TEM Journal. Volume 6, Issue 3, Pages 436-444, ISSN 2217-8309, DOI: 10.18421/TEM63-02, August 2017.

Mathematical Model and Program for the Sizing of Counter-flow Natural Draft Wet Cooling Towers

Ioana Opriş [1], Victor-Eduard Cenuşă [1]

[1] *University POLITEHNICA of Bucharest, Splaiul Independenței 313, Bucharest, Romania*

***Abstract* – Assuring the necessary temperature and mass flow rate of the cooling water to the condenser represents an essential condition for the efficient operation of a steam power plant. The paper presents equations which describe the physical phenomena and the mathematical model for the design of counter-flow natural draft wet cooling towers. Following is given the flow-chart of the associated computer program. A case study is made to show the results of the computer program and emphasize the interdependence between the main design parameters.**

***Keywords* – cooling tower, mathematical model, computer program, steam power plant.**

1. Introduction

There are several methods to increase the efficiency of Thermal Power Plants (TPP) with steam cycle [1, 2]:

- the increase of the parameters at the hot source (pressure, temperature) [3];
- the decrease of the parameters at the cold source (the condensation temperature of the steam at the outlet of the turbine) [4];
- the preheating of feed water to the steam generator [5];
- steam reheating [6];
- cogeneration [7].

The decrease of the condensation temperature at the cold source (condenser) with only one degree Kelvin can have the same effect on the efficiency of the TPP cycle as the increase of the main steam temperature with 10 – 15 K [8]. Considering the strong influence of the cold source, it is important to maintain the condensing temperature as low as possible. This low temperature can be achieved by:

- decreasing the cooling water temperature at the condenser;
- increasing the mass flow rate of the cooling water at the condenser;
- increasing the heat exchange of the condenser.

Considering the first parameter, respectively the cooling water temperature at the condenser depends on the cooling system which is used.

According to the site's resources and weather conditions, the water cooling may be obtained within the cooling system in a [9, 10]:

- open circuit, if the cool water of a river is used;
- closed circuit, if a cooling tower is used, or
- mixed circuit, if cold water is coming both from a cooling tower and a river.

As the cool water from a river is seldom available in vicinity of the future power plant, the paper considers the more versatile solution given by the closed system, i.e. the cooling tower.

In a closed cooling circuit (Figure 1.), the hot water coming from several surface heat exchangers (out of which the condenser is the most important) is cooled into the cooling tower and then send back to the heat exchangers by pumps [1].

DOI: 10.18421/TEM63-02
https://dx.doi.org/10.18421/TEM63-02

Corresponding author: Ioana Opriș,
University POLITEHNICA of Bucharest, Romania
Email: ioana.opris@upb.ro

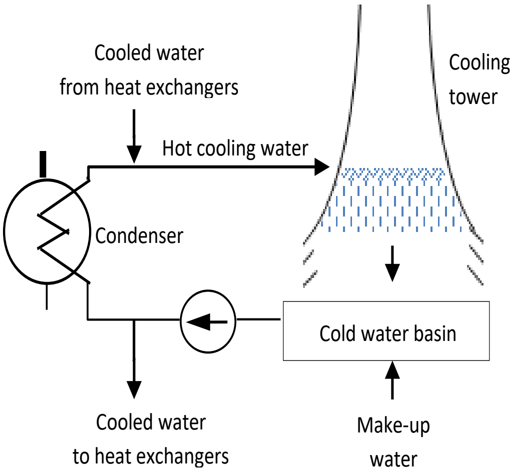

Figure 1. Closed cooling circuit

The most used type of cooling towers for thermal power plants are the counter-flow natural draft wet cooling towers [1].

A make-up water source is also used to compensate for the cooling water which is lost through evaporation, mainly within the cooling tower [9].

The paper considers the common design for the cold source of the thermal power plant: the water cooling is made within a closed circuit by using a natural draft wet cooling tower. Based on the dimensioning methodology of the natural draft wet cooling tower given in [11], the main original elements of the paper are:

- the mathematical model which describes the physical phenomena and of the cooling tower;
- the flow-chart for the computer program;
- the highlight of the interdependence between the main design parameters.

The results of the paper are useful in several fields, as:

- in computing the design parameters of the cooling tower, necessary to ensure the performances of the TPP at the cold source;
- in developing of software applications, based on the given flowchart;
- for the general contractor of a new power plant, in the design phase;
- for students and engineers, to put into evidence the interdependence between the main design parameters (by using the graphical results of the model);
- in education, within interdisciplinary projects including physical phenomena in power plants, mathematical modeling, and computer science.

2. Mathematical model of the cooling tower

Natural draft wet cooling towers are heat exchangers within which the two fluids (water and air) have a direct contact. As a result, heat and mass transfer occur [9]. The temperature of the water is decreased primarily by evaporation, but also by convection [12]. During evaporation, the temperature of the water drops is reduced as result of consuming the vaporization latent heat. During convection, the temperature of the water is lowered as a result of the gap between the temperature of water and air.

Besides complying to the technological requirements, the sizing of the tower must ensure financial requirements (low construction, operation and maintenance expenses). As the construction of a cooling tower implies a significant investment, its design is a very important task [13].

Sizing of the counter-flow natural draft wet cooling tower implies the estimation of the main geometrical dimensions and characteristics of the cooling tower, for some given weather conditions and cooling water parameters.

The physical parameters of the fluids that pass through the cooling tower are:

- For water (w):

t_{w1}, t_{w2}– the input/ output water temperature, in ºC;
c_p – specific isobaric heat capacity, in KJ/kg/ºC;
F_{w1}, F_{w2}– the input/ output water flow rate, in kg/s;
F_{ev} – the water flow rate lost through evaporation, in kg/s;
p_{s1}, p_{s2} – the saturation pressure of water vapors at the input/ output water temperature, in bar;
p_{sm}– the mean saturation pressure of water vapors at the mean water temperature, in bar;
a_{pp} – the approach, in ºC.

- For air (a):

t_{a1}, t_{a2}– the input/ output air temperature, in ºC;
t_{wb}– the ambient wet-bulb temperature, in ºC;
h_{a1}, h_{a2} – the input/ output air specific enthalpy, in kJ/kg;
p_{va1}, p_{va2} – the input/ output pressure of water vapors, in bar;
p_{a1}, p_{a2} – the input/ output air pressure, in bar;
ρ_{a1}, ρ_{a2} – the input/ output air density, in kg/ m^3;
ρ_{am}– the mean air density, in kg/ m^3;
$\varphi_{a1}, \varphi_{a2}$ – the input/ output air relative air humidity, in percentage;
F_a – the dry air flow rate through the tower, in kg/s;
F_{ma} – the moist air flow rate through the tower, in kg/s;
F_{am} – the mean flow rate of air through the cooling section, in kg/s;

w_{a1}– the inlet air velocity in the cooling tower, in m^2/s;
w_{am} – the mean air velocity in the cooling section, in m^2/s.

- For air at saturation (*sa*):

p_{sa1}, p_{sa2} – the input/ output pressure of saturated air, in bar;
p_{s1}, p_{s2} – the input/ output air pressure, in bar;
x_{sa1}, x_{sa2} – the specific humidity at saturation for the input/ output water temperature, in kg of water vapors/ kg of moist air;
h_{sa1}, h_{sa2} – the air enthalpy at saturation of the input/ output water temperature, in kJ/kg;
$|h_{sa} - h_a|_m$= the absolute mean between the enthalpy of saturated and environmental air, in kJ/kg.

- Other geometrical and structural characteristics of the cooling tower:

H_{CT}, D_{CT} – the height/ diameter of the cooling tower, in meters;
H_c – the height of the natural draft zone, in meters;
H_f – the height of the fill, in meters;
H_a – the height of the air inlet window, in meters;
V- the cooling volume of the packing zone, in m^3;
S_b – the base area of the cooling tower, in m^2;
β_{xv} – the substance yielding coefficient, in kg/m^3/h;
q – the spraying density, in m^3/m^2/h;
ξ – the total aerodynamic resistance coefficient of the tower, dimensionless;
k_ξ – the coefficient depending on the packing type;
k_λ – coefficient to consider the quota of the cooling water which is evaporated, dimensionless;
k_w – multiplication coefficient of the inlet air velocity ($k_w = 3 \dots 4$), dimensionless.

The total height of the cooling tower (Figure 2.) results from:

$$H_{CT} = H_c + H_f + H_a \tag{1}$$

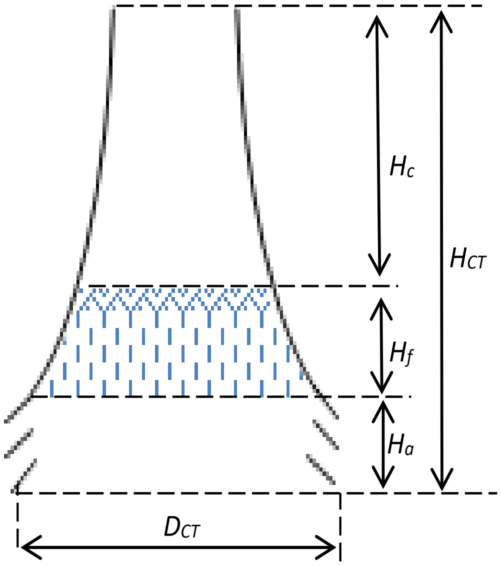

Figure 2. Main dimensions for the preliminary design of a Counter-flow Natural Draft Wet Cooling Tower

The overall energy balance for the cooling tower is given by the equation [9]:

$$F_a \cdot (h_{a2} - h_{a1}) = F_{w1} \cdot (t_{w1} - t_{w2}) \cdot c_p + \Delta Q \tag{2}$$

where ΔQ is the loss of heat through evaporation.

The mass balance equation is:

$$F_{w1} = F_{w2} + F_{ev} \tag{3}$$

The lowest temperature to which water could be cooled theoretically in a cooling tower is the wet bulb temperature corresponding to the surrounding air conditions (temperature, pressure, humidity). Practically, this temperature can never be achieved out of constructive reasons. However, the wet bulb temperature is used to estimate the operation of the cooling tower.

The performance indicator used is the *approach*, as the gap between the outlet cooled water temperature and the ambient wet bulb temperature [14]:

$$a_{pp} = t_{w2} - t_{wb} \tag{4}$$

During operation, due to the different weather conditions, the approach may have different values. A lower design value for the approach means higher performance but a larger and a costlier tower.

The design model for the sizing of the cooling tower presented below is a mixture of physical [9, 14, 15] and empirical relations [16, 17].

To determine the heat exchange, the model considers the following assumptions:

- there is used the Merkel method [15];
- the cooling tower is divided into 3 zones (rain, packing, and the natural draft one) [14], figure 2.;
- for each zone, the heat exchange between air and water is computed by considering the mean values of the parameters [9];
- at the outlet of the cooling tower, the air is saturated with water vapours ($\varphi_{a2} = 100\%$) [9];
- the water drops are modelled as being surrounded by a film of air which is saturated with water vapours [15] (Figure 3.);
- the type of the filling is chosen by the designer; consequently, the substance yielding coefficient (β_{xv}) is a known, input data;
- the air resistance coefficient (ξ) is determined by an experimental relation [16, 17] depending on the fill, the spraying density and the mean air velocity in the cooling section. The relation is adjusted through the k_{ξ} coefficient, to consider different packing types;

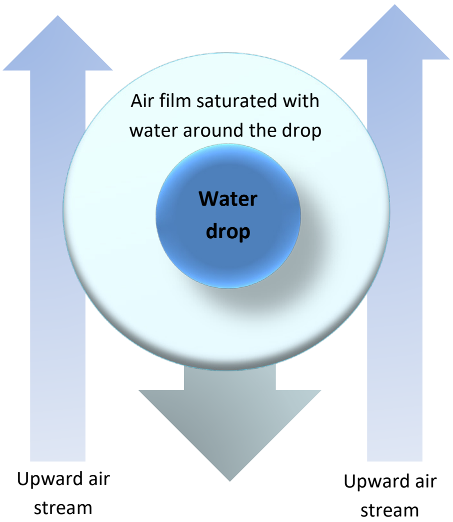

Figure 3. Heat exchange between air and cooling water

- the performance of the cooling tower (the approach, depending on the chosen design air parameters) represents an indirect design requirement for the model [14].

The dimensioning model of the cooling tower follows the flow-chart given in Figure 4. The model is based on a modular approach, to concentrate the parameters with a high interdependency.

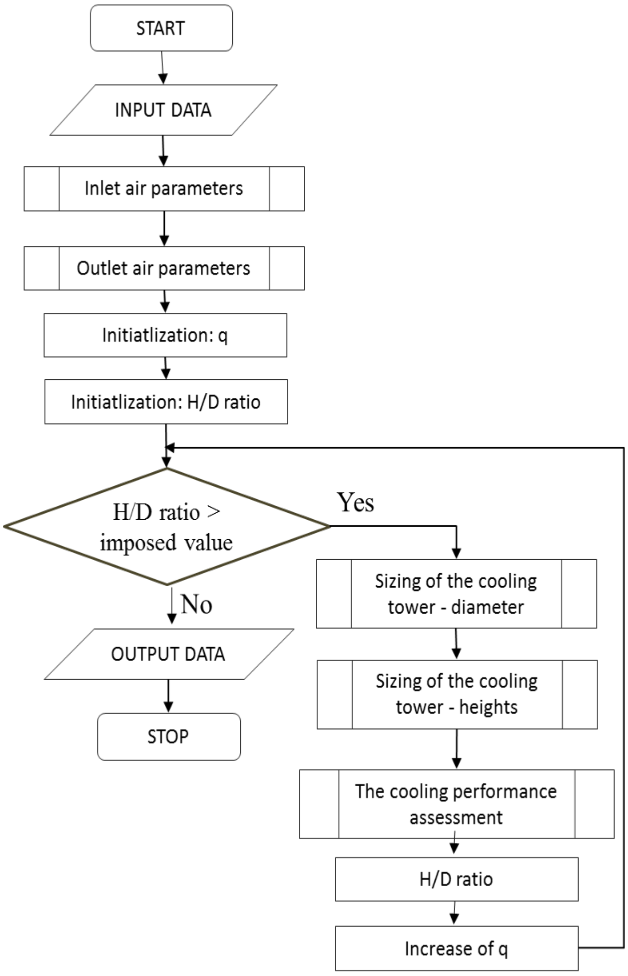

Figure 4. The flow-chart for the dimensioning of the cooling tower.

Starting from a low spraying density, q, its value is increased until the design condition regarding the overall shape of the cooling tower is met. This condition requires the tower to have an imposed *H/D ratio*:

$$H/D\ ratio = H_{CT}/D_{CT} \tag{5}$$

Therefore, iterations are taken for increasing values of the spraying density of the cooling tower until the above condition is met.

The dimensioning mathematical model considered 6 distinct modules for:

- the input data (Figure 5.),
- the inlet air parameters (Figure 6.),
- the outlet air parameters (Figure 7.),
- the sizing of cooling tower - diameter (Fig. 8.),
- the sizing of cooling tower - heights (Fig. 9.),
- the cooling performance assessment (Fig. 10.),
- the output data (Figure 11.).

Input data:

Water:

- Input: t_{w1}, F_{w1}
- Output: t_{w2}

Air:

- Input: $t_{a1}, p_{a1}, \varphi_{a1}$

Tower's Structure: β_{xv}, q

Structural Coefficients: k_w, k_ξ

Figure 5. Input data module

Inlet air parameters:

$$p_{sa1} = f(t_{a1})$$

$$p_{va1} = \varphi_{a1} \cdot p_{sa1}$$

$$x_{a1} = 0{,}622 \cdot \frac{p_{va1}}{p_{a1} - p_{va1}}$$

$$h_{a1} = 1{,}006 \cdot t_{a1} + x_{a1} \cdot (2510 + 1{,}88 \cdot t_{a1})$$

$$\rho_{a1} = 0{,}465 \cdot \frac{750 \cdot p_{a1}}{273{,}16 + t_{a1}} - 0{,}176 \cdot \frac{750 \cdot p_{va1}}{273{,}16 + t_{a1}}$$

$$p_{s2} = f(t_{w2})$$

$$x_{sa1} = 0{,}622 \cdot \frac{p_{s2}}{p_{a1} - p_{s2}}$$

$$h_{sa1} = 1{,}006 \cdot t_{w2} + x_{sa1} \cdot (2510 + 1{,}88 \cdot t_{w2})$$

$$t_{wb} = f(t_{a1}, \varphi_{a1})$$

Figure 6. Inlet air parameters module

Outlet air parameters:

$$p_{a2} \cong p_{a1}$$

$$\varphi_{a2} = 1$$

$$p_{sa2} = f(t_{a2})$$

$$p_{va2} = \varphi_{a2} \cdot p_{sa2}$$

$$x_{a2} = 0{,}622 \cdot \frac{p_{va2}}{p_{a2} - p_{va2}}$$

$$p_{s1} = f(t_{w1})$$

$$p_{sm} = f\left(\frac{t_{w1} + t_{w2}}{2}\right)$$

$$\Delta p_s = 0{,}25 \cdot (p_{s1} + p_{s2} - 2 \cdot p_{sm})$$

$$t_{a2} = t_{a1} + 1{,}38 \cdot (x_{a2} - x_{a1}) \cdot \frac{(t_{w1} + t_{w2}) - (t_{a1} + t_{a2})}{(p_{s1} + p_{s2}) - 2 \cdot \Delta p_s - (p_{v1} + p_{v2})}$$

$$h_{a2} = 1{,}006 \cdot t_{a2} + x_{a2} \cdot (2510 + 1{,}88 \cdot t_{a2})$$

$$\rho_{a2} = 0{,}465 \cdot \frac{750 \cdot p_{a2}}{273{,}16 + t_{a2}} - 0{,}176 \cdot \frac{750 \cdot p_{va2}}{273{,}16 + t_{a2}}$$

$$x_{sa2} = 0{,}622 \cdot \frac{p_{s1}}{p_{a2} - p_{s1}}$$

$$h_{sa2} = 1{,}006 \cdot t_{w1} + x_{sa2} \cdot (2510 + 1{,}88 \cdot t_{w1})$$

Figure 7. Outlet air parameters module

Sizing of cooling tower (diameter):

5 - The diameter of the cooling tower:

$$S_b = 3{,}6 \cdot \frac{F_{w1}}{q}$$

$$D_{CT} = \sqrt{\frac{4 \cdot S_b}{\pi}}$$

Figure 8. Sizing of diameter module

Sizing of cooling tower (heights):

1 - The height of the packing zone (fill zone):

$$|h_{sa}-h_a|_m=\frac{h_{sa1}+h_{sa2}}{2}-\frac{h_{a1}+h_{a2}}{2}$$

$$V=3600\cdot\frac{F_{w1}\cdot c_p\cdot(t_{w1}-t_{w2})}{\beta_{xv}\cdot|h_{sa}-h_a|_m}$$

$$H_f=\frac{V}{S_b}$$

2 - The height of the air inlet window (rain zone):

$$k_\lambda=1-c_p\cdot t_{a2}\cdot\frac{x_{a2}-x_{a1}}{h_{a2}-h_{a1}}$$

$$\lambda=\frac{c_p\cdot(t_{w1}-t_{w2})}{k_\lambda\cdot(h_{a2}-h_{a1})}$$

$$F_a=\lambda\cdot F_{w1}$$

$$F_{ma}=F_a\cdot\left(1+\frac{x_{a1}+x_{a2}}{2}\right)$$

$$w_{am}=\frac{2\cdot F_{ma}}{(\rho_{a1}+\rho_{a2})\cdot S_b}$$

$$w_{a1}=k_w\cdot w_{am}$$

$$H_a=0{,}5\cdot F_{w1}\cdot\frac{\lambda}{w_{a1}\cdot\rho_{a1}}\cdot\sqrt{\frac{w_{am}\cdot(\rho_{a1}+\rho_{a2})}{2\cdot\pi\cdot F_{ma}}}$$

3 - The height of the chimney in the natural draft zone:

$$\xi=\frac{7{,}782}{k_\xi}+\frac{1{,}287}{k_\xi\cdot w_{am}}+\\+\frac{4{,}182}{k_\xi}\cdot\left(\frac{q}{3600}\right)^{0{,}9}\cdot\left(\frac{103{,}56}{{w_{am}}^{0{,}6}}+108\cdot{w_{am}}^{0{,}8}\right)$$

$$H_c=0{,}5\cdot\left[\xi\cdot\frac{w_{am}^2}{2\cdot 9{,}81}\cdot\frac{\rho_{a1}+\rho_{a2}}{\rho_{a1}-\rho_{a2}}+H_f\right]+H_a$$

4 - The total height of the cooling tower

$$H_{CT}=H_c+H_f+H_a$$

Figure 9. Sizing of heights module

Cooling performance assessment:

$$a_{pp}=t_{w2}-t_{wb}$$

Figure 10. Cooling performance assessment module

Output data:

Air:
- Input: $t_{va1}, t_{sa1}, x_{a1}, h_{a1}, \rho_{a1}, p_{s2}, x_{sa1}, h_{sa1}, t_{wb}$
- Output: $t_{a2}, p_{a2}, \varphi_{a2}, t_{va2}, t_{sa2}, x_{a2}, h_{a2}, \rho_{a2}, p_{s1}, x_{sa2}, h_{sa2}$
- Mean values: F_a, F_{ma}, w_{am}

Tower's preliminary sizing:
H_{CT} , $H_c, H_f, H_a, D_{CT}, V, S_b$

Structural data: ξ , q

Tower's performance: a_{pp}

Figure 11. Output data module

3. The flow-chart of the computer program

Based on the model of the natural draft cooling tower, a computer program was developed by using MATLAB® [18]. Figure 12. shows the flow-chart for the sizing of the cooling tower.

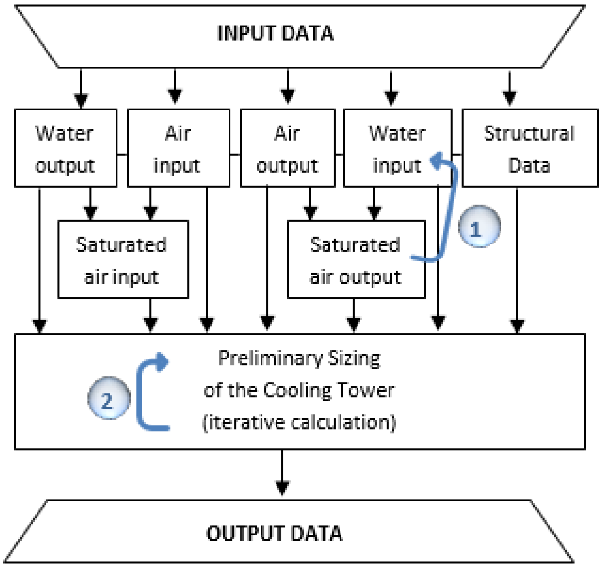

Figure 12. Flow-chart of the computer program

Because of the strong interdependency between the parameters, two cycles of iterations are made inside the program.

The first cycle of iterations (Figure 12.) is made to compute the outlet air temperature and the other air parameters. Based on a first estimation of the outlet air temperature, its value is recalculated along with the other parameters until an imposed error condition is met.

The second cycle of iterations (Figure 12.) aims to meet the design condition regarding the overall shape of the cooling tower. It starts from a minimum value of the spraying density, which is increased slowly until the design condition from Eq. (5) is met.

For the calculation of the calculation of the thermodynamic properties of moist air (p_{sa1}, p_{sa2}, p_{s1}, p_{s2} , p_{sm}, t_{wb}), the available functions from the literature were used [19, 20, 21].

Similar to the mathematical model, the computer program is based on a modular approach (Figures 5. to 11.).

4. Case study and computation example

As an example, we considered a TPP which has the following cooling water requirements:

- the cooling water flow rate of 15 600 t/h;
- the temperature of the hot cooling water to the tower of 30 ºC;
- the temperature of the cooled water from the tower of 20 ºC.

The surrounding weather conditions for the location which were considered during the design are:

- the air temperature of 19 ºC;
- the air pressure of 1.0131 bar;
- the air humidity of 65%.

The substance yielding coefficient of the filling is β_{xv}= 3600 kg/m^3/h, and the imposed *H/D ratio* is considered 1.2.

Figure 13. shows how the second cycle of iterations (Figure 12.) meets the imposed *H/D ratio.* It can be observed that, for the considered case study, the spraying density for which the *H/D ratio* is reached is by 5.1 m^3/m^2/h.

Figures 14. and 15. show how the main dimensions of the tower change with the spraying density during the second cycle of iterations.

While the spraying density is increasing, the cooling tower gets higher and slimmer (with a lower diameter).

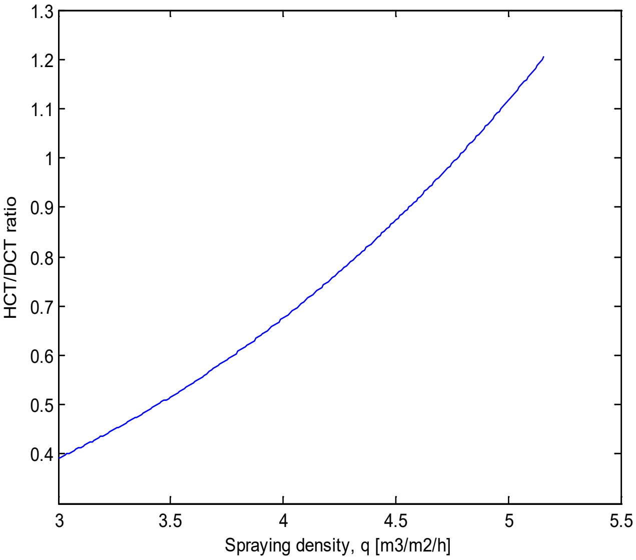

Figure 13. The variation of the H_{CT}/D_{CT} ratio with the spraying density

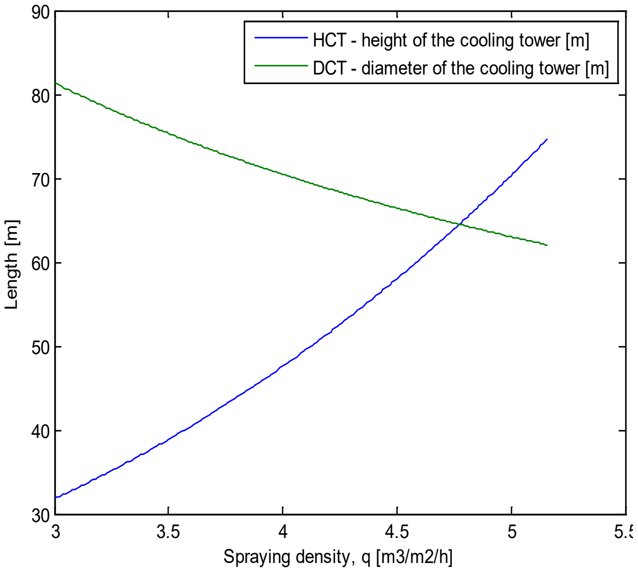

Figure 14. The variation of the cooling tower's dimensions with the spraying density

The increase of the total height of the tower is mainly due to the increase of the height of the natural draft zone of the tower (Figure 15.). The heights of the filling and of the inlet window have a relative smaller variation of values, in opposite directions:

- the height of the filling is slightly decreasing with the increase of spraying density,
- the height of the inlet window is increasing with the increase of spraying density.

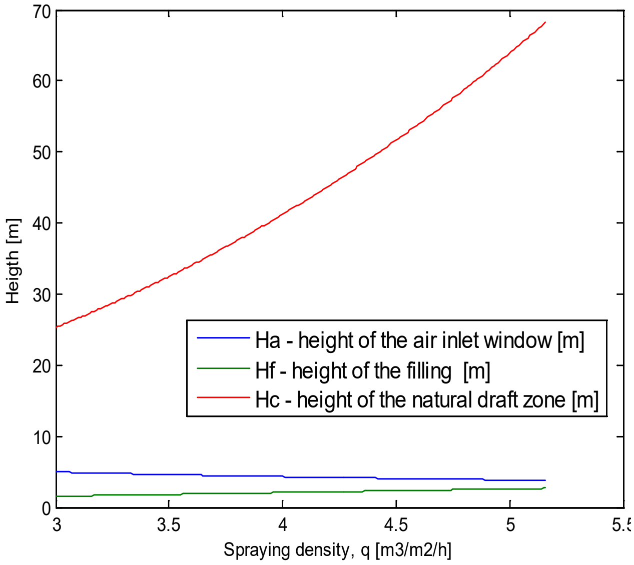

Figure 15. The variation of the main cooling tower's heights with the spraying density

Table 1. centralizes the air and water input and output parameters from the computer program and Table 2. shows the computed design parameters.

Table 1. Air and water input/output parameters of a Counter-flow Natural Draft Wet Cooling Tower

	Parameter	**Unit**	**Input** $i = 1$	**Output** $i = 2$
Air	t_{ai}	°C	19	23.58
	p_{ai}	bar	1.031	1.031
	φ_{ai}	%	65	100
	x_{ai}	$\mathrm{kg_{vapors}/kg_{air}}$	0.0089	0.0183
	h_{ai}	kJ/kg	41.68	70.57
	ρ_{ai}	kg/m^3	1.20	1.17
	p_{vai}	bar	0.0142	0.029
	h_{si}	kJ/kg	99.75	57.44
	p_{sai}	bar	0.0219	0.029
	x_{sai}	$\mathrm{kg_{vapors}/kg_{air}}$	0.0146	0.0271
	h_{sai}	kJ/kg	99.75	57.44
	w_{ai}	m/s	7.3112	-
	w_{am}	m/s	1.8278	-
	F_a	kg/s	6489.3	-
	F_{ma}	kg/s	6577.6	-
	t_{wb}	°C	12.23	-
Cooling water	t_{wi}	°C	30	20
	F_w	kg/s	3888.9	-

Table 2. Design parameters of a Counter-flow Natural Draft Wet Cooling Tower

Parameter	**Unit**	**Value**
H_{CT}	m	74.7
D_{CT}	m	62.04
H_a	m	3.78
H_f	m	2.67
H_c	m	68.247
V	m^3	8074
S_b	m^2	3023.3
ξ	-	7.837
β_{xv}	kg/m^3/h	3600
q	m^3/m^2/h	5.1
a_{pp}	K	7.77

5. Conclusions

A mathematical model and a flow-chart for the computer program for the counter-flow natural draft wet cooling towers of steam power plants are made available. The mathematical model uses a modular approach, based on the type of computed parameters (air, water, geometrical dimensions) and on their degree of interdependency.

Due to the high interdependency, the program performs two cycles of iterations to compute the values of the unknown parameters.

A case study was taken to show the influences of the spraying density on the design parameters. The increase of the spraying density leads to:

- the increase of the height of the tower. The growth is owed especially to the necessity of a higher natural draft zone. The change of the height of the other zones is not significant, as the variation of the values is small and in opposite directions (the height of the filling zone increases, while the height of the inlet air window corresponding to the rain zone decreases).
- the decrease of the diameter of the tower,
- the increase of the height/diameter ratio, emphasizing that the growth of the height is greater than the lowering of the diameter.

The results of the paper are useful in several fields, such as: the design of cooling towers, the development of software applications for power plants, for students and engineers. Also, it is very useful in design management, for the general contractor of a new power plant, during the design phase.

Acknowledgements

This work has been funded by University Politehnica of Bucharest, through the "Excellence Research Grants" Program, UPB – GEX. Identifier: UPB–EXCELENȚĂ–2016. Research project title: "Analiza funcționării centralelor termoelectrice pe combustibil fosil, pentru integrarea optimă în piața de energie" / "The Analysis of the Operation of Fossil Fuel Thermal Power Plants, for the Optimal Integration into the Energy Market". Contract number 88/26.09.2016 (acronym: CETEIOPE).

References

[1]. Bolland, O. (2010). *Thermal power generation.* Department of Energy and Process Engineering NTNU.

[2]. Leyzerovich, A.S. (2008). *Steam turbines for modern fossil-fuel power plants*. The Fairmont Press.

[3]. Darie, G., Petcu, H., Negreanu, G., & Gherghina, V. (2007). Sliding pressure operation of large conventional steam power units. Proceedings of the 5th IASME/WSEAS International Conference on Heat Transfer,Thermal Engineering and Environment (HTE'07), Greece, 299-303.

[4]. Bekdemir, S., Oztiirk, R., & Yumurtac, Z. (2003). Condenser Optimization in Steam Power Plant. *Journal of Thermal Science*, 12(2), 176–178.

[5]. Alexe, F.N., Darie, G., Cenuşă, V.E., Tuţică, D. & Norişor, M. (2015). Recovery of waste heat from generator into the water preheating circuit, at steam thermal power plants, Proceedings of the 9th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Romania, 603-608.

[6]. Alexe, F., Cenusa V.E., & Opris I. (2014). Simultaneous Thermodynamic Optimization for CHPP with Steam Turbines. Recent Advances in Energy, Environment,Biology and Ecology, 119-123.

[7]. Darie, G. & Petcu, H.I. (2007). Methodology and software for prediction of cogeneration steam turbines performances. Co*mputer Aided Chemical Engineering*, 24, 1103-1108.

[8]. Darie, G., Cenușă, V.E., Norișor, M. & Tuțică, D. (2015). *Producerea energiei electrice și termice din combustibili fosili (Power and heat generation from fossil fuels)*. Agir. Bucureşti.

[9]. Leca, A., Motoiu, C., Ionescu, D.C., Bratianu, C., Ionescu, L., & Athanasovici, V. (1977). *Centrale electrice. Probleme (Power plants. Problems)*, Editura Didactica si Pedagogica, Bucuresti.

[10]. Ionescu D.C., Darie G., & Ulmeanu A.P. (1996). *Partea Termomenacnică şi Hidraulică a Centralelor Electrice (The thermomechanical and hidraulical part of power plants)*, Editura Matrix Rom.

[11]. Opris I., Cenusa V.E., & Darie G., (2017). A dimensioning methodology for a Natural Draft Wet Cooling Tower. *TEM Journal*, 6(2). (in print).

[12]. Hemmasian Kashania M.M., & Dobregob K.V. (2013). Heat and mass transfer in natural draft cooling towers, *Journal of Engineering Physics and Thermophysics,* 86(5), 1072-1082.

[13]. Ataei A., Panjeshahi M.H., & Gharaie M. (2009). A New Algorithm for Optimum Design of Mechanical Draft Wet Cooling Towers. *Journal of Applied Sciences,* 9, 561-566.

[14]. Damian M., Motoiu I., & Caracasian L. (1998). A Simulation Software for Cooling Towers Optimal Operation, Proceedings of the American Power Conference (APC), Chicago, 6, PTS I & II, 287-291.

[15]. Merkel, F. (1925), Verdunstungshuhlung, *Zeitschrift desvereines Dentscher Ingenieure (VDI)*, 70, 123–128.

[16]. Dumitru, C., Ciobanu, S., & Duca, P. (1986). Diagrame si relatii generalizatoare privind functionarea turnurilor de racire umede cu tiraj natural si fortat in contracurent (Generalizing Diagrams and Relations Regarding Wet, Counterflow Natural and Forced Draught Cooling Towers), *Energetica* 34(5), 220-227.

[17]. Dumitru, C., Ciobanu, S., & Duca, P. (1987), Determinarea relatiilor generale de calcul global pentru turnurile de racier umede in current transversal cu tiraj natural si fortat (Global calculation relations determination for natural and forced draught cross-current wet rapid towers), *Energetica* 35(9), 400-406.

[18]. MATLAB and Statistics Toolbox Release (2012)b, The MathWorks, Inc., Natick, Massachusetts, United States.

[19]. IAPWS. (2007). Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam, International Association for the Properties of Water and Steam.

[20]. Pop, M.G., Leca, A., Prisecaru, I., Neaga, C., Zidaru, G., Musatescu, V., & Isbasoiu, E.C. (1987). *Indrumar. Tabele, nomograme si formule termotehnice (Handbook. Tables, momograms and termotechnical formulae),* 1, 52-69, Editura Tehnica,

[21]. Handbook, A. S. H. R. A. E. (2001). Fundamentals. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 111.