

A photograph of two large, cylindrical industrial cooling towers against a blue sky with scattered white clouds. The towers are made of a light-colored material, possibly concrete or metal, and have a ribbed texture. The sky is a vibrant blue, and the clouds are soft and white.

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

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Agenda



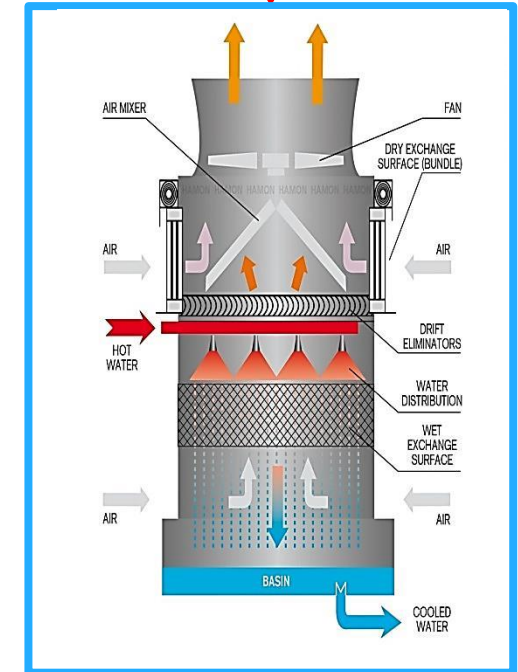
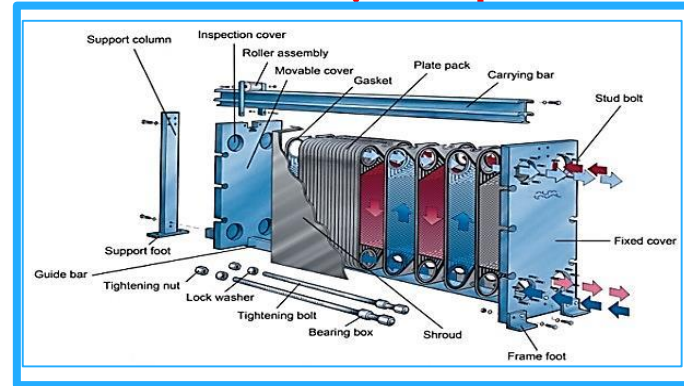
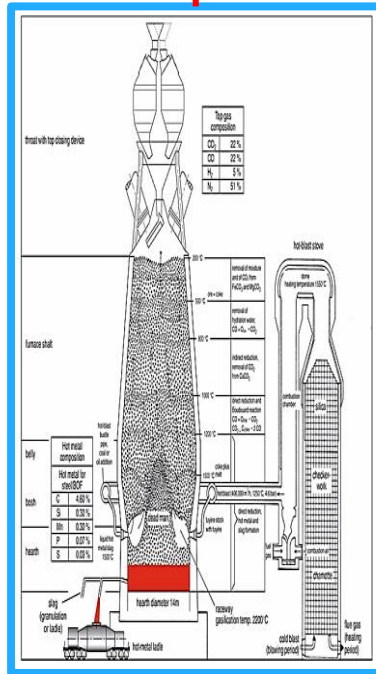
- ❖ **Brief Introduction**
- ❖ **Key Challenges**
- ❖ **Solution Overview**
- ❖ **Objectives & Assumptions**
- ❖ **Approach**
- ❖ **Model Development**
- ❖ **Tools Used**
- ❖ **Optimization Flowchart**
- ❖ **Results and Discussion**
- ❖ **Conclusion**
- ❖ **Future Scope of work**

Brief Introduction

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

Key Challenges



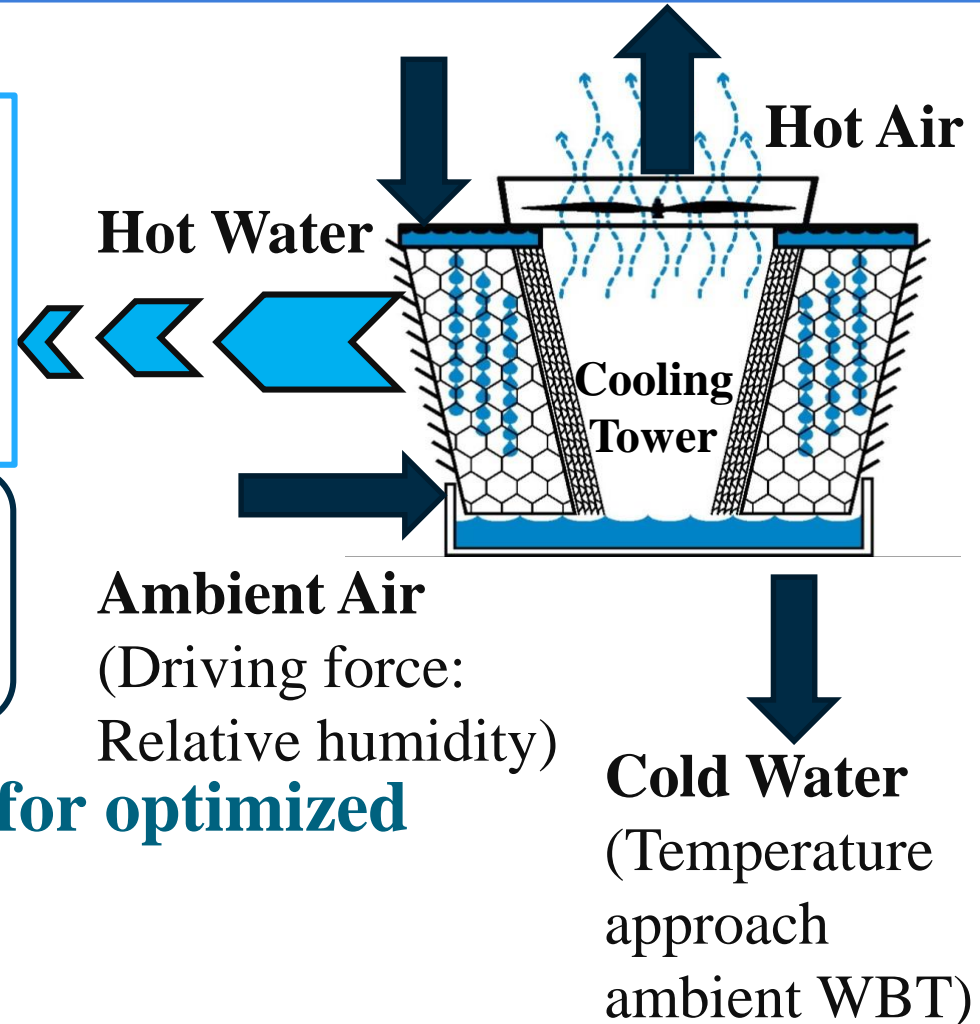
CT Objective

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**



- 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

Approach



**Development of Equilibrium Model
for existing cooling tower**

Mass Balance

Energy Balance

MATLAB

Compiler , Optimization
toolbox & Simulink

Equilibrium Model

Optimized Model

Simulink Model

**Validation and
Implementation**

Model Development



Mass balance for 2 stages

Mass of water *in* = Mass of water out

Stage-1

$$L_0 + GH_2 = L_1 + GH_1 \Rightarrow L_1 = L_0 + G(H_2 - H_1)$$

Stage-2

$$L_1 + GH_3 = L_2 + GH_2 \Rightarrow L_2 = L_1 + G(H_3 - H_2)$$

Energy balance for 2 stages

Sensible heat of inlet air + sensible heat of inlet w

+ 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

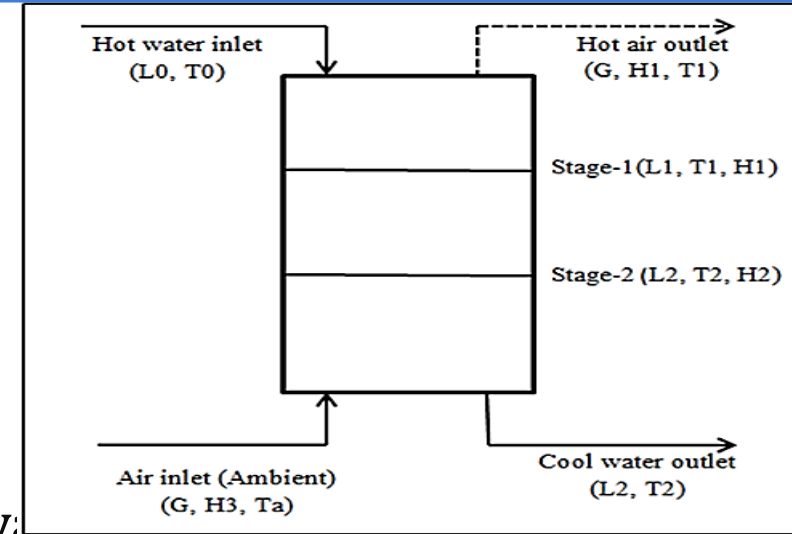
Stage-1

$$\begin{aligned} & (G \times C_{pa} \times T_2) + (L_0 \times C_{pw} \times T_0) + (G \times H_2 \times C_{pv} \times T_2) + (G \times H_2 \times \lambda) \\ & = (G \times C_{pa} \times T_1) + (L_1 \times C_{pw} \times T_1) + (G \times H_1 \times C_{pv} \times T_1) + (G \times H_1 \times \lambda) \end{aligned}$$

Stage-2

$$(G \times C_{pa} \times T_a) + (L_1 \times C_{pw} \times T_1) + (G \times H_3 \times C_{pv} \times T_a) + (G \times H_3 \times \lambda)$$

$$\text{TATA STEEL} \quad (G \times C_{pa} \times T_2) + (L_2 \times C_{pw} \times T_2) + (G \times H_2 \times C_{pv} \times T_2) + (G \times H_2 \times \lambda)$$



Model Development(Contd.)



- **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

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

- **Equations obtained for '2' stages are**

$$Y_1 = E_1(YS_1 - Y_2) + Y_2$$

$$Y_2 = E_2(YS_2 - Y_3) + Y_3$$

- **H_1 and H_2 can be calculated from Y_1 and Y_2**

$$H_1 = \frac{Y_1}{1 - Y_1} * \frac{M_{H_2O}}{M_{Air}}$$

$$H_2 = \frac{Y_2}{1 - Y_2} * \frac{M_{H_2O}}{M_{Air}}$$

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

Tools Used

A blue and orange 3D-rendered software box for MATLAB R2016b. The box is angled, showing its top and front faces. The word 'MATLAB' is printed in white on the front face. Below it, there is smaller text including 'License', '© 2015 The MathWorks, Inc.', and 'R2015a'. The MathWorks logo is at the bottom left.

MATLAB R2016b

Simulink

MATLAB Compiler

Optimization toolbox

Coding

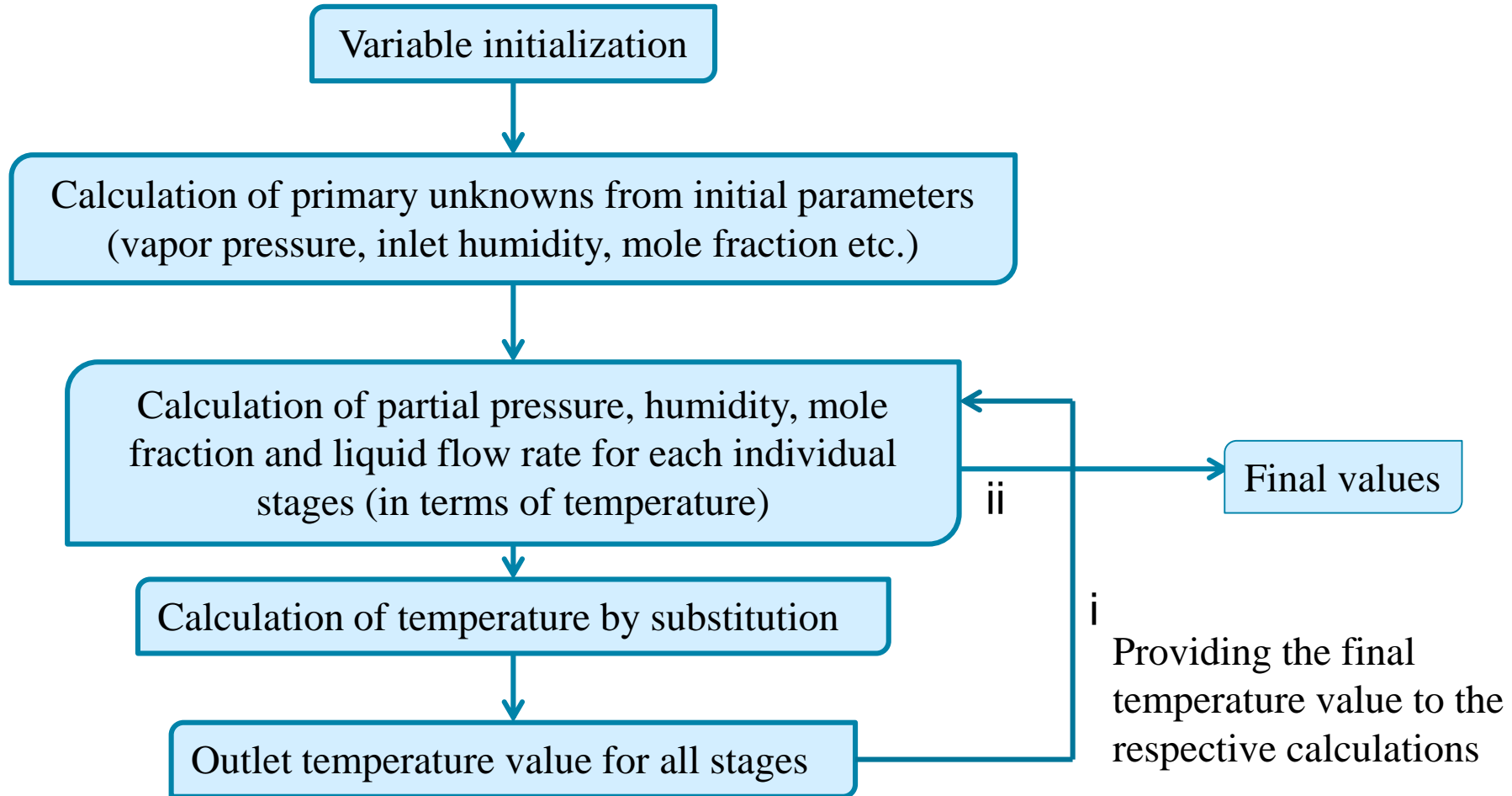


Current Fold
Workspace

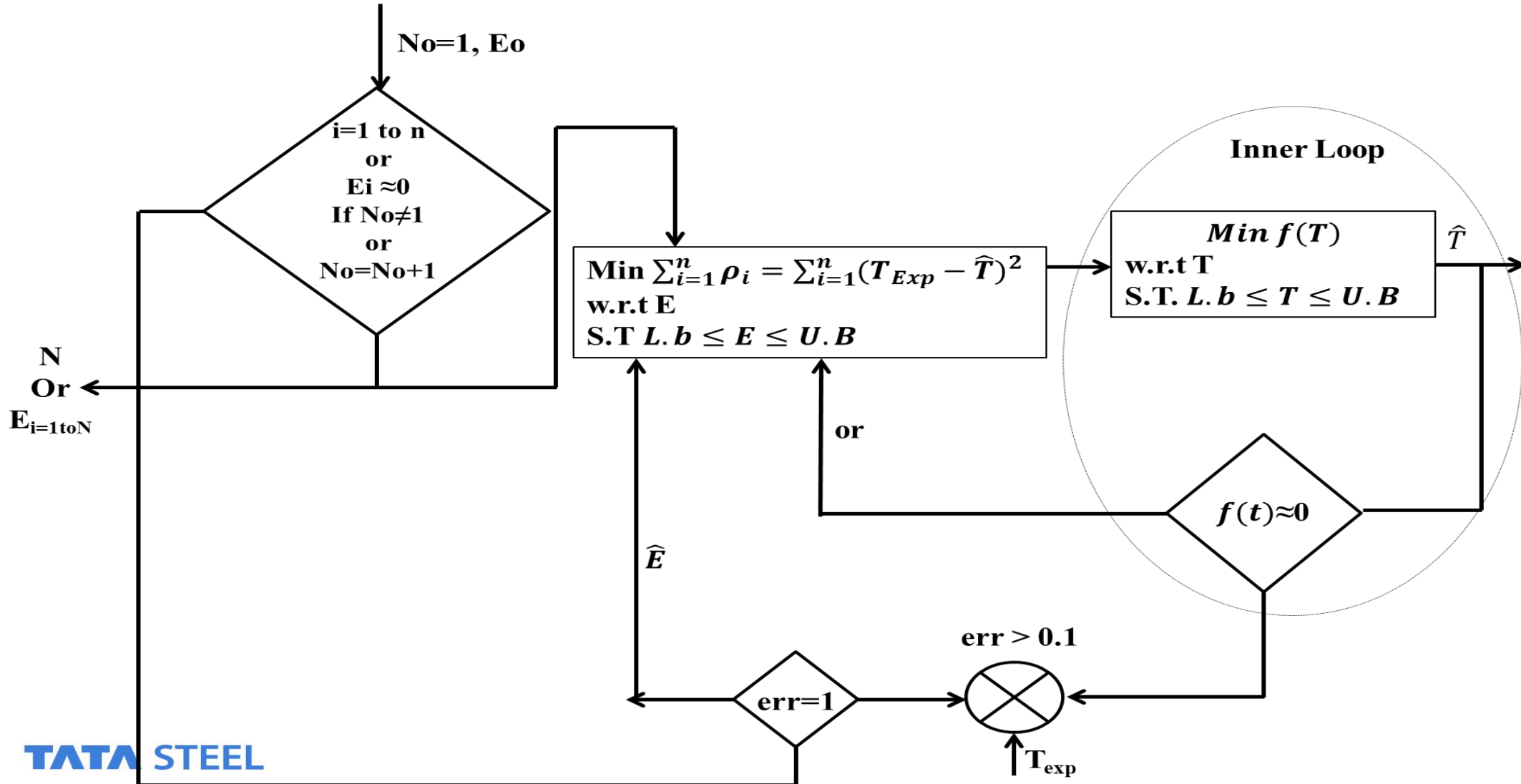
calc_opt.m x cmpN.m x itl.m x OPT1.m x HUM.m x HUMm.m x RH.m x RH1.m x DBT.m x VAP.m x +

```
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
81 - RHs(1)=(pao(1)/pavo(1));
82 - for i=2:n
83 -     RHs(i)=(pao(i)/pavo(i)); %stage Relative humidity
84 - end
85 - disp('Relative humidity of each stage:')
86 - disp(RHs)
87 - 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;
88 - for i=2:n
89 -     e(i)=L(i-1)*cpw*T(i-1)+g*cpa*T(i+1)+g*H(i+1)*cpv*T(i+1)+g*H(i+1)*hv-g*cpa*T(i)-L(i)*cpw*T(i)-g*H(i)*cpv*T(i)-g*H(i)*hv;
90 - end
91 - % loss=g*(H(1)-H(n+1))
92 - % loss1=L0-L(n)
93 - f=[e];
94
```

Steps involved in solving the Code



Optimization Flowchart



Optimization Process



Main function

```
global double ii Dt tr
% clc;
tr=8;
Dt=zeros(20,20);
ii=0;
% ii=5;|
% % for normal check
% options= optimoptions(@lsq
options= optimoptions(@lsq
% % options = optimoptions(@
% a= lsqnonlin(@OPT1,0.5*ones

for i=1:tr

    ii=ii+1;
[X RESNORM,RESIDUAL,EXITFLA
```

Data set

```
function f=OPT1(x)
global RHg Pg tag t0g index E ii g L0
E=x;
n=20;
index=0;
g=4505000.71; %gas rate in kg/hr
L0=5678000*1; %Liquid rate in kg/hr
gcpw=4.2; % Specific heat of water
cpa=1; % Specific heat of air
cpv=2; %specific heat of humid air
hv=2257; % latent heat of water

%PH20=[33.1108 32.7867 32.3976 31.9063
% L0=[5676100 5671800 5664700 5653800
RHg=[0.97 0.9165 0.728 0.6762 0.8715 0
Pg= [760.8624478 764.6877617 764.46274
tag=[17.45 15.97 21.29 20.26 17.03 21.2
```

Function solver

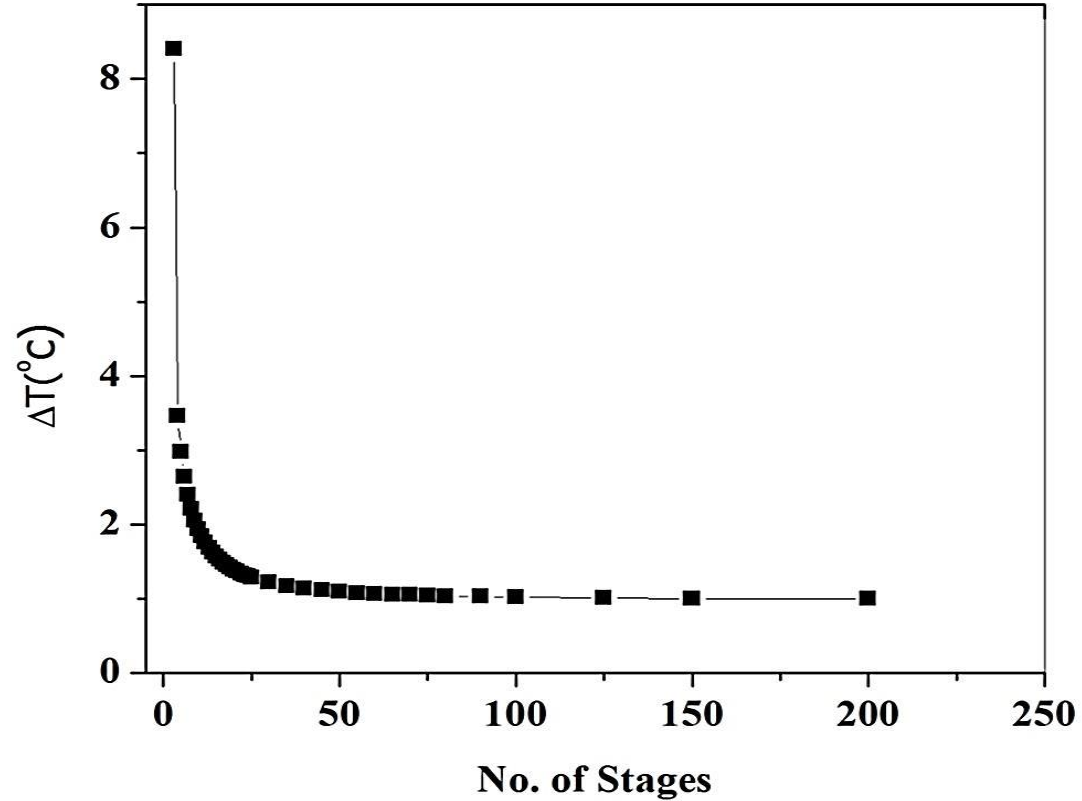
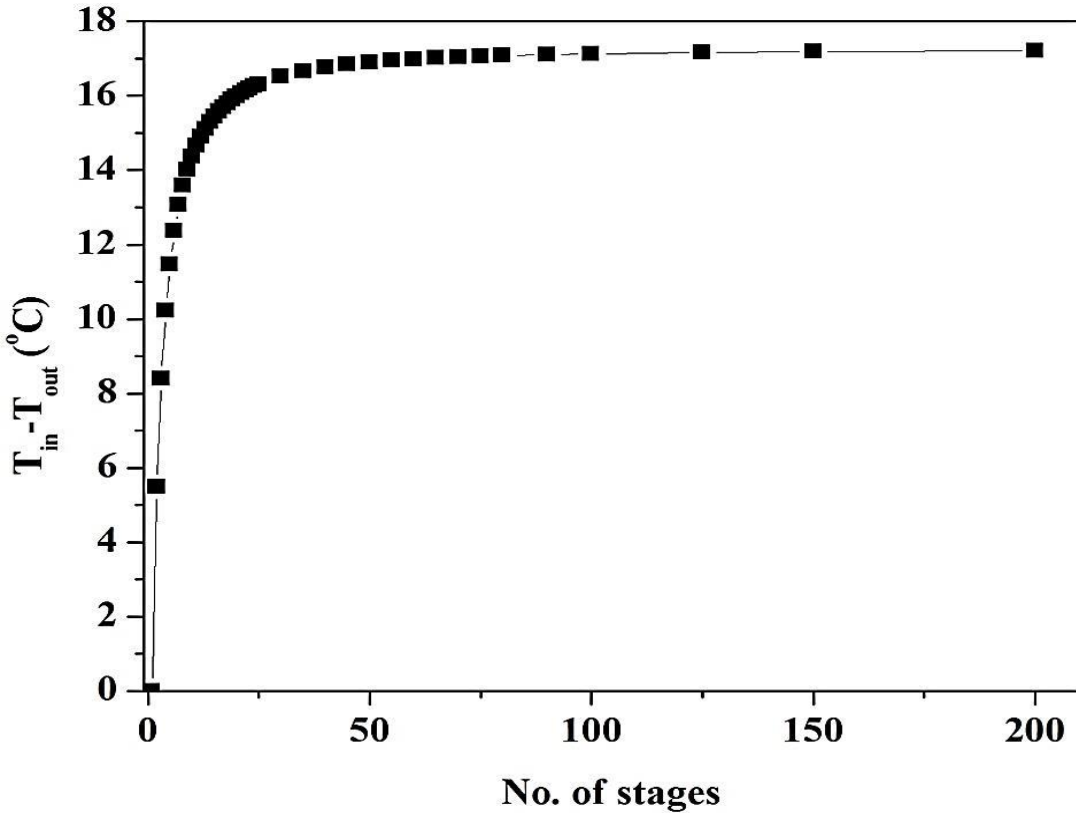
```
function f=calc_opt(x)
global RHg Pg tag t0g index E
n=ii;
for i=1:n
T(i)=x(i);
end
% gg=4505000; %gas rate in kg/
% L0=5678000; %Liquid rate in
cpw=4.2; % Specific heat of wa
cpa=1; % Specific heat of air
cpv=1.9; %specific heat of hum
hv=2257; % latent heat of wate
RH=RHg(1,index); %Relative Hum
P=Pg(1,index); %total pressure
t0=t0g(1,index); %inlet water
ta=tag(1,index); %ambient air
Tak=ta+273; %ambient temperatur
pay=(exp(11.96481-(3984.923/(T
```

Error<0.1

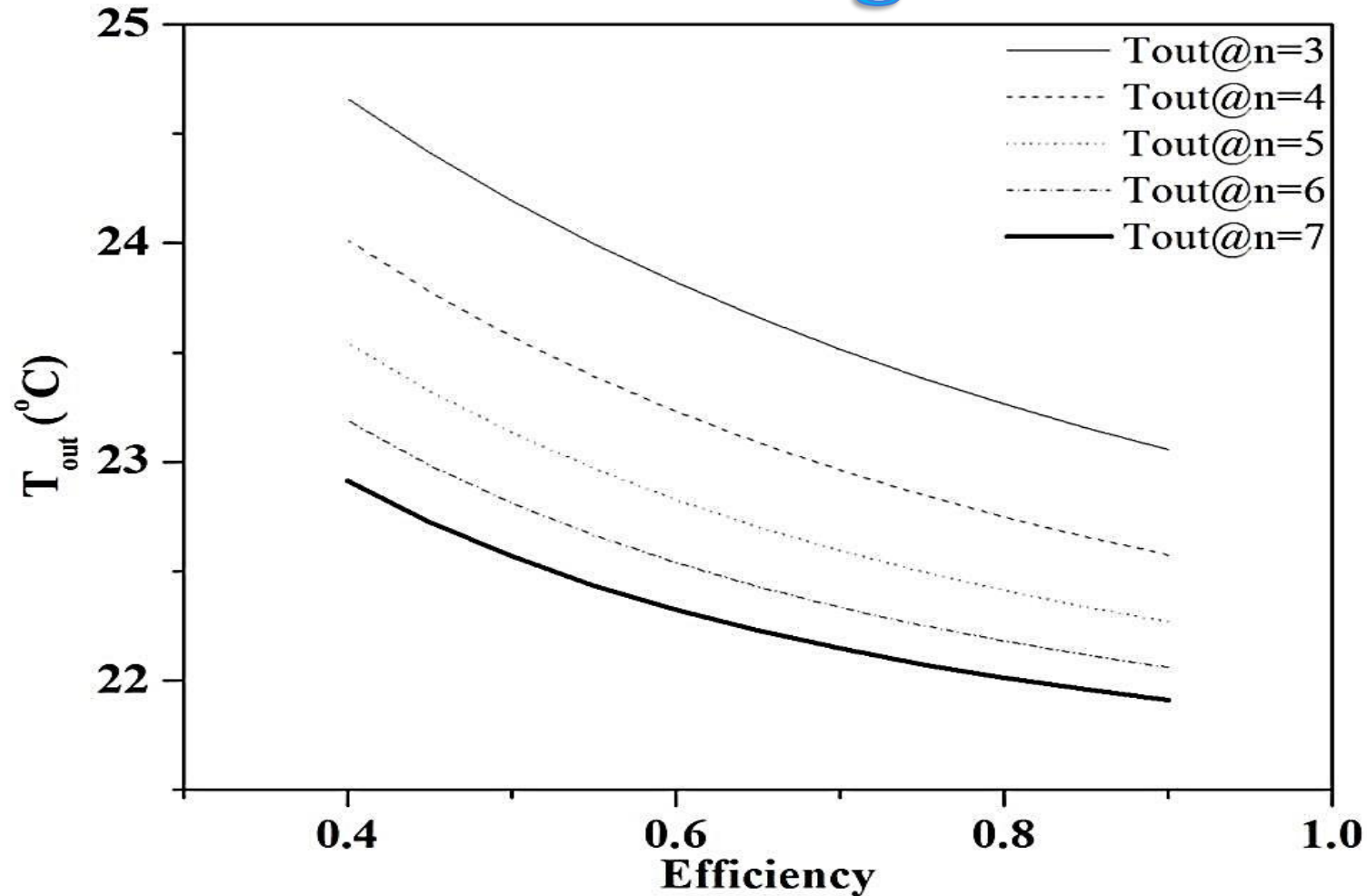
Optimized efficiency
and number of stages

Temperature value

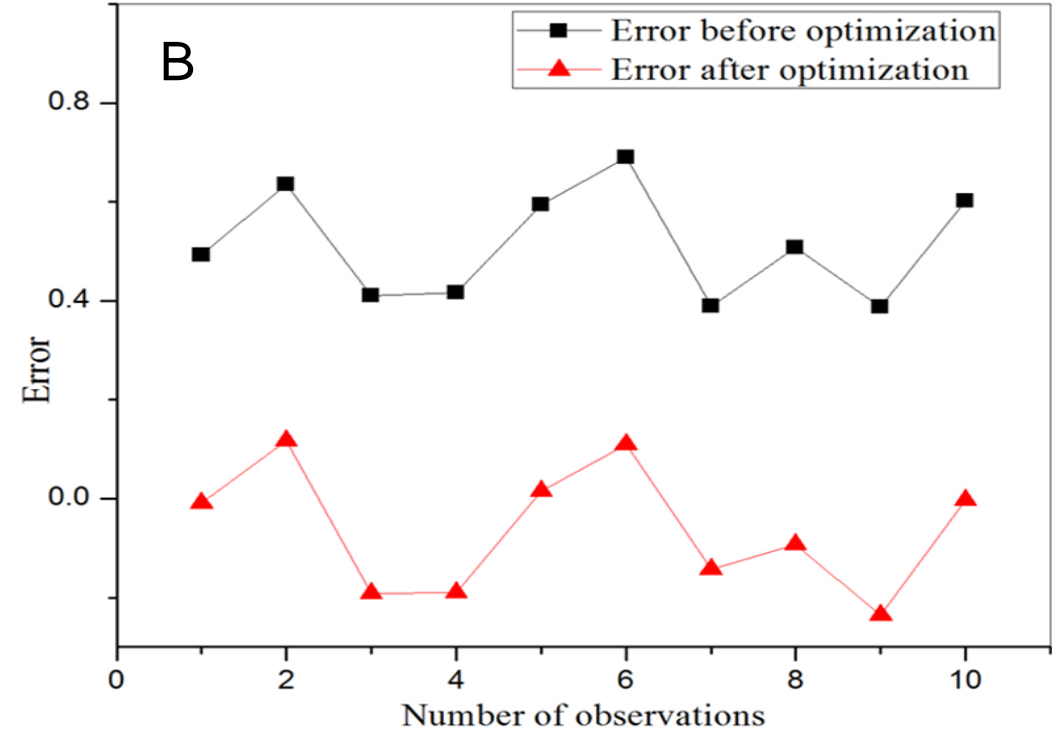
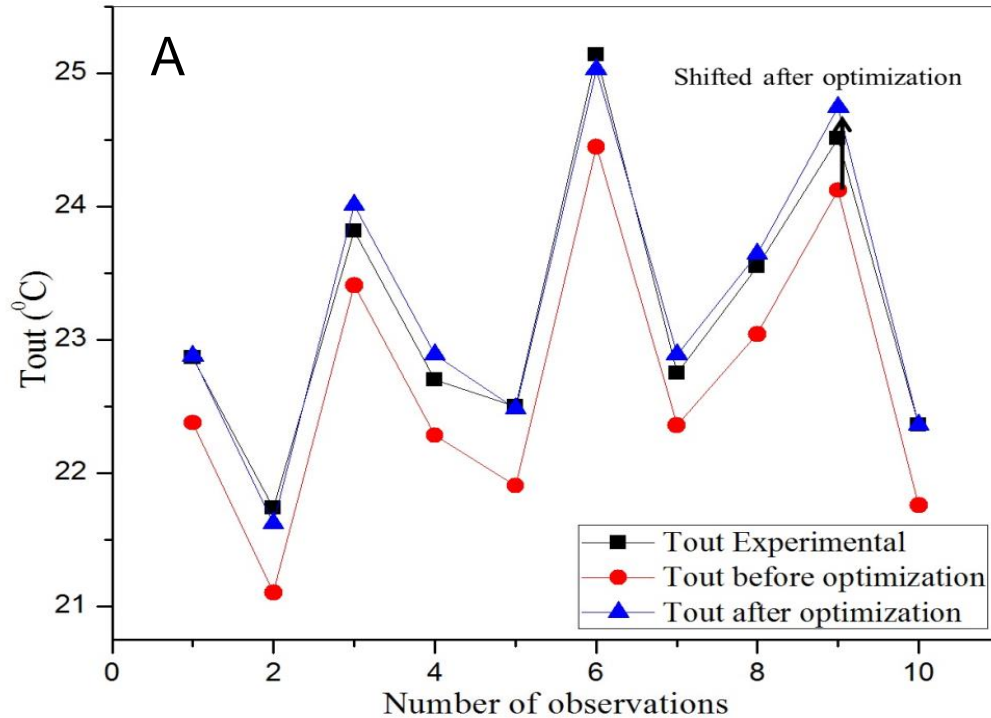
Effect of No. of Stages on Cooling Tower Outlet Temperature



Effect of Murphree Efficiency on Number of Stages

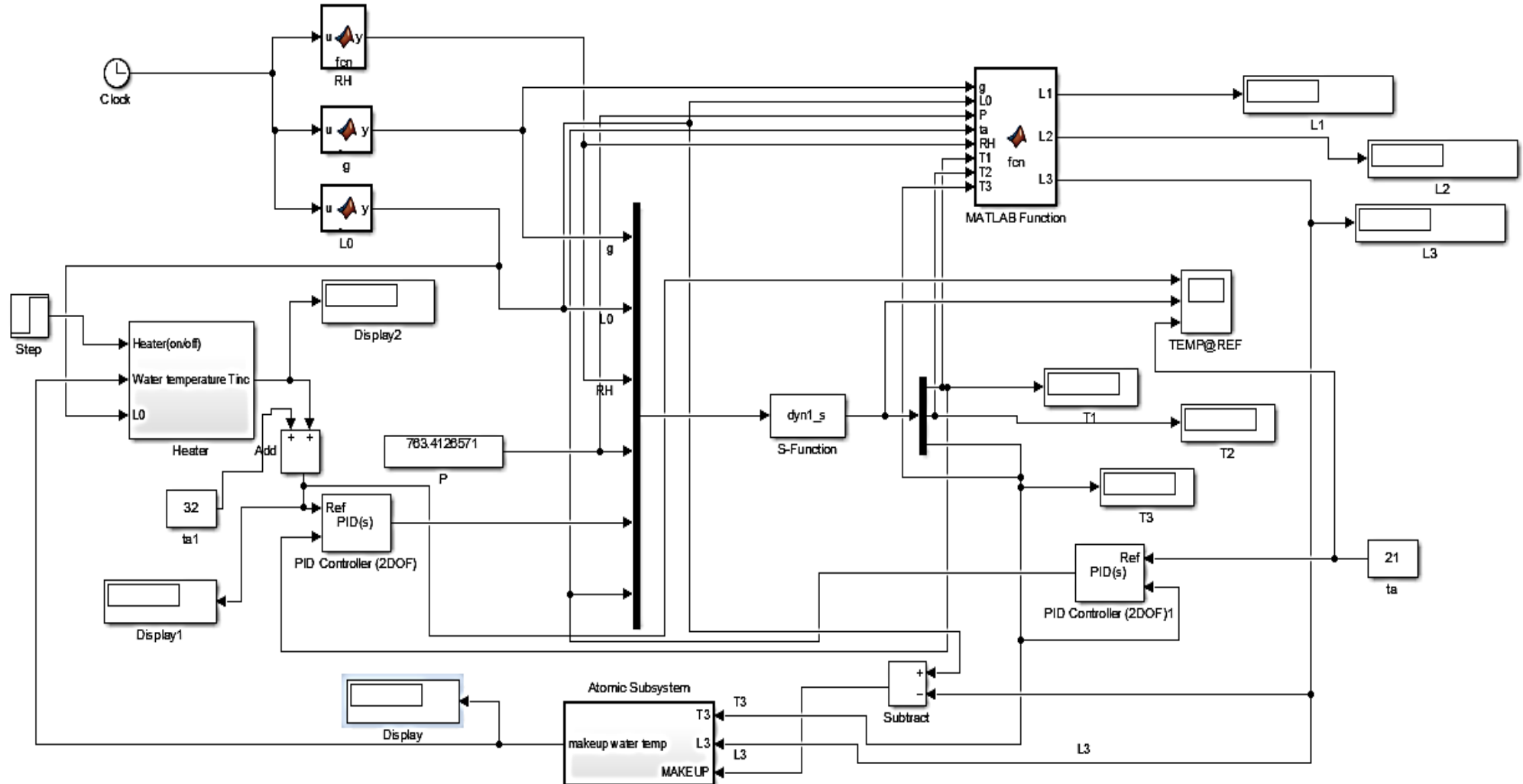


Comparison of experimental data with optimized data

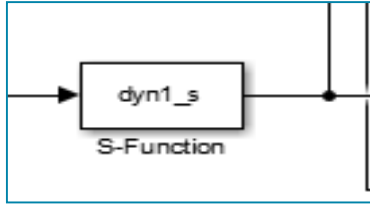


A: Comparison of initial MATLAB model with optimized model validated with experimental data. **B:** Error Comparison before optimization and after optimization

Control Strategy

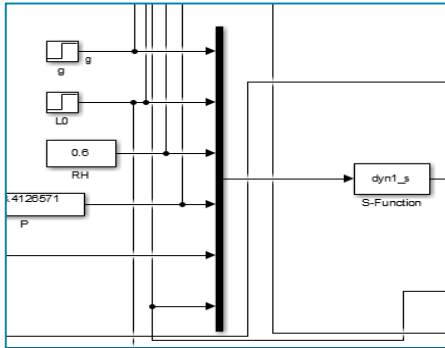


Control Strategy (Contd.)



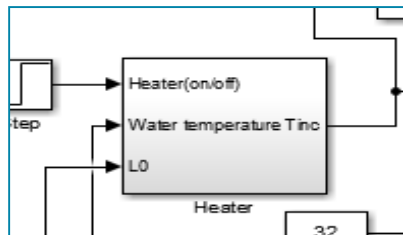
S-Function block

- 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



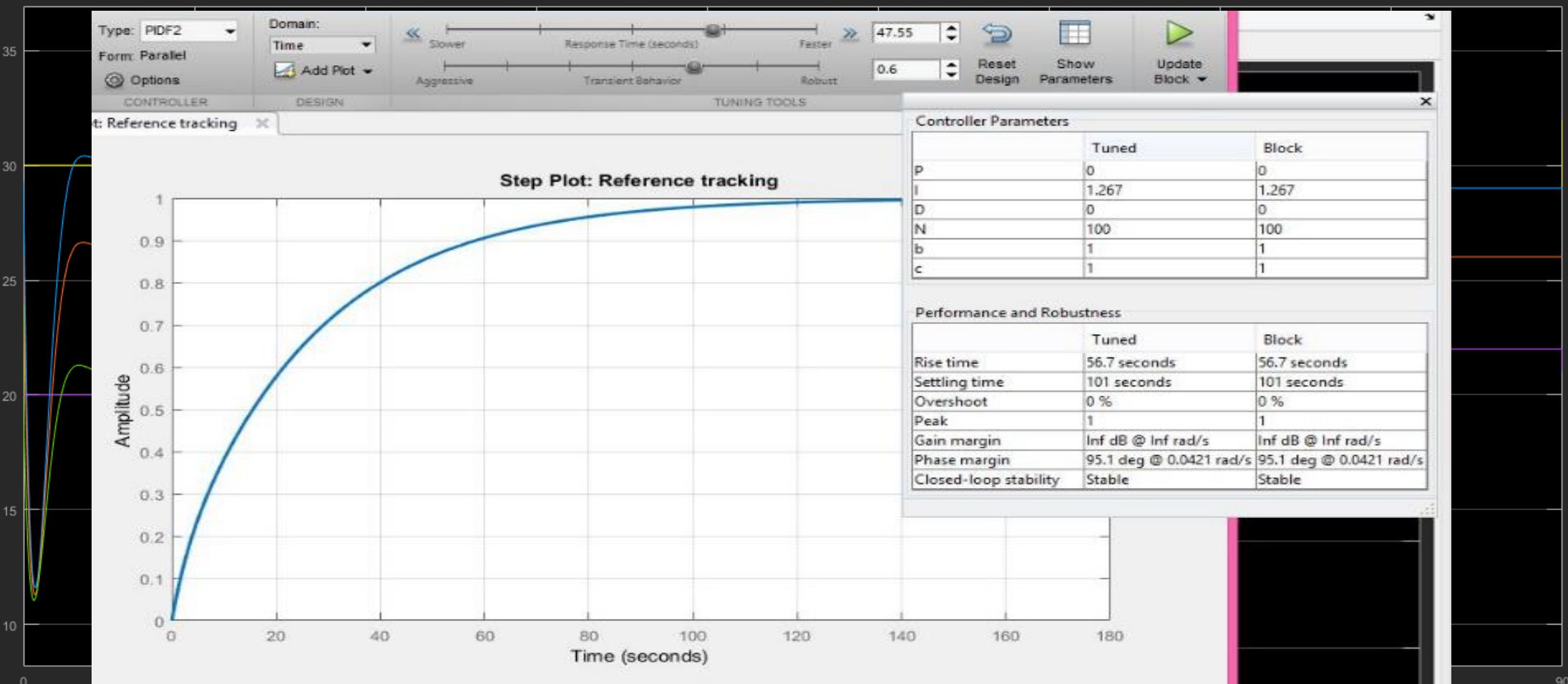
Heater

- Input: water temperature, flowrate, constant heat supply
- Output: heat gain (increase in temperature due to heat supply)

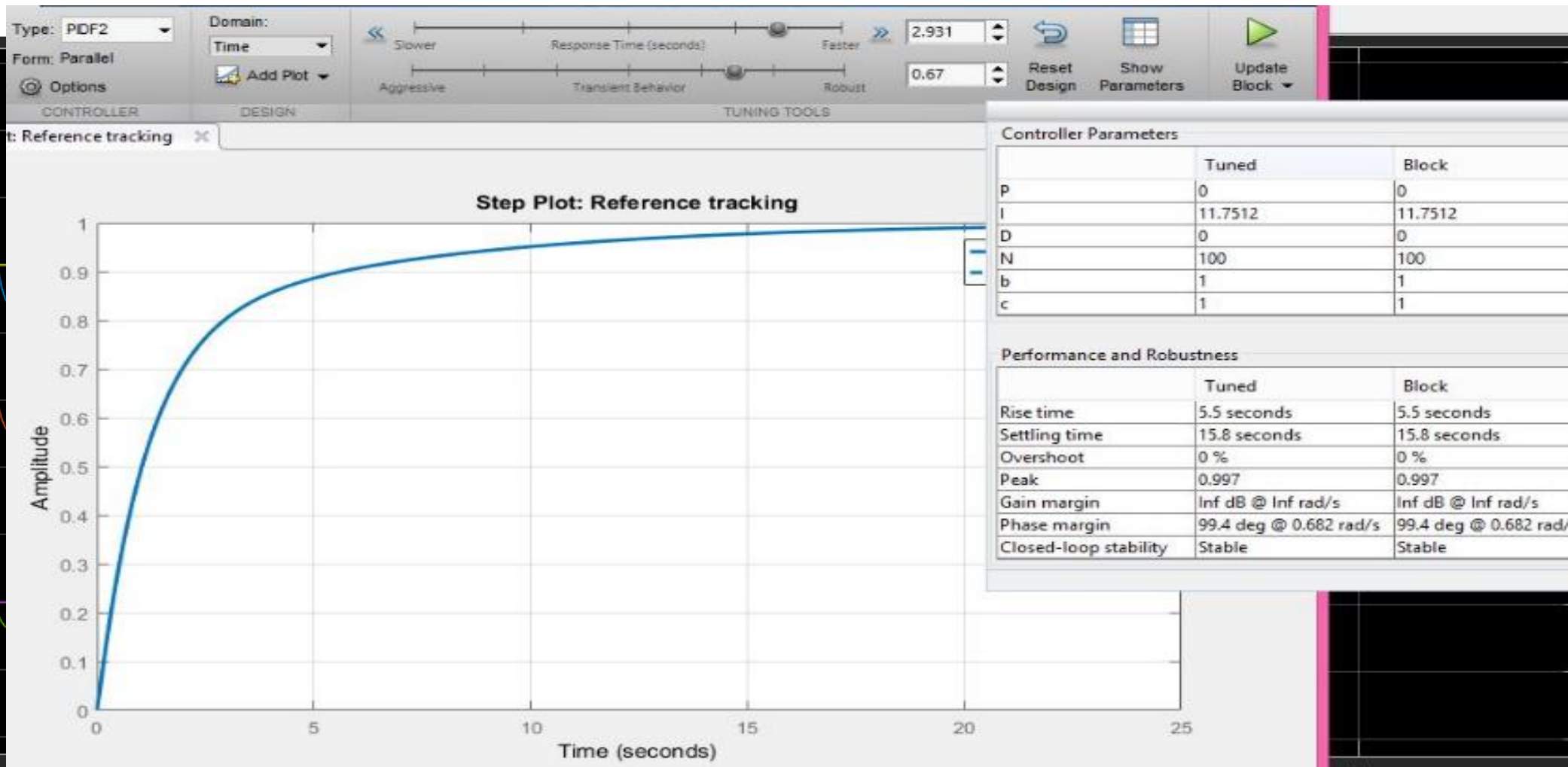
PID Controller tuning



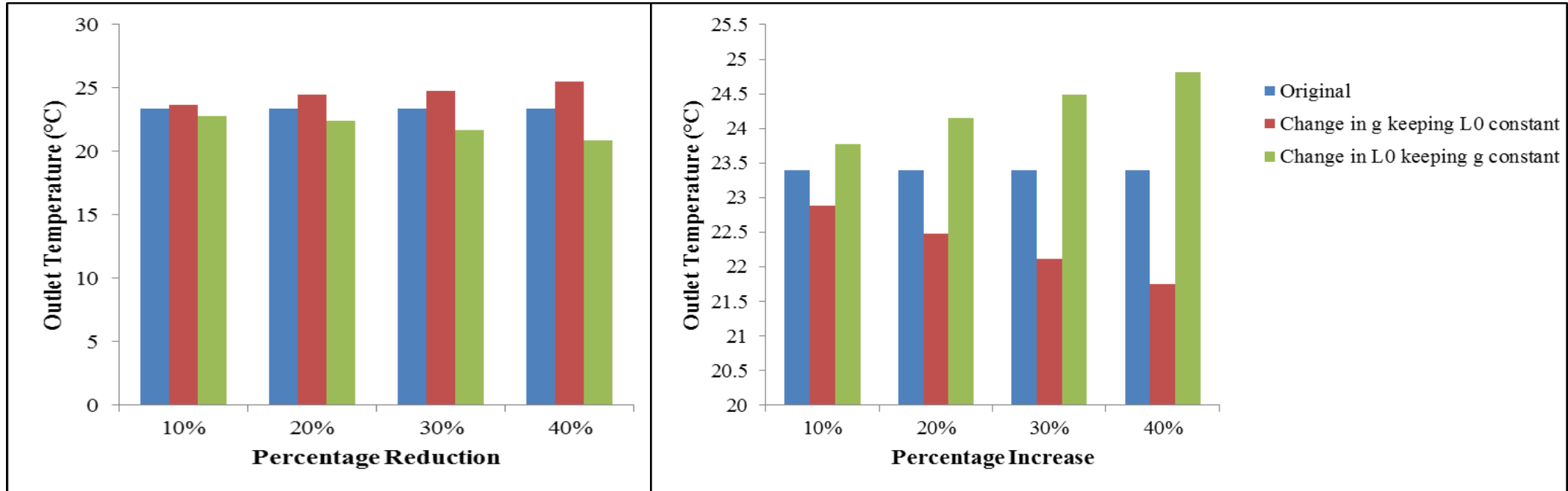
-Controllers were tuned by auto tuning method and by adjusting time and robustness



PID Controller tuning(Contd.)



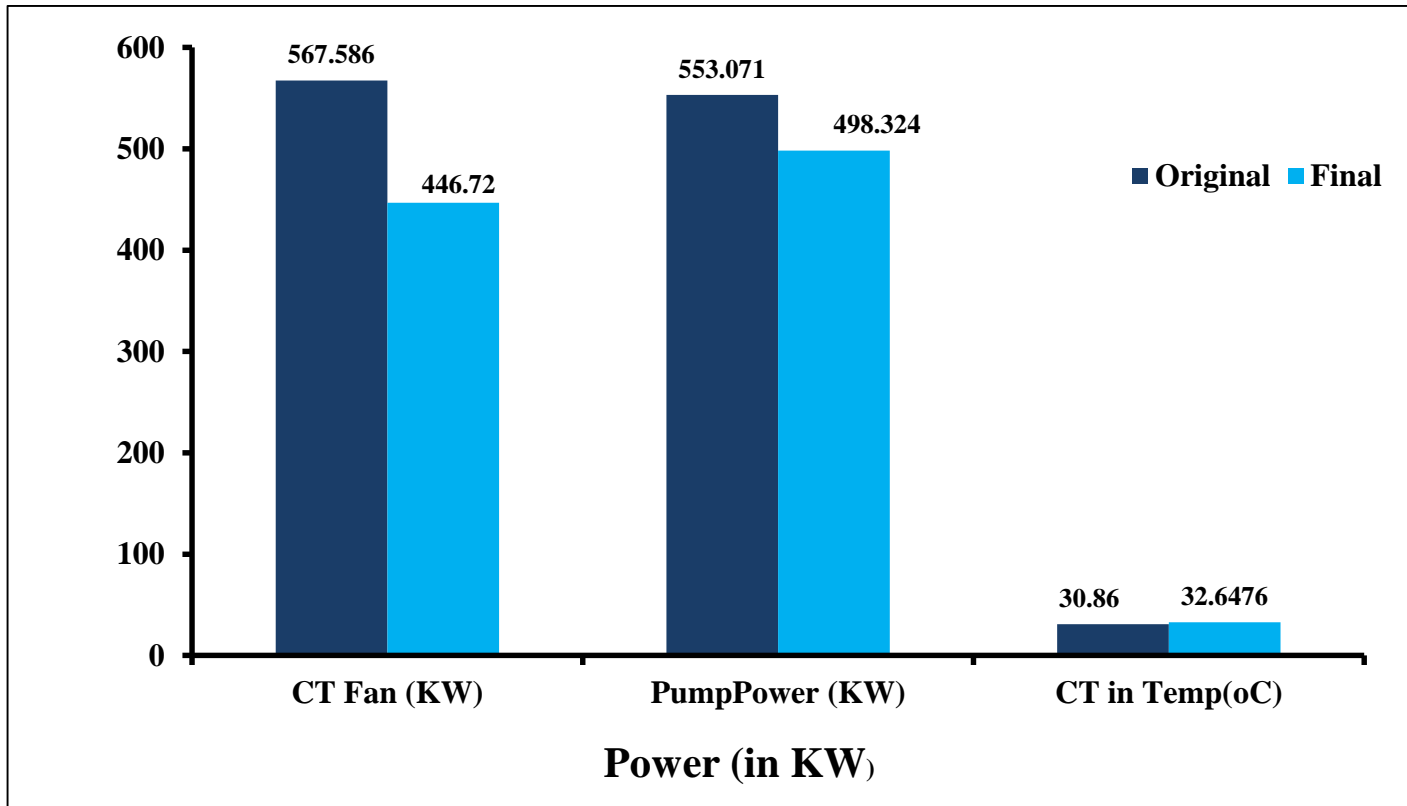
Effect of change in liquid flow rate and gas flow rate on outlet temperature



Effect of change in liquid flow rate on power consumption



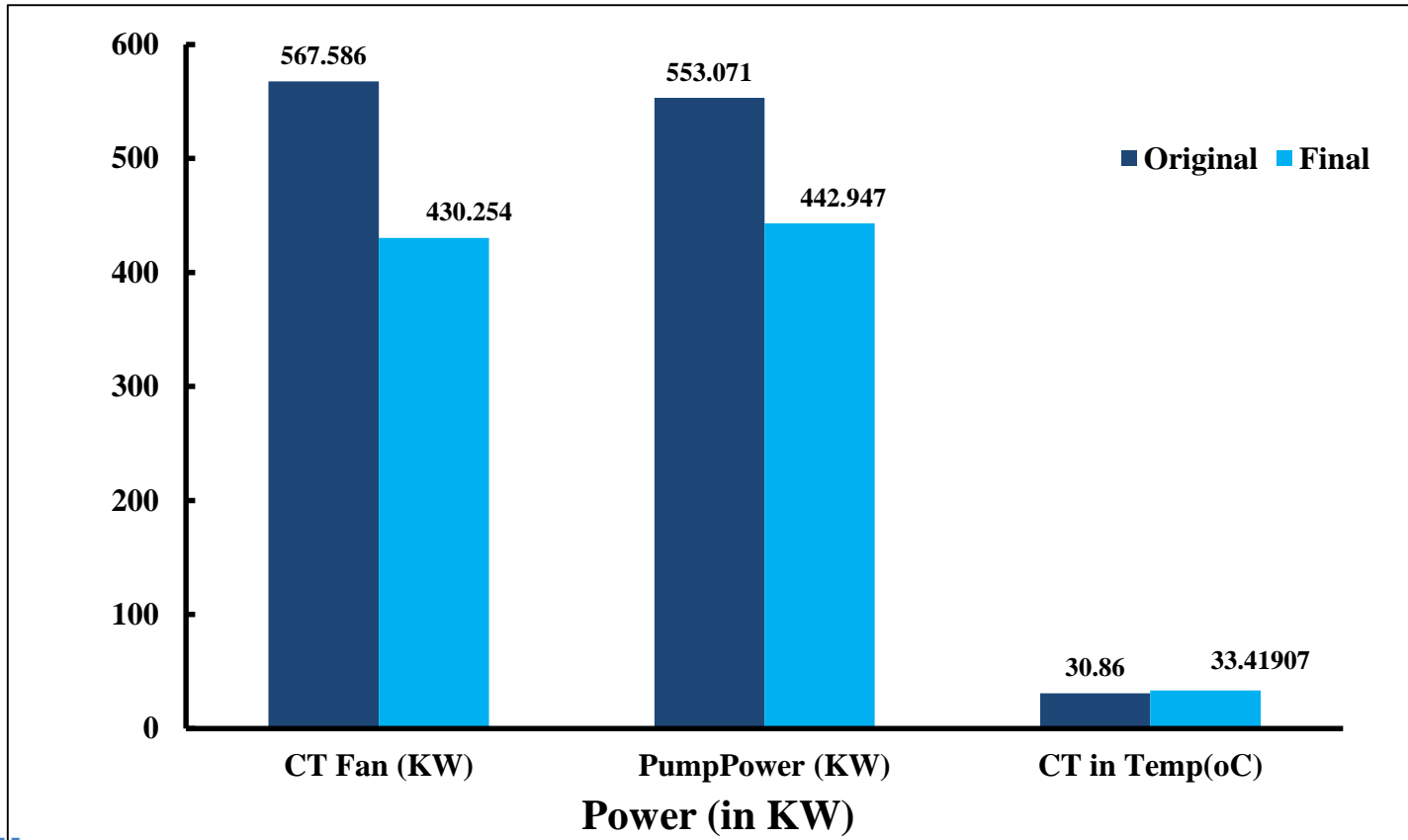
10% reduction in liquid flowrate



Effect of change in liquid flow rate on power consumption(Contd.)



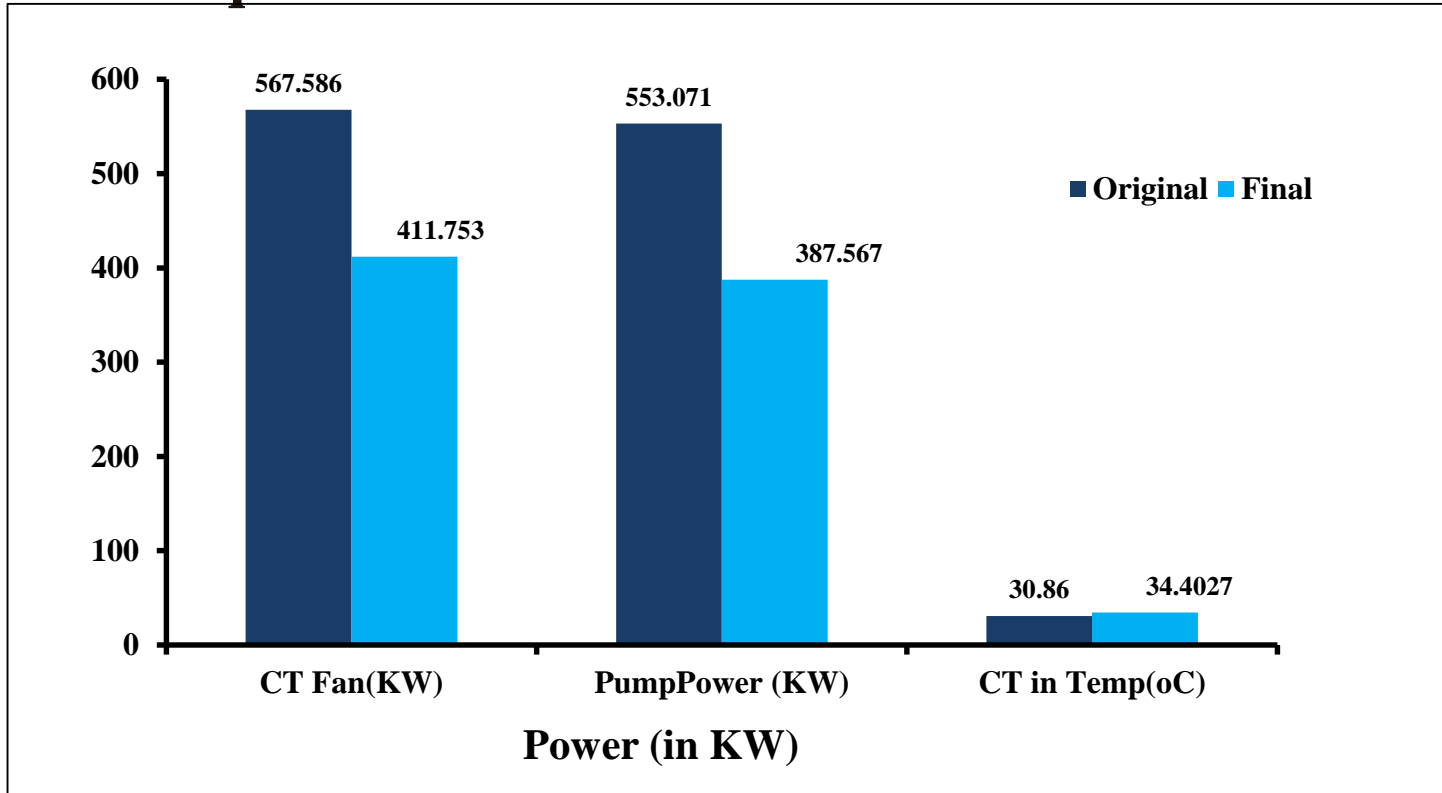
20% reduction in liquid flowrate



Effect of change in liquid flow rate on power consumption(Contd.)



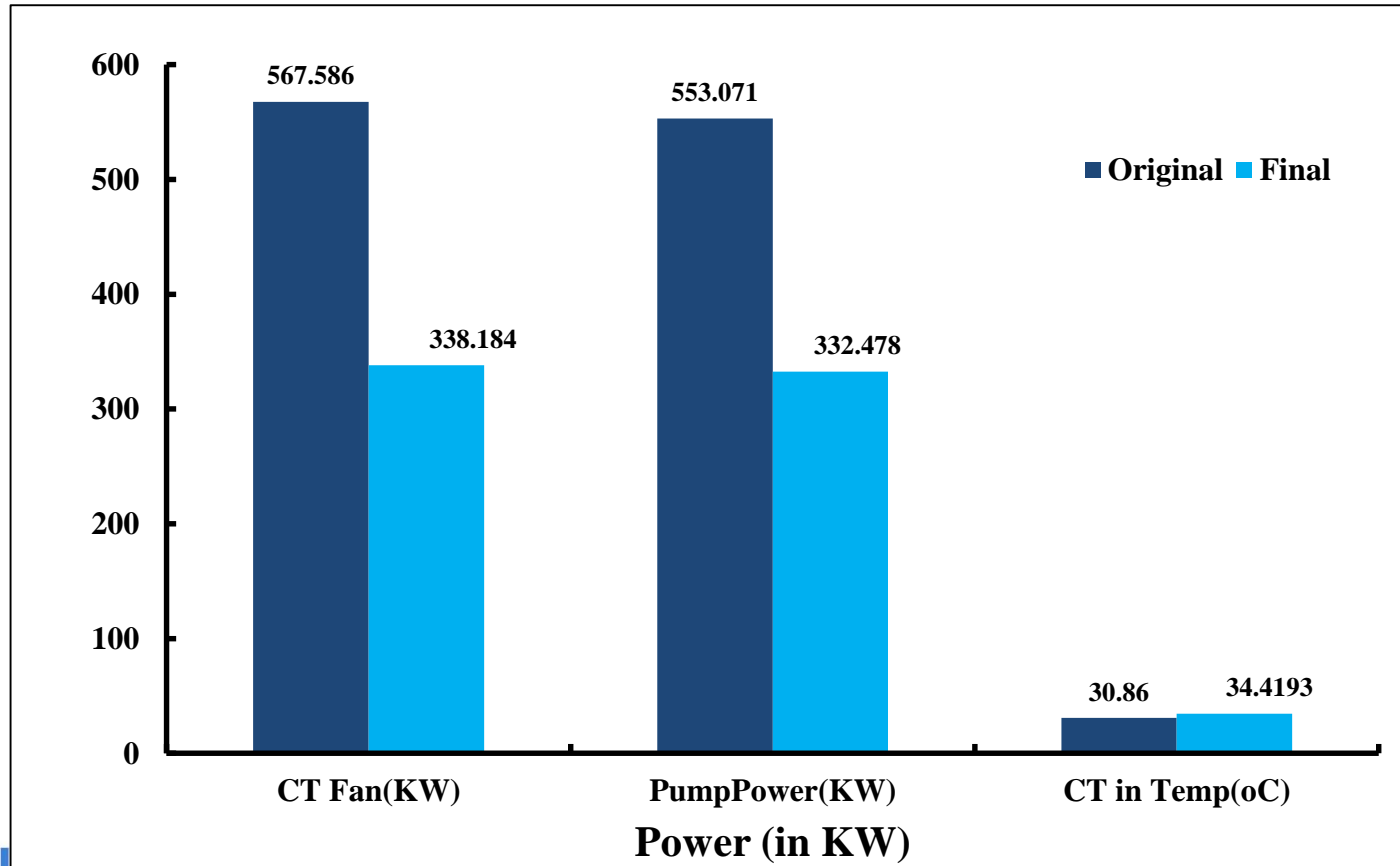
30% reduction in liquid flow rate



Effect of change in liquid flow rate on power consumption(Contd.)



40% reduction in liquid flow rate

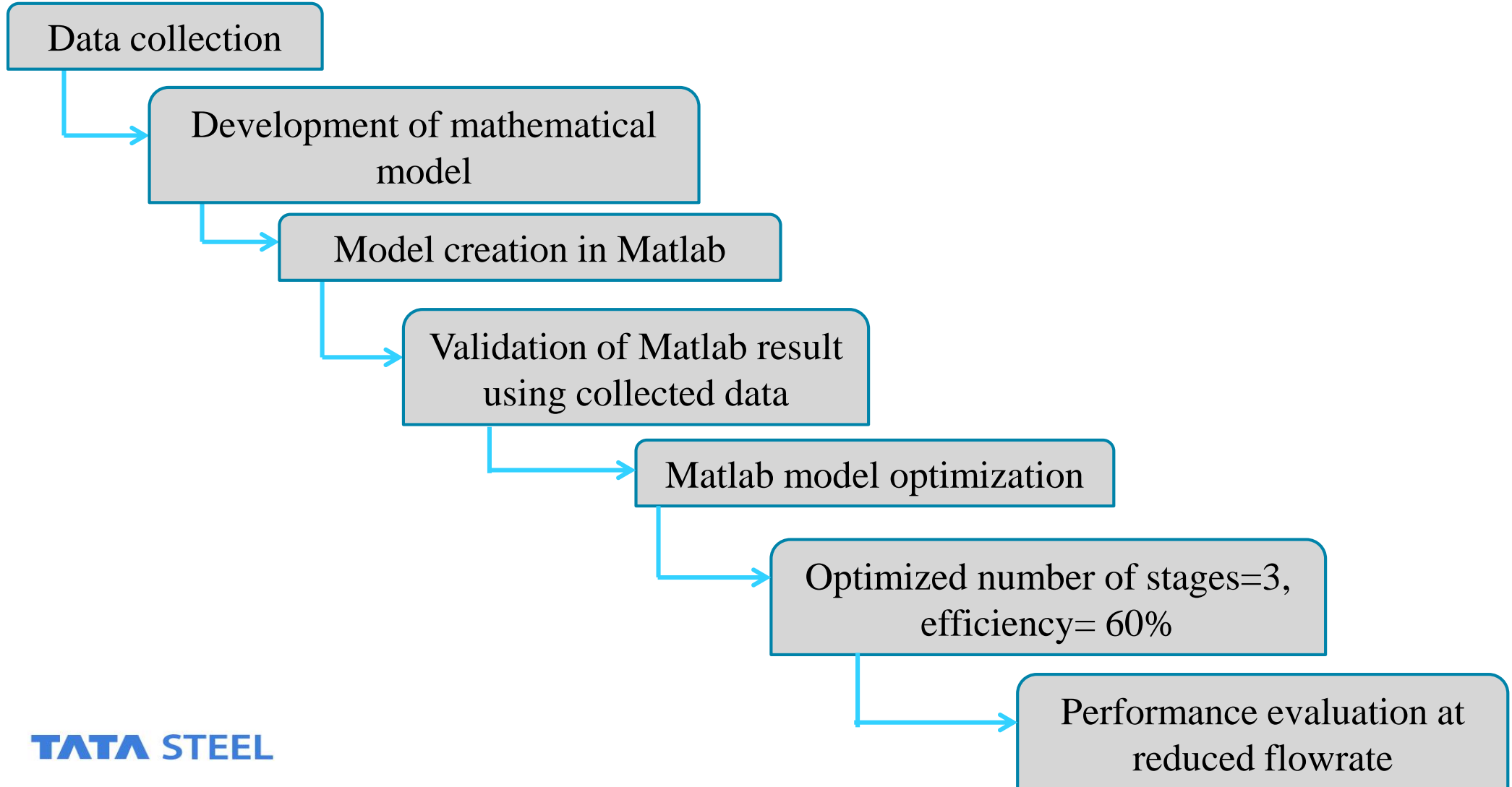


Conclusion



- 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

Conclusion



Future Scope of Work



Control Application based on MIMO system

Model predictive control, robust control

*Thank
You!*