A Systematic Control Approach to Improve Energy Efficiency of Industrial Cooling Towers

Dr. Pinakpani Biswas
Principal Scientist
R&D, SS
TATA Steel
Jamshedpur

Sayani Adhikari, ME, BIT Mesra
Arunima Giri, Mtech, VIT, Vellore
Agenda

- Brief Introduction
- Key Challenges
- Solution Overview
- Objectives & Assumptions
- Approach
- Model Development
- Tools Used
- Optimization Flowchart
- Results and Discussion
- Conclusion
- Future Scope of work
A device used to COOL hot water stream based on evaporative cooling

**Hot stream (DM Water)**

**Warm Process Water**

**Cold stream (DM Water)**

**Cold Process Water**
CT Objective
To decrease hot water temperature by 4-8 degrees (TATA Steel Jamshedpur)

Cooling tower is an energy intensive process

➢ Tuning cooling tower parameters for optimized operation
➢ Optimizing Energy Consumption

Key Challenges

- Hot Air
- Hot Water
- Ambient Air (Driving force: Relative humidity)
- Cold Water (Temperature approach ambient WBT)
Solution Overview

Monitor Operation/
Collect data

MATLAB/Simulink
Simulation

Implementation

Validation

MATLAB Program

Optimization:
E value obtained

MATLAB/Simulink
Simulation

Validation

Data acquisition
instrument
Objectives

- Tune the model parameters to decrease energy consumption

Assumptions

- Stage efficiency was assumed to be equal for all stages for basic simulation purpose which later on to be optimized with the help of available data
- Vapor liquid equilibrium
Development of Equilibrium Model for existing cooling tower

Mass Balance

Energy Balance

MATLAB
Compiler, Optimization toolbox & Simulink

Equilibrium Model

Optimized Model

Validation and Implementation

Simulink Model
Mass balance for 2 stages

Stage-1

\[ L_0 + GH_2 = L_1 + GH_1 => L_1 = L_0 + G(H_2 - H_1) \]

Stage-2

\[ L_1 + GH_3 = L_2 + GH_2 => L_2 = L_1 + G(H_3 - H_2) \]

Energy balance for 2 stages

Sensible heat of inlet air + sensible heat of inlet water + sensible heat of inlet water vapour + latent heat of inlet water vapour = sensible heat of exit air + sensible heat of exit water + sensible heat of exit water vapour + latent heat of exit water vapour

Stage-1

\[
(G \times C_{pa} \times T_2) + (L_0 \times C_{pw} \times T_0) + (G \times H_2 \times C_{pv} \times T_2) + (G \times H_2 \times \lambda) \\
= (G \times C_{pa} \times T_1) + (L_1 \times C_{pw} \times T_1) + (G \times H_1 \times C_{pv} \times T_1) + (G \times H_1 \times \lambda)
\]

Stage-2

\[
(G \times C_{pa} \times T_a) + (L_1 \times C_{pw} \times T_1) + (G \times H_3 \times C_{pv} \times T_a) + (G \times H_3 \times \lambda) \\
= (G \times C_{pa} \times T_2) + (L_2 \times C_{pw} \times T_2) + (G \times H_2 \times C_{pv} \times T_2) + (G \times H_2 \times \lambda)
\]
Unknowns: $L_2$, $L_1$, $T_2$, $T_1$, $H_2$, $H_1$ (No of unknowns is 6)

No of equations: 4

Degrees of freedom=2

To eliminate one set of unknowns in order to make the number of unknowns and number of equations equal murphy efficiency equation is used

$$E_n = \frac{Y_n - Y_{(n+1)}}{Y_{Sn} - Y_{(n+1)}}$$

Equations obtained for ‘2’ stages are

$$Y_1 = E_1(Y_{S1} - Y_2) + Y_2$$

$$Y_2 = E_2(Y_{S2} - Y_3) + Y_3$$

$H_1$ and $H_2$ can be calculated from $Y_1$ and $Y_2$

$$H_1 = \frac{Y_1}{1 - Y_1} \times \frac{M_{H2O}}{M_{Air}}$$

$$H_2 = \frac{Y_2}{1 - Y_2} \times \frac{M_{H2O}}{M_{Air}}$$

Degrees of freedom after variable substitution:  No. of variables 4 and No. of equations 4. This implies D.O.F=0
Tools Used

- MATLAB R2016b
- Simulink
- MATLAB Compiler
- Optimization toolbox
Coding

```
68 -  pao(1)=(Mair*P*H(1))/(Mair*H(1)+MH2O);
69 -  for i=2:n
70 -     pao(i)=(Mair*P*H(i))/(Mair*H(i)+MH2O); %output partial pressure
71 -  end
72 -  disp('partial pressure')
73 -  disp(pao)
74 -  pavo(1)=(exp(11.96481-(3984.923/((T(1)+273)-39.724))))*750;
75 -  for i=2:n
76 -     pavo(i)=(exp(11.96481-(3984.923/((T(i)+273)-39.724))))*750; %vapour pressure of each stage
77 -  end
78 -  disp('output vapour pressure:')
79 -  disp(pavo)
80 -  RHs(1)=(pao(1)/pavo(1));
81 -  for i=2:n
82 -     RHs(i)=(pao(i)/pavo(i)); %stage Relative humidity
83 -  end
84 -  disp('Relative humidity of each stage:')
85 -  disp(RHs)
86 -  e(1)=L0*cpw*t0+g*cpa*T(2)+g*H(2)*cpv*T(2)+g*H(2)*hv-g*cpa*T(1)-L(1)*cpw*T(1)-g*H(1)*cpv*T(1)-g*H(1)*hv;
87 -  for i=2:n
88 -     e(i)=L(i-1)*cpw*T(i-1)+g*cpa*T(i)+g*H(i)*cpv*T(i)+g*H(i)*hv-g*cpa*T(i)-L(i)*cpw*T(i)-g*H(i)*cpv*T(i)-g*H(i)*hv;
89 -  end
90 -  % loss=g*(H(n)-H(n+1))
91 -  % loss1=L0-L(n)
92 -  f=[e];
93 -
94 -
```
Variable initialization

Calculation of primary unknowns from initial parameters (vapor pressure, inlet humidity, mole fraction etc.)

Calculation of partial pressure, humidity, mole fraction and liquid flow rate for each individual stages (in terms of temperature)

Calculation of temperature by substitution

Outlet temperature value for all stages

Final values

i
Providing the final temperature value to the respective calculations

ii
Optimization Flowchart

\[ \text{Min } \sum_{i=1}^{n} \rho_i = \sum_{i=1}^{n} (T_{Exp} - \hat{T})^2 \]

w.r.t \( T \)
S.T. \( L.b \leq T \leq U.B \)

Inner Loop

\[ f(t) \approx 0 \]

err > 0.1

err = 1

\[ T_{exp} \]
**Main function**

```matlab
global double ii Dt tr
clc;
ii=0;
for ii=1:5
	for tr=8;
		Dt=zeros(20,20);
		ii=0;
		if for normal check
			options= optimoptions(@lsqnonlin); % Set options
			options= optimoptions(@lsqnonlin); % Set options
			if a= 1+ii*ones(1,20)
				for i=1:ii
					ii=ii+1;
				end
			end
		end
end
```

**Data set**

```matlab
function f=OPT1(x)
global RHg Pg tag t0g index E ii \sigma L0
E=x;
ii=0;
index=0;
g=4505000.71; %gas rate in kg/hr
L0=5678000; %Liquid rate in kg/hr
CPW=4.2; % Specific heat of water
CPA=1; % Specific heat of air
CPV=2; % Specific heat of humid air
CH=2257; % latent heat of water

PH20=[33.1108 32.7867 32.3976 31.9063
5.676100 5671800 5664700 5653800];
RHg=[0.97 0.9165 0.728 0.6762 0.8715 0]
P= [760.8624478 761.6877617 764.462741
784.8624478];
tag=[17.45 15.87 21.29 20.26 17.03 21.]
```

**Function solver**

```matlab
function f=calc_opt(x)
ii = 1:
for i=1:n
I(1)=X(1);
end
```

**Optimized efficiency and number of stages**

- Error < 0.1
- Temperature value
Effect of No. of Stages on Cooling Tower Outlet Temperature

The graphs illustrate the relationship between the number of stages and the temperature difference ($T_{in} - T_{out}$ in °C) and the number of stages and the temperature difference ($\Delta T$ in °C). As the number of stages increases, the temperature difference decreases, approaching a constant value.
Effect of Murphree Efficiency on Number of Stages

- T_{out} (°C)
- Efficiency

Graph showing the effect of different Murphree efficiencies on T_{out} for stages n=3 to n=7.
A: Comparison of initial MATLAB model with optimized model validated with experimental data. B: Error Comparison before optimization and after optimization
Control Strategy (Contd.)

S-Function block

- Used to solve differential equations with initial conditions
- Conditions: flag=0 initialization, flag=1 derivatives
- Flag=3 output, flag=2 discrete, flag=9 termination

Temperature calculation module

- Input to the module: gas and liquid flow rate, relative humidity, partial pressure, ambient air temperature, inlet liquid temperature
- Output of the module: stage temperatures, liquid flow rate at each stage

Heater

- Input: water temperature, flowrate, constant heat supply
- Output: heat gain (increase in temperature due to heat supply)
Controllers were tuned by auto tuning method and by adjusting time and robustness.

- **PID Controller tuning**

![PID Controller tuning diagram](image-url)
PID Controller tuning (Contd.)
Effect of change in liquid flow rate and gas flow rate on outlet temperature

![Bar chart showing the effect of change in liquid flow rate and gas flow rate on outlet temperature.](image)
Effect of change in liquid flow rate on power consumption

10% reduction in liquid flowrate

![Bar chart showing the comparison of CT Fan (KW), PumpPower (KW), and CT in Temp(oC) before and after a 10% reduction in liquid flowrate.](image)
20% reduction in liquid flowrate
Effect of change in liquid flow rate on power consumption (Contd.)

30% reduction in liquid flow rate

- **CT Fan (KW):**
  - Original: 567.586
  - Final: 411.753

- **Pump Power (KW):**
  - Original: 553.071
  - Final: 387.567

- **CT in Temp (°C):**
  - Original: 30.86
  - Final: 34.4027
40% reduction in liquid flow rate
Conclusion

- Cooling tower outlet temperature was predicted by mathematical model created.
- Created model was optimized dynamically.
- Improved efficiency and optimized number of stages were obtained.
- Three stages with 60% efficiency.
- Cooling tower can be operated by decreasing the water flowrate up to 30% without affecting the overall performance.
Data collection

Development of mathematical model

Model creation in Matlab

Validation of Matlab result using collected data

Matlab model optimization

Optimized number of stages=3, efficiency= 60%

Performance evaluation at reduced flowrate
Future Scope of Work

Control Application based on MIMO system

Model predictive control, robust control
Thank You!