used fuel (coal-lignite) is of 152 C and the cold pre-heater's zone height is of 0.25 m (25 cm).

The temperature points used in order to find out on the pre-heater's height in which point does the metal acid corrosion appear are the temperatures from the cold pre-heater zone in the flue gases flow $t_{ui}(1,1)$, $t_{ui}(2,2)$, $t_{ui}(3,3)$, $t_{ui}(4,4)$. From **Table 5.15** and **fig. 5.6** is observed that, for the 4 tests on different loads of the steam generator, the following conclusions take contour:

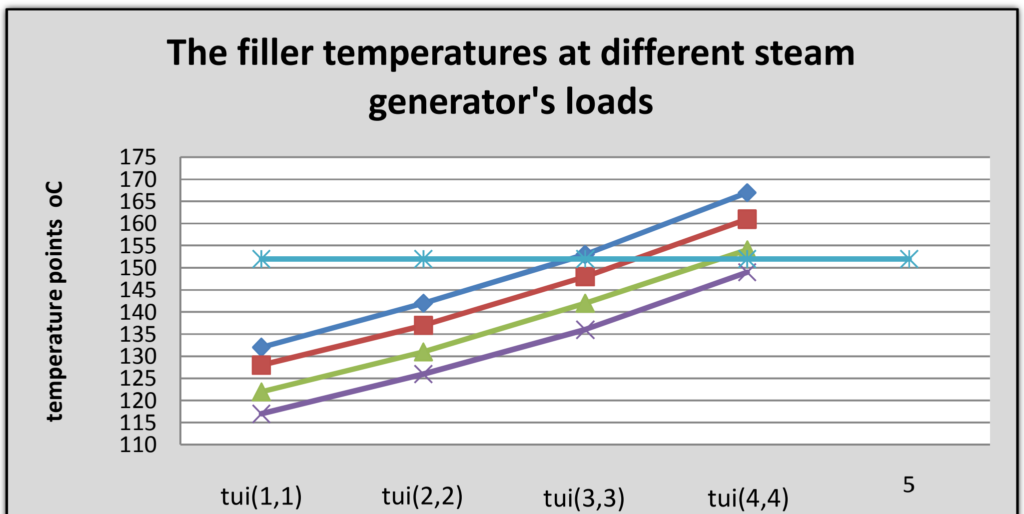
- for the nominal test (test no.0) $t_{ra} \approx t_{ui0}(3,3) = 153\ ^oC$, the acid dew phenomena appears in the cold zone, at the pre-heater's height of 0.189 m (18.9 cm).

- for the test at the generator's partial load of 86 % (test no. 1) t_{ra} is situated between $t_{ui1}(3,3) = 148\ ^oC$ and $t_{ui1}(4,4) = 161\ ^oC$, results that the acid dew phenomena appears in the cold zone, at the pre-heater's height of 0.22 m (22 cm).

- for the test at the generator's partial load of 72 % (test no. 2) $t_{ra} \approx t_{ui2}(4,4) = 154$ ^oC, results that the acid dew phenomena appears in the cold zone, at the pre-heater's height of 0.25 m (25 cm).

- for the test at the steam generator's partial load of 58 % (test no. 3) $t_{ra} > t_{ui3}(4,4) = 149\ ^oC$, results that the acid dew phenomena appears in the cold zone, at the pre-heater's height of 0.28 m (28 cm).

In **fig. 5.7** the filler temperatures are represented as chart for the 4 generator's loads shown above, in report with the acid dew temperature.



	1.1	2.2	3.3	4.4	5
tui0, oC	132	142	153	167	
tui1, oC	128	137	148	161	
tui2, oC	122	131	142	154	
tui3, oC	117	126	136	149	
tra, oC	152	152	152	152	152

Fig. 5.7- The filler temperatures obtained at different loads, in report with the acid dew temperature

Data were obtained that could be useful in the geometrical dimensioning of such pre-heater cold zone. The height may be increased in such way that the acid dew point to be under the temperature point of the metal filler at this zone entry.

Only 4 points of temperature were effected for each one of the four steam generator functioning loads. The calculation methodology may be extended on to as many temperature points as desired. The calculations were made only for the cold zone of the pre-heater but they may be extended to the hot zone.

5.3.4 Measurements performed at CET Isalnita

Temperature measurements were performed (that validate the mathematical model presented in the previous chapters) and of environment conditions on one of the two rotating-plate regenerative air functional pre-heaters of the 7B Steam Generator from Isalnita thermal power plant. The determining were made with the following measuring means:

- pirometer Powerfix HG00304 with serial no 271160;
- termo-higro-barometer PCE- THB- 40 with serial no Q704356.

The measurements of environment conditions (see **Table 5.17**) were made on 20 minutes period with the thermo-hygro-barometer mentioned.

Table 5.17 Measurements of the environment parameters

Position	Date	Time	Ch1_ Value	Ch1_ Unit	Ch2_ Value	Ch2_ unit	Ch3_ Value	Ch3_ unit
1	7/14/2016	12:00:14	46,2	%RH	000027,6	DEGREE C	000749,2	mm Hg
2	7/14/2016	12:05:14	46,7	%RH	000027,7	DEGREE C	000749,1	mm Hg
3	7/14/2016	12:10:14	46,8	%RH	000027,7	DEGREE C	000749,0	mm Hg
4	7/14/2016	12:15:14	45,7	%RH	000027,8	DEGREE C	000749,1	mm Hg
5	7/14/2016	12:20:14	45,3	%RH	000027,9	DEGREE C	000749,0	mm Hg

Temperature measurements were made in the flue gases evacuation part from the air pre-heater, through a visiting door, see **Fig. 5.10** and the results made on a period of time of 20 min (with the mentioned pyrometer and presented in **Fig. 5.9** and in **Table 5.18**) were shown in **Table 5.19**.

Table 5.19. Measurement of the filler temperature $t_{ui}(h,0)$ ^{o}C, at $h = 0$, $\varphi = 0$, obtained at the steam generator's partial load of 72%.

Nr. Crt.	**Date**	**Time**	**Tmeperature value** ***$t_{ui}(h,0)$***	**Measure unit**
1	6/14/2016	12:00:14	117	^{o}C
2	6/14/2016	12:02:14	118	^{o}C
3	6/14/2016	12:04:14	119	^{o}C
4	6/14/2016	12:06:14	119	^{o}C
5	6/14/2016	12:08:14	118	^{o}C
6	6/14/2016	12:10:14	119	^{o}C
7	6/14/2016	12:12:14	118	^{o}C
8	6/14/2016	12:14:14	119	^{o}C
9	6/14/2016	12:16:14	118	^{o}C
10	6/14/2016	12:18:14	117	^{o}C

In **Fig. 5.10** it is shown the modality of performing the temperature measurements on the analyzed pre-heater of CET Isalnita Thermal Power Plant.

Fig. 5.14 The modality of performing the temperature measurements on the analyzed pre-heater.

The average values obtained by pyrometer measuring for the steam generator load of 72 % is of approximately 118 ^{o}C. From calculation it results, with the help of the mathematical model a filler temperature of almost 116 ^{o}C.
If a comparison is made by a relative error measuring between the results, a value of 1,8 % is obtained or, if it is taken into consideration a measurement one this is of almost 2 ^{o}C. A relative error of 2 may be covering, and the two results shall be considered as close if it is taken into account the numerous influences that can be calculated at the functioning of such heat exchanger.

CHAPTER 6

CONCLUSIONS. PERSONAL CONTRIBUTION. PERSPECTIVES

CONCLUSIONS

In this chapter the conclusions resulted from this doctorate work are presented. The authors' personal contributions are underlined by ideas debating, theories that shall lead to future preoccupations regarding the type of rotating-plate regenerative air pre-heater studied.

In this work the development of a scientific idea I have conducted regarding the optimization of the rotating-plate regenerative air pre-heaters, idea that led to making them more efficient during functioning.

Thermal regimes, dimensions, used materials I have analyzed, all related to the heat exchanger. Case studies were performed on the pre-heater: the points and the areas of corrosion phenomena from the metal filler material, the heat exchanges in function of the pre-heater rotation speed, its functioning at partial loads, the influence of the temperature of the combustion air on entry over its acid corrosion; a model for numeric calculation I have been elaborating, model that simulates the pre-heater functioning.

In the introduction part the thermal calculation of a steam generator as an example I presented, together with the two identical Ljungstrom type pre-heaters. The presented steam generator uses fuel oil which contains Sulphur in a proportion of 4.5%. This example I had elected in order to underline the effect of the acid corrosion phenomena, although since 1996 the Sulphur content must not exceed 1 %. I have calculated the acid dew temperature in function of the used fuel, then the use of a special filler for the last exchanger step was used (its cold zone). I also showned how the pre-heater was divided in the scope of determining the flue gases and combustion air temperatures in the points that delimitate the two zones, hot and cold. In this chapter I was found some parameters for future determining.

I had presented the cold zone thermal regime, regime that implied calculation of the significant temperature points that vary on a linear mathematical function, from inside the metal comb of the heat exchanger function on its height h and the angle that this makes during its rotation φ. I had founded the temperatures, on the flue gases cooling part as well as on the heating part respectively cooling of the metal filler from inside the heat exchanger.

I have presented the air pre-heater functioning in the partial load regime (steam generator load of 80 %) and the influence of this functioning over the acid corrosion phenomena. I noticed that at partial loads the thermal regime of the heat exchanger decreases, the flue gases on evacuation temperature decreases and also the temperature of the preheated air. This aspect I had underlined more profoundly on in the previous chapters in which 3 functioning partial loads for the steam generator are studied. I had analyzed the evolution of the metallic filler temperature in parallel for the two functioning loads of the generator:

100 % and 80 %.

I have analyzed the acid dew phenomena, phenomena that destroys the metallic filler of the air pre-heater. The forming of the Sulphur acid from Sulphur anhydrate vapors that combine with water vapors condensed on the inner wall of the metallic comb of the heat exchanger was shown.

I have displayed the possibilities of controlling the acid dew phenomena by presenting of two methods of controlling or stopping this phenomena. The first method is represented by the rotation speed of the pre-heaters' rotor over the heat exchanges and, implicitly, over the metal filler acid corrosion prevention. The first two preheaters rotor speed rotation shown are used in reality, the other two were chosen in order to underline the phenomena better, even if they are outside the practical field.

I have noticed that the rotation speed, for this preheater's case has little influence over the thermal regime of the heat exchanger. I had shown that the filler temperature at the pre-heater end, in the flue gases flow sense, at height h and angle $\varphi = 0$, $t_{ui}(h,0)$, ^{o}C, does not significantly differ by rotation increase. The calculation was made both for nominal as well as for partial steam generator 80 % load.

The second method for stopping the Sulphur acid apparition inside the heat exchanger, which I have presented, consists in increasing the air temperature at pre-heater's entry $t_a{}'$, from 90 ^{o}C to 120 ^{o}C, for different pre-heater rotation. By increasing of this temperature, the acid dew phenomena is diminished or even disappears, obviously with the disadvantages related to the consumed energy. I reminded here that the most important temperature point related to the acid dew is $t_{ui}(h,0)$ and the increase in the $t_a{}'$ temperature leads to this temperature increase. If $t_{ui}(h,0) > t_{ra}$ then the acid dew phenomena does not appear inside the heat exchanger. This might be accomplished for instance by pre-heating the air from a calorifier connected to any of the turbine socket.

I have presented also two ideas for pre-heaters possible research, one of separating the pre-heater thermal zones, the cold one being easier to be changed or used with another rotation speed than the hot one; and the second presents the usage of very small sensors mounted in the pre-heater's metal filler, that can broadcast wireless the signal to an outside controller from the pre-heater's exterior, in this way the thermal regime of the heat exchanger being monitored in real time.

I have created a mathematical model that simulates the pre-heater's functioning and with whose help the inner temperatures are highlighted: the metallic filler, flue gases and combustion air temperature in the significant points of the metallic comb, in function of the height h and its center angle formed by its spinning φ.

I had applied the mathematical model on the pre-heater's studied case, for its last (cold) thermal zone. 12 temperature points were analyzed on the cooling of the flue gases, respectively heating of the combustion air. The results were presented for the nominal load steam generator functioning for the two heating, respectively cooling zones. The temperature evolution in the analyzed points is decreasing for the gas flue flow zone and increasing for the combustion air zone, including the metallic filler temperatures, which are decreasing in the gases zone and increasing in the air zone, evolutions that are normal and that validate the mathematical presented model.

I have implemented the mathematical model of theoretical calculation analyzed on a real case of air pre-heater, Rotermuhle type, on the 7B Steam Generator from CET Isalnita Power Plant, that functioned on coal (lignite) with a calorific inferior value $Q_i^i = 7836$ *kJ/kg* and the Sulphur content of $S_i = 0.74$ %. Even if the generator has an air pre-heater, Rotermuhle type (with fix rotor) the results can be validated, because, as shown in the previous chapters, the rotation speed has very little influence on the pre-heater's thermal regime and besides this aspect, both metal combs use metal filler, which leads to similar heat exchanges. The partial loads were taken from the functioning history of the steam generator from CET Isalnita. In this chapter, I had applied the mathematical model for 4 temperature points and 4 partial loads of the steam generator.

The most important conclusion that I had unraveled after applying the mathematical model on the real case of air pre-heater is pointed out in the following:

The acid dew temperature for the fuel used (coal-lignite) is of 152 ^oC, and the cold zone height is of 0.25 m (25 cm).

After the calculation, I have noted that the acid dew phenomena appears on a pre-heater's height:

- for the steam generator at a nominal load at 0.189 m (18.9 cm)
- for the steam generator at a partial load of 86 % at 0.22 m (22.0 cm);
- for the steam generator at a partial load of 72 % at 0.25 m (25.0 cm);
- for the steam generator at a partial load of 58 % at 0.28 m (28.0 cm);

From the steam generator project, the pre-heater's cold zone has 25 cm. This is formed from a metallic comb with metal filler specially treated or thicker than the filler used in the hot zone. The height mentioned coincides with the effective cold zone one, for the fuel used in the analyzed case, when the generator functions on a partial load of 72 %. But when the steam generator's load decreases under 72 %, 58 % for instance the cold zone height must be at least of 28 cm in order for the acid dew phenomena not to form in the superior pre-heater zone, in which the metal sheet of the filler is not a special one and does not resists well to corrosion. For this case, an optimal height of the heat exchanger cold zone would be of 30 cm. With the help of what was presented, for the case in which the replacement of the metal comb is desired, at the repairing of the generator time, the acquisition of a special filler for the last step, with a higher height, optimal, calculated in the same way as the presented model, in order for the Sulphur acid not to damage the destructible material.

In addition, in order to validate the mathematical model temperature filler tests I had performed on one of the two rotating-plate regenerative air functional pre-heaters of the 7B Steam Generator from Isalnita CET Thermal Power Plant. The results that I obtained by means of the mathematical model compared to the real ones were close, if taken into consideration the numerous influences that might be taken into account at the functioning of such heat exchanger, an error relative of 2 % being obtained between the two results.

Steam generator 7A of the above mentioned thermal power plant was in revision and repairs in the determining period. I had been shown the corroded filler due to the Sulphur acid formation and the pre-heater's interior in the servicing period.

The thesis final scope, obtained after conducting of an exploiting analysis rotating-plate regenerative air pre-heater was to determine the optimum height of the cold zone (exposed to the acid corrosion) of such heat exchanger in order to replace it during repairing time or to re-technologize the steam generator. I mentioned that this height of the cold zone, due to the partial load functioning of the steam generator or to the number of starts/stops differs from the height of this zone used at steam generator projection.

With help from the facts presented in this work the exact point in which the Sulphur acid appears on the pre-heater height can be calculated. This phenomena can be stopped by an optimum regulation of the generator's load or, the usage of the last step in regime of acid corrosion could be brought into discussion but, for this last case it is important to take into consideration the optimum height and the special materials, resistant to corrosion, these issues I have analyzed in detail in this paper.

The thesis was structured in 6 chapters and 29 figures (pictures, sketches or charts) and 30 tables.

PERSONAL CONTRIBUTION

Within this thesis, the author had personal contributions that structured the whole work content. From which, the followings are reminded:

- I have projected of a steam generator together with the corresponding rotating-plate regenerative air pre-heaters, in which is included the determining of the acid dew temperature, very important in the corrosion process of the pre-heater material. I pointed out that the fuel used was fuel oil with a high Sulphur content, which is important in order to stress the thesis final scope. I presented the acid dew phenomena. I have analyzed the partial loads influence on the acid corrosion phenomena. All this has been done to brought me closer to the phenomenon.
- I had divided of the pre-heater in two thermal zones, their calculation and finding of the temperature points before and after each zone to delimit the two zones of the heat exchanger.
- I had made the calculation of the last step thermal regime of the Ljungstrom type pre-heater, calculation that implies temperature determining from inside the metal filler of the heat exchanger that first varies after a mathematical linear analysis function of its height h and the angle that this forms φ.
- I had presented the possibilities of controlling the acid dew phenomena. Besides what we know, I stopped on two methods:
  - the influence on the corrosion of the rotor' speed rotation on the acid corrosion phenomena;
  - the influence of the increasing combustion air temperature at pre-heater entry on the acid corrosion phenomena.
- I have presented two ideas for future preoccupations/ research. The first one is represented by the constructive separation of the two zones (hot and cold), in such way that the rotor and carcass to be made in two steps and the gear to be separated in order to function at different rotation speed. The second method is the mounting of small temperature wireless sensors inside the metal filler, for monitoring in real time the thermal regime of the pre-heater.

- I have created a original mathematic model, that was done in a mathematical computing program (mathcad) and which simulated the rotating-plate regenerative air pre-heaters functioning from the thermal point regime of view that works in report with the corrosion of the heat exchanger material. I have applied the mathematical model on a real rotating-plate regenerative air pre-heater, Rotermuhle type, belonging to a steam generator that functions on coal (lignite).
- I have calculated the point on the pre-heater height whereas the Sulphur acid that destroys the metal filler material appears. Then I have been determining of the optimum height of the cold zone, in order to replace the filler of this zone in repairing periods or steam generator's re-technologizing. I have noticed that the height of the cold area of the preheater increases with the number of operating hours of the steam generator. In the analyzed case, I have noticed that this height increased from 0.25 m in the case of commissioning in 1968 to 0.28 m in the case of the current operation.
- During the thesis writing process, I had published 5 articles in scientific magazines, which present studies/ methods presented in this doctorate thesis [105-109].

PERSPECTIVES

Taking into consideration the research performed in the present work, as perspectives, the following directions may be mentioned:

The mathematic model can be implemented on the rotating-plate regenerative air pre-heaters, of Ljungstrom or Rotermuhle type and offers main data related to the optimum height of the last heat exchanger zone (its cold zone), for the periods in which the metal filler change is desired. With the mathematical model the temperature points are established for different steam generator functioning loads that, function of the acid dew temperature establish the pre-heater's cold zone optimum height level that needs to be changed. This height needs to be known for the corrosion phenomena to appear in this zone that uses a special treated filler or a thicker one that resist corrosion better.

The model can be used also on a whole pre-heater (hot zone together with cold zone) when the operator needs to know at some point during the heat exchanger functioning, in which point on the height the acid corrosion appears and if the steam generator load in report with the optimal functioning of the air pre-heater needs to be regulated.

The case studies and ideas reminded may represent a starting point for subsequent researches.

With the help of what is presented in this work, the rotating-plate regenerative air pre-heaters may be manipulated/operated with a better precision and professionalism, which, in the end, brings lower costs, not at least unneglectable, in the exploiting of these thermic equipment type.

In the future, the present work may represent a starting point for parties interested in solving these imperfections (the acid dew phenomena) that the rotating-plate regenerative air pre-heaters do have.

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