HANARO Secondary Cooling System Behavior Prediction based on Deep Neural Network and Data Augmentation

Seung Geun Kim[a], Geunhyeong Lee[a], Min Woo Lee[b], Yonggyun Yu[a]
KAERI(Korea Atomic Energy Research Institute)
[a]Applied Artificial Intelligence Section, [b]HANARO Management Division

2023. 05. 19 (Fri)

Contents

I. Introduction

I. Introduction

- Artificial intelligence in nuclear field : in the perspective of control/automation
  - Among 118 domestic nuclear power plant incidents (2012~2021), 15 incidents (12.7%) were caused by human error.
  - Small modular reactor should be operable with lesser number of operators.

Aiding operator's tasks : Operation support system, decision support system
Performing operator's tasks : Automation/autonomous operation

Manual system

Automated system

Autonomous system

Workflow

	ROLES			
LEVEL OF AUTOMATION	MONITORING	GENERATING	SELECTING	IMPLEMENTING
1. Manual Control	Human	Human	Human	Human
2. Action Support	Human/Computer	Human	Human	Human/Computer
3. Batch Processing	Human/Computer	Human	Human	Computer
4. Shared Control	Human/Computer	Human/Computer	Human	Human/Computer
5. Decision Support	Human/Computer	Human/Computer	Human	Computer
6. Blended Decision Making	Human/Computer	Human/Computer	Human/Computer	Computer
7. Rigid System	Human/Computer	Computer	Human	Computer
8. Automated Decision Making	Human/Computer	Human/Computer	Computer	Computer
9. Supervisory Control	Human/Computer	Computer	Computer	Computer
10. Full Automation	Computer	Computer	Computer	Computer

Level of automation(LOA) Taxonomy (Endsley and Kaber, 1999)

- For HANARO reactor, anomaly detection system, secondary cooling system decision support system, core bubble detection systems are under development.

I. Introduction

- HANARO (High-flux Advanced Neutron Application ReactOr)
  - Multi-purpose research reactor with 30MWth power output
  - Located in KAERI(Korea Atomic Energy Research Institute)
  - Has been operated over 100 periods from its construction in 1995.
  - Includes following facilities:
    - Radioisotope product facility
    - Thermal neutron research facility (TNRF)
    - Cold neutron research facility (CNRF)
    - Fuel test loop (FTL)

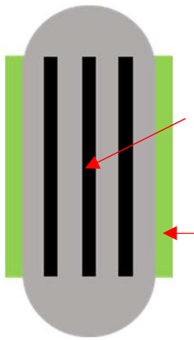
HANARO Reactor Building

Thermal Neutron Research Facility

Cold Neutron Research Facility

I. Introduction

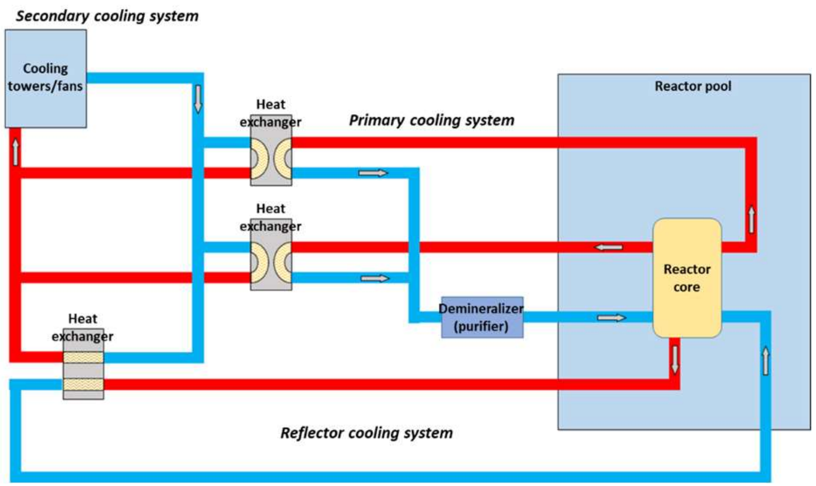
- Cooling systems of HANARO



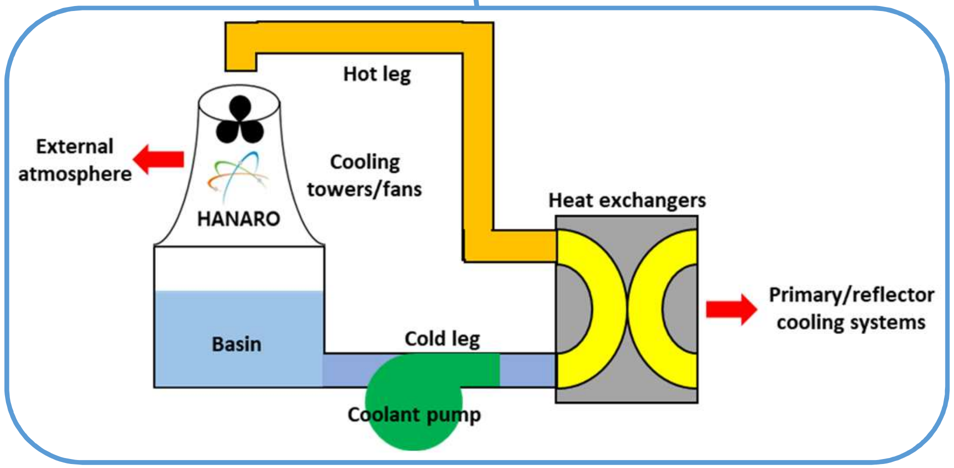
Reactor core → Primary cooling system

Reflector → Reflector cooling system

→ Secondary cooling system → Heat sink (atmosphere)



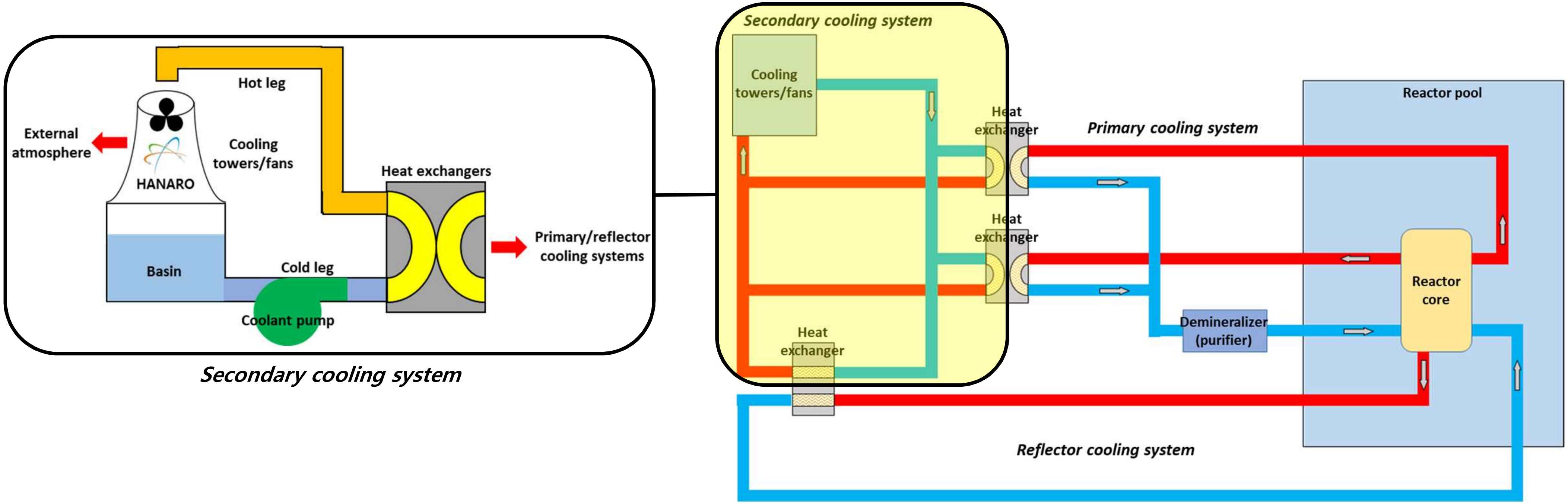
Schematic of HANARO cooling systems



Schematic of HANARO secondary cooling system

I. Introduction

- Operation of HANARO secondary cooling system
  - Removes heat from primary/reflector cooling system to the atmosphere (heat sink).
  - Flow path of [cold leg → heat exchangers → hot leg → cooling towers/fans → basin → cold leg] is formed with coolant pump.
  - There are four cooling tower/fan pairs, and each cooling fans can be operated as stop/slow/fast operation mode.



Secondary cooling system

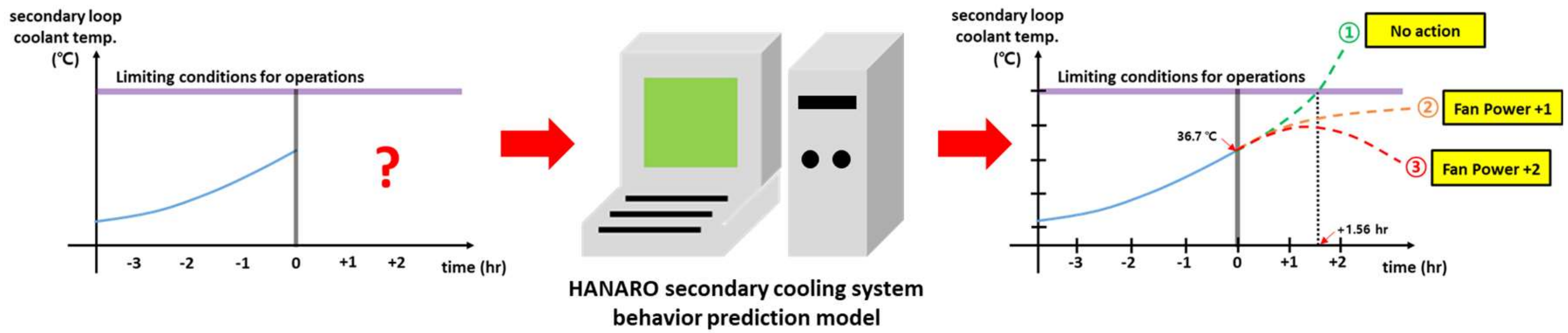
I. Introduction

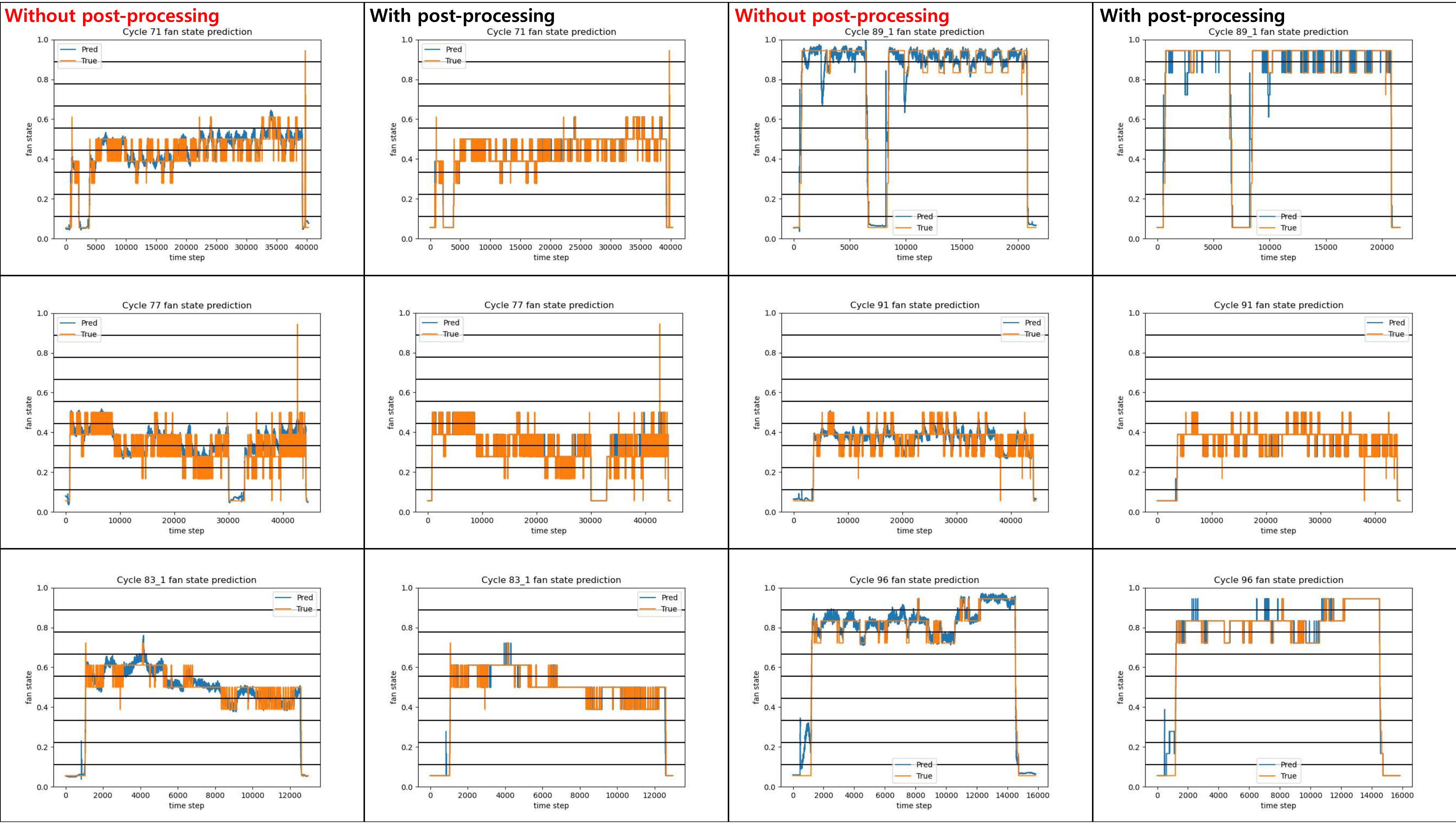
- As part of secondary cooling system is exposed to the external atmosphere, its behavior is affected by atmospheric conditions.
  - When temperature and humidity is high → Cooling efficiency is decreased (usually in summer)
  - When temperature and humidity is low → Cooling efficiency is increased (usually in winter)
- Operators make decisions about how to operate cooling fans to maintain the cooling tower outlet temperature within the range of 29~32℃.
  - Operators should consider not only HANARO operation variables, but also atmospheric conditions to make proper decisions.
- Operators are operating cooling fans, relying on their empirical knowledge.
  - Current manual for cooling fan operation does not consider the atmospheric conditions.
  - Cooling fans can be operated as 'auto' mode, while it is mostly not used since the underlying logic is too simple.

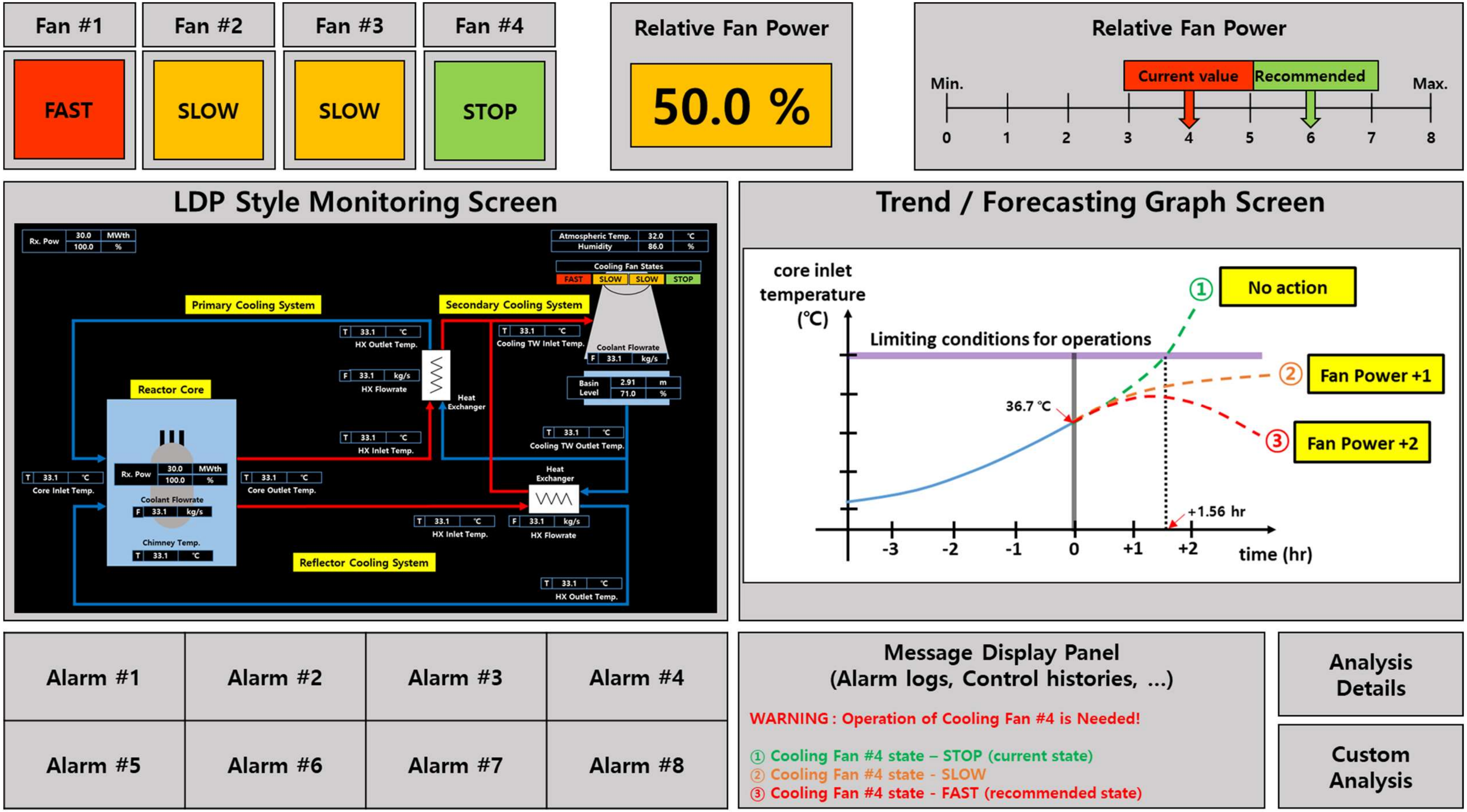
I. Introduction

- Research objective
  - HANARO secondary cooling system decision support system
- Research scope
  - Development of cooling fan operation mode prediction model
  - Development of secondary cooling system behavior prediction model
  - Development of secondary cooling system decision support system prototype

Development of cooling fan operation mode prediction model → **Development of system behavior prediction model** → **Development of decision support system prototype**




Without post-processing
With post-processing
Without post-processing
With post-processing
Cycle 71 fan state prediction
Cycle 89_1 fan state prediction
Cycle 77 fan state prediction
Cycle 91 fan state prediction
Cycle 83_1 fan state prediction
Cycle 96 fan state prediction
Pred
True
fan state
time step


Fan #1
Fan #2
Fan #3
Fan #4
FAST
SLOW
SLOW
STOP
Relative Fan Power
50.0 %
Relative Fan Power
Current value
Recommended
Min.
Max.
0 1 2 3 4 5 6 7 8
LDP Style Monitoring Screen
Rx. Pow 30.0 MWth 100.0 %
Atmospheric Temp. 32.0 ℃
Humidity 86.0 %
Cooling Fan States
FAST SLOW SLOW STOP
Primary Cooling System
Secondary Cooling System
HX Outlet Temp.
HX Flowrate
Heat Exchanger
Cooling TW Inlet Temp.
Coolant Flowrate
Basin Level 2.91 m 71.0 %
Reactor Core
HX Inlet Temp.
Cooling TW Outlet Temp.
Core Inlet Temp.
Core Outlet Temp.
Coolant Flowrate
Chimney Temp.
Reflector Cooling System
HX Inlet Temp.
HX Flowrate
HX Outlet Temp.
Trend / Forecasting Graph Screen
core inlet temperature (℃)
Limiting conditions for operations
① No action
② Fan Power +1
③ Fan Power +2
36.7 ℃
+1.56 hr
-3 -2 -1 0 +1 +2
time (hr)
Alarm #1
Alarm #2
Alarm #3
Alarm #4
Alarm #5
Alarm #6
Alarm #7
Alarm #8
Message Display Panel
(Alarm logs, Control histories, ...)
WARNING : Operation of Cooling Fan #4 is Needed!
① Cooling Fan #4 state – STOP (current state)
② Cooling Fan #4 state - SLOW
③ Cooling Fan #4 state - FAST (recommended state)
Analysis Details
Custom Analysis

II. Behavior Prediction Model Development

Ⅱ. Behavior Prediction Model Development

- Data acquisition
  - HANARO operation variable data
    - Data from 65^{th} period (in year 2010) to 96^{th} period (in year 2014) was acquired from HANARO database (totally 36 periods).
    - 24 kinds of variables that are related to the operation of secondary cooling system were selected.
    - Data points have 1 minute interval.
  - Meteorological data
    - Data from 2010 to 2014 was acquired from Daejeon meteorological administration center.
    - Only temperature and humidity were selected for model development.
    - Data points have 1 hour interval.
  - Assumptions
    - Atmospheric conditions between these two points are almost identical.
    - Atmospheric conditions are identical for one hour to match the time window.

Selected variables for model development

Category	Variables (numbers)
Core	Thermal output (2), Core inlet temp. (1), Core outlet temp. (1)
Primary cooling system	Coolant flowrate (2), Heat exchanger inlet temp. (2), Heat exchanger outlet temp. (2)
Secondary cooling system	Coolant flowrate (2), Cooling tower inlet temp. (2), Cooling tower outlet temp. (2), Cooling tower in/out temp. difference (2), Basin water level (1), Basin water temp. (1), Cooling fan operation status (1)
Reflector cooling system	Coolant flowrate (1), Heat exchanger inlet temp. (1), Heat exchanger outlet temp. (1)
Atmospheric conditions	Temperature (1), Humidity (1)

II. Behavior Prediction Model Development

- Data preprocessing
  - Missing values were replaced to the previous value or 0.
  - Minimum-maximum normalization was applied.
  - Cooling fan operation modes were transformed into relative cooling capacity.
    - Assumption: the cooling capacity of fast mode operation is twice of slow mode operation.
    - Since there are 4 cooling fans, relative cooling capacity has the range of 0~8.

Set of operation modes and corresponding relative cooling capacities

Set of operation modes (# of stop/slow/fast)	Relative cooling capacity (stop=0, slow=1, fast=2)
(4, 0, 0)	0
(3, 1, 0)	1
(2, 2, 0), (3, 0, 1)	2
(1, 3, 0), (2, 1, 1)	3
(0, 4, 0), (1, 2, 1), (2, 0, 2)	4
(0, 3, 1), (1, 1, 2)	5
(0, 2, 2), (1, 0, 3)	6
(0, 1, 3)	7
(0, 0, 4)	8

II. Behavior Prediction Model Development

- If there are two or more sensor data for same variable, their mean value is used.
  - Behavior prediction model's input is consist of,
    - 16 kinds of HANARO operation variables (for past 1hr)
    - 2 kinds of atmospheric conditions (for past 1hr)
    - 1 kind of future cooling fan operation mode (for future 1hr)
  - Behavior prediction model's output is future 1 hour trend of cooling tower outlet temperature.
- Training/validation/testing data sets were manually selected to evenly distribute seasonality and atmospheric conditions.
  - 36 periods of data were separated into,
    - 24 periods of training data
    - 6 periods of validation data
    - 6 periods of testing data

Period numbers and operation dates corresponding to the validation data and testing data

Testing data		**Testing data**	
Period number	**Operation dates**	**Period number**	**Operation dates**
66 period	10.06.14 ~ 10.07.22	71 period	11.03.15 ~ 11.04.11
70 period	11.01.30 ~ 11.02.20	77 period	12.01.16 ~ 12.02.15
74 period	11.09.05 ~ 11.10.03	83-1 period	12.10.25 ~ 12.11.02
84-1 period	12.12.03 ~ 12.12.19	89-1 period	13.08.05 ~ 13.08.19
86-1 period	13.03.04 ~ 13.03.18	91 period	13.12.06 ~ 14.01.13
88 period	13.07.01 ~ 13.07.28	96 period	14.06.30 ~ 14.07.10

II. Behavior Prediction Model Development

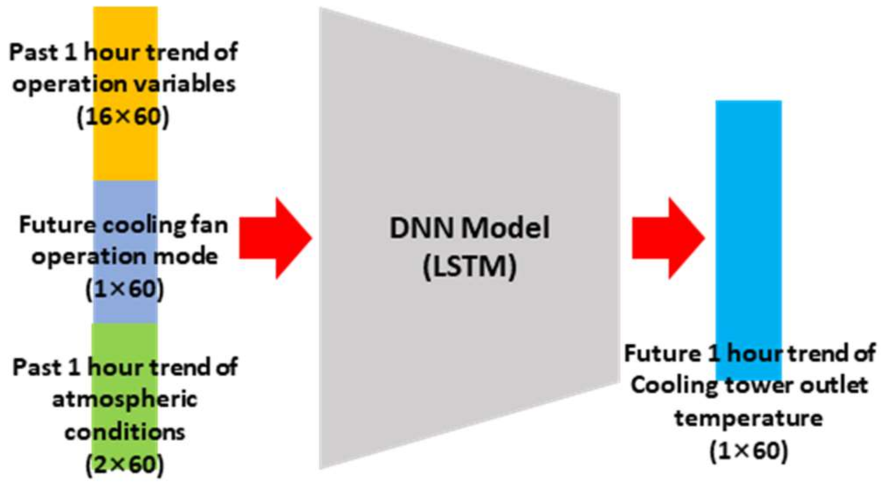
- Data Augmentation
  - Data imbalance problem is alleviated by applying data augmentation method.
  - Data augmentation through noise infusion:
    - Artificial noise is generated and added to the original data.
    - Noise is sampled from the Gaussian distribution with 0 mean and 1 variance.
    - Cooling fan operation mode is assumed to be same with original data.
  - Data augmentation through interpolation:
    - Augmented data is generated through linear interpolation between two data.
    - Cooling fan operation mode is assumed to be in middle of two data.
    - If cooling fan operation mode of data 1 is A, cooling fan operation mode of data 2 is B, then cooling fan operation mode of newly generated data $\frac{\boldsymbol{A}+\boldsymbol{B}}{\boldsymbol{2}}$.

Number of data before and after the augmentation according to the relative cooling capacity

(relative) cooling capacity	# of data (before augmentation)	# of data (after augmentation)
0	150,233	151,902
1	5,342	144,000
2	116,849	152,872
3	304,423	304,423
4	236,596	247,503
5	179,240	203,912
6	111,519	144,000
7	72,335	146,448
8	102,183	179,211
Total	1,278,720	1,674,271

II. Behavior Prediction Model Development

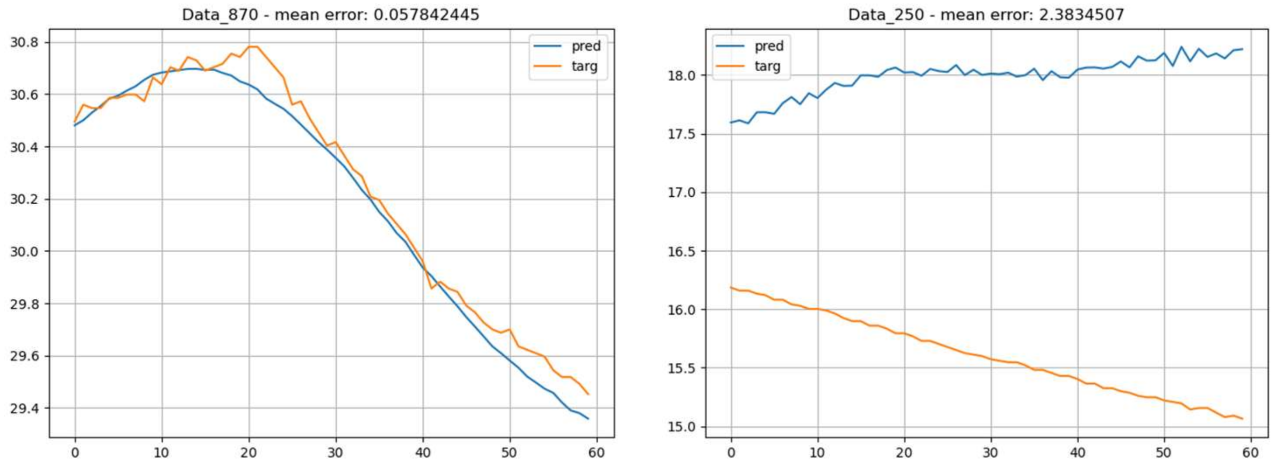
- Model development and training
  - Model based on MLP, LSTM architecture is developed (transformer architecture is currently under experiment).
  - Performance of LSTM model is much better than MLP model.
  - LSTM model consist of single LSTM layer, and 3 fully-connected layer after the LSTM layer.
  - MSE(mean-squared error) is applied as loss function, and Adam optimizer is used.



Input and output configurations for LSTM-based behavior prediction model

II. Behavior Prediction Model Development

- Experiment results
  - Trained LSTM-based model can predict future cooling tower outlet temperature with error about 0.18℃.
    - Without data augmentation, prediction error was about 0.24℃
  - For the data corresponds to full-power or near-full-power operation, prediction error of the model was about 0.10℃.
    - For MLP-based model, prediction error was about 0.47℃.
  - For the data corresponds to low-power operation and the data with severe temperature fluctuation, the prediction error tended to be higher, larger than 0.20℃.
    - In particular, since the cause of the relatively high error for the low-power operation data is likely to be another data imbalance problem, it is expected that the model's prediction error could be further reduced through the application of additional data augmentation.



Example of predictions
(left) example of result with relatively low error
(right) example of result with relatively high error

III. Conclusion

III. Conclusion

- Conclusion
  - HANARO secondary cooling system behavior prediction model is developed.
  - To consider the atmospheric conditions, both HANARO operation variable data and atmospheric data are acquired.
  - Developed LSTM-based model can predict cooling tower outlet temperature within about 0.18℃ error in average.

- Limitations
  - For the data correspond to low-power operation and the data with severe temperature fluctuation, the prediction error tended to be higher, larger than 0.20℃.
  - Conditions related to the basin and external water supply is not considered.

- Future works
  - Development of decision support system prototype based on developed behavior prediction model.
  - Improvement of model via applying additional data augmentation to cover the data corresponds to low power operation and the data with severe temperature fluctuation.
  - Development of more realistic model by considering external water supply.

Acknowledgment

This research was supported by a grant from Korea Atomic Energy Research Institute (KAERI) (No. KAERI-524450-23)

Thank you for your listening