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# A FIRST APPROACH TO MODELLING A STEAM GENERATOR BASED ON HEAT EXCHANGERS NETWORK METHOD

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**Abstract.** *This paper presents a simulation of a real steam generator from a coal-fired power plant using a network of heat exchangers. The proposed approach is a combination of the Heat Exchanger Network method with the least squares method to represent the overall heat transfer coefficient as a linear function, which depends only of the flue gas flow, aiming to calculate the temperatures in between the heat exchangers in different operations situations. The data base used is a heat and mass balance provided by the partner enterprise. Steady state and one dimensional flow were considered. The result obtained by the Heat Exchanger Network method was limited by the approximation quality of the overall heat transfer coefficient and the heat transfer area product, obtaining a relative error in the order of 5 % for most values and reaching an error of 18 % in the worst case.*

**Keywords:** *steam generator modelling, lumped model, heat exchanger network*

## 1. INTRODUCTION

Thermal power plants are the main source of global energy generation, as presented by IEA (2018) World Energy Outlook. The steam generator is a fundamental section of these plants, and understanding its behavior is extremely important in an efficient decision-making of the plant operation.

Representing the steam generator thought a lumped model provides a quick and simple analysis of its functioning, differently from some traditional methodologies, as Computational Fluids Dynamics (CFD), which demand high processing and are more suited to offline simulation.

Moreover, traditional approaches for heat exchanger's representation,  $LMTD$  and  $\varepsilon - NUT$ , are of a complicated application in steam generators, since it requires the inlet and outlet temperature information for each stream of each Heat Exchanger (HE). The intermediate temperatures of the HE are precisely the results envisioned on this study. Dezhnev *et al.* (2007) developed a solution for this problem with a mathematical model, based on Luo *et al.* (2002), with some improvements on the calculations of the temperatures in the HEs. His method establishes a general solution for one-dimensional multistream heat exchangers, treating them as a network. It's main advantage is the possibility to solve the entire Heat Exchanger Network (HEN) knowing only the temperatures of the inlet streams and the heat capacity flow for each HE.

Other authors have already applied the HEN method for the purpose of projecting and sizing heat recovery systems. Ravagnani *et al.* (2005) and Wu *et al.* (2006) proposed a technique that aims to find an optimum HEN configuration using the minimum utilities consumption of the HEN with genetic algorithm. The authors reached satisfactory results. Even though this method is already consolidated for designing new HE arrangements, it hasn't yet been used for a steam generator and its particularities, as radiation exposure.

### List of Symbols

$\dot{m}$	Fluid mass flow rate, kg/s
$\dot{q}$	Heat transfer rate, W
$\epsilon_{cc}$	Effectiveness complement of heat exchanger cold side
$\epsilon_{ch}$	Heat exchanger effectiveness weighted by the heat capacity ratio
$\epsilon_{hc}$	Heat exchanger effectiveness
$\mathbf{V}$	Matrix of effectiveness
$\epsilon_{hh}$	Effectiveness complement of the heat exchanger hot side
$A$	Total heat transfer area, m <sup>2</sup>
$c_p$	Specific heat at constant pressure, kJ/kgK
$NTU_i^*$	Number of Transfer Units
$R$	Heat capacity ratio
$T_{c,in}$	Inlet temperature of the heat exchanger cold side, K
$T_{c,out}$	Outlet temperature of the heat exchanger cold side, K
$T_{h,in}$	Inlet temperature of the heat exchanger hot side, K
$T_{h,out}$	Outlet temperature of the heat exchanger hot side, K
$U$	Overall heat transfer coefficient, W/(m <sup>2</sup> K)

Therefore, this paper proposes the application of Dezhnev *et al.* (2007) method to a coal-fired boiler single-furnace unit, which supplies a 360 MW power plant situated in the port of PECÉM, Brazil. The furnace operates under balanced draught conditions, with natural circulation and steam reheating and has a parallel back end forming two separated gas paths for the primary superheater and reheater banks. Some adjustments were made to fit the HEN method to the plant's case: the effectiveness correlation matrix was adjusted and the heat exchangers were separated by their specific functionality, so the proper equations were used to determine the overall heat transfer coefficient.

## 2. METHODOLOGY

### 2.1 Heat exchanger network

The heat transfers that occur in the steam generator were calculated by the HEN method, developed by Dezhnev *et al.* (2007), which was originally conceived to model counter flow heat recovery systems and solves the temperatures in the HE's channels using three matrices that correlate the HE's inlet and outlet flows. The method won't be explained in this paper.

To apply the method in a steam generator, it was adapted by changing the effectiveness matrix ( $\mathbf{V}$ ), Eq. (1), using an effectiveness correlation to the case  $R_{min}$  mixed and  $R_{max}$  unmixed.

$$\mathbf{V} = \begin{bmatrix} \epsilon_{hh} & \epsilon_{hc} \\ \epsilon_{ch} & \epsilon_{cc} \end{bmatrix} = \begin{bmatrix} 1 - \exp\left[-\frac{\exp(-R_i NTU_i^*)}{R_i}\right] & \exp\left[-\frac{\exp(-R_i NTU_i^*)}{R_i}\right] \\ R \exp\left[-\frac{\exp(-R_i NTU_i^*)}{R_i}\right] & 1 - R \exp\left[-\frac{\exp(-R_i NTU_i^*)}{R_i}\right] \end{bmatrix} \quad (1)$$

$$R_i = \frac{(\dot{m}c_p)_{hi}}{(\dot{m}c_p)_{ci}} \quad (2)$$

$$NTU_i^* = \frac{UA_i}{(\dot{m}c_p)_{hi}} \quad (3)$$

Where  $R_i$  is the heat capacity ratio between the heat capacity hot side's inlet,  $(\dot{m}c_p)_{hi}$ , and heat capacity cold side's inlet,  $(\dot{m}c_p)_{ci}$ , of the channel  $i$ . The  $NTU_i^*$  is the Number of Transfer Units for the channel  $i$  calculated in the hot side inlet with overall heat transfer coefficient ( $U$ ) and total heat transfer area ( $A$ ). In the HEN method, the HE's inlet and outlet temperatures can be associated using Eq. (1) through Eq. (4).

$$\begin{bmatrix} T_{h,o} \\ T_{c,o} \end{bmatrix} = \begin{bmatrix} \epsilon_{hh} & \epsilon_{hc} \\ \epsilon_{ch} & \epsilon_{cc} \end{bmatrix} \begin{bmatrix} T_{h,i} \\ T_{c,i} \end{bmatrix} \quad (4)$$

In Eq. (1) and Eq. (4), the index  $\epsilon_{hc}$  represents the heat fraction at hot side inlet that its transferred to the cold side and the  $\epsilon_{hh}$  its the fraction that remains on the hot side. The  $\epsilon_{ch}$  represents the heat fraction that the cold side received from the hot side, while the  $\epsilon_{cc}$  represents the heat fraction at the cold inlet remaining in the cold side.

## 2.2 Overall heat transfer coefficient

Starting from the power plant's heat and mass balance (HMB), it was possible to obtain the coefficient  $U$  for twenty different operation situations for each of the seven heat exchangers integrating the steam generator. In order to obtain the  $U$  value, Eqs. (5) and (6) from Stoecker (1980) were used.

$$\dot{q} = \dot{m}c_p\Delta T \quad (5)$$

$$\dot{q} = UA \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \quad (6)$$

As the heat transference surface does not change, we can treat the product  $UA$  as a single value. As it was evaluated in various operations, the product  $UA$  obtained was not constant. Therefore, a linear regression was calculated to predict de  $UA$  value in function of the flue mass flow, using least squares method with the *Minitab* software.

## 2.3 Case study

A HEN with four streams can represent the case studied: one hot stream where the flue gas is flowing, two cold streams where steam is flowing and one cold stream with compressed liquid. The Figure 1 presents a scheme of the boiler HEN, which is consisted by seven heat exchangers and thus fourteen channels.

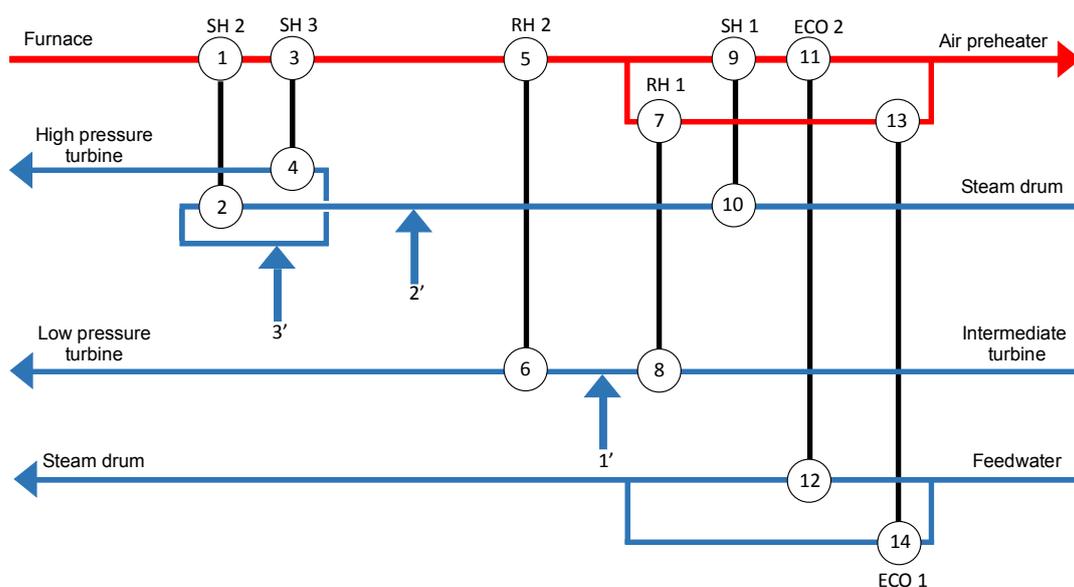


Figure 1. Heat network representing the steam generator. The red line is the gas path and the blues lines are the liquid and steam path

The cold steam streams correspond to the superheaters (SH) and re-heaters (RH) flow while the cold compressed liquid stream correspond to the economizers (ECO) flow. The superheaters path is the main steam path. There are three desuperheatings, represented by the arrows in Figure 1, two in the main steam path (2' and 3') and one in the re-heater path (1').

The beginning of the flue gas line correspond to the furnace outlet, and it ends at the air preheater. The main steam line is the path between the steam drum and the high pressure turbine. The reheater stream line comes from intermediate turbine and goes to low pressure turbine. Finally, the compressed liquid comes from the feedwater and goes to the steam drum.

No information was provided on the division of the amount of gases that follow by the superheater and reheater, it was assumed that the gas is divided equally between each side. Similarly it was done with the division of the compressed liquid among the economizers.

The heat capacity in Eq. (3) and Eq. (2) is considered in each HE's inlet and outlet. The water properties were considered the IAPWS 97 (International Association for the Properties of Water and Steam) based on the Wagner and Kretzschmar (2007) book. For the gas properties, NIST (2019) correlations were used. Aiming to consider the heat capacity variation in each line, iterations were required to recalculate the properties. The convergence criteria adopted was the variation of less than 1 °C between two consecutive iterations.

### 3. RESULTS

Table 1 shows the UA's expressions obtained for the HEs that compose the boiler's HEN where the flue gas flow is used as independent variable. This approach proved to be valid for most of the boiler's HEs, with high coefficient of determination and acceptable standard deviation. However, this approach is not satisfactory for the second superheater, which is located soon after the furnace and therefore is the most affected by radiation. The furnace outlet's temperature value was assumed constant to obtain the linear regression of the second super heater. The linear regression for the Economizer 1 also shows a large standard deviation, which is probably due to uncertainty in flows divisions in both sides.

Table 1. Linear regressions representing the variation of the overall heat transfer coefficient.

HE	Linear regression	Standard deviation	$R^2$ (%)
First super-heater	UA= 130.49+1.204 $\dot{m}_h$	7.54	98.90
Second super heater	UA= 65.4+0.277 $\dot{m}_h$	50.23	20.92
Third super heater	UA= 42.83+0.188 $\dot{m}_h$	3.95	95.14
First re-heater	UA= 146.1+2.213 $\dot{m}_h$	13.58	97.59
Second re-heater	UA= 43.25+0.210 $\dot{m}_h$	3.33	97.60
Economizer 1	UA= -18.9+2.188 $\dot{m}_h$	45.75	77.38
Economizer 2	UA= 72.53+0.772 $\dot{m}_h$	5.06	98.73

The Eq. (7) is the simulated case's effectiveness matrix used to obtain the temperatures values of the Tables 2 and 3, in this matrix the main diagonal's submatrices are one heat exchanger each one.

$$\mathbf{V} = \begin{bmatrix}
 0.75 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0.06 & 0.94 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0.82 & 0.18 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0.07 & 0.93 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0.82 & 0.18 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0.17 & 0.83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 0.75 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0.31 & 0.69 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.29 & 0.71 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.04 & 0.96 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.31 & 0.69 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.26 & 0.74 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.47 & 0.53 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.10 & 0.90
 \end{bmatrix} \quad (7)$$

The temperatures values in the inlet of each heat exchanger composing the HEN are presented in Table 2. The model's entries are the temperatures of indexes 1, 10, 8, 12 and 14. The furnace outlet's temperature, index 1, is not provided in the HMB. Therefore, the value used was obtained by another simulation work. The Table 3 shows the outlets temperatures values of the HES' channels that form the HEN. Index values 11 to 14 are not provided in the HMB. It is noticed by the Tables 2 and 3 that the temperatures obtained by the model match the data provided by the HMB in most HEs, except for the points where the linear regression is not satisfactory or where there is an uncertainty in the amount of gas flow division that takes place in the final gas path, at the Air preheater downstream.

It is observed that, in the case of one HE transferring less heat than expected, the following HE's performance is impacted, as seen in Index 4 from Table 2. The steam arrives with a lower temperature due to the second super heater performance, which impacts the Third super heater outlet's temperature. The larger relative error was 18.03 % (Index 7 in Table 3) for the gas side and 15,90 % (Index 4 in Table 3) for the steam side.

Table 2. Inlet temperatures values obtained with the HEN model and the temperatures values given by the power plant heat mass balance. The index correspond at the HE channel number of Figure 1.

HE inlet temperatures			
Index	HMB (°C)	Model Result (°C)	Relative Error (%)
1	-	1372.0	-
2	388.7	381.7	1.84
3	1063	1121.6	5.23
4	482.9	420.3	14.90
5	950	996.5	4.67
6	480.2	511.1	6.05
7	849.9	908.7	6.47
8	329.2	329.2	0.00
9	849.9	908.7	6.47
10	364.1	364.1	0.00
11	546.6	521.7	4.77
12	277.4	277.4	0.00
13	390	475.8	18.03
14	277.4	277.4	0.00

Table 3. Outlet temperatures values obtained with the HEN model and the temperatures values given by the power plant heat mass balance. The index correspond at the HE channel number of Figure 1.

HE outlet temperatures			
Index	HMB (°C)	Model Result (°C)	Relative Error (%)
1	1063	1121.6	5.23
2	499.5	443.3	12.67
3	950	996.5	4.67
4	541	466.8	15.90
5	850	908.7	6.46
6	541	594.3	8.96
7	390	475.8	18.03
8	480.2	511.1	6.05
9	546.6	521.7	4.77
10	391.7	387.2	1.16
11	-	352.1	-
12	-	339.7	-
13	-	370.9	-
14	-	296.6	-

#### 4. CONCLUSIONS

The steam generator studied is from a thermal power plant in Brazil and it's understanding is essential to have an efficient decision making in the plant.

The heat exchanger network method was implemented applying it for the first time in a steam generator. A new matrix of effectiveness was used, considering the minimal heat capacity flow mixed and the maximal heat capacity flow unmixed. A linear regression was obtained from 20 different heat cases of heat mass balance provided by the partner enterprise, this regression was incorporated into the method to consider the variation of the UA product of each heat exchanger under different operations loads.

Results achieved are limited by the linear regression used for the UA product. In cases where this approximation presented low coefficient of determination, the temperatures values calculated were close to the provided by the heat mass balance. Therefore, the heat exchanger networks method can be used in the modeling of a steam generator but it is necessary to refine the UA variation approach for different operating situations, integrating radiation and convective correlations.

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#### 6. REFERENCES

- Dezhen, C., Shanshan, Y., Xing, L., Qingyun, W. and Hugen, M., 2007. "An explicit solution for thermal calculation and synthesis of superstructure heat exchanger networks". *Chinese Journal of Chemical Engineering*, Vol. 15, No. 2, pp. 296–301.
- IEA, 2018. *World Energy Outlook 2018 Executive Summary*. International Energy Agency.
- Luo, X., Li, M. and Roetzel, W., 2002. "A general solution for one-dimensional multistream heat exchangers and their networks". *International Journal of Heat and Mass Transfer*, Vol. 45, No. 13, pp. 2695–2705.
- NIST, 2019. "Nist: National institute of standards and technology". NIST: National Institute of Standards and Technology. 05 May. 2019 <<https://webbook.nist.gov>>.
- Ravagnani, M., Silva, A., Arroyo, P. and Constantino, A., 2005. "Heat exchanger network synthesis and optimisation using genetic algorithm". *Applied Thermal Engineering*, Vol. 25, No. 7, pp. 1003–1017.
- Stoecker, W.F., 1980. *Design of thermal systems*. BOOK. McGraw Hill Book Company.
- Wagner, W. and Kretzschmar, H.J., 2007. *International Steam Tables-Properties of Water and Steam based on the Industrial Formulation IAPWS-IF97: Tables, Algorithms, Diagrams, and CD-ROM Electronic Steam Tables-All of the equations of IAPWS-IF97 including a complete set of supplementary backward equations for fast calculations of heat cycles, boilers, and steam turbines*. Springer Science & Business Media.
- Wu, X., Hongguang, D., Xinqiang, L., Pingjing, Y., Xing, L. and Wilfried, R., 2006. "Synthesis of large-scale multistream heat exchanger networks based on stream pseudo temperature". *Chinese Journal of Chemical Engineering*, Vol. 14, No. 5, pp. 574–583.

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