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A Dimensioning Methodology for a Natural Draft Wet Cooling Tower

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***Abstract* – The paper proposes a methodology for the dimensioning of a natural draft wet cooling tower. The main geometrical dimensions depend on the packing type, the cooling and the weather conditions. The study is based on splitting the tower in three main zones: the spray and packing zone, the rain zone and the natural draft zone. The methodology is developed on modular bases, by using block-modules both for the three main zones of the cooling tower and for the inlet/outlet air properties. It is useful in explaining to the students the complex physical phenomena within the cooling tower but also for the development of a computer program to be used in engineering, management and education.**

***Keywords* – cooling tower, methodology, flow-chart, power plant, heat exchange.**

1. Introduction

Thermal power plants are used to produce electricity and/or heat within a Rankine-Hirn cycle [1]: the steam produced within a hot source (the steam generator) is expanded in a turbine to obtain energy, condensed within a cold source (the condenser). Then, the condensate is returned to the hot source through the feed pumps [2]. The process is schematized in Figure 1. Within the figure, there are emphasized the main cycle's input/output links of the thermodynamic cycle:

- At the hot source: fuel and air are introduced into the steam generator to produce steam [3]; the main residues of the process consist in slag/ash and noxes in the exhausted flue gases;
- At the turbine: the power produced in the steam turbine, which represents the useful output of the Rankine-Hirn cycle [4];
- At the feed pump: there is no link outside the cycle, as the feed water pump consumes a quota of the energy produced by the turbine;
- At the cold source [5]: through the condenser, the heat is discharged into the environment. The residual heat is evacuated into the environment through a cooling fluid (usually water) within a cooling system [6]. In the absence of a cold-water source (a river, a lake, a sea) a cooling tower is used.

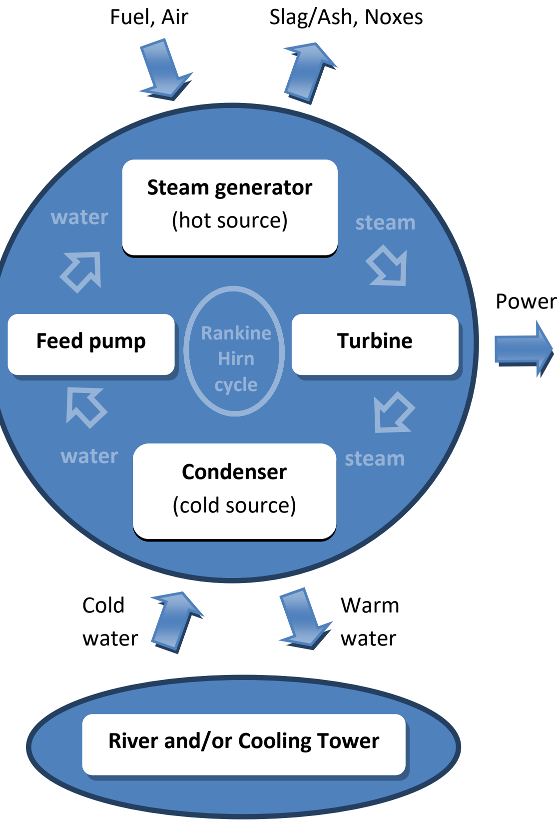

Figure 1. The Rankine-Hirn cycle

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The main parameters of the cycle are established during the first design steps of the power plant. The efficiency of the Rankine-Hirn cycle and the output power generated within the turbine can be increased by using higher parameters at the hot source, lower parameters at the cold source and/or by preheating the feed-water entering the steam generator [7].

The paper focuses on the cold source of the thermodynamic cycle, respectively on the discharge of the heat into the atmosphere through the cooling tower [8].

The complex phenomena in a cooling tower can be described by several models: mathematical, numerical or experimental. Such models are based on different methods and hypotheses of using the heat and mass balance equations: by general simplified formulas [9], by enthalpies and humidity [10, 11], by the derivation of the differential equations [12, 13, 14], by finite differences [15], by empirical relations [16]. Hemassian and Dobregob [8] give a compact overview of publications in the domain of heat and mass transfer in cooling towers. Comparative studies on cooling towers are given by [17] and [18].

This paper presents a methodology for the dimensioning of the natural draft wet cooling tower. The main geometrical dimensions of the cooling tower result from a combination of physical and empirical parameters. Such a dimensioning methodology is useful in different fields, as:

- engineering, as a fast tool to determine the main characteristics necessary for design;
- education, as a tool for students to understand the interdependence between the physical and the geometrical parameters;
- power plant management, as input data for the investment computation.

The flow charts presented in the paper can be used for the development of software applications to be used in the prior mentioned fields. A smart strategy for higher education links the mentioned fields.

2. The Natural Draft Wet Cooling Tower

The shape of the cooling tower is a hyperboloid of rotation (Figure 2.). Its shape and height are chosen to generate an upward air current by natural draft. Because of the lower density of the cold dry air than the density of the warm moist air, the cold air rises. Figure 2. presents a Counter-flow Natural Draft Wet Cooling Tower used for thermal power plants.

The natural draft wet cooling towers are contact (open) heat exchangers, in which heat and mass transfer occur by the direct contact between the cooling-water and the air [19]. The water is sprayed into a natural draft air flow and it is cooled by the following main mechanisms of heat transfer:

- *Evaporation*, due to the latent heat of vaporization used for the mass transfer through evaporation of a quota of the water flow,
- *Convection*, due to the heat transfer allowed by the temperature difference between air and water.

Most of the cooling (about 95%) is obtained by evaporation, only the rest (about 5%) resulting from convection [8].

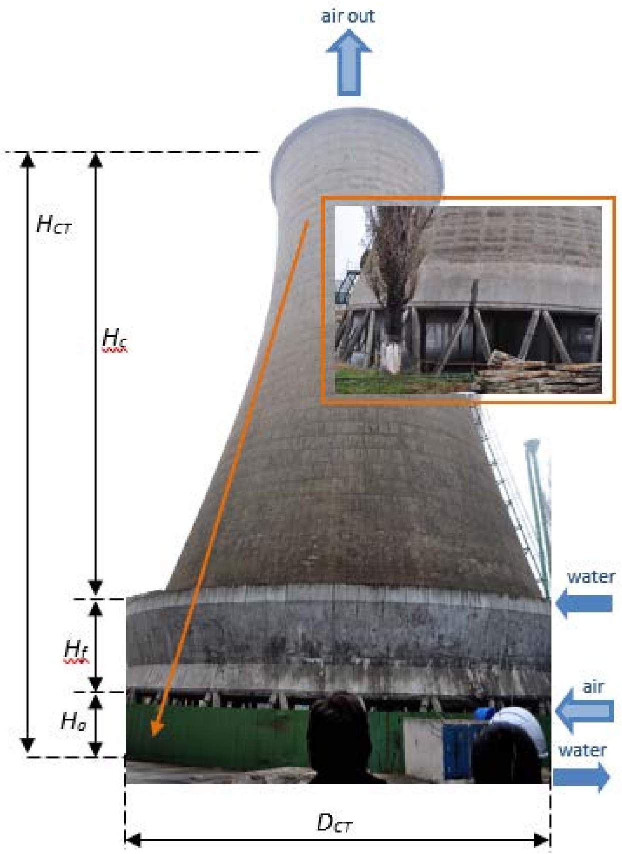

Figure 2. Counter-flow Natural Draft Wet Cooling Tower

In accordance to the energy conservation law, the heat gained by the air (Q_{air}) equals the heat lost by the water (Q_{water}) and the loss of heat through evaporation ($Q_{evaporation}$) [20]:

$$Q_{air} = Q_{water} + Q_{evaporation} \quad (1)$$

Inside the cooling tower, the heat and mass exchange takes place between water and air within the following zones [21]:

- the spray zone: the hot water entering through a distribution system is sprayed over the whole area of the packing zone by spray nozzles;

- the packing (or exchange) zone: a fill (film or splash packing) is used to increase the contact area between air and water and to increase the water flowing time through the tower and thus the contact time;

- the rain zone: next to the air inlet, water droplets are falling towards the cooled water basin.

The cooled water basin is placed at the bottom of the tower, beneath it.

Above the hot water distribution system there are mounted drift eliminators, to stop the water droplets that escape within the air stream towards the atmosphere. Towards it, the natural draft zone begins up to the top of the tower.

The main geometrical dimensions which are calculated during the design of the cooling tower are shown in Figure 2.: the height (H_{CT}) and diameter (D_{CT}) of the cooling tower and the heights of the three important zones of the tower: the height of the natural draft zone (H_c), the height of the spray and packing/fill zone (H_f) and the height of the rain zone (H_a).

As shown in Figure 2., the total height of the cooling tower is given by the sum:

$$H_{CT} = H_c + H_f + H_a \quad (2)$$

After the final configuration of the entire power plant is set up, the detailed design of the cooling tower is made through thermo-economic optimization [21].

3. The Methodology for the Cooling Tower Dimensioning

3.1. Input parameters

The input data considered for the dimensioning of the cooling tower are given in Table 1.

The data includes three types of parameters, regarding:

- the cooling water,
- the surrounding weather conditions for the location,
- the geometrical characteristics (design) of the tower.

Table 1. Input parameters

Type	Parameter	Notation	Unit
Cooling water	Flow rate of water at the input of the tower	F_{w1}	kg/s
	Temperature of water at the input of the tower	t_{w1}	ºC
	Temperature of water at the output of the tower	t_{w2}	ºC
Air	Air temperature at the input of the tower	t_{a1}	ºC
	Air pressure at the input of the tower	p_{a1}	bar
	Relative air humidity at the input of the tower	φ_{a1}	%
Design	Substance yielding coefficient of the filling	β_{xv}	kg/m^3/h
	Spraying density	q	m^3/m^2/h

3.2. The methodology assumptions

The methodology presented below is based on the method of Merkel [9]. Separate block-modules are used for the three main zones of the cooling tower (the natural draft zone, the spray and fill zone and the rain zone, as in Figure 2.) and for the inlet/outlet air properties.

3.3. The inlet air block-module

Table 2. contains the notations of the parameters used in the module, with the specification of their source (input into the block-module or determined within it). The parameters are obtained from air properties, through the methodology shown in the flow chart of Figure 5.

Table 2. Parameters of the inlet air block-module

Parameter	Notation	Unit	Origin
Inlet air temperature	t_{a1}	°C	Input
Inlet air pressure	p_{a1}	bar	Input
Inlet air density	ρ_{a1}	kg/ m^3	Calculus
Inlet air enthalpy	h_{a1}	kJ/kg	Calculus
Inlet relative air humidity	φ_{a1}	%	Input
Inlet specific air humidity	x_{a1}	kg$_{vapors}$/ kg$_{air}$	Calculus
Inlet air pressure of water vapors	p_{va1}	bar	Calculus
Saturated inlet air pressure	p_{sa1}	bar	Calculus
Air specific humidity at saturation at the inlet water temperature	x_{sa1}	kg$_{vapors}$/ kg$_{air}$	Calculus
Air enthalpy at saturation at the inlet water temperature	h_{sa1}	kJ/kg	Calculus
Ambient wet-bulb temperature	t_{wb}	°C	Calculus
Outlet water temperature	t_{w2}	°C	Input
Saturation pressure of water vapors at the outlet water temperature	p_{s2}	bar	Calculus

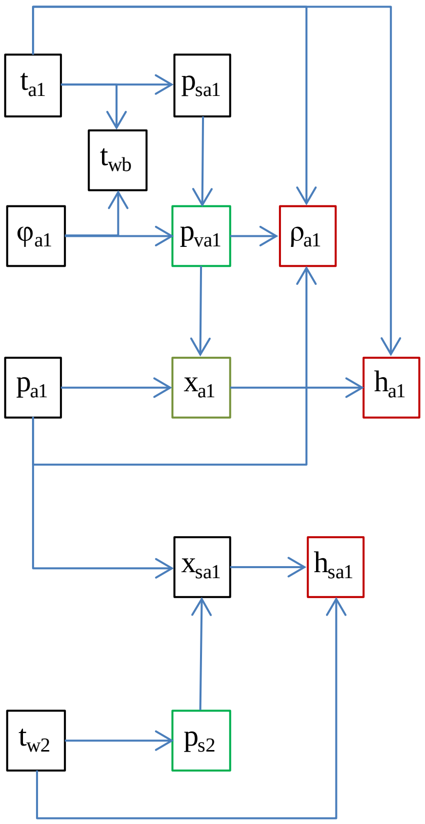

Figure 5. Flow-chart for the inlet air block-module

3.4. The outlet air block-module

Table 3. contains the notations of the parameters used in the outlet air block-module, with the specification of their origin.

The outlet air parameters are determined through the methodology shown in Figure 6. The methodology uses an iterative cycle for the outlet air temperature [10] and for the corresponding parameters. Based on a first estimation of the outlet temperature, its value is recalculated, until an imposed error condition is met.

One can observe that the t_{a2} is depending on several parameters:

$$t_{a2} = \text{function}(t_{a1}, x_{a1}, x_{a2}, p_{s1}, p_{s2}, p_{sm}, p_{v1}, p_{v2}) \quad (4)$$

Some of the parameters in (4) are entry data in the module and others are determined inside or outside of the iterative cycle.

Table 3. Parameters of the outlet air block-module

Parameter	**Notation**	**Unit**	**Origin**
Inlet air temperature	t_{a1}	°C	Input
Outlet air temperature	t_{a2}	°C	Calculus
Inlet air pressure	p_{a1}	bar	Calculus
Outlet air pressure	p_{a2}	bar	Output
Outlet air density	ρ_{a2}	kg/m^3	Calculus
Outlet air enthalpy	h_{a2}	kJ/kg	Calculus
Outlet relative air humidity	φ_{a2}	%	Input
Inlet specific air humidity	x_{a1}	kg_{vapors}/kg_{air}	Input
Outlet specific air humidity	x_{a2}	kg_{vapors}/kg_{air}	Calculus
Inlet air pressure of water vapors	p_{va1}	bar	Input
Outlet air pressure of water vapors	p_{va2}	bar	Calculus
Saturated outlet air pressure	p_{sa2}	bar	Calculus
Air specific humidity at saturation at the outlet water temperature	x_{sa2}	kg_{vapors}/kg_{air}	Calculus
Air enthalpy at saturation at the outlet water temperature	h_{sa2}	kJ/kg	Calculus
Outlet water temperature	t_{w2}	°C	Calculus
Saturation pressure of water vapors at the inlet water temperature	p_{s1}	bar	Calculus
Saturation pressure of water vapors at the outlet water temperature	p_{s2}	bar	Input
Saturation pressure of water vapors at the mean water temperature	p_{sm}	bar	Input

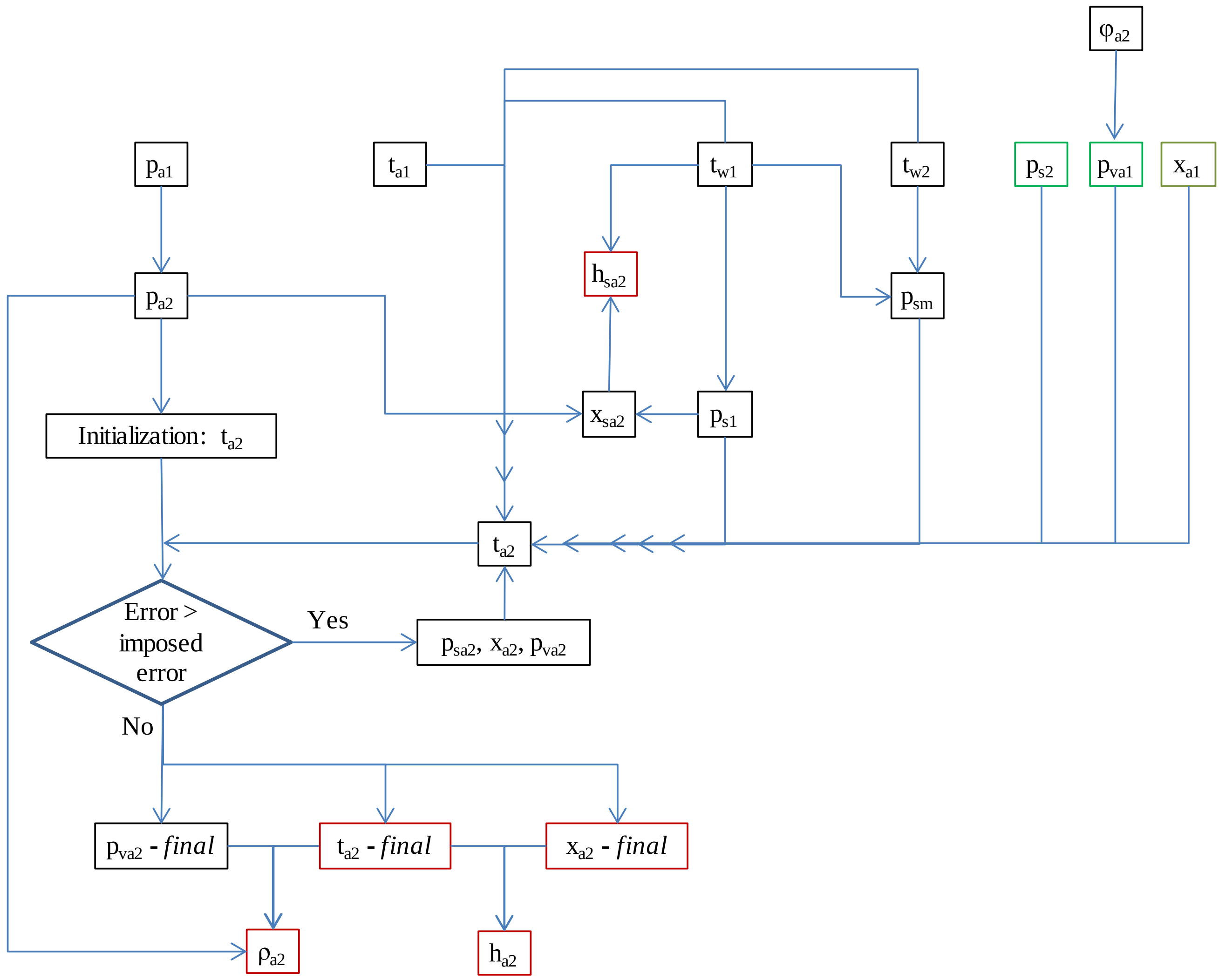

Figure 6. Flow-chart for the outlet air block-module

3.5. The block-module for obtaining the height of the packing

Table 4. contains the notations of the parameters used in the block-module to determine the height of the packing. This is obtained through the methodology shown in the flow chart of Figure 7.

The absolute mean enthalpy difference between the saturated air and the environmental air ($|h_{sa} - h_a|_m$) is used to estimate the heat transfer through the tower. The volume of the packing results from the relation of Merkel [9]. Finally, the base area of the cooling tower (S_b) is obtained from the water flow rate (F_{w1}) and the spraying density (q).

3.6. The block-module for obtaining the height of the rain zone

Table 5. contains the notations of the parameters used in the block-module for the determination of the height of the rain zone (the same as the height of the air inlet window). The source of each variable is specified within the table.

The height of the rain zone is obtained through the methodology shown in Figure 8. Within this block-module are first determined the air flow rate through the cooling tower and the ratio between the air and water flow rate (λ). Then, by finding the mean air velocity in the cooling tower and the inlet air velocity, the necessary height of the inlet air zone into the tower (H_a) is obtained to assure the above air parameters.

Table 4. Parameters of the height of filling block-module

Parameter	Notation	Unit	Origin
Inlet air enthalpy	h_{a1}	kJ/kg	Input
Outlet air enthalpy	h_{a2}	kJ/kg	Input
Air enthalpy at saturation of water inlet	h_{sa1}	kJ/kg	Input
Air enthalpy at saturation of water outlet	h_{sa2}	kJ/kg	Input
Absolute mean enthalpy difference of saturated and environmental air	$\lvert h_{sa} - h_a \rvert_m$	kJ/kg	Calculus
Inlet water temperature	t_{w1}	°C	Input
Outlet water temperature	t_{w2}	°C	Input
Specific isobaric heat capacity of water	c_p	kJ/kg/°C	Input
Input water flow rate	F_{w1}	kg/s	Input
Substance yielding coefficient	β_{xv}	$kg/m^3/h$	Input
Spraying density	q	$m^3/m^2/h$	Input
Cooling volume of the packing zone	V	m^3	Calculus
Base area of the cooling tower	S_b	m^2	Calculus
Height of the fill	H_f	m	Calculus

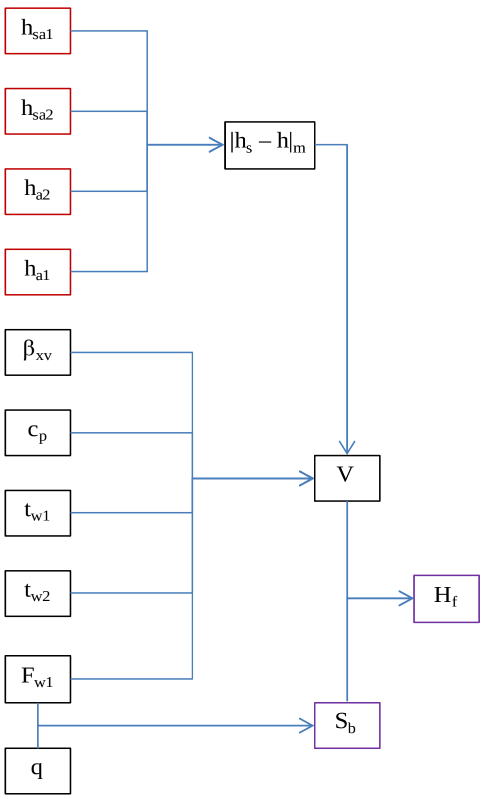

Figure 7. Flow-chart for the height of filling block-module

Table 5. Variables of the rain zone block-module

Parameter	Notation	Unit	Origin
Outlet air temperature	t_{a2}	°C	Input
Inlet air density	ρ_{a1}	kg/m^3	Input
Outlet air density	ρ_{a2}	kg/m^3	Input
Inlet air enthalpy	h_{a1}	kJ/kg	Input
Outlet air enthalpy	h_{a2}	kJ/kg	Input
Inlet specific air humidity	x_{a1}	kg_{vapors}/kg_{air}	Input
Outlet specific air humidity	x_{a2}	kg_{vapors}/kg_{air}	Calculus
Inlet water temperature	t_{w1}	°C	Input
Outlet water temperature	t_{w2}	°C	Input
Specific isobaric heat capacity of water	c_p	kJ/kg/°C	Input
Input water flow rate	F_{w1}	kg/s	Input
Flow rate of dry air through the tower	F_a	kg/s	Calculus
Flow rate of moist air through the tower	F_{ma}	kg/s	Calculus
Inlet air velocity	w_{a1}	m^2/s	Calculus
Mean air velocity in the cooling section	w_{am}	m^2/s	Calculus
Coefficient to consider the quota of the cooling water which is evaporated	k_λ	-	Calculus
Air-water flow ratio	λ	-	Calculus
Height of the air inlet window (the rain zone)	H_a	m	Calculus

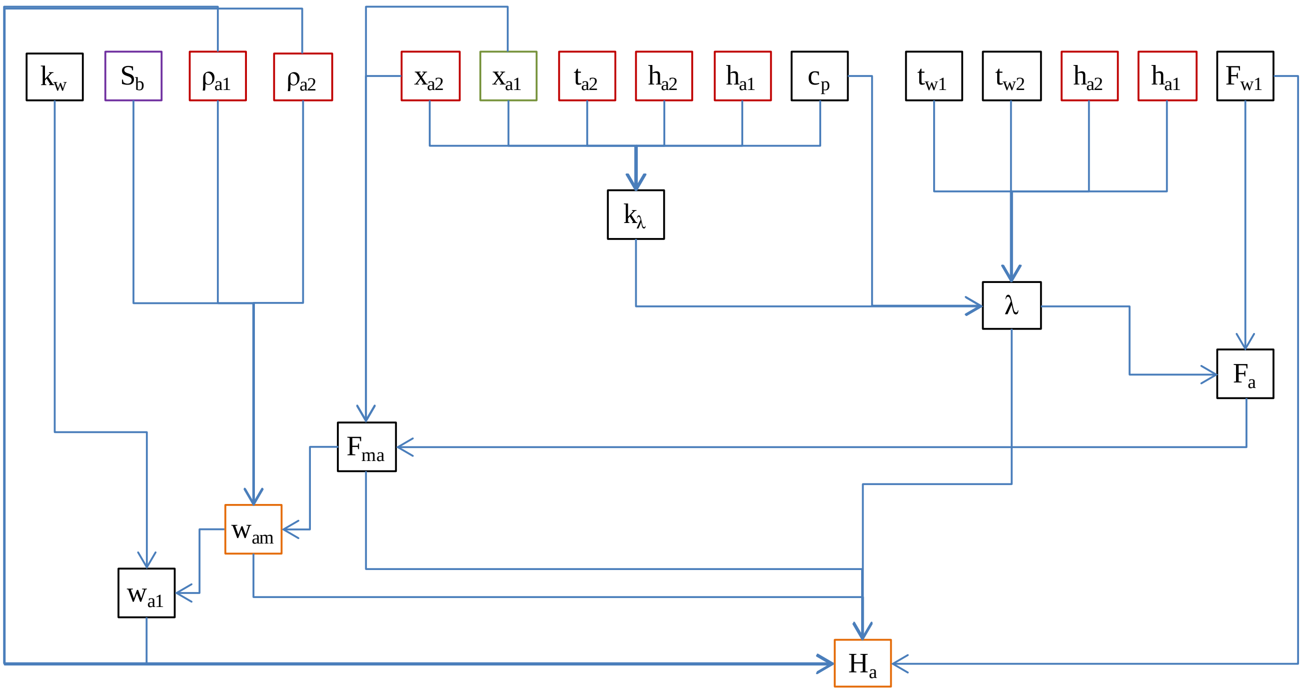

Figure 8. Flow-chart for the height of the rain zone block-module

3.7. The block-module for obtaining the height of the natural draft zone

Table 6. contains the notations of the parameters used in the block-module which determines the height of the chimney corresponding to the natural draft zone. The source of each variable is specified within the table. The height of the natural draft zone is obtained through the methodology shown in Figure 9.

Table 6. Parameters of the natural draft zone block-module

Parameter	**Notation**	**Unit**	**Origin**
Inlet air density	ρ_{a1}	kg/ m^3	Input
Outlet air density	ρ_{a2}	kg/ m^3	Input
Mean air velocity in the cooling section	w_{am}	m^2/s	Input
Spraying density	q	m^3/m^2/h	Input
Height of the air inlet window (the rain zone)	H_a	m	Input
Height of the fill	H_f	m	Input
Total aerodynamic resistance coefficient of the tower	ξ	-	Calculus
Height of the of the chimney in the natural draft zone	H_c	m	Calculus

The height of the natural draft zone must assure the upward air circulation. The natural draft of air is due to the difference of air density at different temperatures: the inlet air temperature and outlet air temperature. The block-module obtains the height of the natural draft zone from the known air parameters and the total aerodynamic resistance (ξ). The last value can be determined by an experimental relation depending on the fill, the spraying density and the mean air velocity in the cooling section.

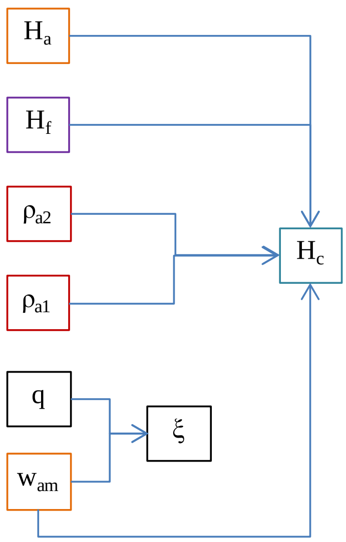

Figure 9. Flow-chart for the height of the natural draft zone block-module

3.8. The block-module for obtaining the height and diameter of the cooling tower

Table 7. contains the notations of the parameters used in the block-module and Figure 10. contains the block-module which determines the height and the diameter of the cooling tower.

The geometrical dimensions result easily from the known heights (of the rain zone, filling and natural draft zone) and the base area of the cooling tower.

Table 7. The cooling tower height block-module

Parameter	Notation	Unit	Origin
Height of the fill	H_f	m	Input
Height of the air inlet window (the rain zone)	H_a	m	Input
Height of the of the chimney in the natural draft zone	H_c	m	Input
Height of the cooling tower	H_{CT}	m	Calculus
Base area of the cooling tower	S_b	m^2	Input
Diameter of the base of the cooling tower	D_{CT}	m	Calculus

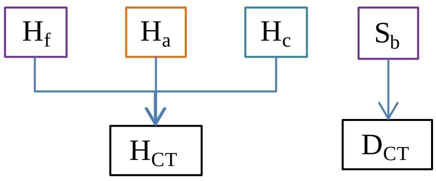

Figure 10. Flow-chart for the height of the natural draft zone block-module

The dimensioning methodology determines the geometrical dimensions within an iterative cycle.

4. Conclusion

As the cooling tower is an important and expensive equipment, several solutions are considered in the design of a power plant. This is why the use of a dimensioning methodology for the sizing of the cooling tower is very useful and helpful in the early design phase.

The paper presents a methodology for the dimensioning of natural draft wet cooling towers. The block-modules defined within it are based on considering the different physical phenomena that occurs in the three main zones of a cooling tower: the spraying and filling zone, the rain zone and the natural draft zone. These block-modules highlight the correlations between the thermo-dynamical and geometrical parameters.

The proposed dimensioning methodology can be used in education, for explaining to the students the complex heat exchange mechanism in a cooling tower, the design procedure and the influence of different input requirements on the tower dimensions.

Moreover, the methodology represents a starting point for developing a dimensioning computer program for the natural draft cooling tower.

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