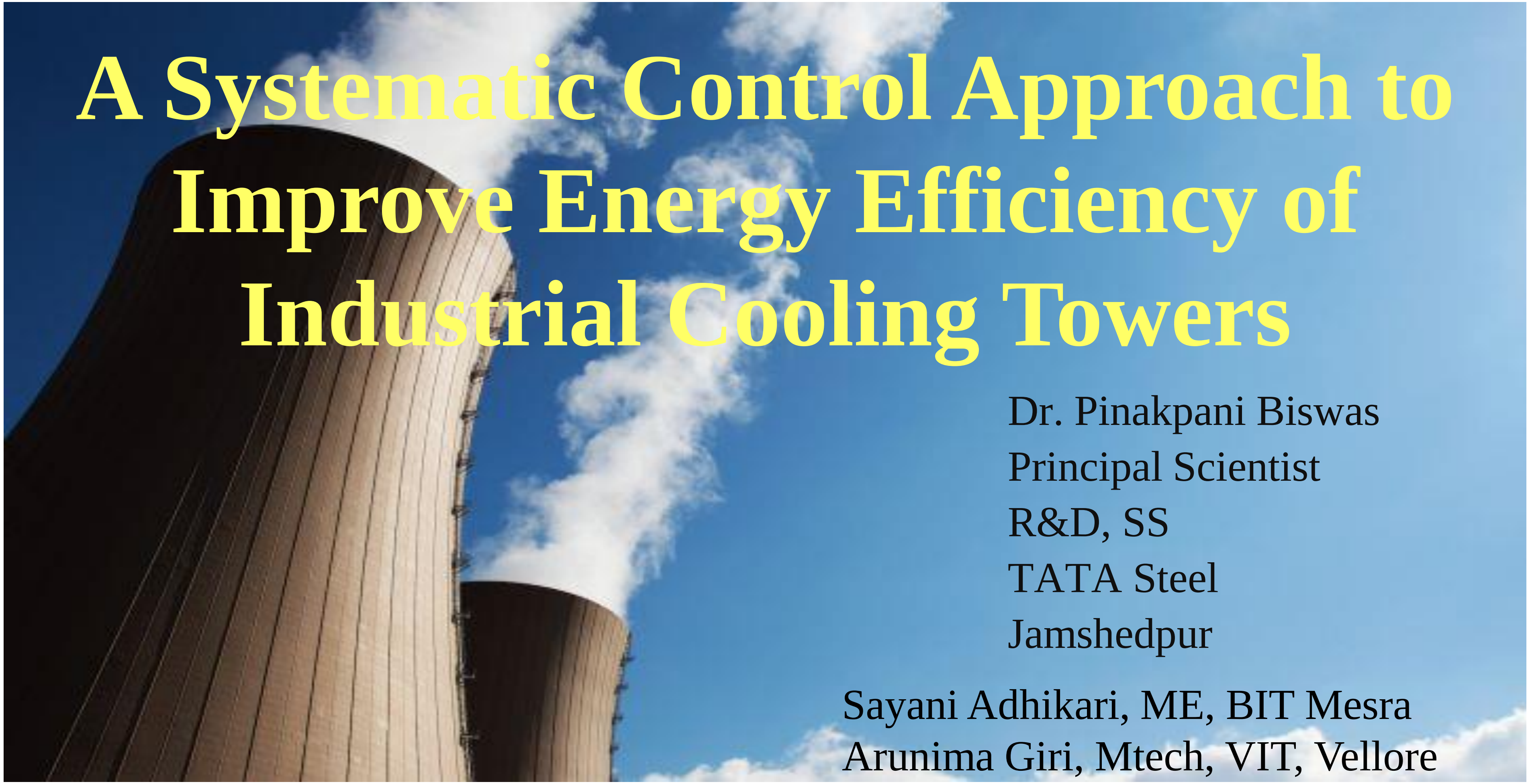

A Systematic Control Approach to Improve Energy Efficiency of Industrial Cooling Towers

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TATA Steel
Jamshedpur

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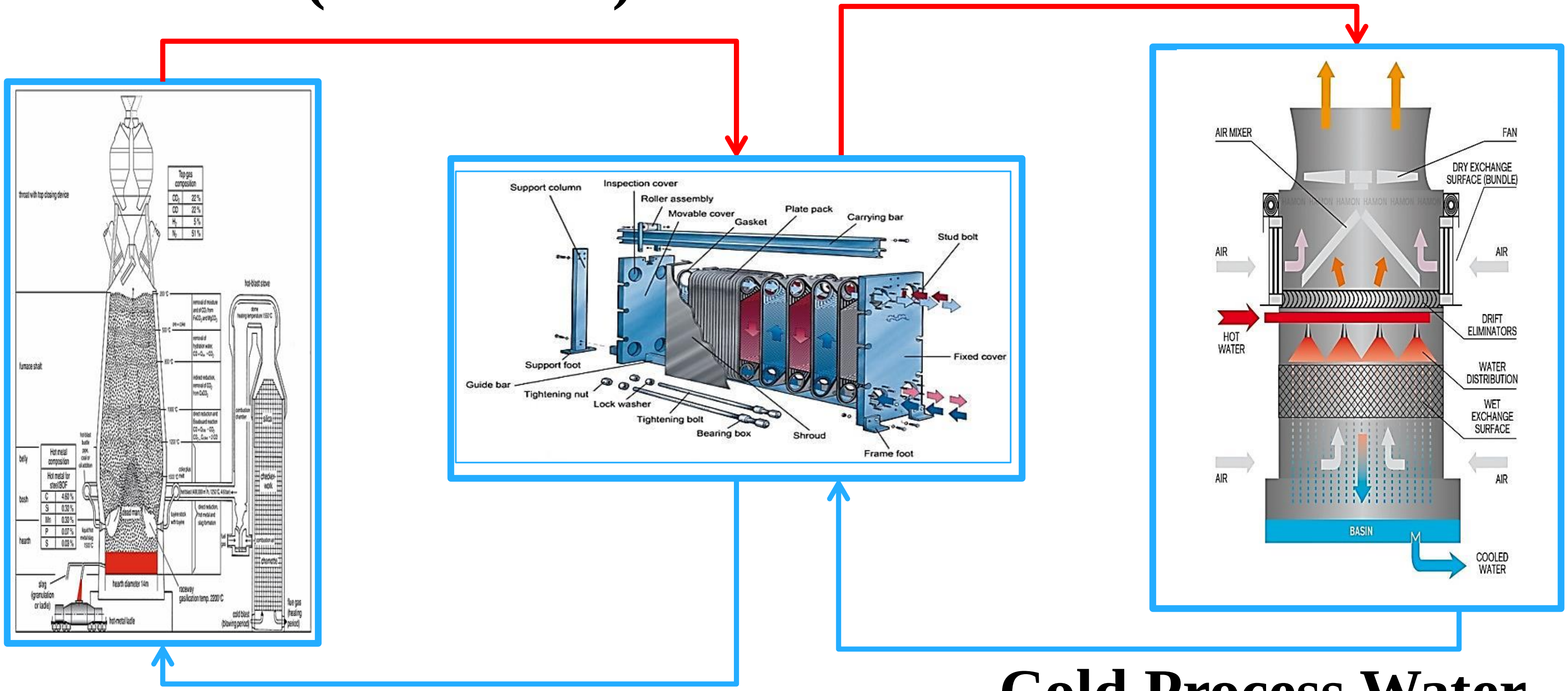
Agenda

- 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)

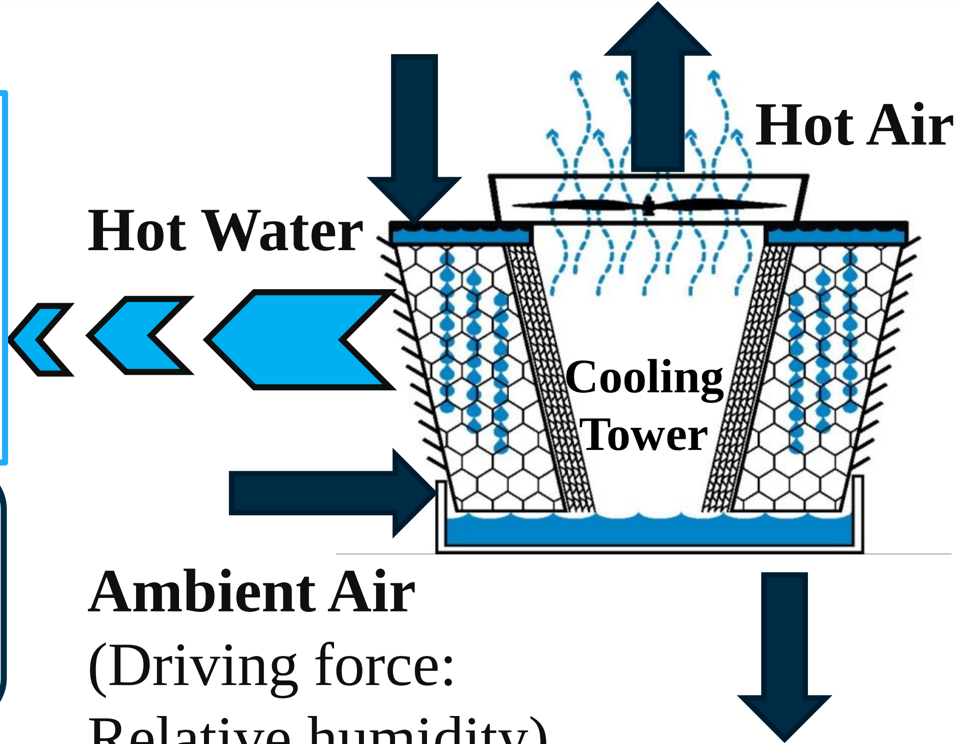
Cold Process Water

Key Challenges

CT Objective

To decrease hot water temperature by 4-8 degrees (TATA Steel Jamshedpur)

Cooling tower is an energy intensive process



Hot Air

Hot Water

Cooling Tower

Ambient Air
(Driving force:
Relative humidity)

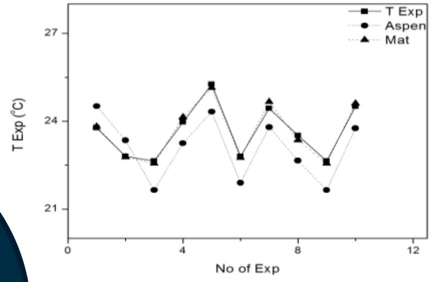
Cold Water
(Temperature
approach
ambient WBT)

- **Tuning cooling tower parameters for optimized operation**
- **Optimizing Energy Consumption**

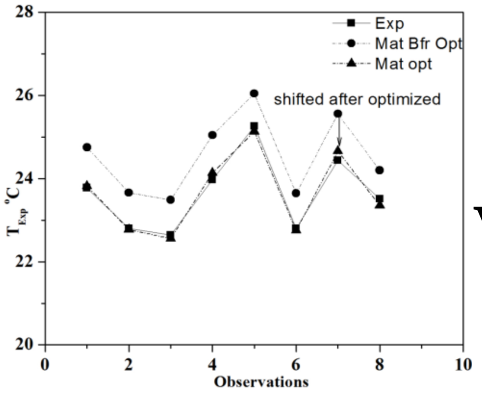
Solution Overview

MATLAB/Simulink Simulation

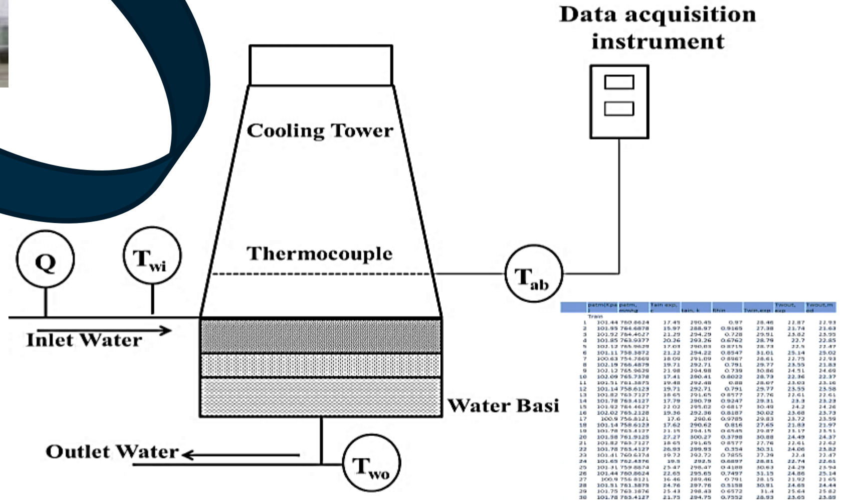
Implementation



Validation



Monitor Operation/ Collect data



	patm(Kpa)	patm, mmhg	Tain exp, c	tain, k	Rhin	Twin,exp	Twout, exp	Twout,mod
Train								
1	101.44	760.8624	17.45	290.45	0.97	28.46	22.87	22.93
2	101.95	764.6878	15.97	288.97	0.9165	27.38	21.74	21.63
3	101.92	764.4627	21.29	294.29	0.728	29.51	23.82	23.95
4	101.85	763.9377	20.26	293.26	0.6762	28.79	22.7	22.85
5	102.12	765.9629	17.03	290.03	0.8715	28.73	22.5	22.47
6	101.11	758.3872	21.22	294.22	0.8547	31.01	25.14	25.02
7	100.63	754.7869	18.09	291.09	0.8967	28.61	22.75	22.93
8	102.19	766.4879	19.71	292.71	0.791	29.77	23.55	21.83
9	102.12	765.9629	21.98	294.98	0.739	30.86	24.51	24.69
10	102.09	765.7378	17.41	290.41	0.8022	28.79	22.36	22.37
11	101.51	761.3875	19.48	292.48	0.88	28.67	23.03	23.16
12	101.14	758.6123	19.71	292.71	0.791	29.77	23.55	23.58
13	101.82	763.7127	18.65	291.65	0.8577	27.76	22.61	22.61
14	101.78	763.4127	17.79	290.79	0.9247	29.81	23.3	23.23
15	101.92	764.4627	22.02	295.02	0.6817	30.49	24.2	24.26
16	102.02	765.2128	19.36	292.36	0.8187	30.02	23.68	23.73
17	100.9	756.8121	17.6	290.6	0.9785	29.83	23.72	23.59
18	101.14	758.6123	17.62	290.62	0.816	27.65	21.83	21.97
19	101.78	763.4127	21.15	294.15	0.6545	29.87	23.17	23.51
20	101.58	761.9125	27.27	300.27	0.3798	30.88	24.49	24.37
21	101.82	763.7127	18.65	291.65	0.8577	27.76	22.61	22.62
22	101.78	763.4127	26.93	299.93	0.354	30.31	24.06	23.82
23	101.41	760.6374	19.72	292.72	0.7855	27.29	22.4	22.47
24	101.65	762.4376	19.5	292.5	0.6897	28.81	22.74	22.61
25	101.31	759.8874	25.47	298.47	0.4188	30.63	24.29	23.94
26	101.44	760.8624	22.65	295.65	0.7497	31.15	24.86	25.14
27	100.9	756.8121	16.46	289.46	0.791	28.15	21.92	21.65
28	101.51	761.3875	24.76	297.76	0.5158	30.91	24.65	24.44
29	101.75	763.1876	25.43	298.43	0.6572	31.4	25.64	25.82
30	101.78	763.4127	21.75	294.75	0.7552	28.93	23.65	23.88

MATLAB Program

```
global   RHg Pg tag tOg index E ii g L0
% clc;
tr=0;
Dt=zeros(20,20);
ii=0;
%  ii=5;
% for normal check
% options=  optimoptions(@lsqnonlin, 'Algorithm','levenberg-marquardt','Display','iter');
 options = optimoptions(@lsqnonlin,'Algorithm','trust-region-reflective','Display','iter');

% x= lsqnonlin(@OPT1,0.5*ones(1,ii),[],[],options)

 for i=1:tr

    ii=ii+1;
  [X RESNORM,RESIDUAL,EXITFLAG]= lsqnonlin(@OPT1,[0.5*ones(1,ii)],[zeros(1,ii)],[ones(1,ii)],options);

  % for wrting the data
  for j=1:ii
  Dt(ii,j)=X(j);
  end
   Dt(ii,ii+3)=RESNORM;


   if X(1,1)<=0.01
       disp('end of the function at iteration: ');
       disp(ii);
```

Optimization: E value obtained

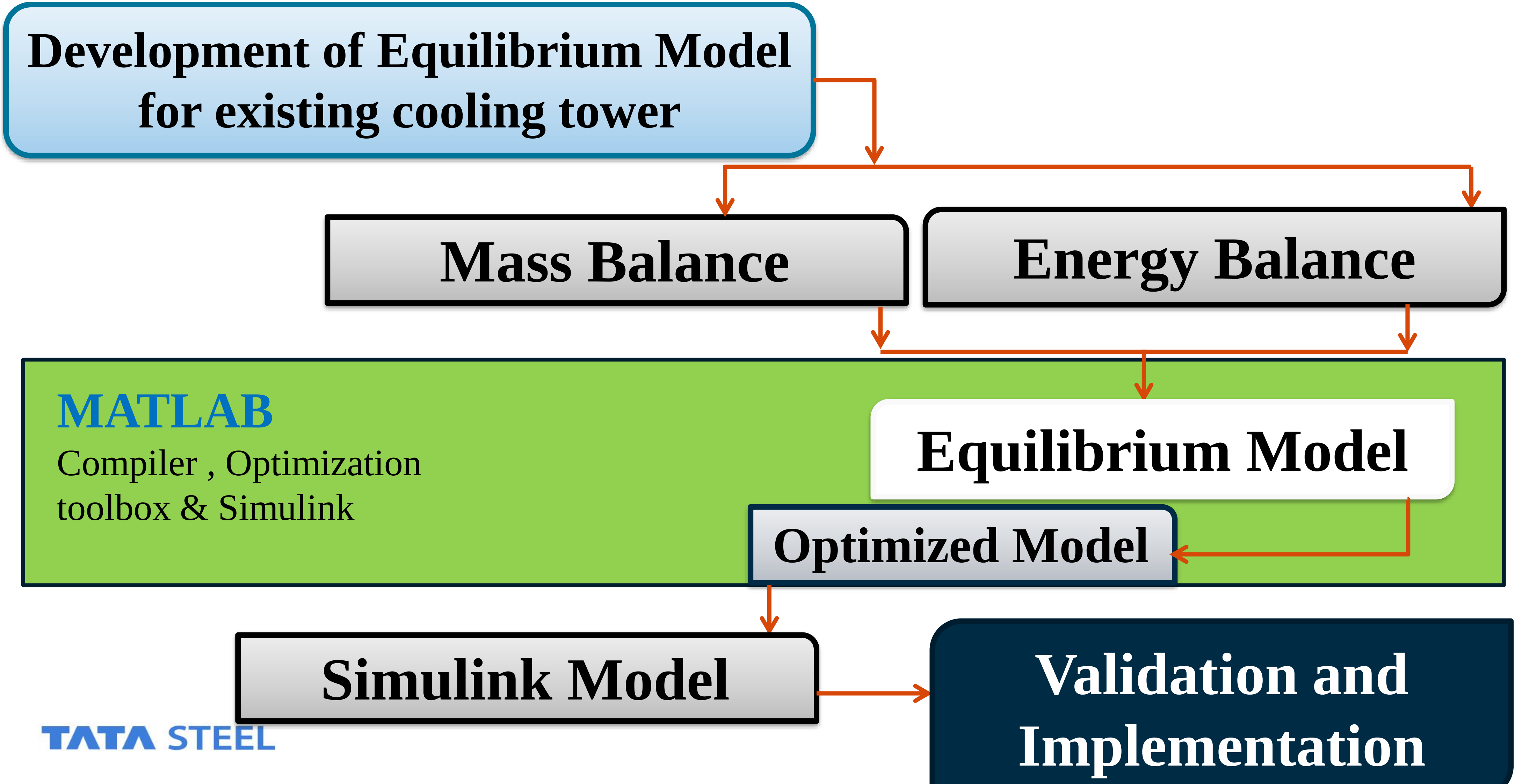
Objectives

- 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

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

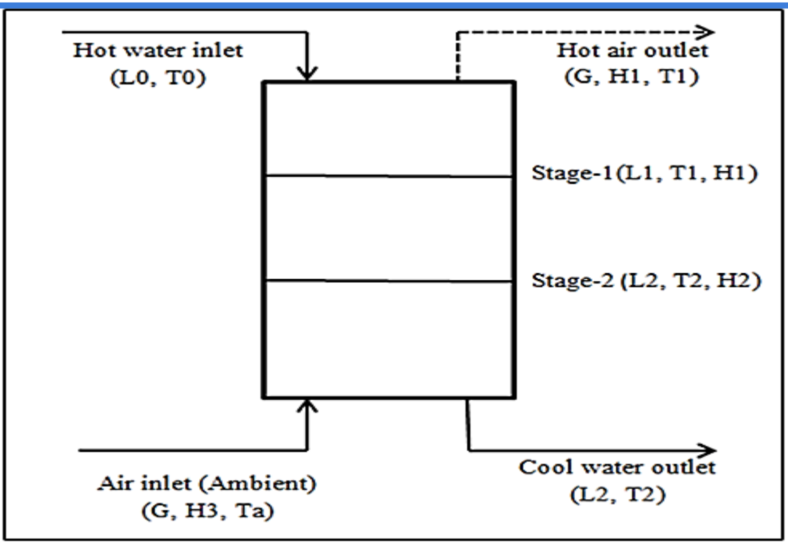
$$\text{Mass of water } in = \text{Mass of water out}$$

Stage-1

$$L_o + GH_2 = L_1 + GH_1 => L_1 = L_o + G(H_2 - H_1)$$

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 wa
+ 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

$$(G \times C_{pa} \times T_a) + (L_1 \times C_{pw} \times T_1) + (G \times H_3 \times C_{pv} \times T_a) + (G \times H_3 \times \lambda)$$
$$= (G \times C_{pa} \times T_2) + (L_2 \times C_{pw} \times T_2) + (G \times H_2 \times C_{pv} \times T_2) + (G \times H_2 \times \lambda)$$

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

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

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

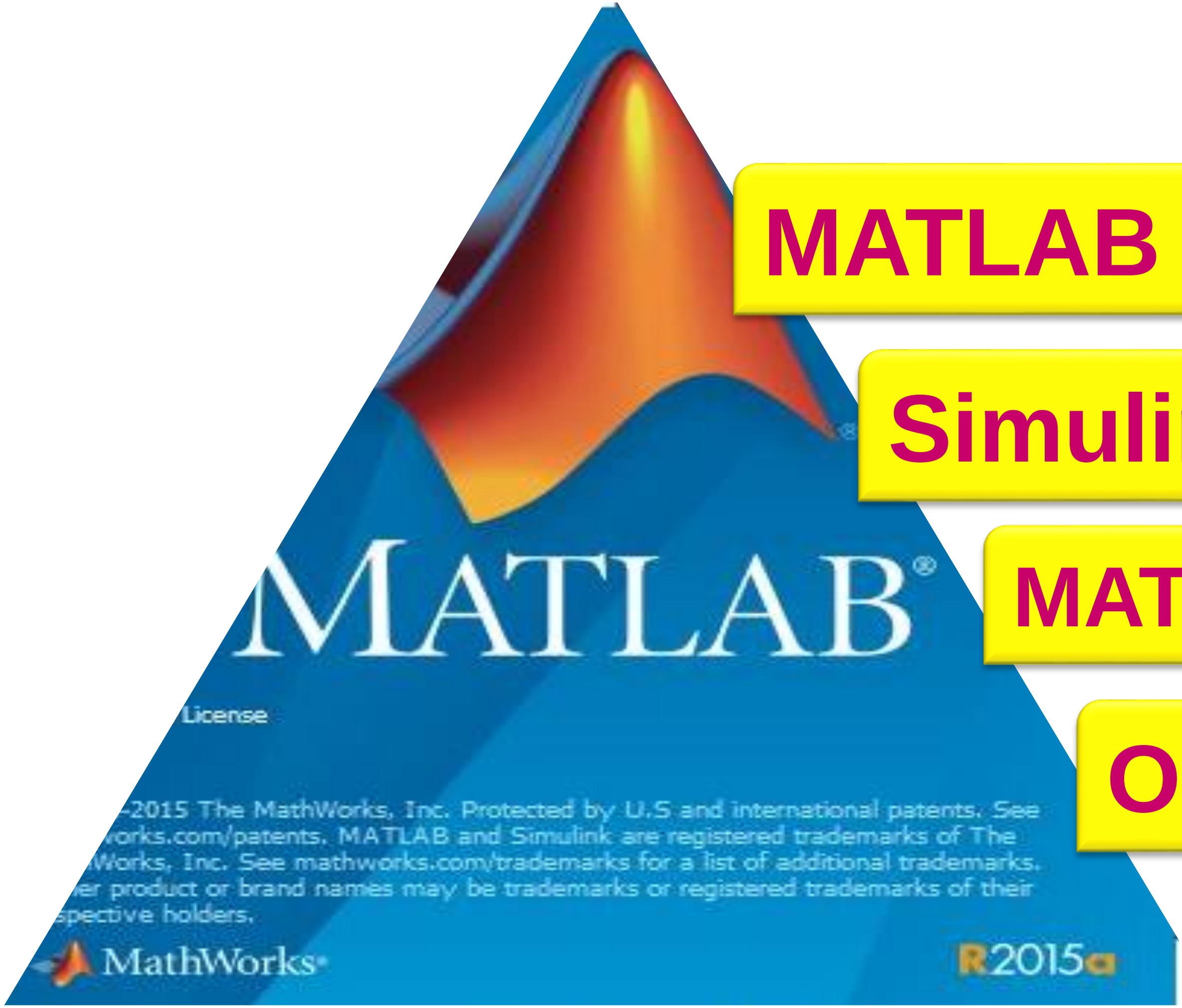
- H_1 and H_2 can be calculated from Y_1 and Y_2

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

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

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

Tools Used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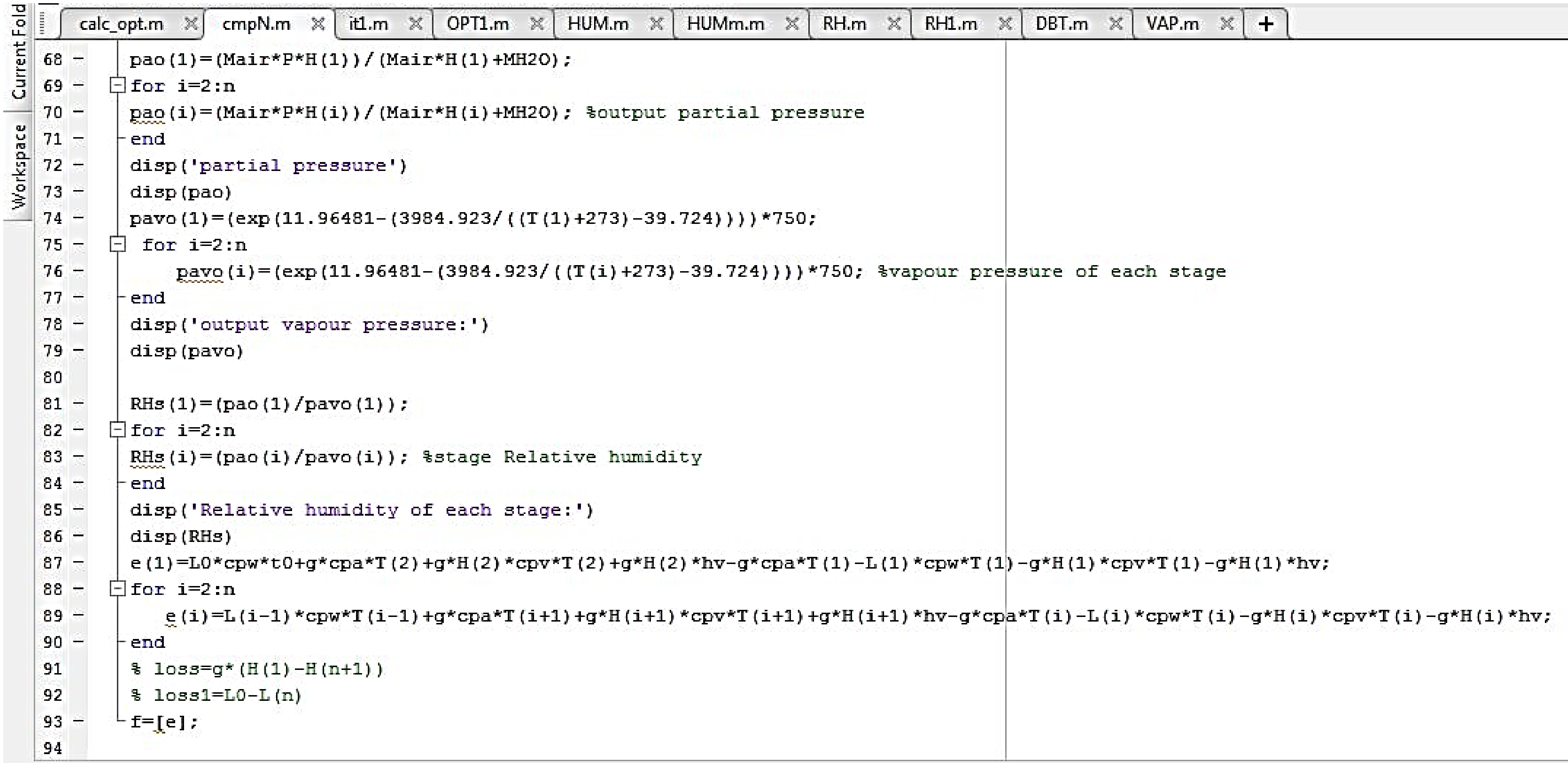
MATLAB R2016b

Simulink

MATLAB Compiler

Optimization toolbox

Coding

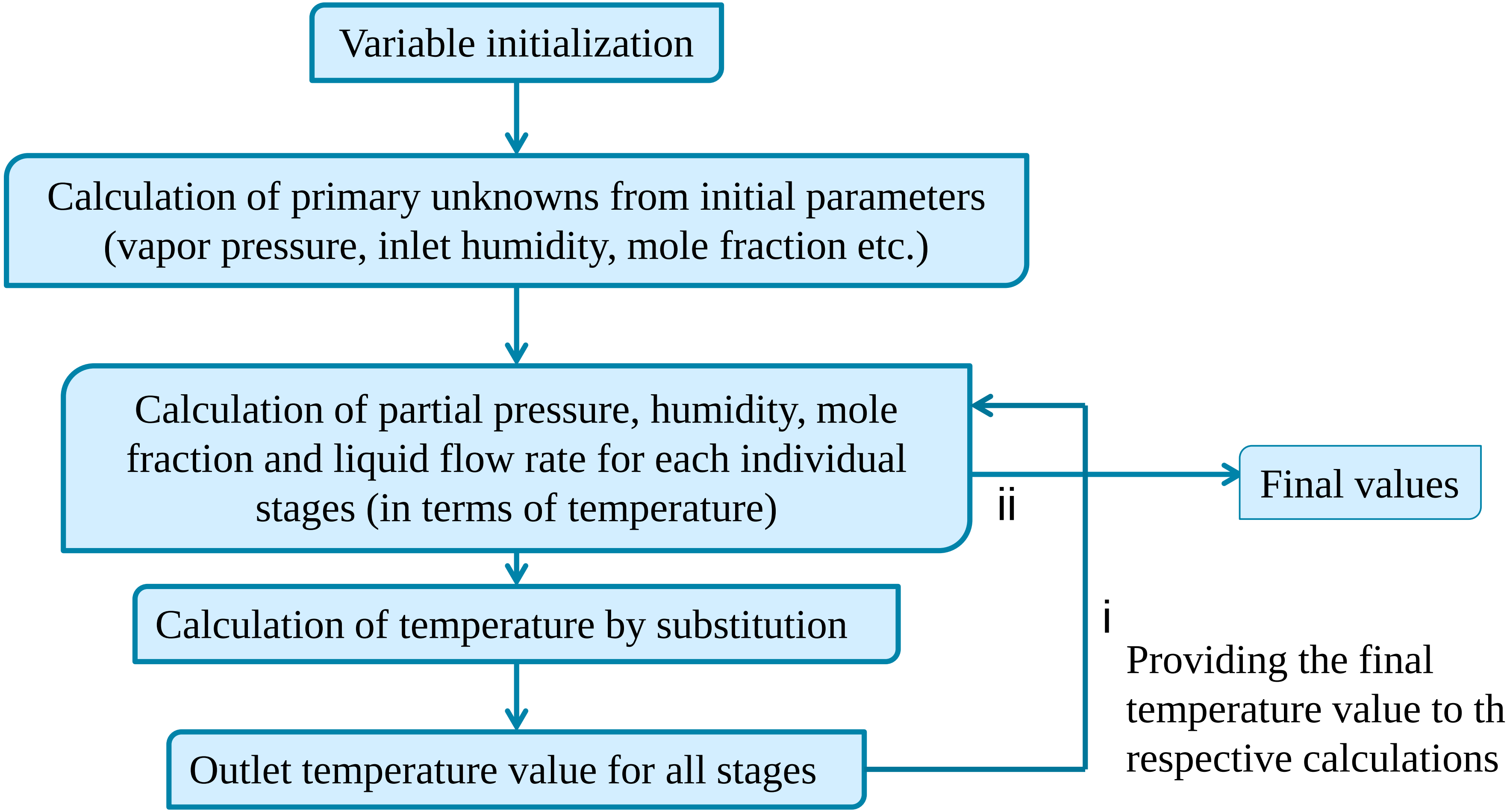


```
pao(1)=(Mair*P*H(1))/(Mair*H(1)+MH2O);
for i=2:n
pao(i)=(Mair*P*H(i))/(Mair*H(i)+MH2O); %output partial pressure
end
disp('partial pressure')
disp(pao)
pavo(1)=(exp(11.96481-(3984.923/((T(1)+273)-39.724))))*750;
 for i=2:n
    pavo(i)=(exp(11.96481-(3984.923/((T(i)+273)-39.724))))*750; %vapour pressure of each stage
end
disp('output vapour pressure:')
disp(pavo)

RHs(1)=(pao(1)/pavo(1));
for i=2:n
RHs(i)=(pao(i)/pavo(i)); %stage Relative humidity
end
disp('Relative humidity of each stage:')
disp(RHs)
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;
for i=2:n
   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;
end
% loss=g*(H(1)-H(n+1))
% loss1=L0-L(n)
f=[e];

```

Steps involved in solving the Code



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

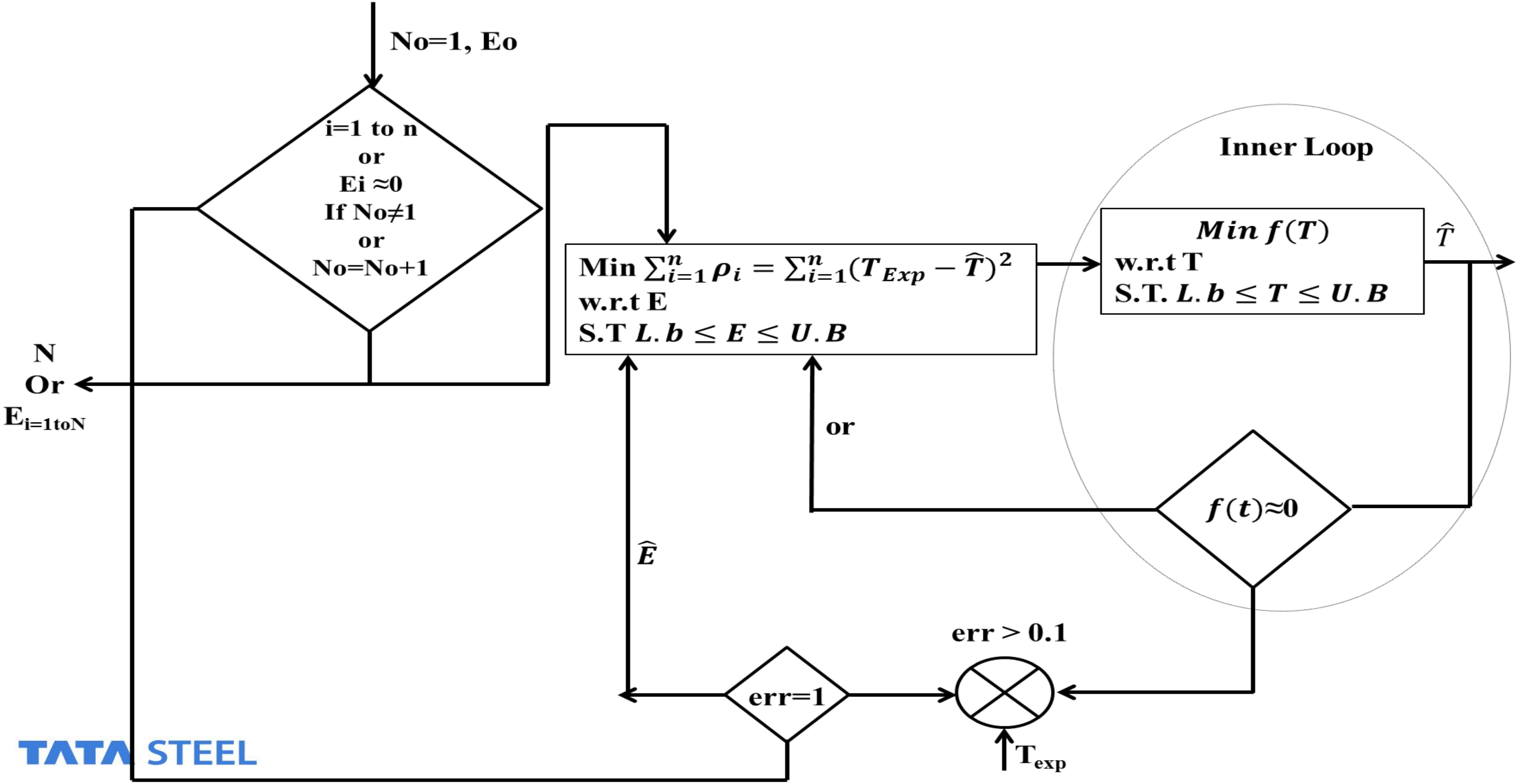
Final values

ii

i

Providing the final temperature value to the respective calculations

Optimization Flowchart



No=1, Eo

i=1 to n
or
Ei ≈0
If No≠1
or
No=No+1

N
Or
$E_{i=1toN}$

Min $\sum_{i=1}^{n}\rho_i = \sum_{i=1}^{n}(T_{Exp} - \widehat{T})^2$
w.r.t E
S.T $L.b \le E \le U.B$

Inner Loop

$Min\ f(T)$
w.r.t T
S.T. $L.b \le T \le U.B$

$\hat{T}$

$f(t)\approx 0$

or

$\widehat{E}$

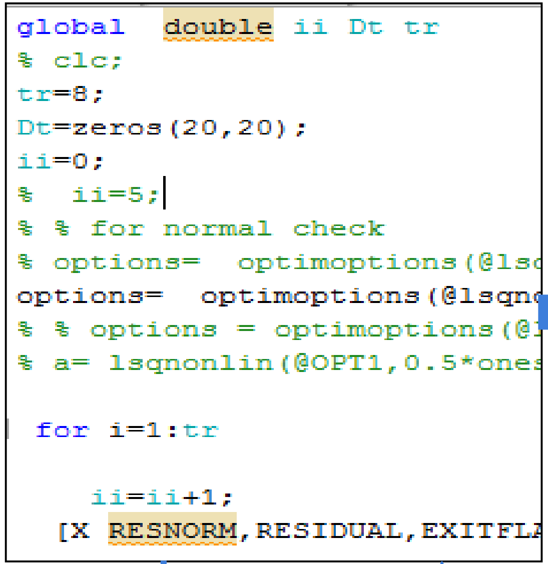
err=1

err > 0.1

T_{exp}

Optimization Process

Main function

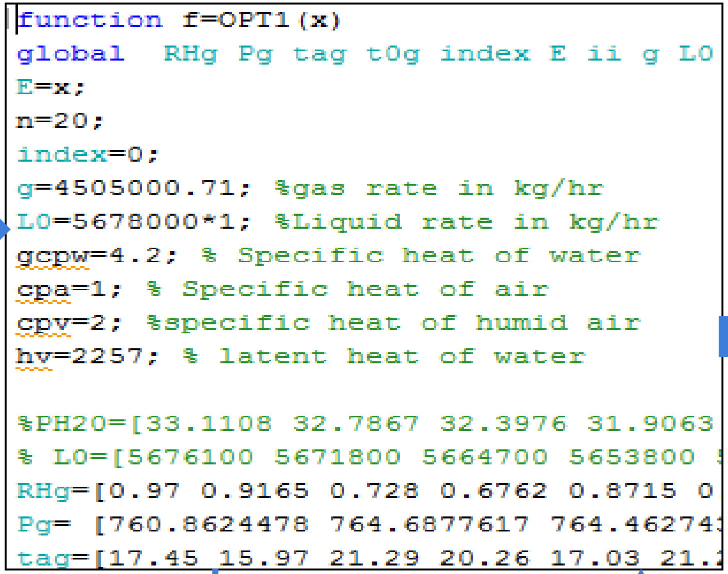


```
global  double ii Dt tr
% clc;
tr=8;
Dt=zeros(20,20);
ii=0;
%  ii=5;
% % for normal check
% options=  optimoptions(@ls
options=  optimoptions(@lsqn
% % options = optimoptions(@
% a= lsqnonlin(@OPT1,0.5*ones

 for i=1:tr


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

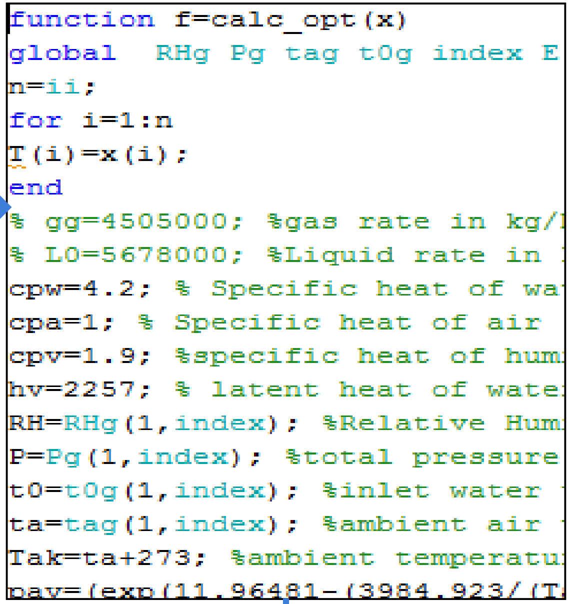
Data set



```
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.
```

Function solver



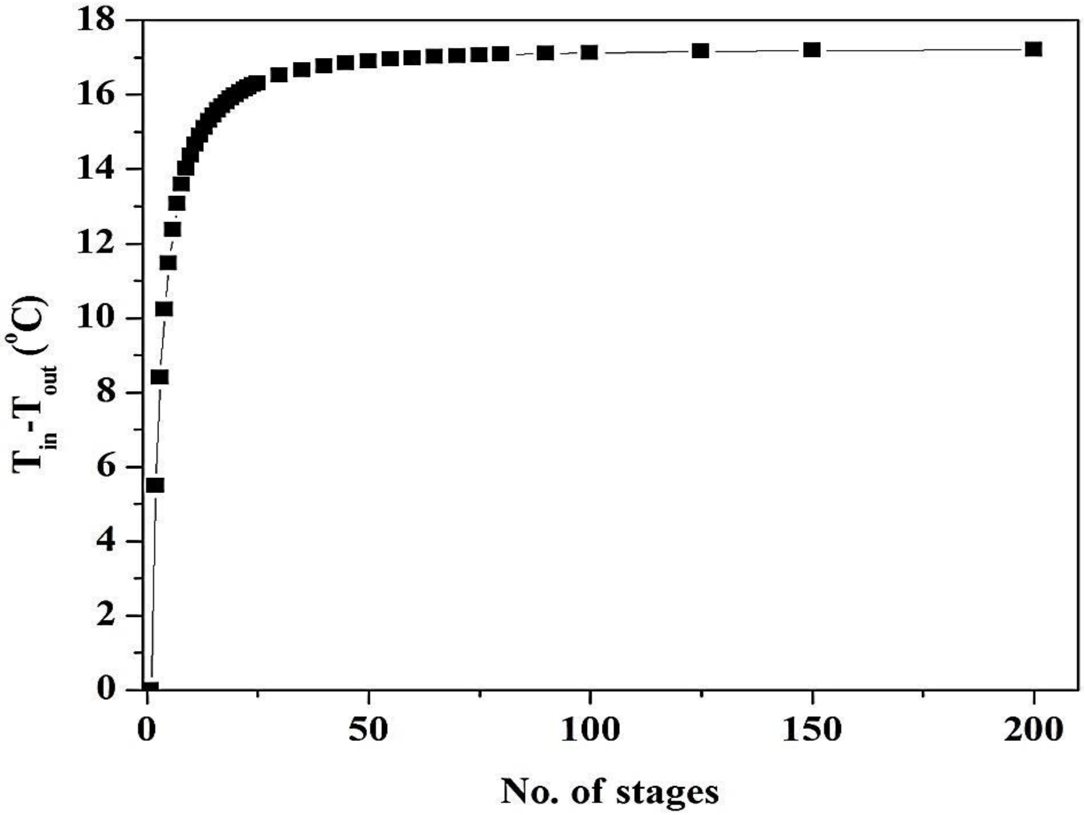
```
function f=calc_opt(x)
global  RHg Pg tag t0g index E
n=ii;
for i=1:n
T(i)=x(i);
end
% gg=4505000; %gas rate in kg/
% L0=5678000; %Liquid rate in
cpw=4.2; % Specific heat of wa
cpa=1; % Specific heat of air
cpv=1.9; %specific heat of hum
hv=2257; % latent heat of wate
RH=RHg(1,index); %Relative Hum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

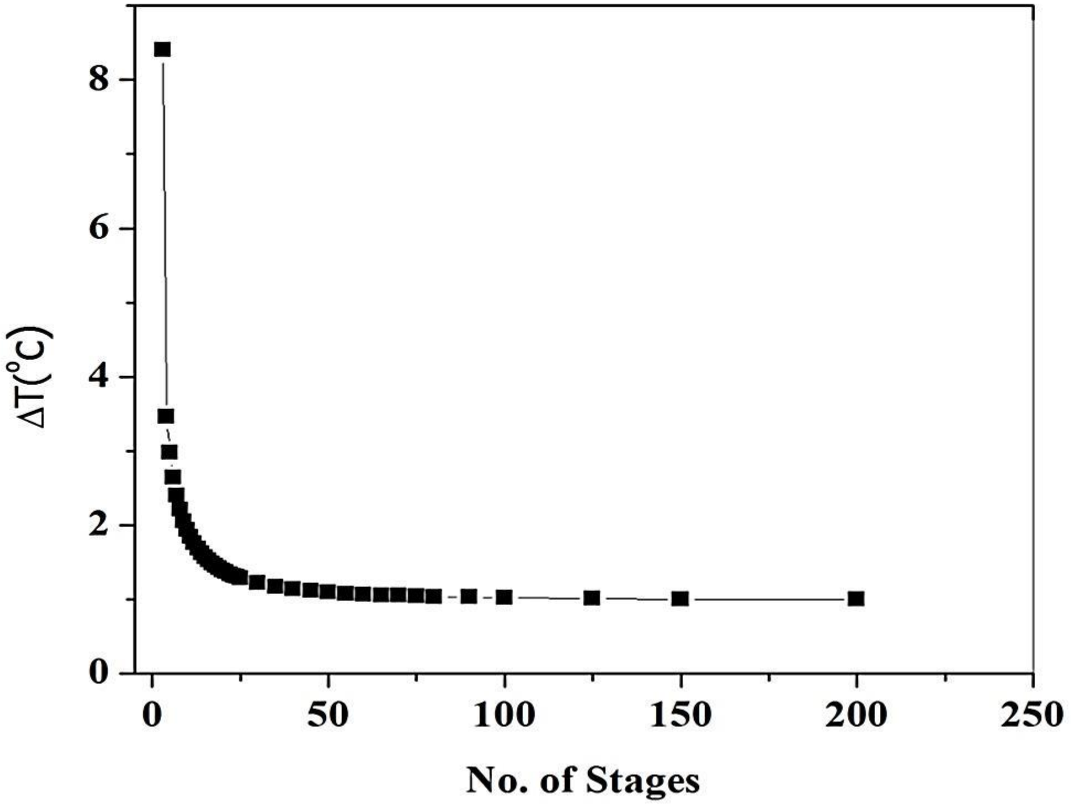
Error<0.1

Temperature value

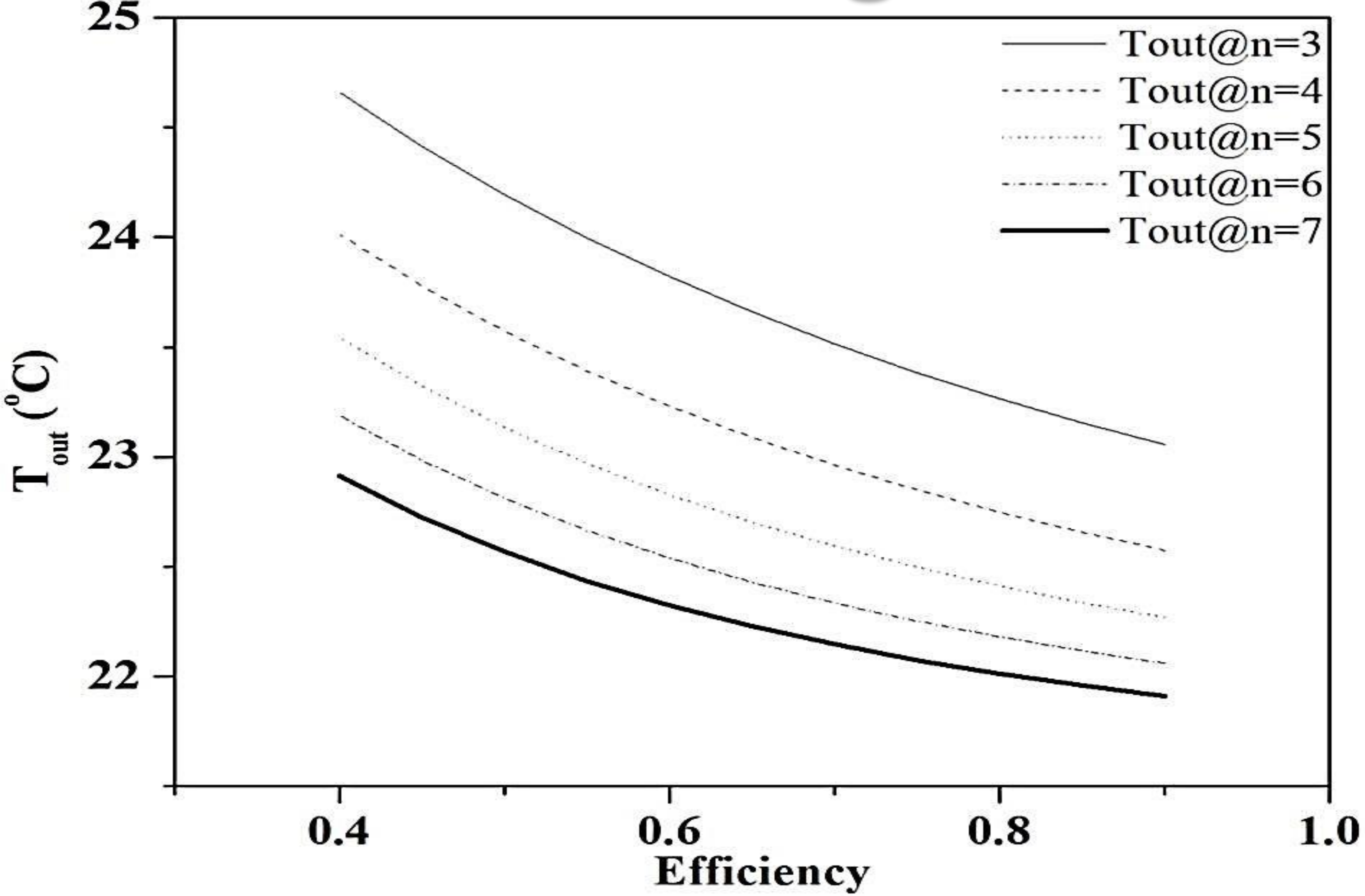
Optimized efficiency and number of stages

Effect of No. of Stages on Cooling Tower Outlet Temperature

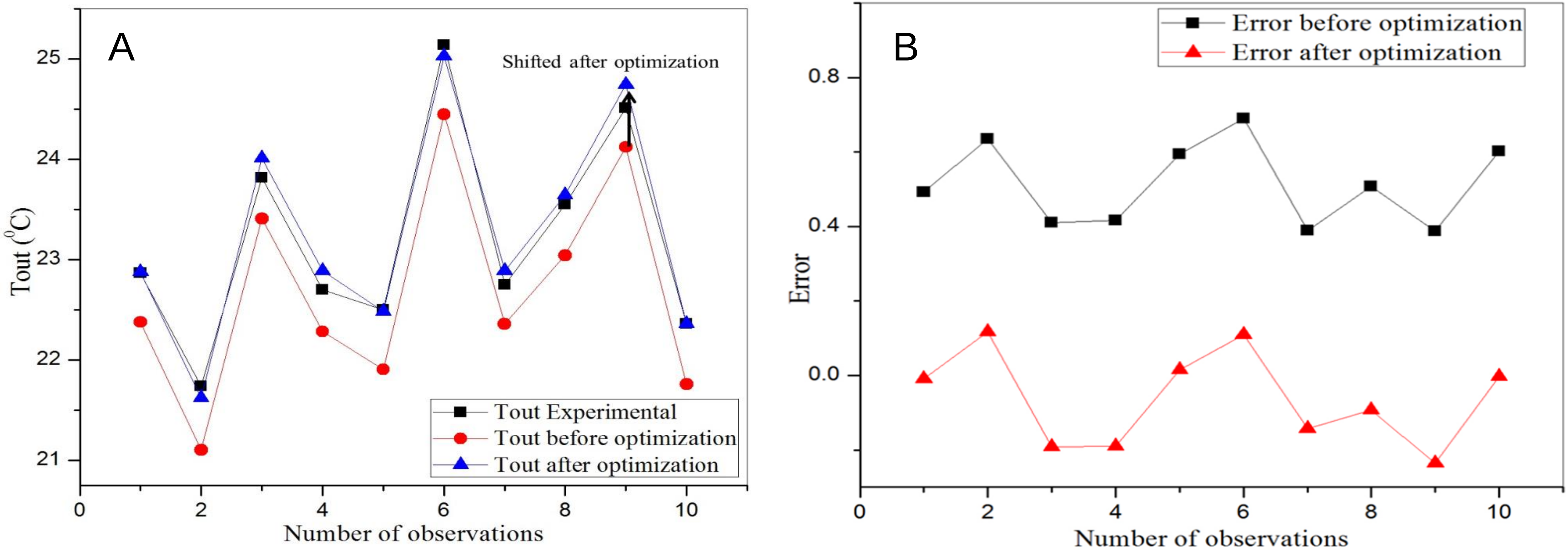




Effect of Murphree Efficiency on Number of Stages

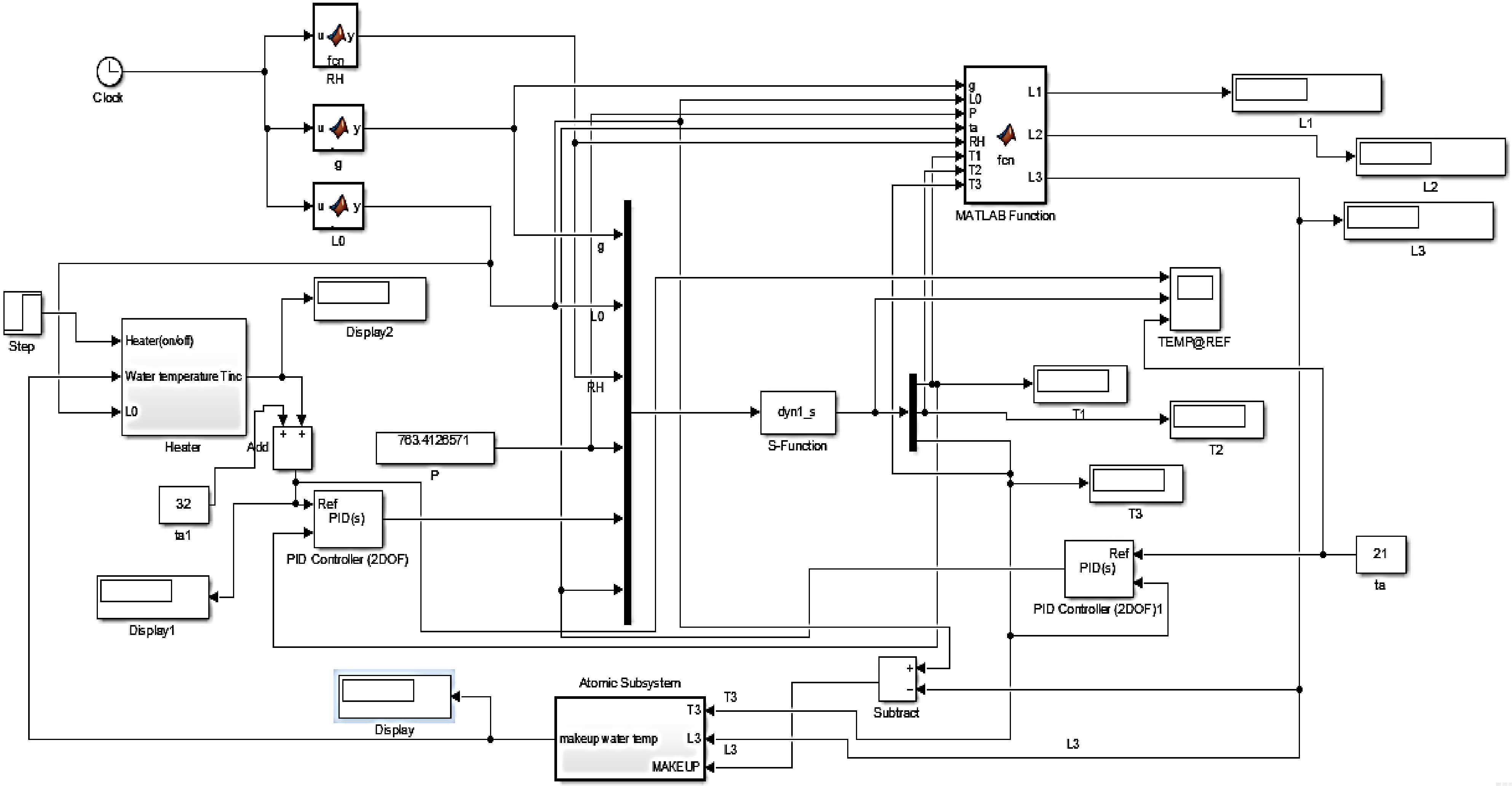


Comparison of experimental data with optimized data

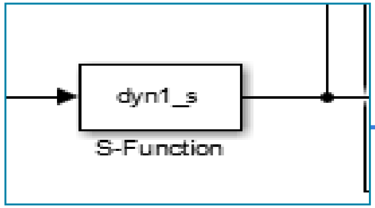


A: **Comparison of initial MATLAB model with optimized model validated with experimental data.** **B**: **Error Comparison before optimization and after optimization**

Control Strategy



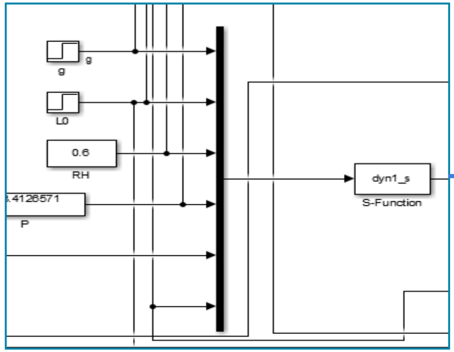
Control Strategy (Contd.)



S-Function block

Used to solve differential equations with initial conditions

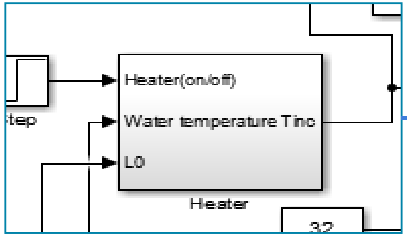
Conditions: flag=0 initialization, flag=1 derivatives
Flag=3 output, flag=2 discrete, flag=9 termination



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



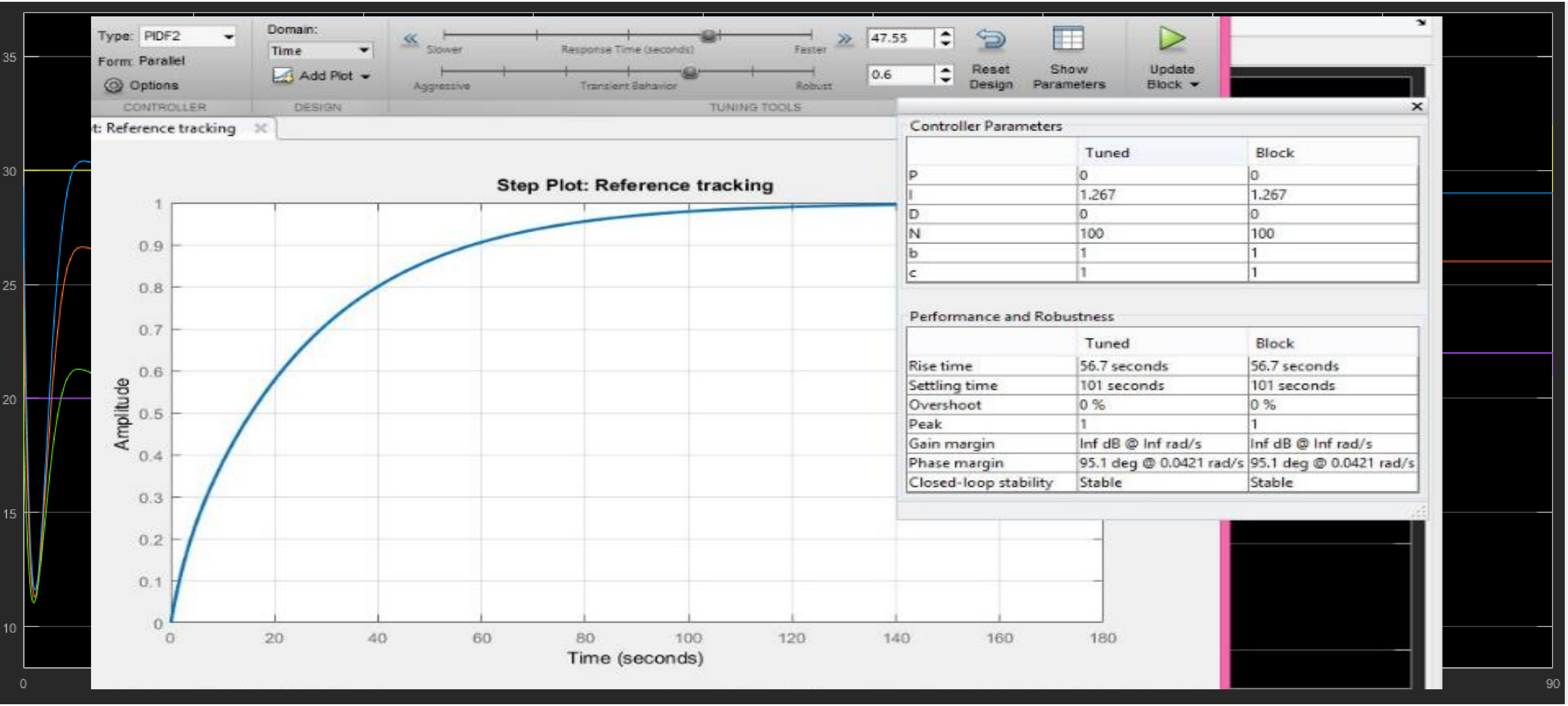
Heater

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



Type: PIDF2

Form: Parallel

Domain: Time

Response Time (seconds): 47.55

Transient Behavior: 0.6

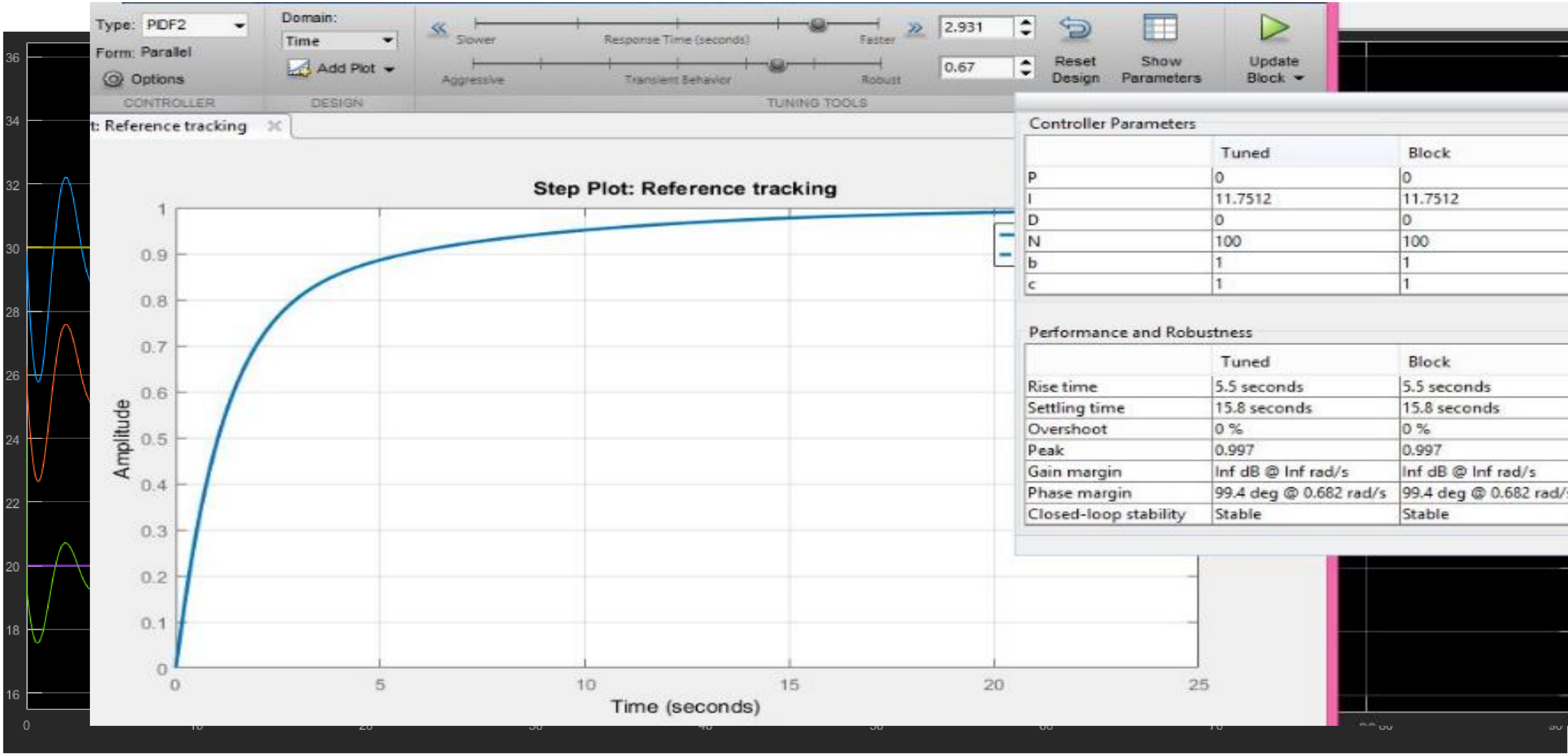
Controller Parameters

	Tuned	Block
P	0	0
I	1.267	1.267
D	0	0
N	100	100
b	1	1
c	1	1

Performance and Robustness

	Tuned	Block
Rise time	56.7 seconds	56.7 seconds
Settling time	101 seconds	101 seconds
Overshoot	0 %	0 %
Peak	1	1
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	95.1 deg @ 0.0421 rad/s	95.1 deg @ 0.0421 rad/s
Closed-loop stability	Stable	Stable

PID Controller tuning(Contd.)



Type: PIDF2

Form: Parallel

Domain: Time

Response Time (seconds): 2.931

Transient Behavior: 0.67

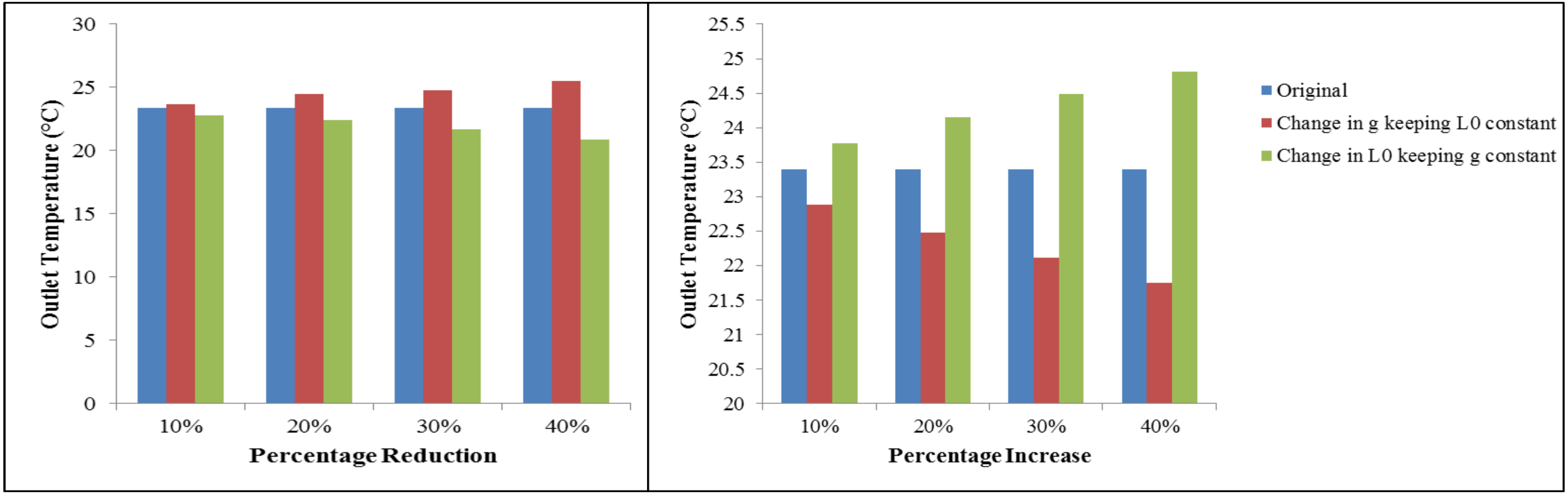
Controller Parameters

	Tuned	Block
P	0	0
I	11.7512	11.7512
D	0	0
N	100	100
b	1	1
c	1	1

Performance and Robustness

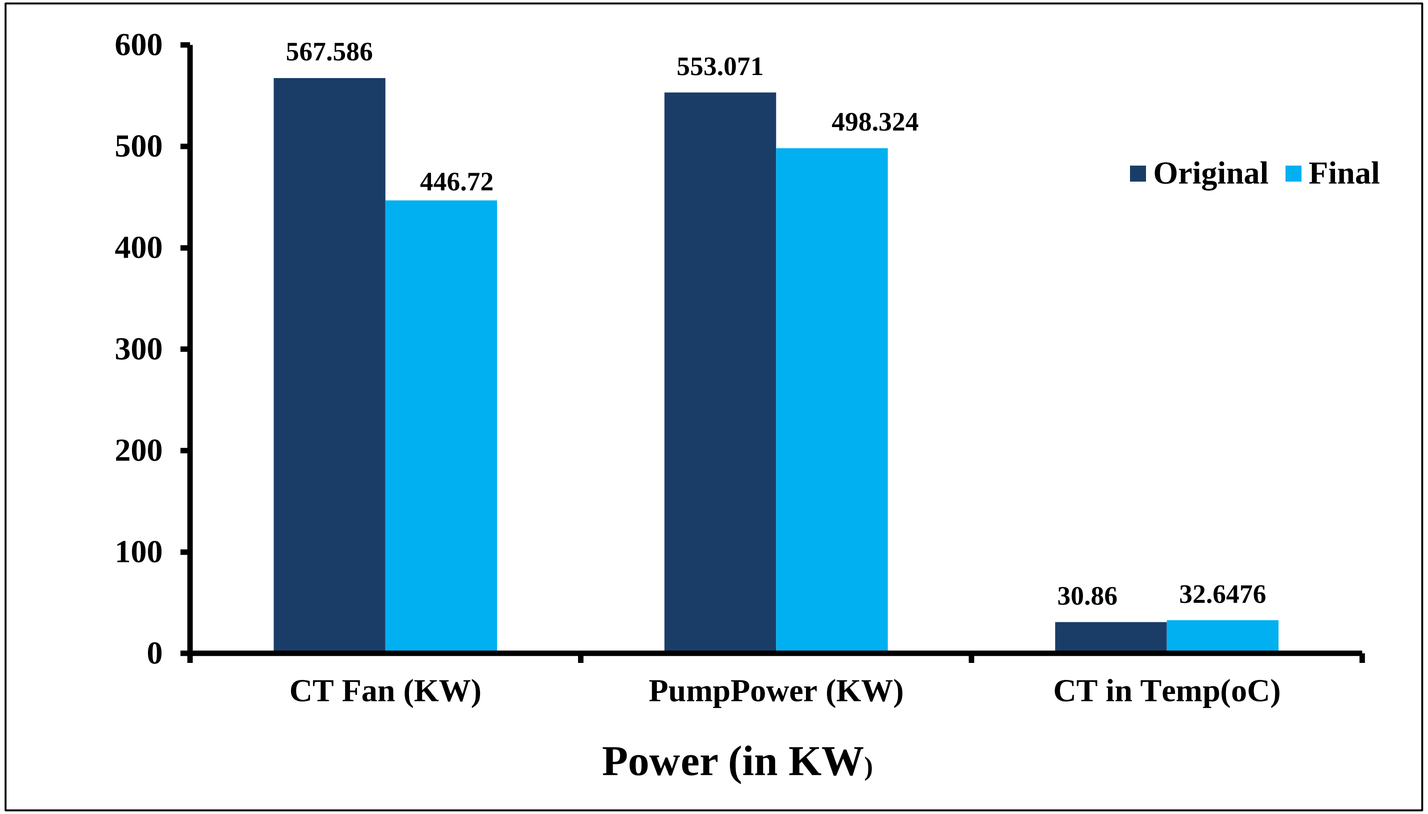
	Tuned	Block
Rise time	5.5 seconds	5.5 seconds
Settling time	15.8 seconds	15.8 seconds
Overshoot	0 %	0 %
Peak	0.997	0.997
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	99.4 deg @ 0.682 rad/s	99.4 deg @ 0.682 rad/
Closed-loop stability	Stable	Stable

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



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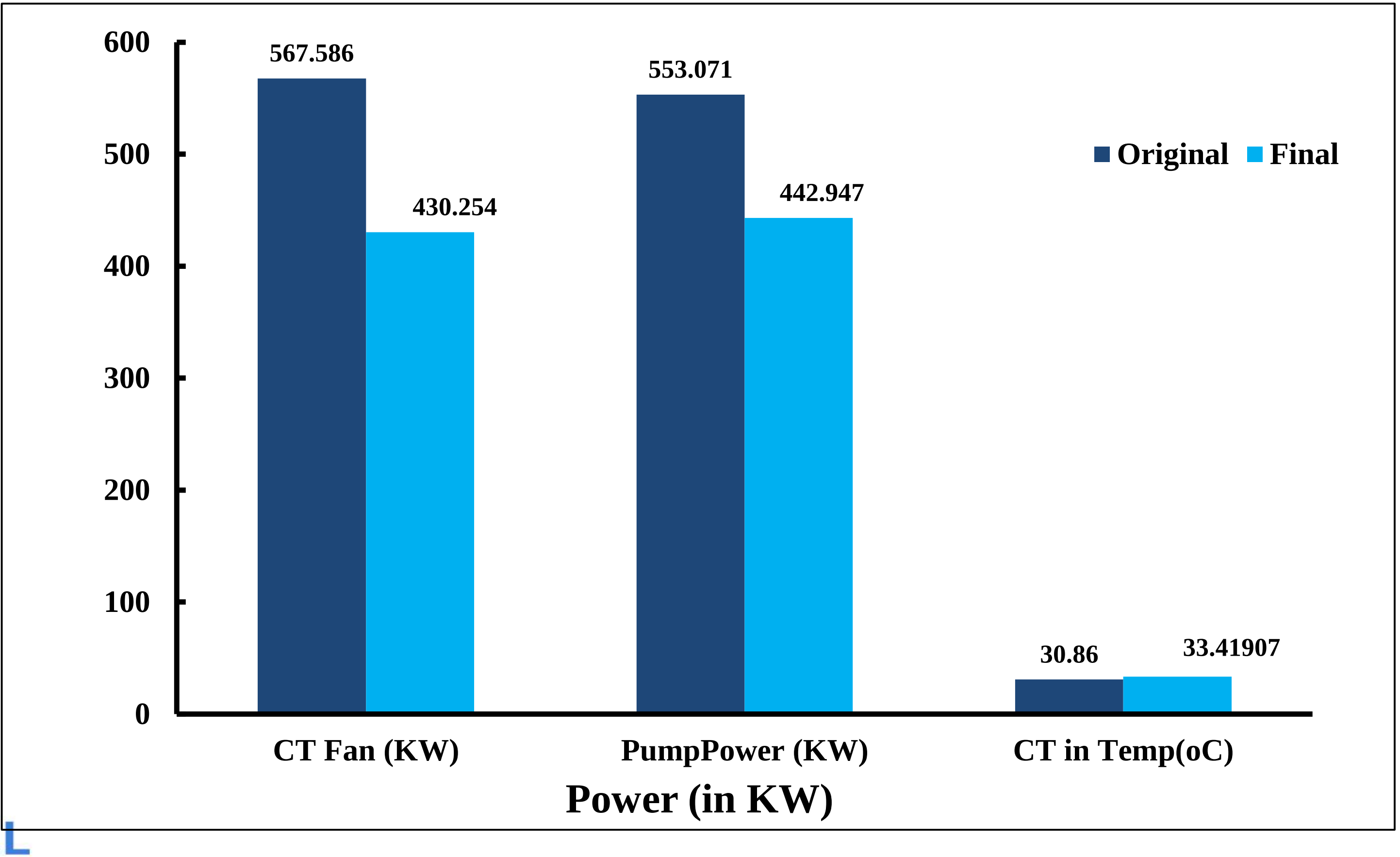
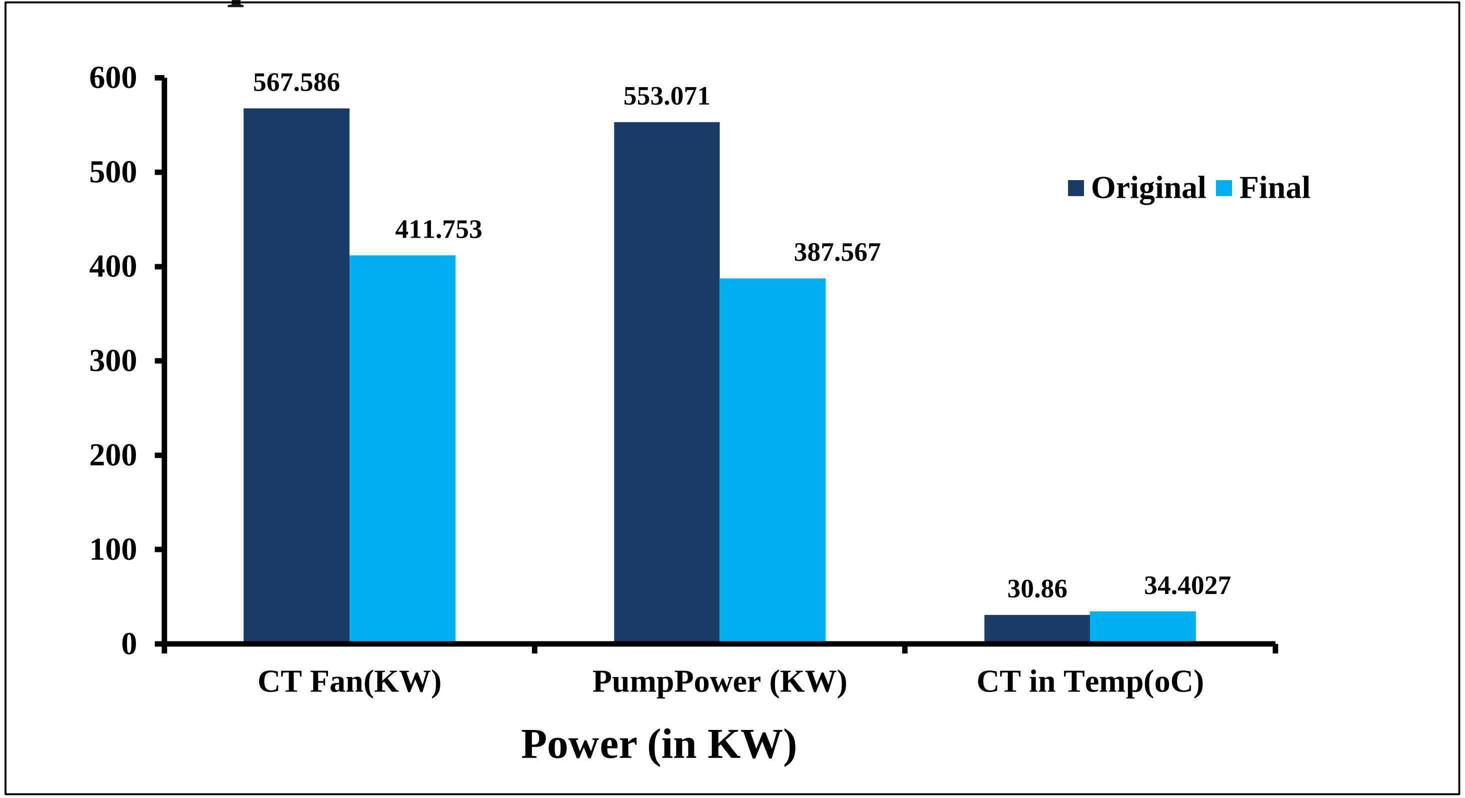
Effect of change in liquid flow rate on power consumption(Contd.)

20% reduction in liquid flowrate



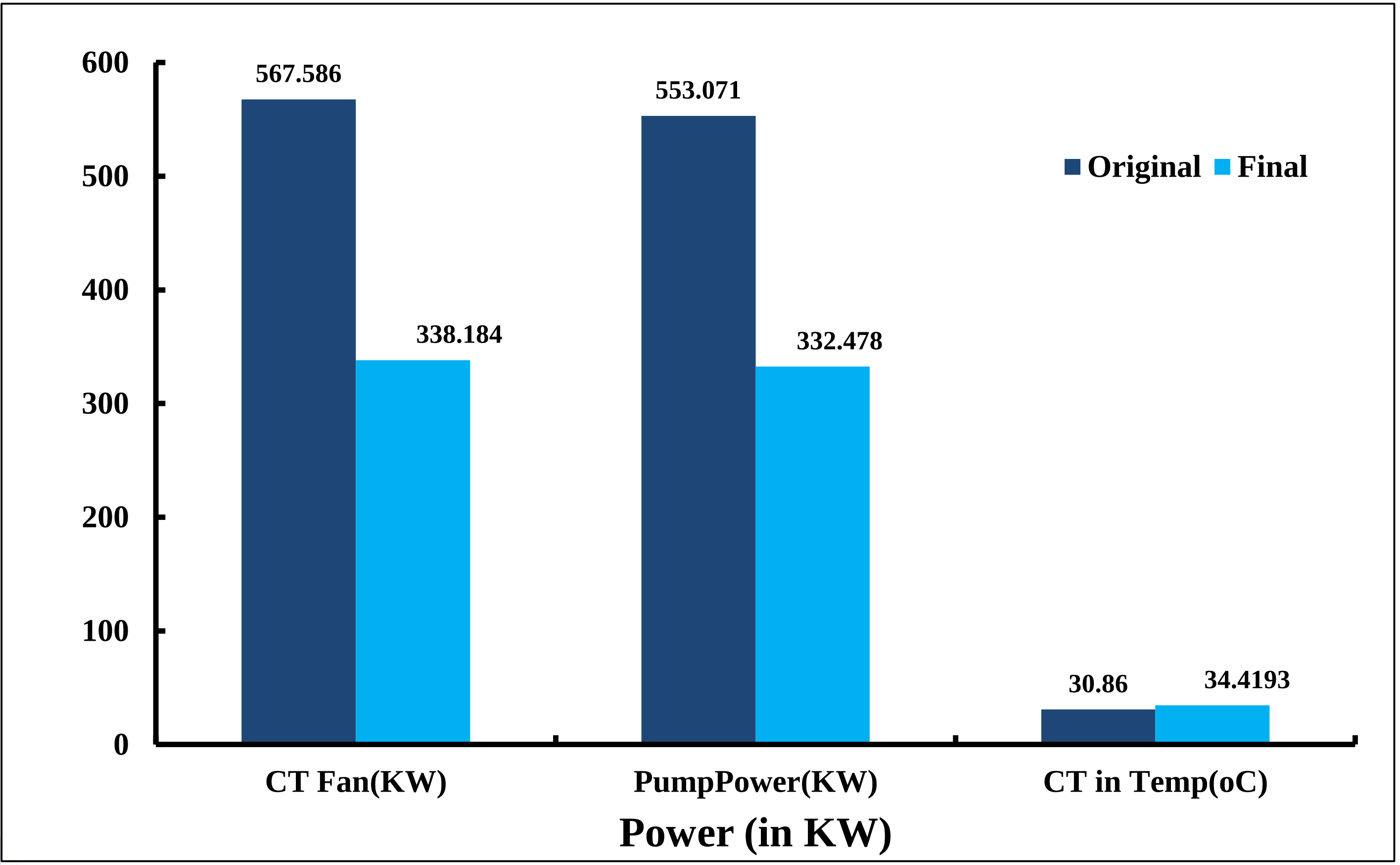
Effect of change in liquid flow rate on power consumption(Contd.)

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

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!