Cooling Water Systems Featuring Heat Exchanger Design and Variable Outlet Temperature

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Introduction

- Water cooling system

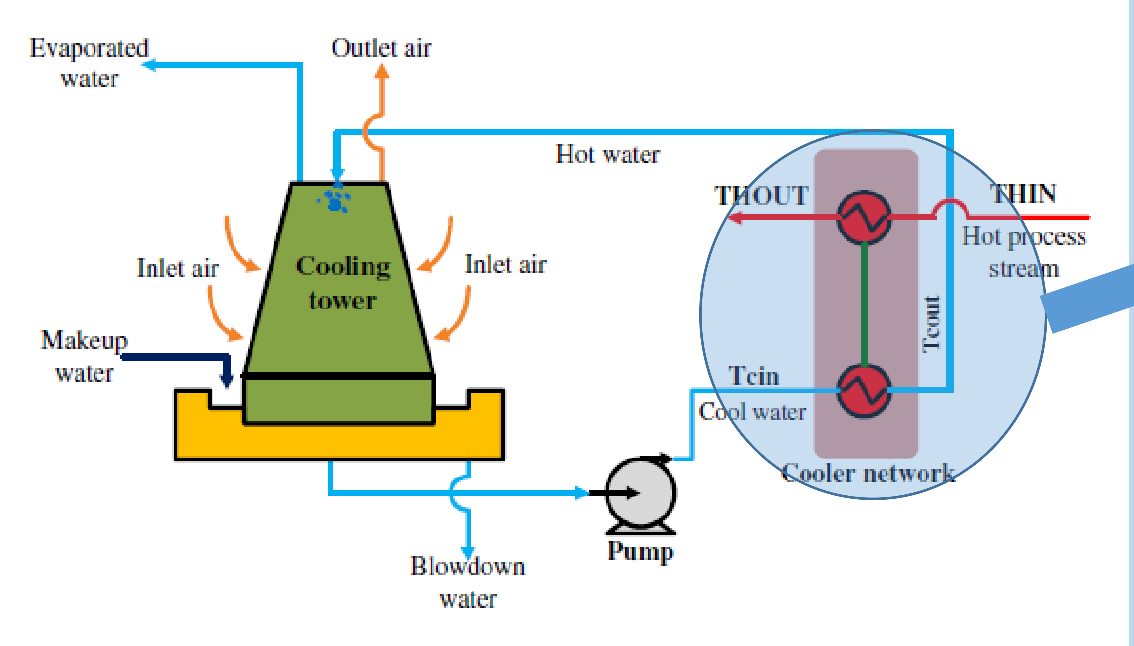
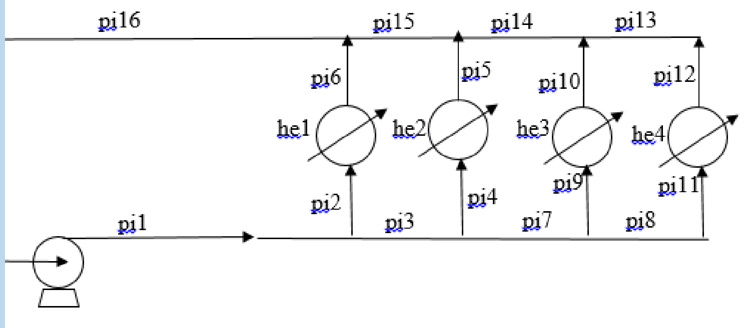


Fig. 1. Components of a typical re-circulating cooling water system.

Castro et al, 2013.



- In our case, we only solve this part of the system
- We determine piping diameters (lengths are fixed) and full cooler geometry

Introduction

Our previous model (Levy et al, 2019) aimed at designing the piping and the exchangers simultaneously:

- Using the Kern model for heat exchangers
- Using Hazen Williams model for pressure drop in pipes.
- Outlet Temperature of exchangers fixed.

MILP – SIMULTANEOUS DESIGN

- Results for fixed cooler outlet temperature (4 Coolers)

cost ($/year)	simultaneous design
pump cost	1455.21
heat exchanger cost	48350.33
pipe cost	15606.02
operational cost	20739.07
total cost	86150.64

MODEL EXTENSION

- Variable temperature at the outlet of each cooler
- Variable temperature returning to the cooling tower inside a small window

THIS PROBLEM PRESENTED DIFFERENT CHALLENGES

We now show different attempts to solve it

MILP – DISCRETE TEMPERATURE REPRESENTATION

Temperature of the water flowrates of each heat exchanger - discrete variables.

- Range of cooling water return temperature.
- Some heat exchangers temperatures combinations selected - return temperature range - “if” loop prior to optimization.
- The optimization is performed in one step.

MILP – DISCRETE TEMPERATURE REPRESENTATION

Results

MILP – DISCRETE TEMPERATURE- 1 STEP	Temperature of the water flow rates of each heat exchanger as discrete variables and an allowable range of cooling water return temperature. Heat exchanger model - yrow	Reduced 3T options	1	3019	3004	7965
			5			
		Complete 3T options	1	739467	739452	2239949
			5			

Model	Description	Options	CPLEX
MILP – DISCRETE TEMPERATURE- 1 STEP	Temperature of the water flow rates of each heat exchanger as discrete variables and an allowable range of cooling water return temperature. Heat exchanger model - yrow	Reduced 3T options	Converge
		Complete 3T options	Converge*[1]

MINLP – with auxiliary variables

- One binary (yrow) to represent each possible cooler geometry (developed by Gonçalves et al.; 2017)
- Temperature of the water flowrates of each heat exchanger is a continuous variable
- Permissible range of cooling water return temperature.
- Hazen-williams Equation – auxiliary variable

MINLP – with auxiliary variables

Results

Model	Description	Options	Number of HC	Number of variables	Number of binary variables	Number of equations
MINLP WITH LINEARIZATIONS	Temperature of the water flow rates of each heat exchanger as continuous variables and there is a permissible range of cooling water return temperature. Hydraulic model – linearizations Heat exchanger model - yrow	Reduced	1	8894	1501	26261
			5	45674	7461	137689
		Complete	1	2217968	369725	7044317
			5			

MINLP – with auxiliary variables

- Results

Model	Description	Options	CPLEX	Baron
MINLP WITH LINEARIZATIONS	Temperature of the water flow rates of each heat exchanger as continuous variables and there is a permissible range of cooling water return temperature. Hydraulic model – linearizations Heat exchanger model - yrow	Reduced	-	Converge
		Complete		Interrupted after more than 6 h – (UERJ)*2

MINLP – with exchanger candidate binary representation (yrow)

- hydraulic model – no auxiliary variables

- **Results**

Model	Description	Options	Number of HC	Number of variables	Number of binary variables	Number of equations
MINLP WITHOUT LINEARIZATIONS IN THE HYDRAULIC MODEL	Hydraulic model – no linearization Heat exchanger model - yrow	Reduced	1	2982	1501	2635
			5	45674	7461	137689
		Complete	1	739348	369725	1310818
			5			

MINLP – with exchanger candidate binary representation (yrow)

- **Results**

Model	Description	Options	CPLEX	Baron	Antigone	Initial guess	Sbb
MINLP WITHOUT LINEARIZATIONS IN THE HYDRAULIC MODEL	Hydraulic model – no linearization	Reduced	-	-	Converge	Equal to optimal point of MILP	Converge
	Heat exchanger model - yrow	Complete			Interrupted after more than 24 h – (UERJ)		Interrupted after more than 24 h – (UERJ)

MINLP –

- Heat exchanger model - original format.

- Hydraulic model - original format.

MINLP –

- Results

Model	Description	Options	Number of HC	Number of variables	Number of binary variables	Number of equations
MINLP WITHOUT LINEARIZATIONS IN THE HYDRAULIC MODEL AND IN THE HEAT EXCHANGER MODEL (WITHOUT YROW), AND WITH F INSIDE OF Q EQUATION	Heat exchanger model- without yrow or any other linearization The LMTD correction factor equation (F) was included in the heat transfer rate equation. Hydraulic model – no linearization	Reduced	1	87	63	61
			5	359	271	245
		Complete	1	212	188	61
			5	880	792	245

MINLP –

- Results

Model	Description	Options	CPLEX	Baron	Antigone	Initial guess	Sbb	Dicopt
MINLP WITHOUT LINEARIZATIONS IN THE HYDRAULIC MODEL AND IN THE HEAT EXCHANGER MODEL (WITHOUT YROW), AND WITH F INSIDE OF Q EQUATION	Heat exchanger model- without yrow or any other linearization The LMTD correction factor equation (F) was included in the heat transfer rate equation. Hydraulic model – no linearization	Reduced	-	Converge	Interrupted after more than 24 h – (UERJ)	Equal to optimal point of MILP	Converge quickly	Converge quickly
						Without initial guess Bounds on all variables	locally infeasible	locally infeasible
						Initial guess equal optimal point in 40°C Bounds on all variables*3	locally infeasible	locally infeasible
		Complete		Interrupted itself	Interrupted after more than 24h – (UERJ)	Equal to optimal point of MILP	converge	converge
						Without initial guess Bounds on all variables	Didn't do it, because of the results of "reduced options".	Didn't do it, because of the results of "reduced options".
						Initial guess equal optimal point in 40°C Bounds on all variables*3	Didn't do it, because of the results of "reduced options".	Didn't do it, because of the results of "reduced options".

Current Approach: Set trimming, NLP and MILP tools

- We propose to use a set trimming step for the coolers individually
- We follow with a determination of the minimum flowrate for each exchanger candidate
- This lead to a large MILP where each exchanger candidate has its own flowrate.
- This large MILP does not fit in regular laptops and desktops
- We are testing Smart Enumeration.

Conclusions

- MILP model of cooling water systems, considering the Kern model for heat exchangers presents high number of variables, being a barrier for the software GAMS.

- The more nonlinear the models, the fewer the variables, but convergence problems appear.

- The next steps are set trimming and smart enumeration, along with the use of NLP to determine the minimum flowrate for each exchanger.