부산대학교
PUSAN NATIONAL UNIVERSITY

Computational Multi-Fluid Dynamics Lab.

Research activities and plans

March 2022

June Kee Min

Professor

June Kee Min, Ph.D. (Professor)

▪ Education

- 1999 Ph.D. Dept. of Mechanical Engineering, KAIST
- 1990 M.S., Dept. of Mechanical Engineering, KAIST
- 1988 B.S., Dept. of Naval Architecture, Seoul National University

▪ Professional experiences

- 2017 ~ Present: Pusan National University, School of Mechanical Engineering, Professor
- 2021 ~ 2022: University of Florida, Visiting Professor
- 2013 ~ 2017: Pusan National University, Rolls-Royce University Technology Centre, Assistant Professor
- 2008 ~ 2013: Pusan National University, Rolls-Royce University Technology Centre, Research Professor
- 2003 ~ 2008: Samsung Electronics Co. LTD., Principal Engineer
- 2000 ~ 2002: LG Electronics Inc., Senior Engineer
- 1990 ~ 1993: LG Electronics Inc., Junior Engineer

▪ Projects (On-going)

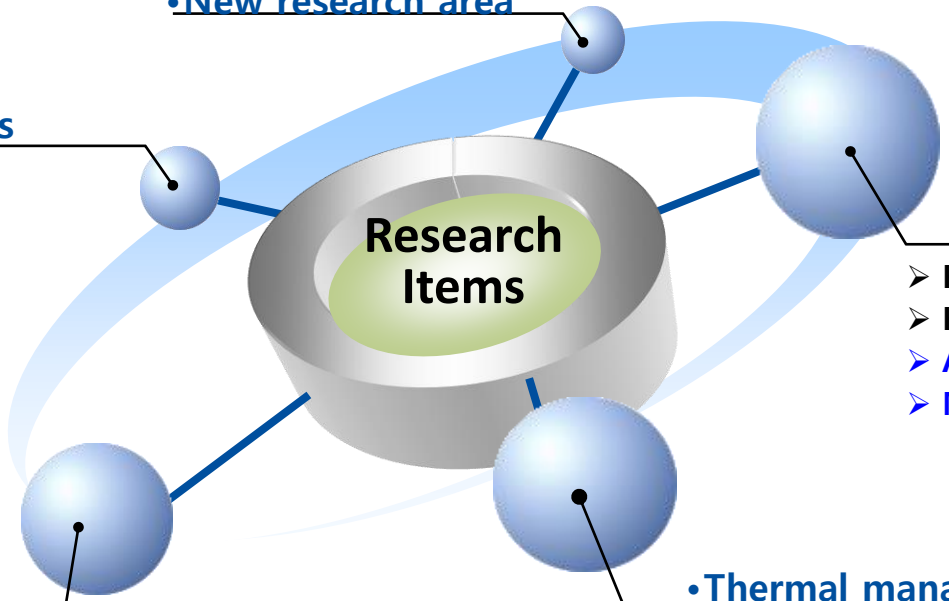
- National Research Foundation of Korea (NRF)
- Korea Institute of Energy Technology Evaluating and Planning (KETEP)
- Agency for Defense Development (ADD)
- Rolls-Royce plc
- LG electronics
- Research Institute of Industrial Science & Technology (RIST)
- Daewoo Shipbuilding & Marine Engineering (DSME)

CFD and CMFD

- **CFD**
  - ✓ Computational Fluid Dynamics
- **CMFD**
  - ✓ Computational Multi-Fluid Dynamics
- **Multi-**
  - ✓ Multi-phase
  - ✓ Multi-Physics
  - ✓ Multi-Objective
  - ✓ Multi-Disciplinary

Research area

"Advanced CFD modeling and thermal management technology for future power-energy system"

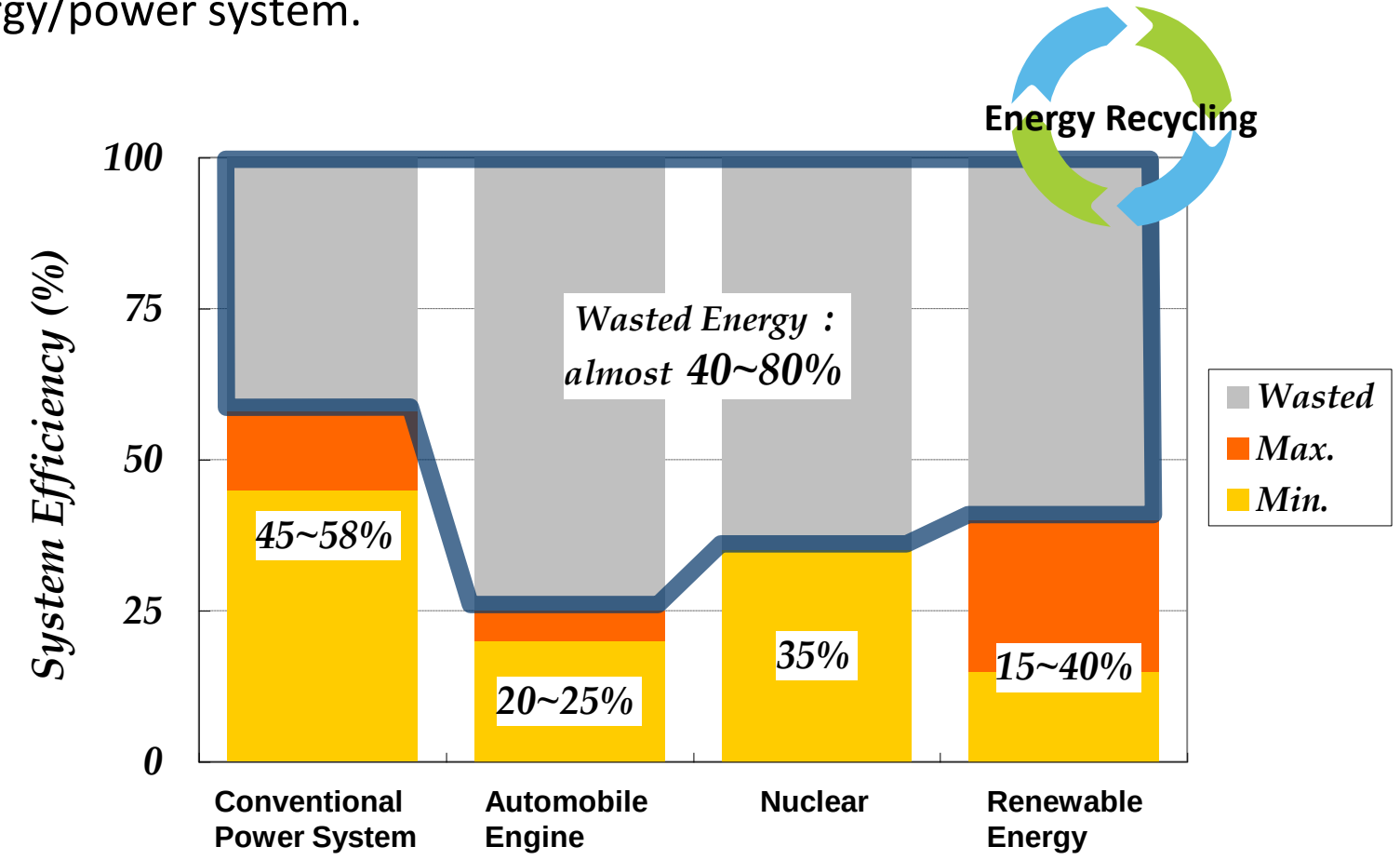


- New research area
- Industrial applications
  - Foaming
  - Freezing
  - Frosting/Condensation
  - Heat Exchanger
  - Fluid machinery
- Advanced numerical modeling
  - Fluid-Structure Interaction
  - HX shape optimization
  - Aero-thermal topology optimization
  - Machine learning(ANN/CNN/GAN)
- CFD for multi-phase flow
  - HVAC&R
  - Cryogenic
  - Multi-phase design tool
  - Nuclear system
  - 3D CFD multi-phase model
- Thermal management technology
  - Novel heat exchanger (future power-energy system)
  - Electro-chemical system
  - Cryogenic system
  - Heat Pipe & Integrated HM project
  - Oil de-congealing
  - Design tools
  - Gas turbine (HPHT)
  - Battery thermal management

- **Thermal management technology**
- Advanced numerical model for aero-thermal system
- CFD for multi-phase flow
- Research programs

Why thermal management technology?

- In conventional power system, **40-80% energies are wasted.**
- The development of **Thermal Management Technology** is a key for the future energy/power system.



Application of thermal management tech

Power and
Industrial Plant

Aerospace
(Civil/UAV)

Thermal
Management

Naval
Marine

Hybrid
Fuel Cell

Carbon Capture
& Storage

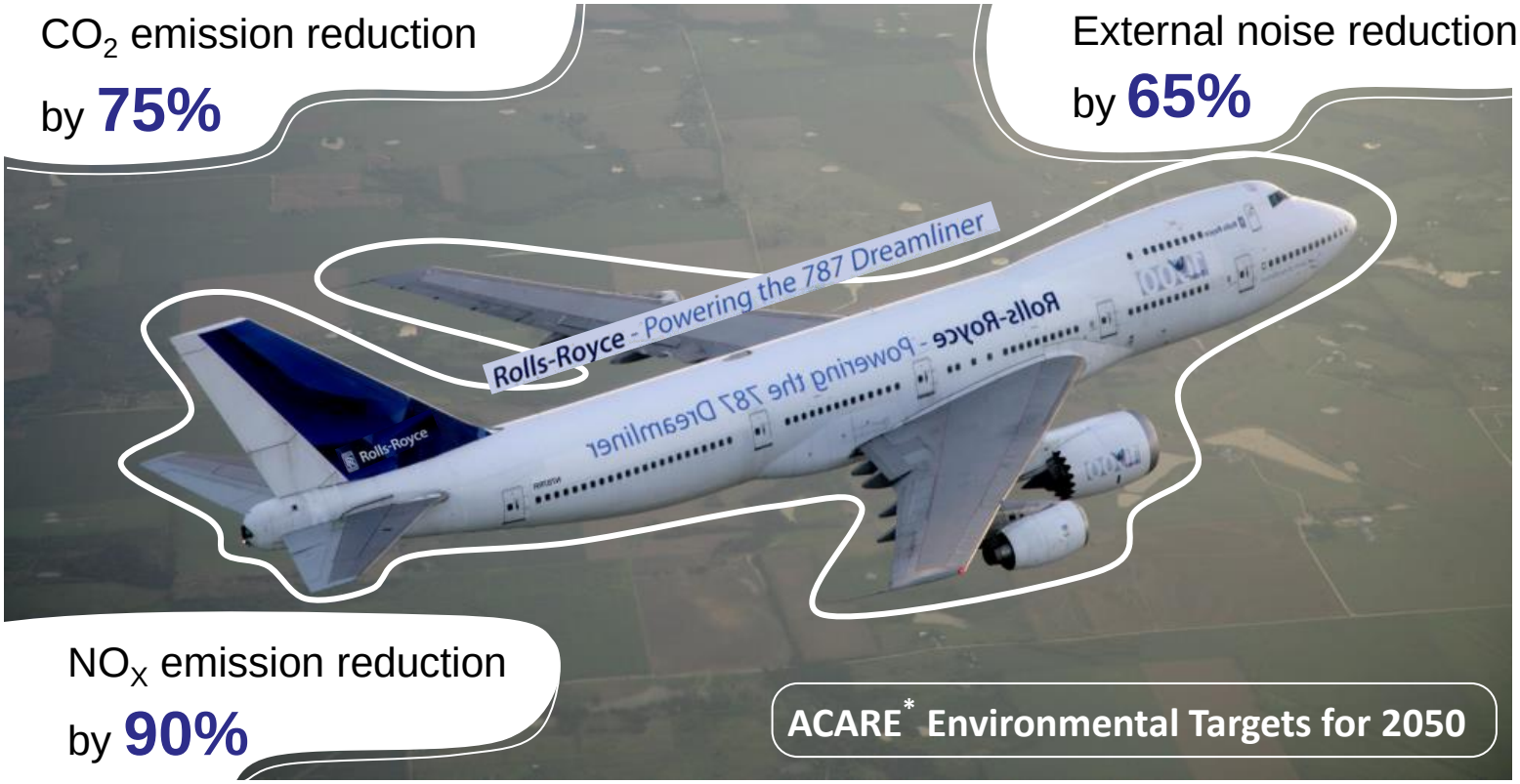
Advanced gas-turbine cycle for aero-engine

- **FlightPath 2050 goals (2011)**

  : Relative to the capabilities of typical new aircraft in 2000.

CO_2 emission reduction by **75%**

External noise reduction by **65%**



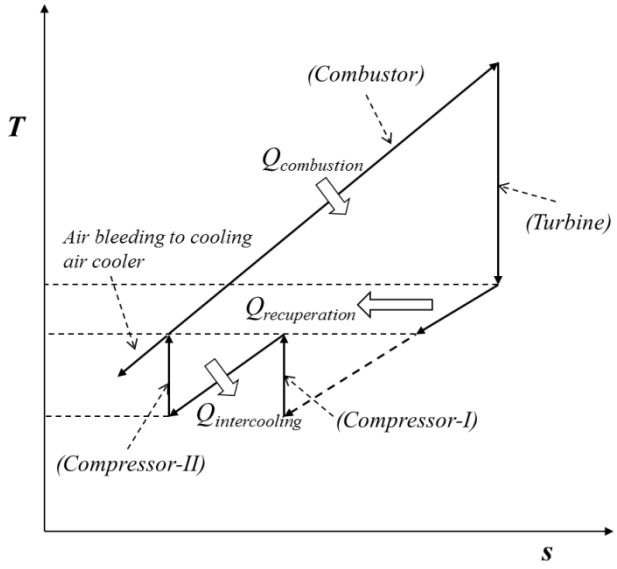
NO_X emission reduction by **90%**

ACARE* Environmental Targets for 2050

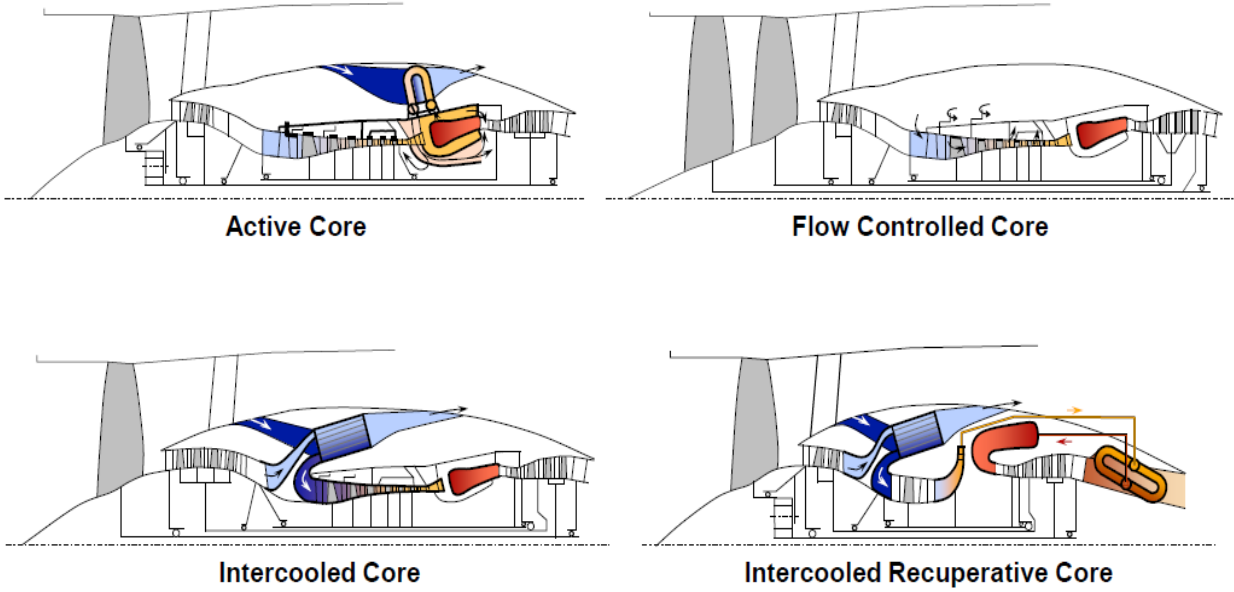
***Advisory Council for Aerospace Research in Europe**

Advanced gas-turbine cycle for aero-engine

- Development of **ultra-light and highly reliable novel thermal management system** for **HTHP condition**.



Advanced Brayton cycle with recuperator, intercooler and cooling air cooler

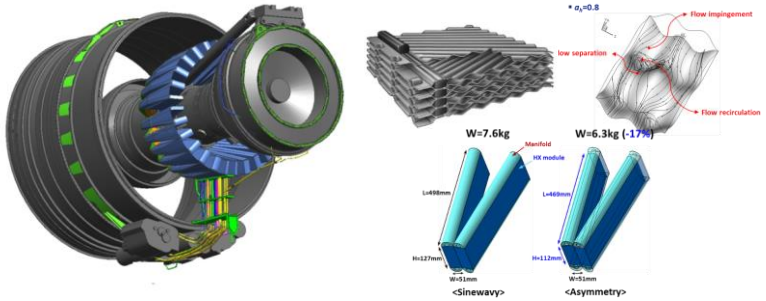


Various concepts for aero-engines (EU-FP NEWAC programme)

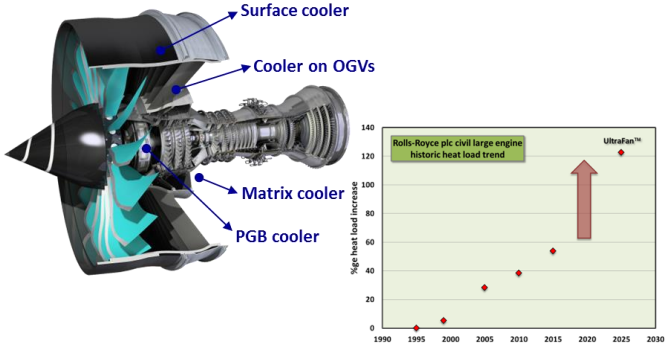
Novel HXs: gas turbine application

- Development of **ultra-light and highly reliable novel thermal management system** for **HTHP condition**.

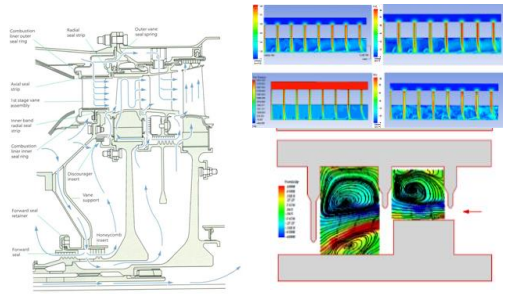
- **Intercooler for aero-engine (EU-NEWAC programme)**



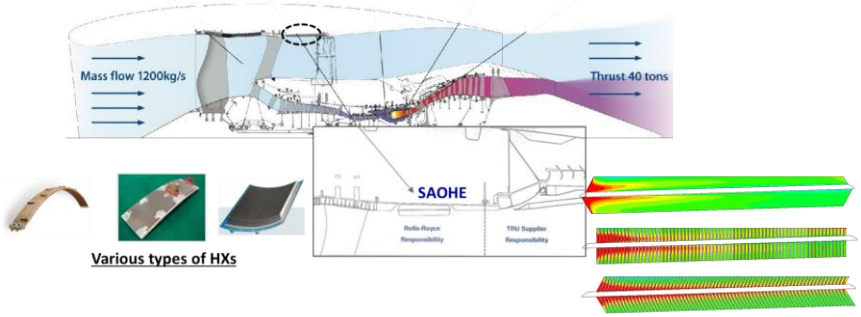
- **Ultra-fan oil cooling (EU-NEWAC programme)**

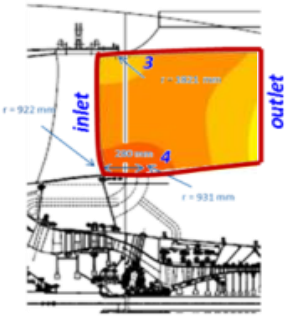


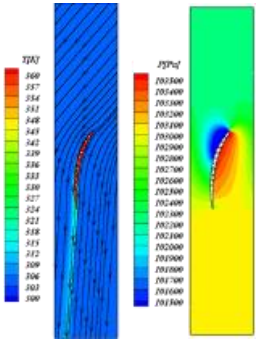
- **GT Case cooling (MOD UAV-project)**



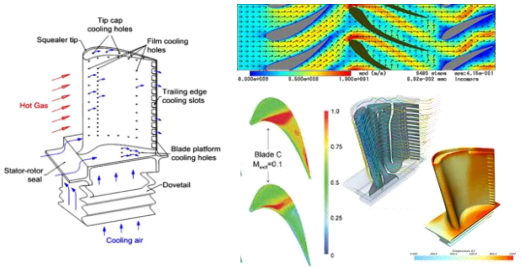
- **Surface cooler (Trent-XWD aero-engine)**







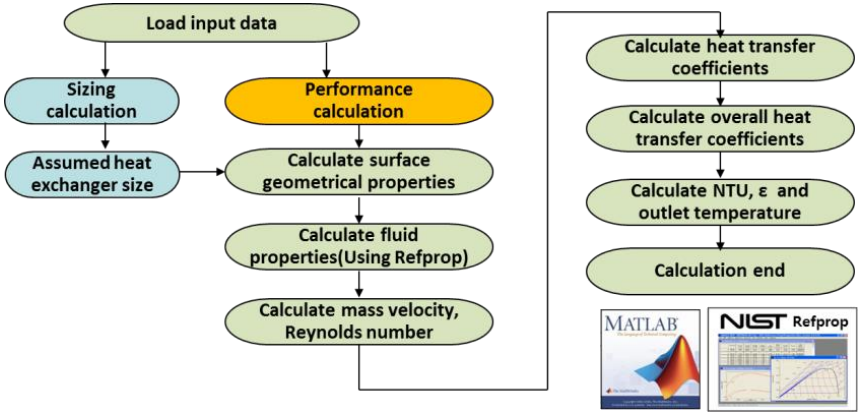
- **Turbine blade cooling for power gen**

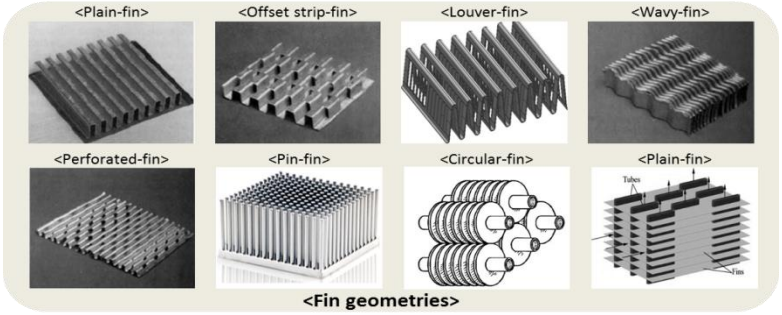


Novel HXs: In-house design tools

• Ranking program (HXRP)

- HXRP (latest version: **HXRP v3.0**)

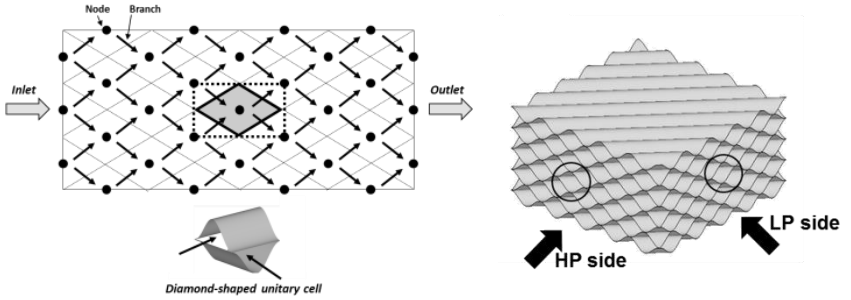




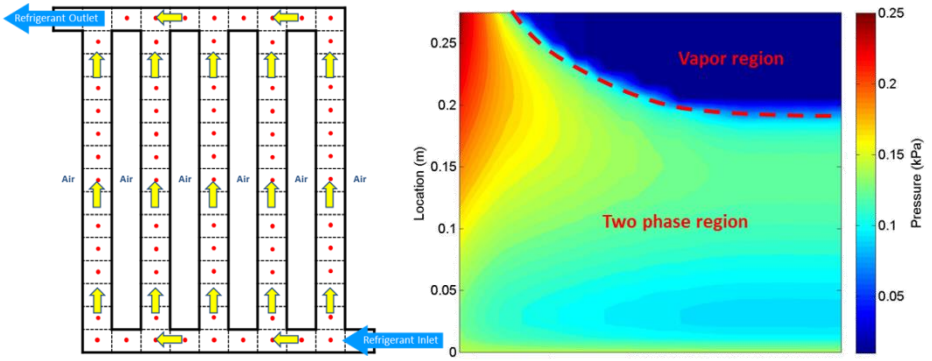
<Fin geometries>

• 1D network program

- Flow network analysis



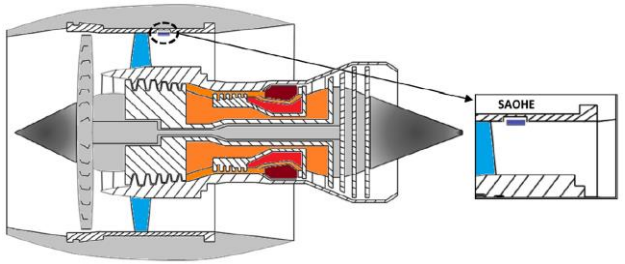
- Two-phase flow

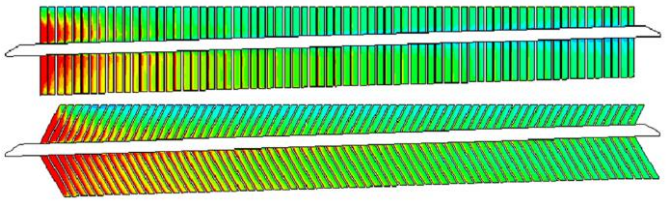


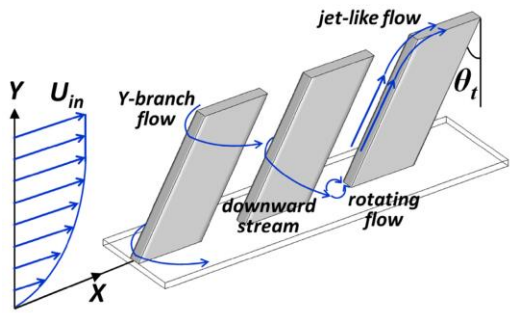
<MCHE matrix in 1D code>

Novel HXs: New heat sink

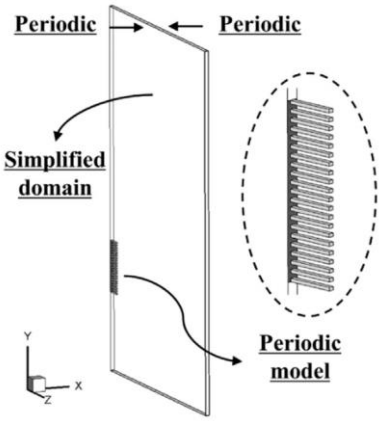
- Slanted-pin-fin cooler under a high-speed-condition

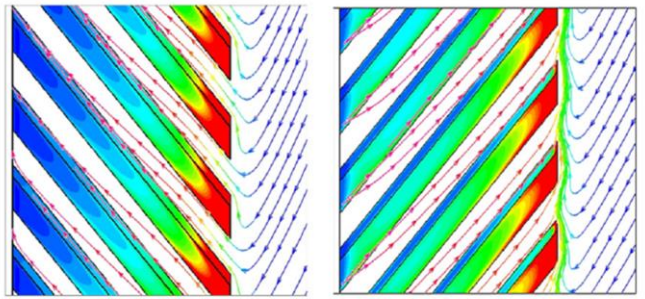




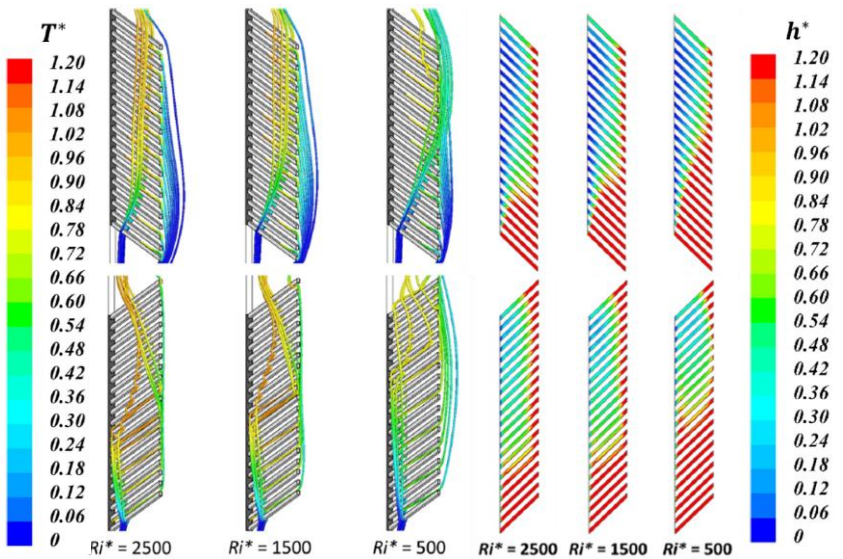


- Slanted-pin fins mounted on a vertical plate





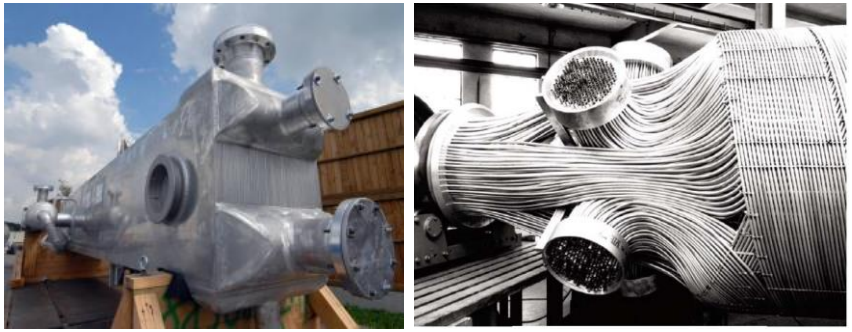
Natural convection



Mixed convection

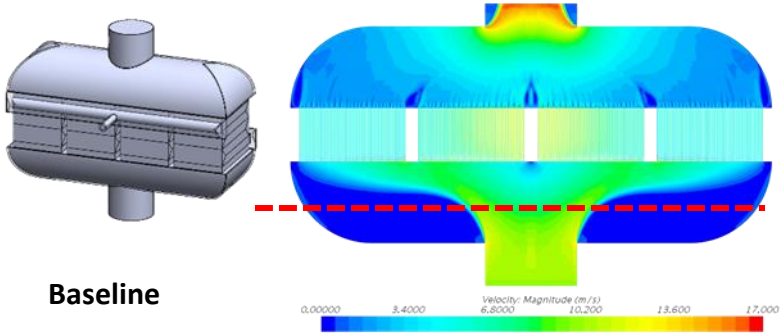
Novel HXs: Cryogenic (below -160℃)

- **Thermal design for multi-stream/multi-pass HX**

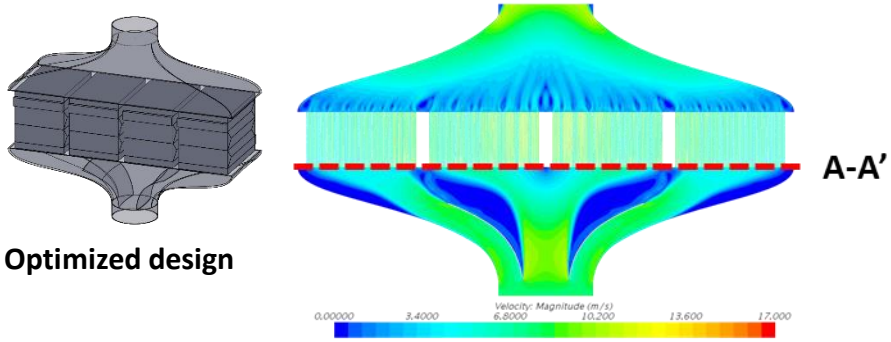


Engineering application: LNG tanker

- **Printed Circuit Heat Exchanger(PCHE) under supercritical conditions**

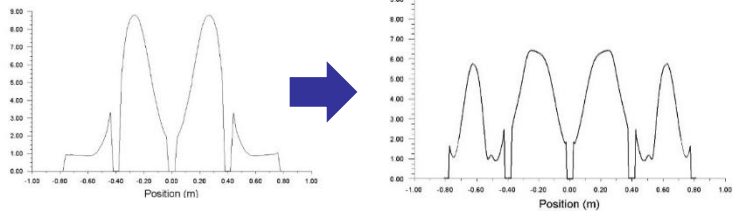


Baseline



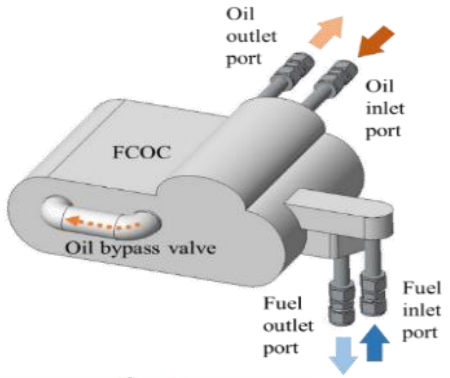
Optimized design

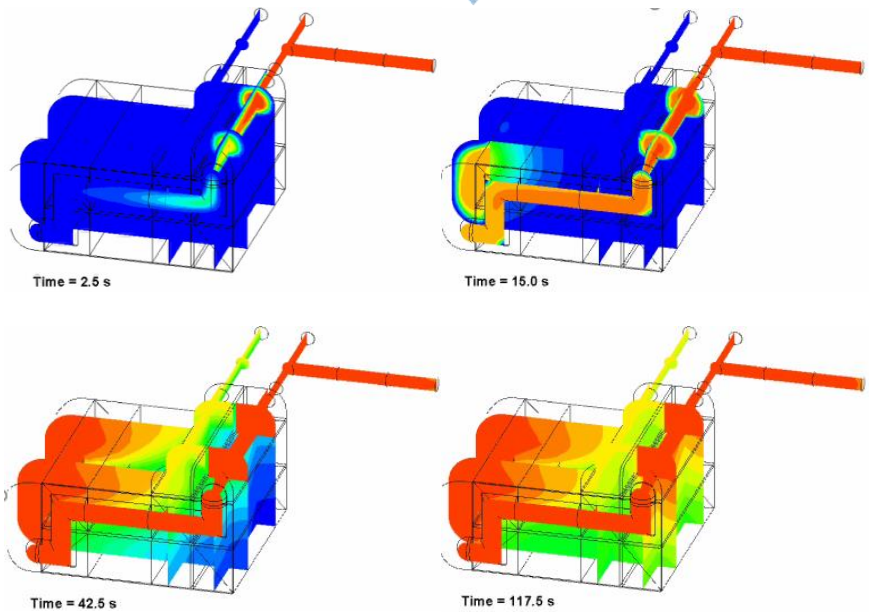
A-A'

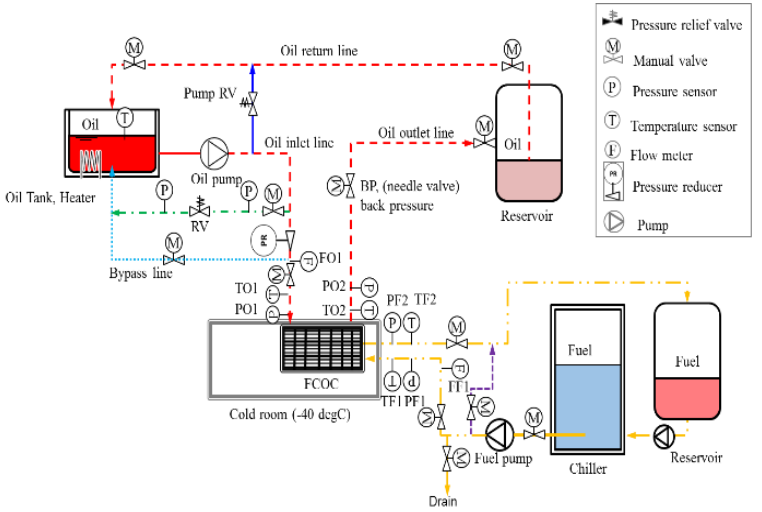


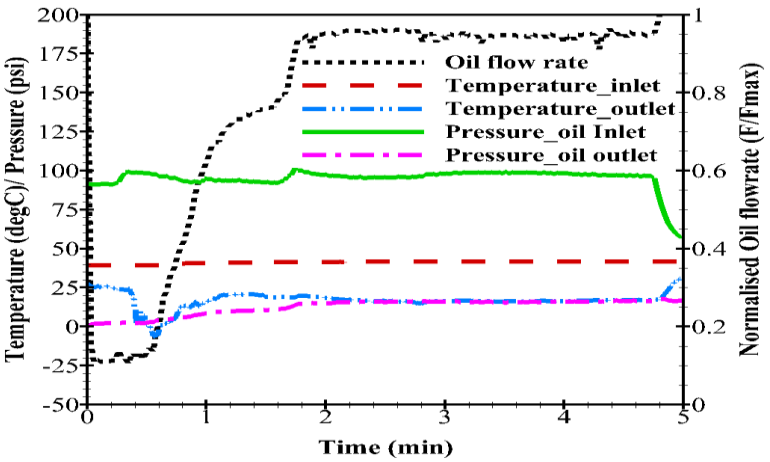
HXs: New challenges

- Oil-congealing inside a heat exchanger (Transient temp variation from -40 ℃)
  - Improved HX CFD models
  - Experiment





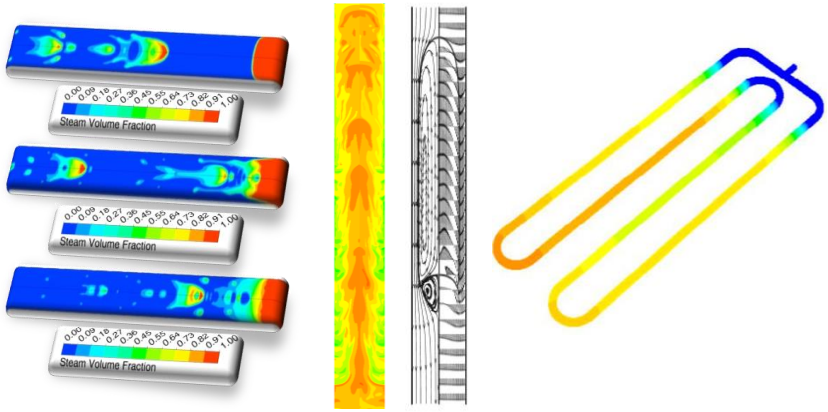




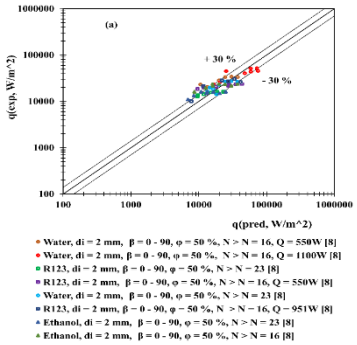
New challenges

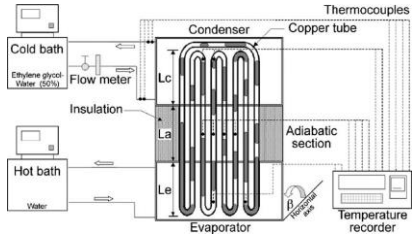
•Design tech for Heat Pipe application
(Harsh operating condition and large-scale)

- **3D CFD**



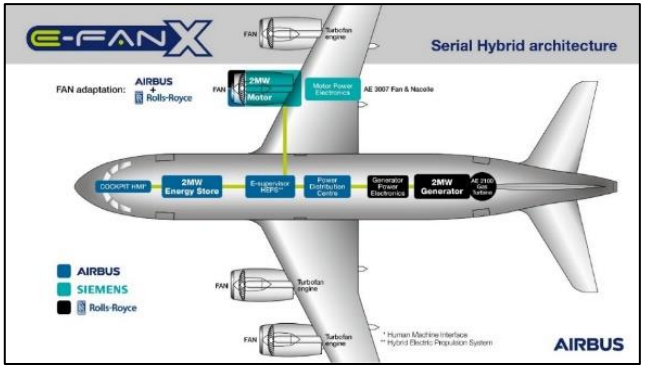
- **Performance correlations**



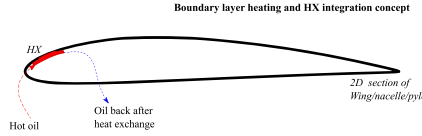


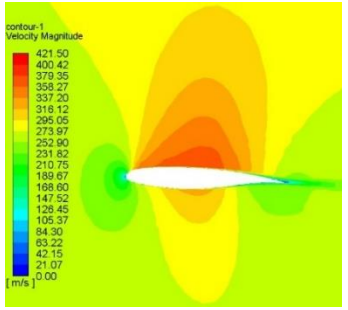
•Integrated heat management system
(For future aircraft thermal management)

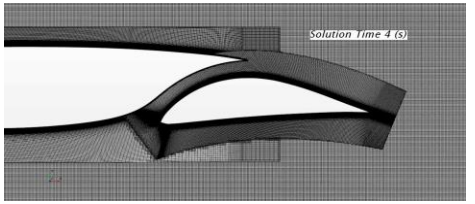
- **Increased electrification**

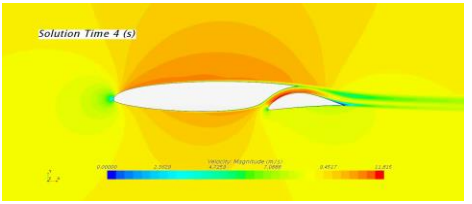


- **Airframe surface heating for HX integration concept**



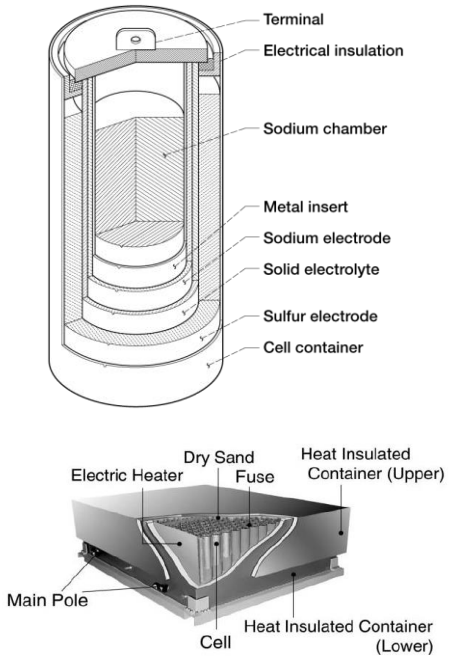




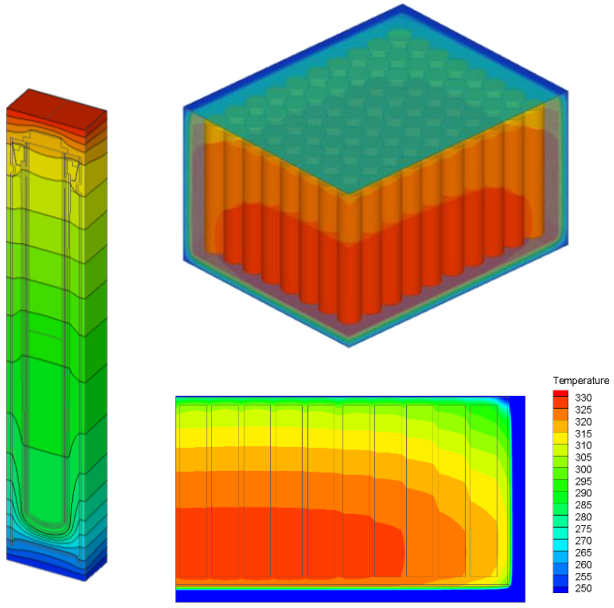


Thermal management for electro-chemical system

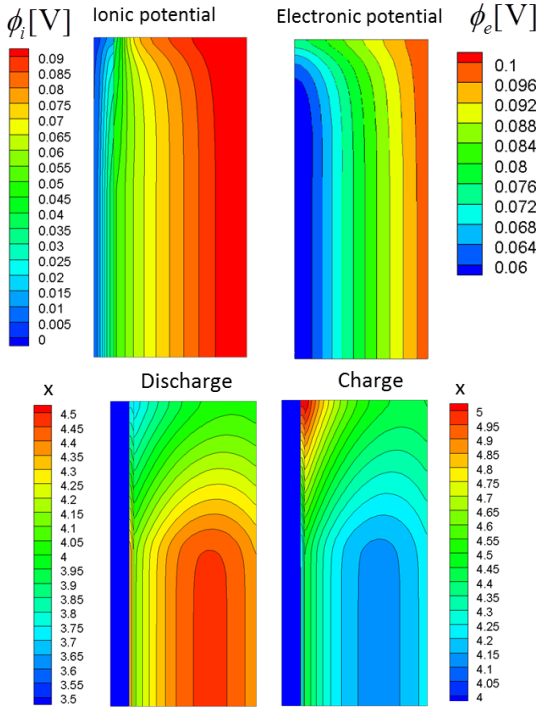
- **Thermal management inside a battery system (ESS): Molten NAS battery, 300-350℃**
  - **Temperature uniformity inside a ESS module**



Molten sodium-sulfur battery cell and module



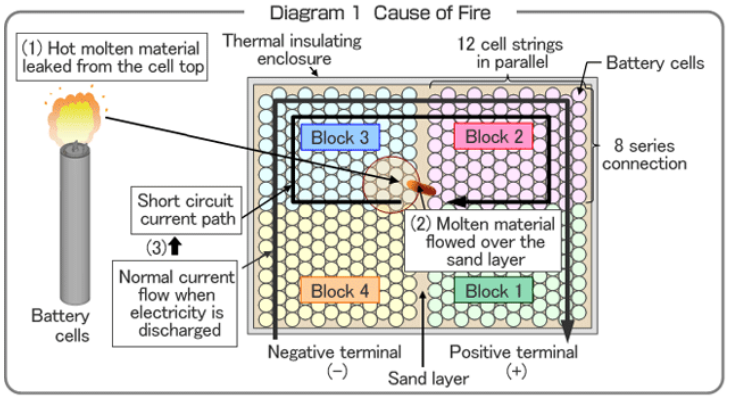
Temperature distribution inside the module during discharging/charging cycle



Potential and reactant distribution inside the cathode

Thermal management for electro-chemical system

- **Safety analysis methodology : temperature rise in the cell under failure mode (crack).**
  - **Accident report in ESS, Japan (2011)**



  - **Leak flow model**

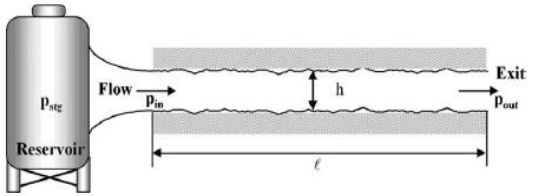
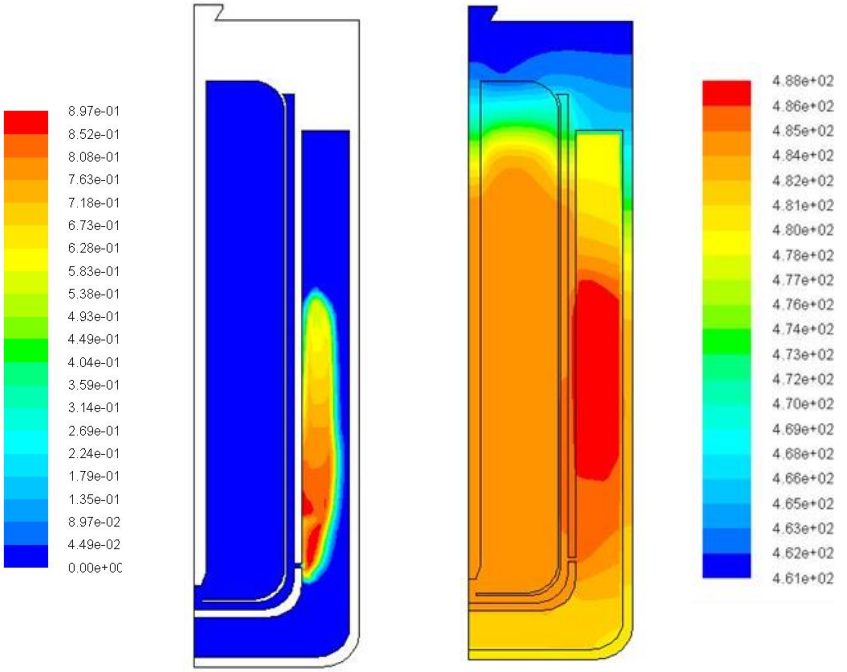


Fig. 1 Flow model in a narrow crack

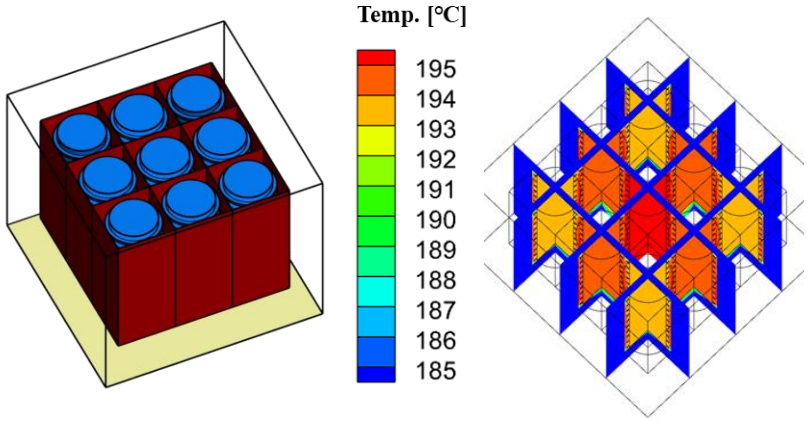


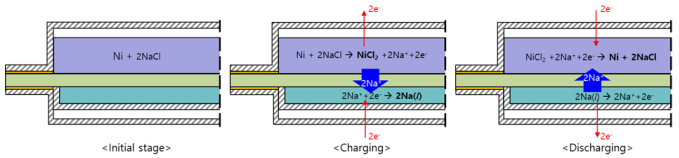
Mass fraction of reactant **Temperature distribution**

Thermal management for electro-chemical system

- **Thermal management inside a battery system (ESS): Na-$NiCl_2$, 190-200℃**
  - **Thermal design of ESS hotbox considering novel manufacturing process**

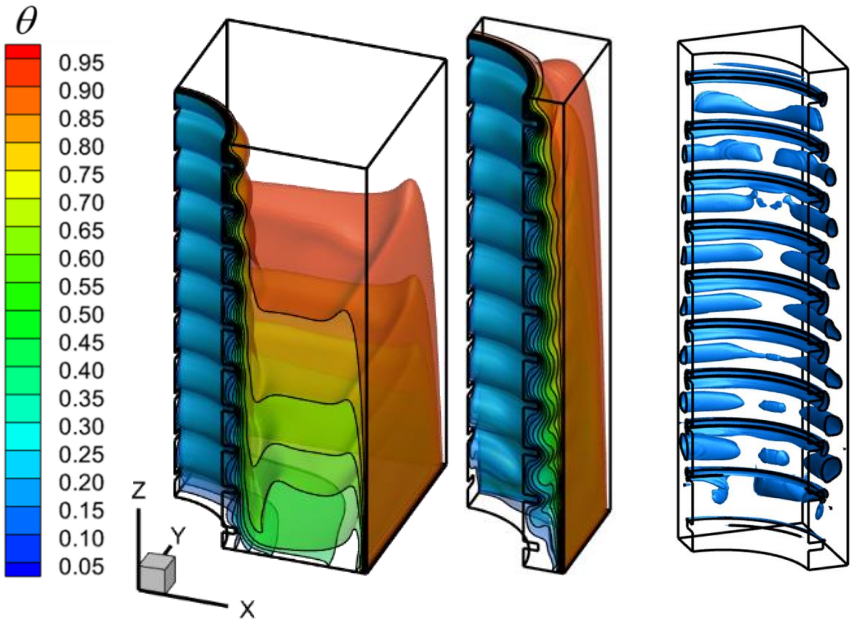
Temperature distribution





Electro chemical reaction

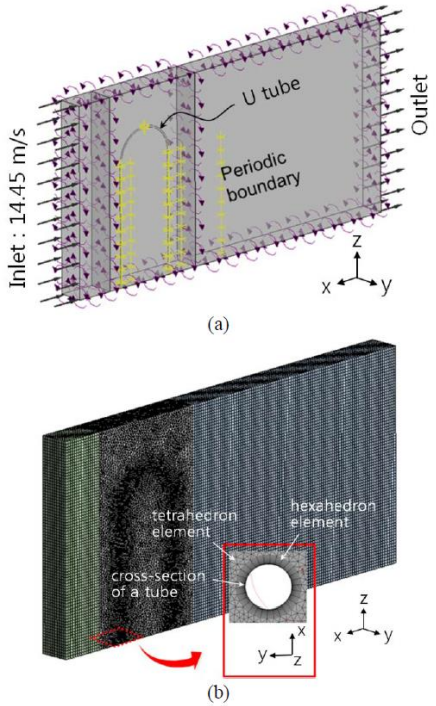
3D CFD



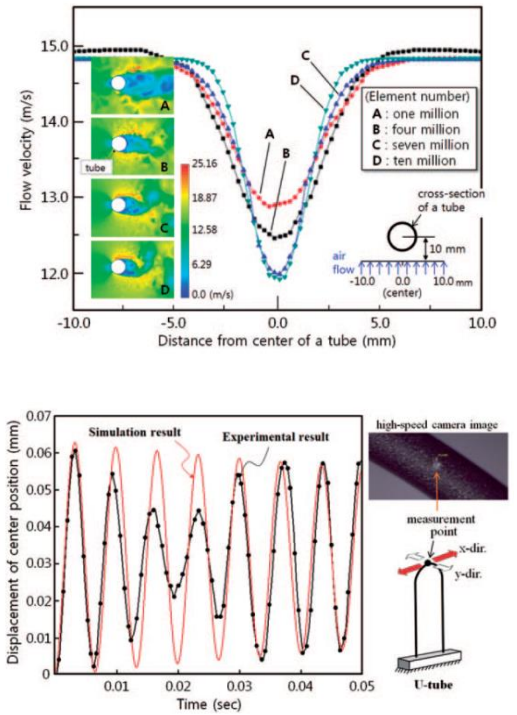
- Thermal management technology
- **Advanced numerical model for aero-thermal system**
- CFD for multi-phase flow
- Research programs

Fluid-Structure Interaction

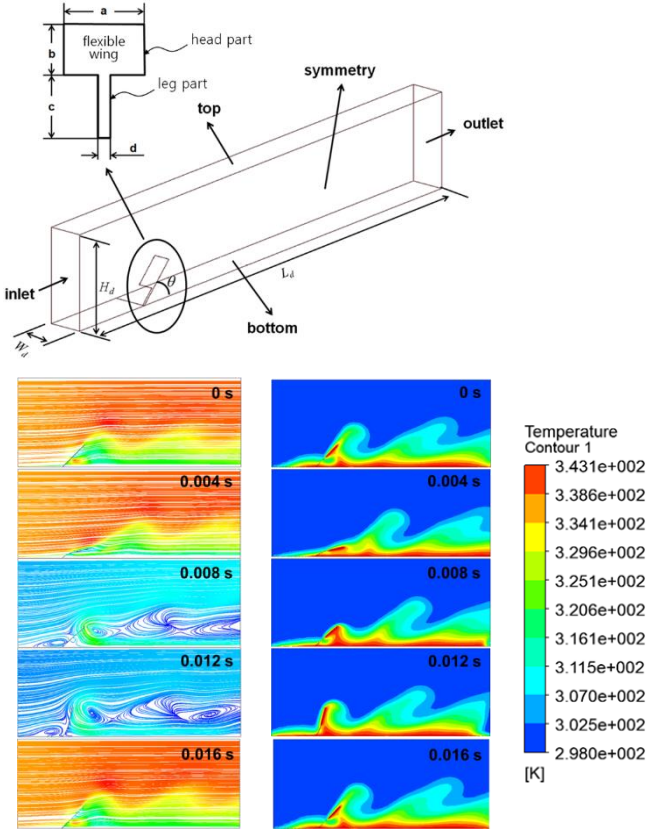
- **Vortex shedding and deformations of U-shaped mini-tube** for HX application
- **A study on a flexible wing with up-down vibration in a pulsating flow** of cooling air to improve heat transfer efficiency



Problem set-up



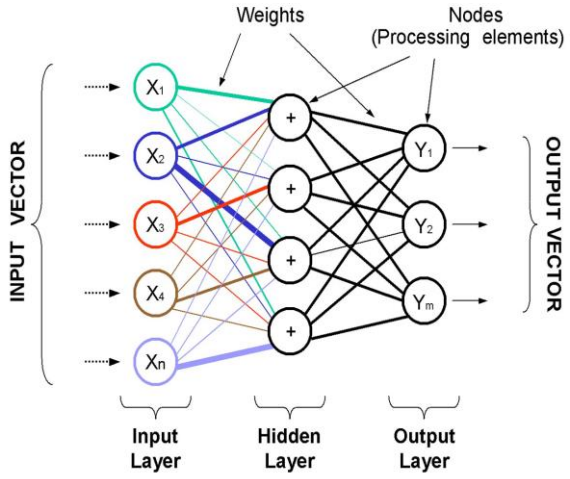
Comparison with experiment



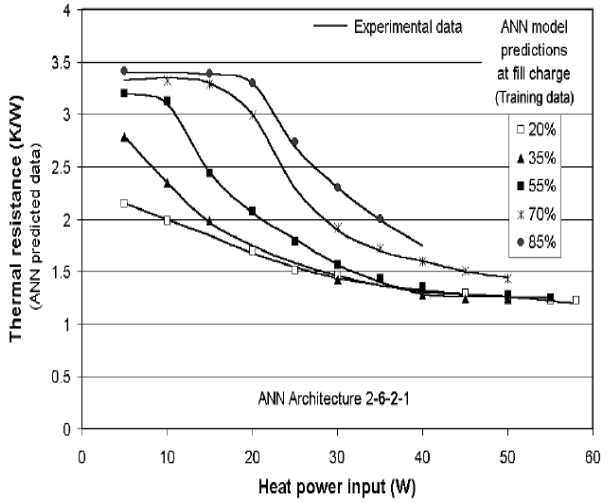
Flow and temperature field

Artificial Neural Network

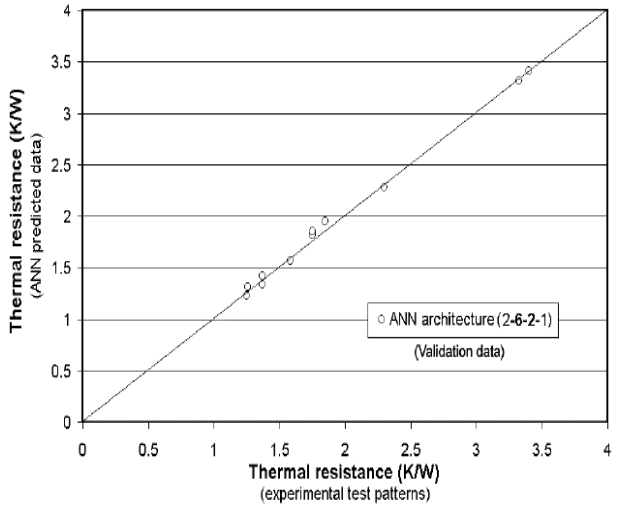
- **Performance correlations for Heat Pipe using ANN**
  - **Imitating and applying the utilities of human brain neurons** to predict the heat transfer of heat pipes. Used for highly non-linear predictions within an identified operating space.
  - **Faster speed,** high flexibility and high accuracy in prediction within the identified space
  - **Input layer : Heat flux and fluid filling ratio, Output layer :** thermal resistance



ANN neuron layout



ANN prediction of experimental data

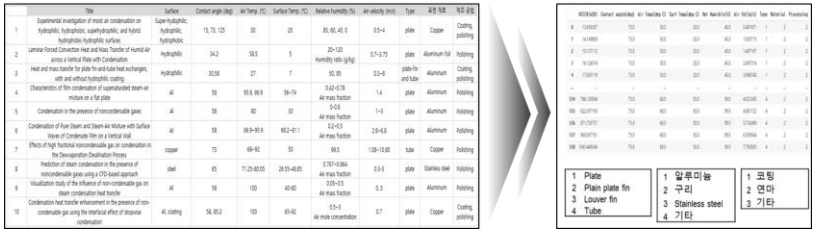


ANN validation of experimental data

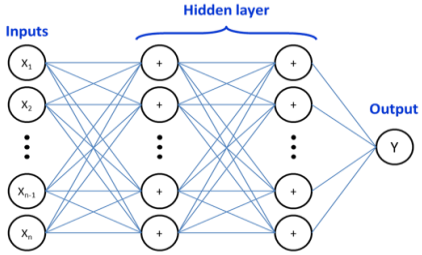
Challenges: Condensation application

•Development of ANN model

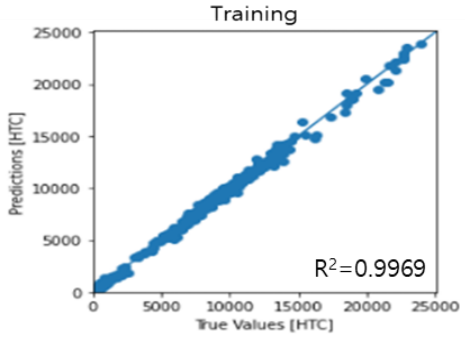
•ANN data processing

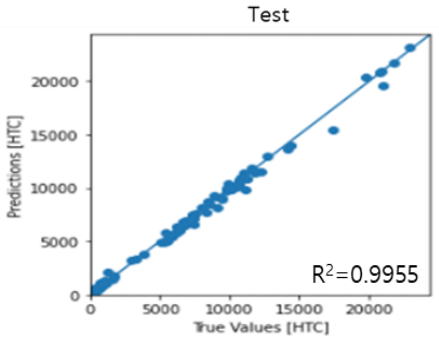


•Model development & prediction



Python/Tensorflow





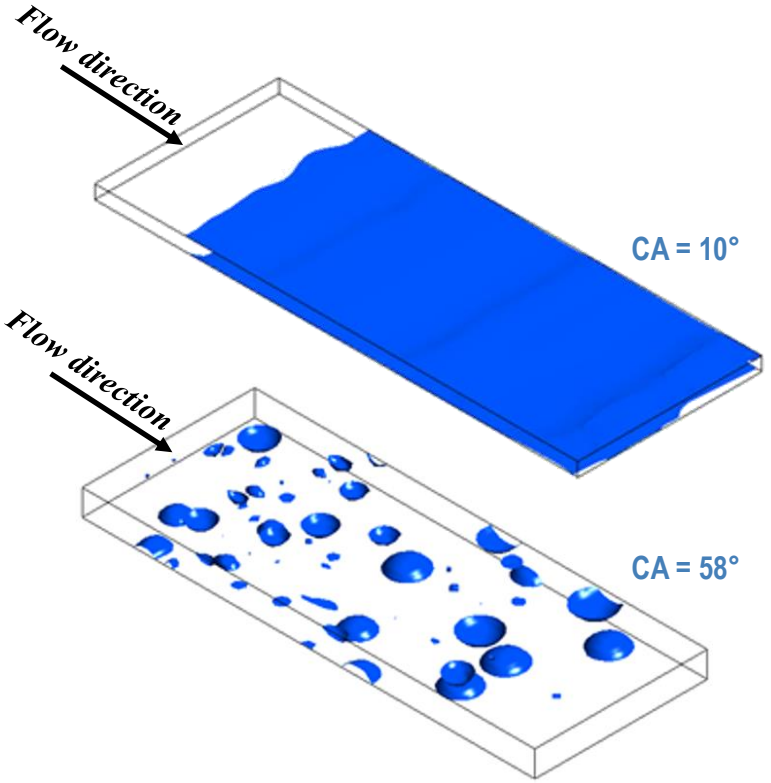
•CFD based on FVM

•CFD condensation results

Lee model (evaporation & condensation)

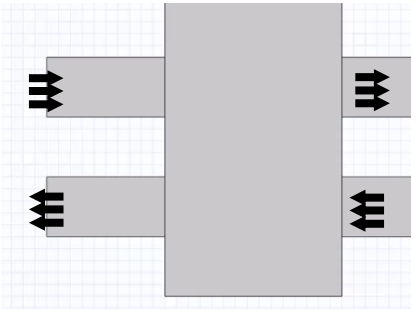
$$\dot{m}_v = r\alpha_v\rho_v\frac{T-T_{sat}}{T_{sat}}$$

tuning parameter from ANN prediction

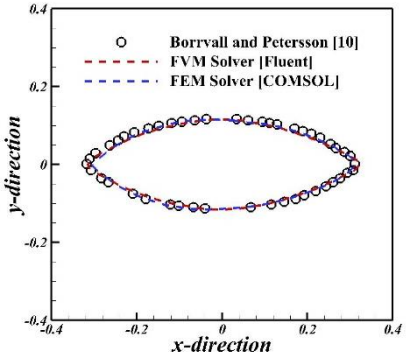


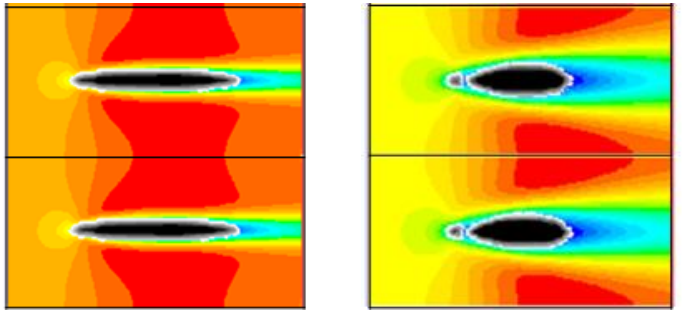
Challenges: Topology optimization

- **Topology optimization in thermo-hydraulic system**
  - Finite-Volume based topology optimization



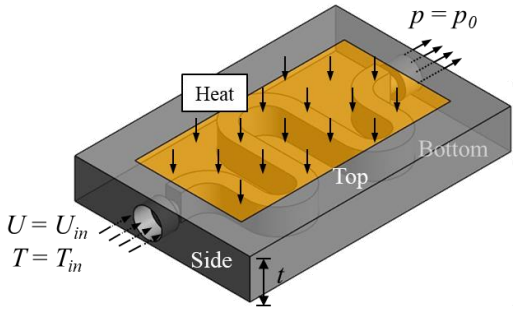
Duct design



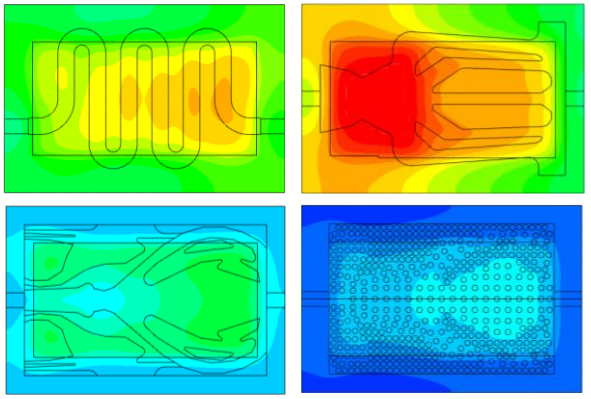


FVM based topology optimization (In-house code)

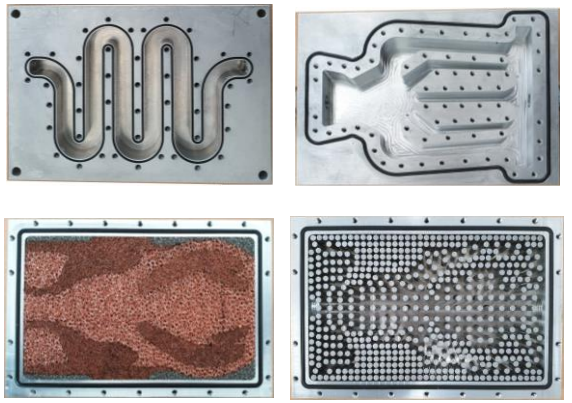
- **Application for aero-thermal topology optimization**



Path design for liquid-cooled heat sink



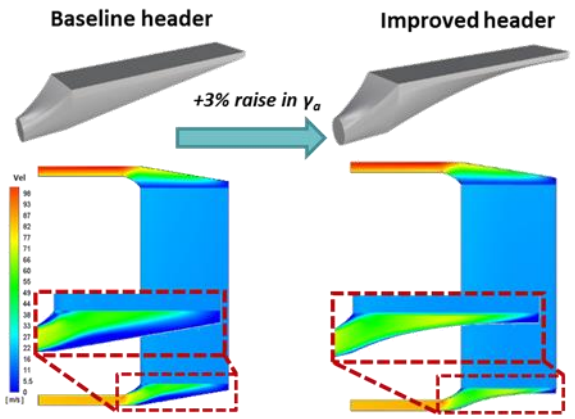
Temperature distribution



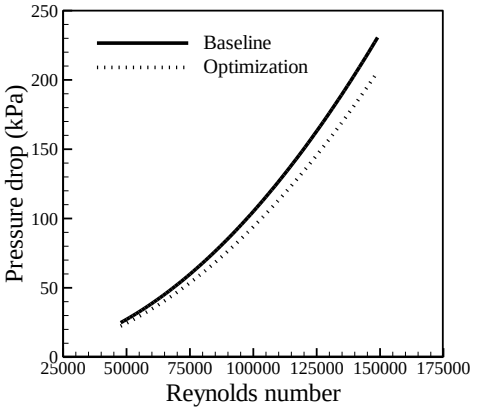
Manufacture

Challenges: Optimization for industrial

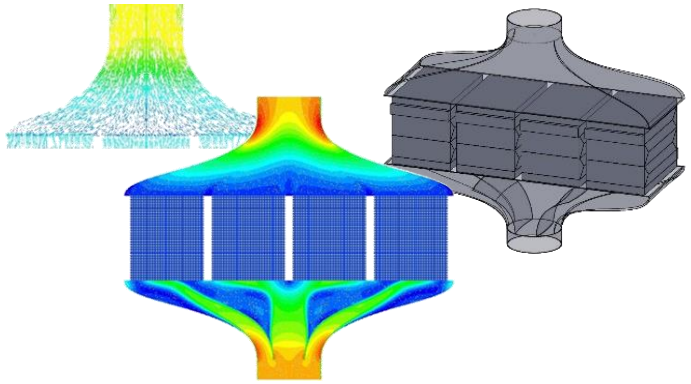
- **Shape optimization of HXs**
  - **HPHT conditions (1000K 50 bar)**



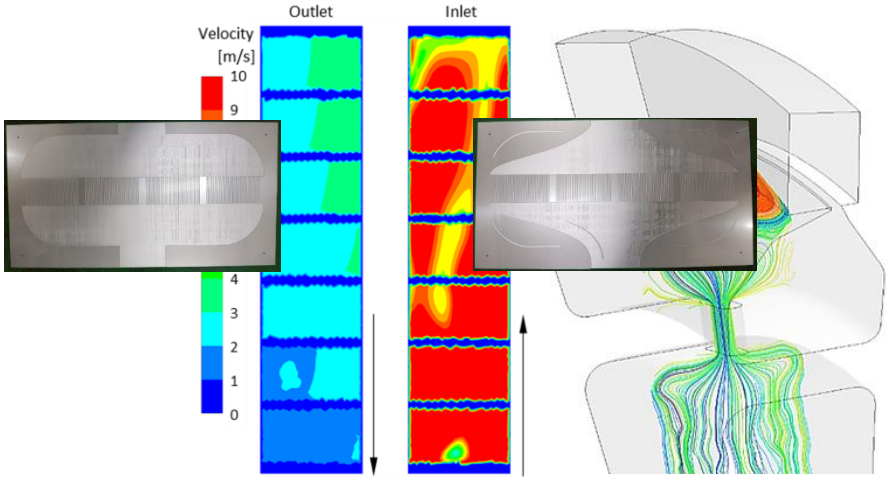
  - **Experiment**



  - **Cryogenic conditions (below -100℃)**

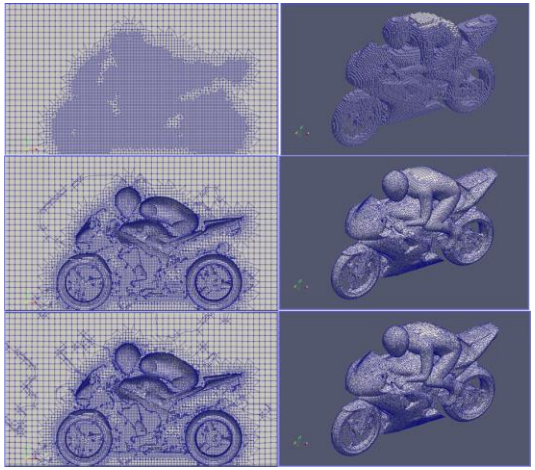


  - **Time-dependent HX evaluation**

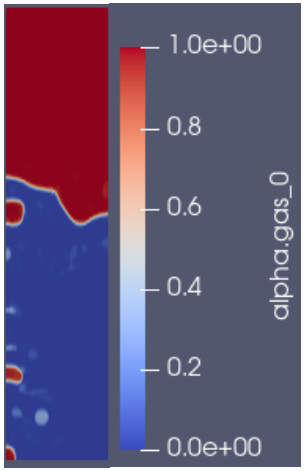


Challenges: OpenFOAM base solver dev.

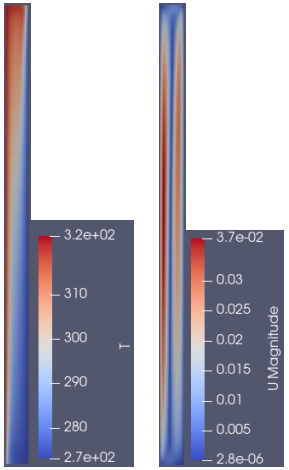
• Applications for OpenFOAM built-in function & solver



[Mesh generation]



[Phase change: Boiling]



[Natural convection: Boussinesq approximation]

• Advanced solver development

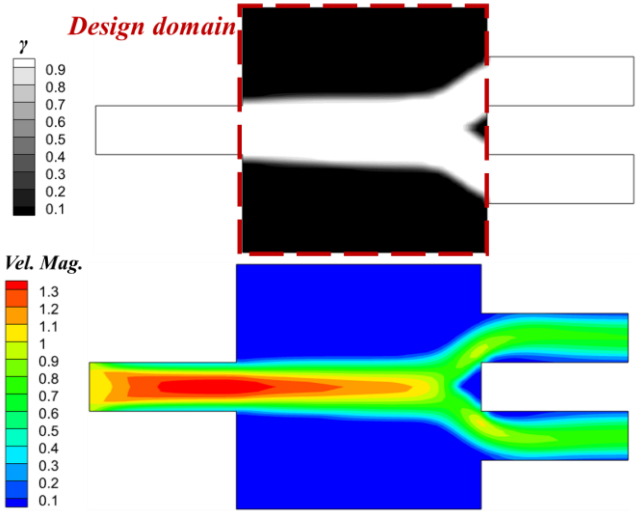
$$\alpha = \alpha_{\min} + (\alpha_{MAX} - \alpha_{\min})(1-\gamma)^P$$

$$\gamma = \begin{cases} 0 & (solid) \\ 1 & (fluid) \end{cases}$$

$$P = 3 \ \ (usually)$$

$$\phi = \int_\Omega \left\{ \frac{1}{2}\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \alpha(\gamma) u_i u_i \right\} d\Omega$$

$$\frac{d\phi}{d\gamma} \approx \frac{\partial \alpha_2}{\partial \gamma} = -p(\alpha_{\max} - \alpha_{\min})\gamma^{p-1}$$

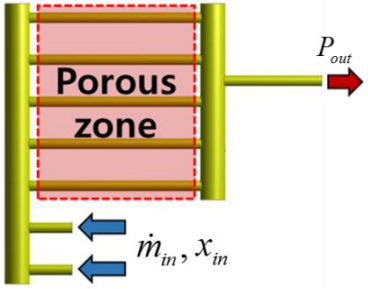


- Thermal management technology
- Advanced numerical model for aero-thermal system
- **CFD for multi-phase flow**
- Research programs

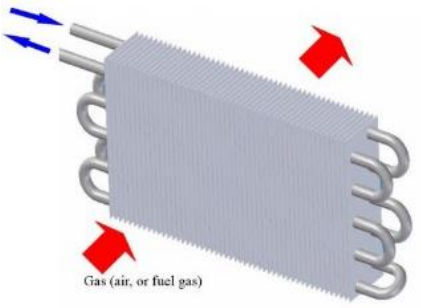
HVAC&R

- **3D CFD on the mal-distribution in multi-phase HX**
- **Development of improved phase change** model
- **Prelim code : 0D lumped model and 1D network solver**

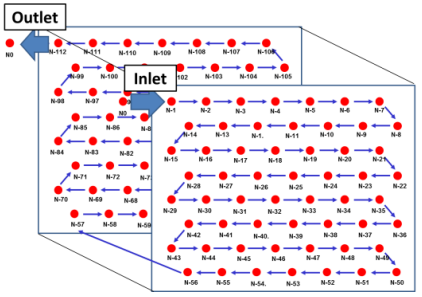
Actual header geometry



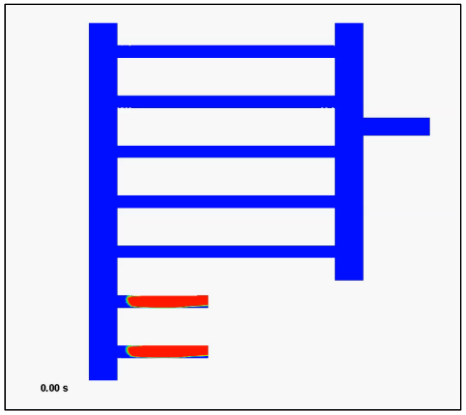
Equivalent HX model



Tube-fin multi-phase HX



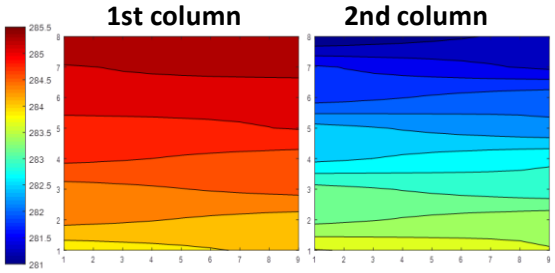
1D network model

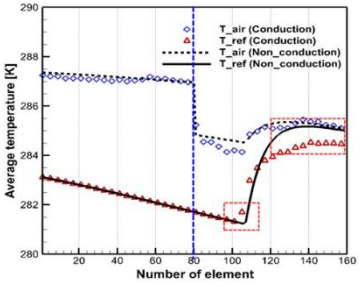


Volume fraction contour
(without phase-change)

Volume fraction contour

Temperature contour



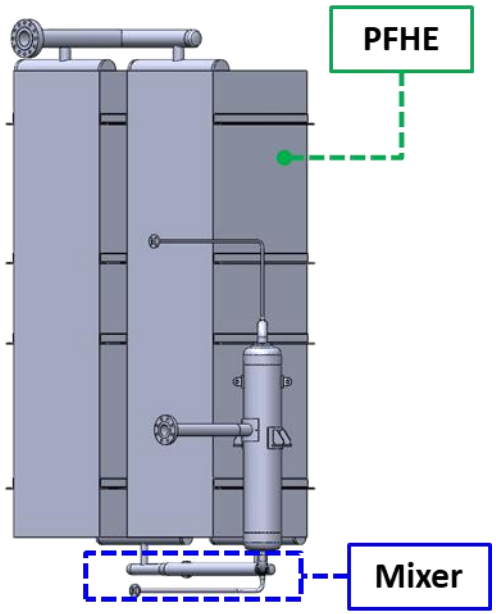


Temperature distribution of HX

Cryogenic: Liquefaction

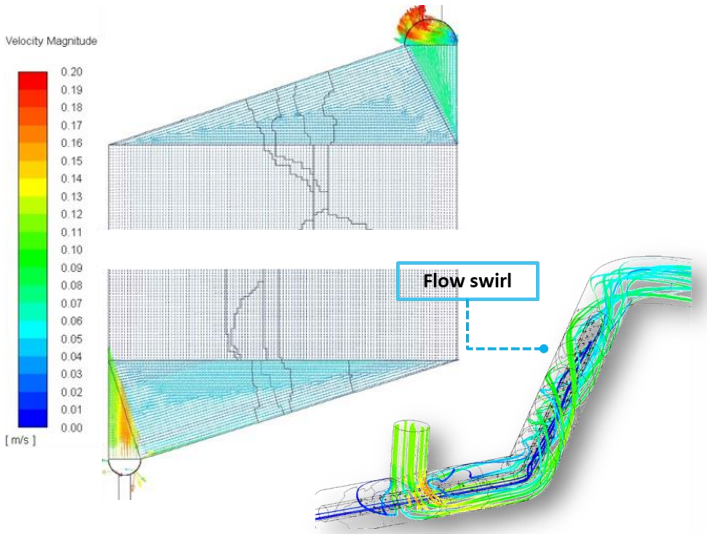
- CFD modeling for HXs, Mixers, Manifolds

- Cryogenic HX

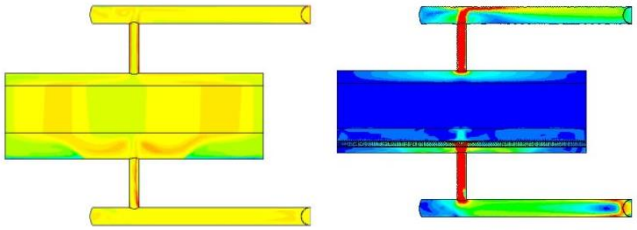


PFHE system

- Full-scale analysis

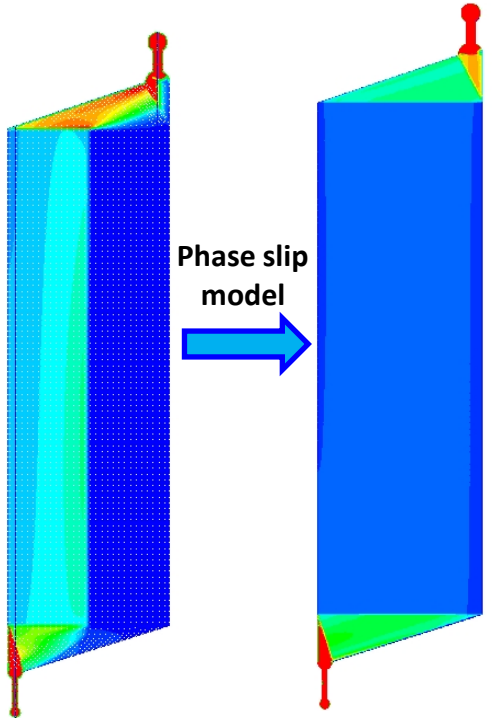


- Equivalent model development



Phase Velocity

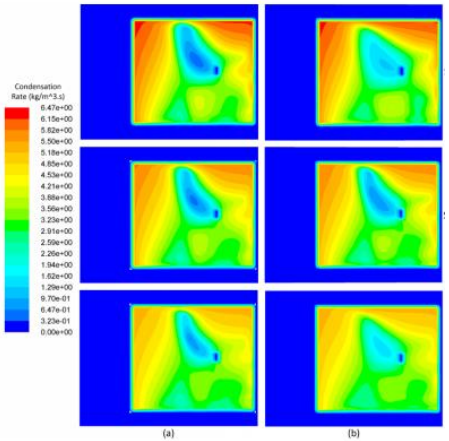
- Improved multi-phase model



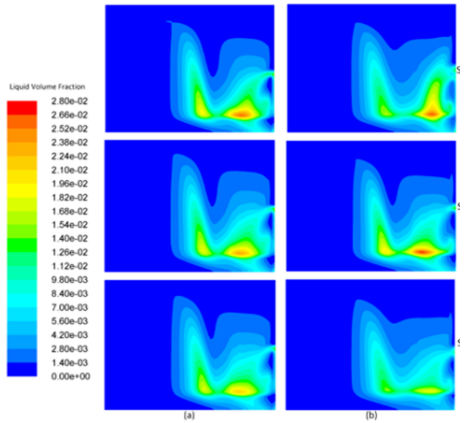
Visualization of internal HX flow pattern

Nuclear system

- Numerical analysis of the Condenser

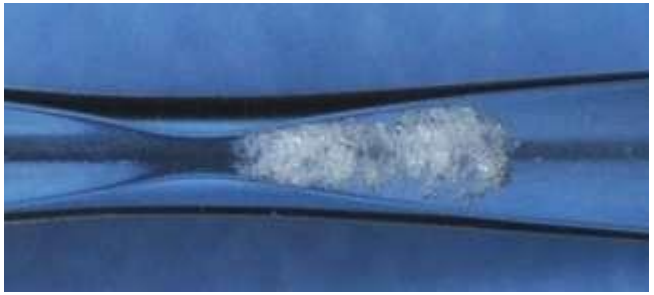


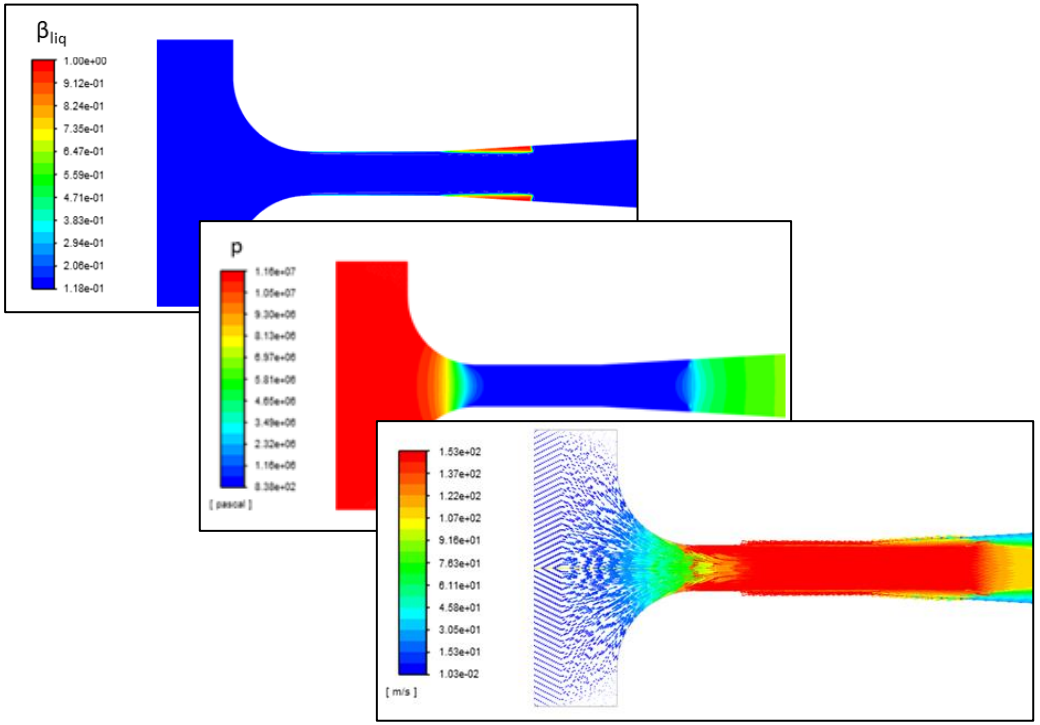
Condensation rate



Volume fraction

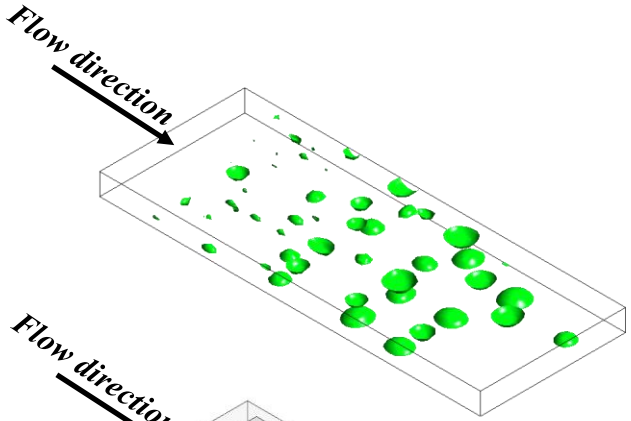
- Flow control of cavitation Venturi tube



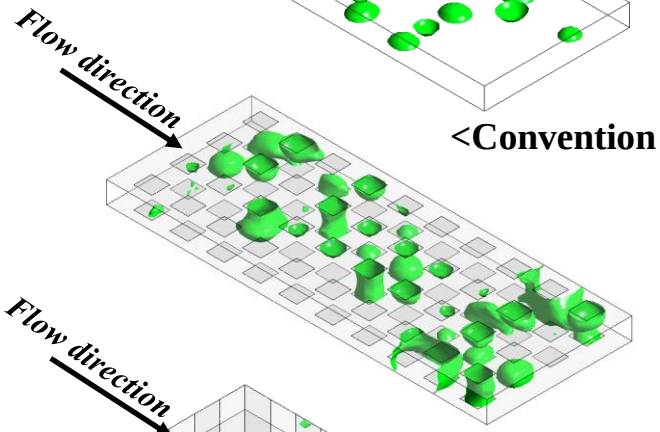


Condensation

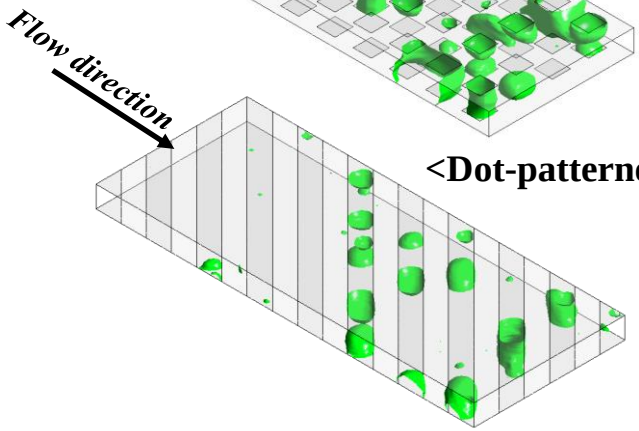
- **Fundamental study of condensation**



<Convention channel >

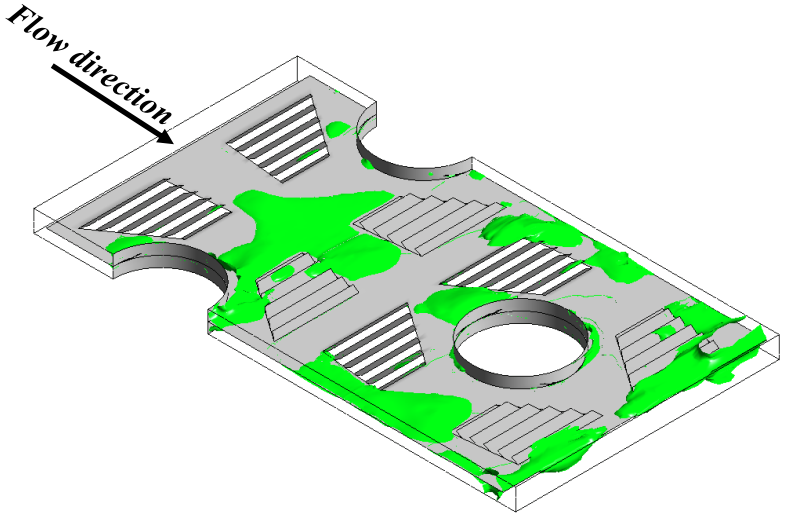


<Dot-patterned channel>

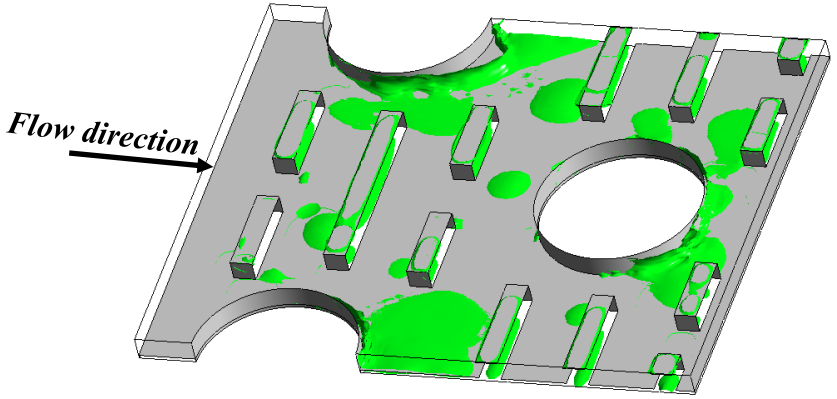


<Diagonal-patterned channel>

- **Unit cell analysis for a commercial heat exchanger**



<Louver fin >



<Slit fin >

Condensation film flow with DNS

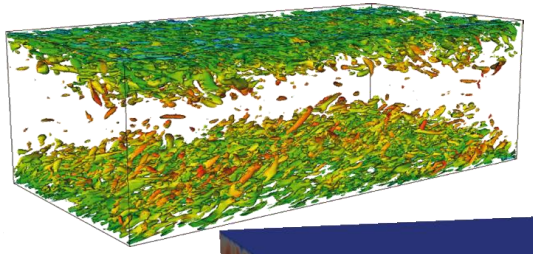
- **Spectral Element Method (Nek5000)**
  - Combined DNS + Film flow solver development through global research collaboration.

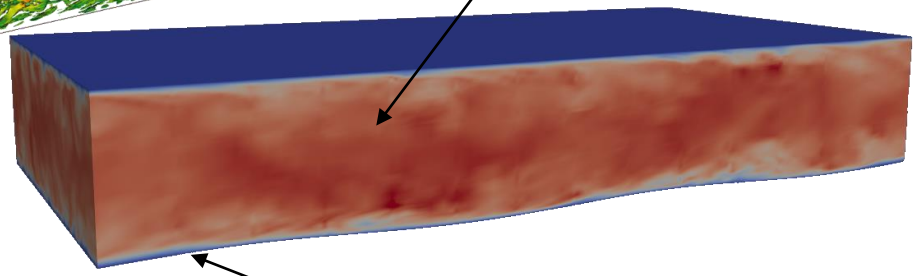
부산대학교 PUSAN NATIONAL UNIVERSITY

UF UNIVERSITY of FLORIDA

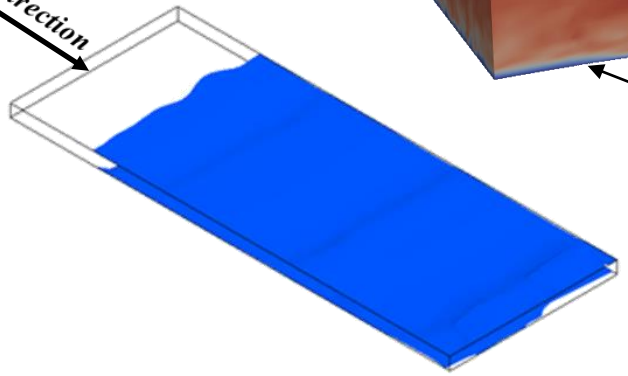
Nek5000

Argonne NATIONAL LABORATORY

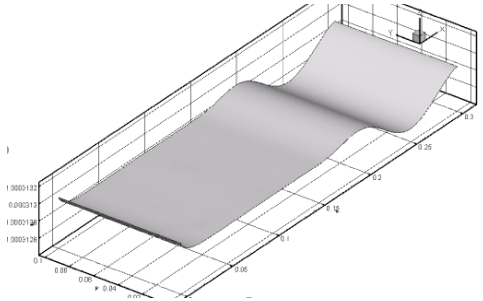


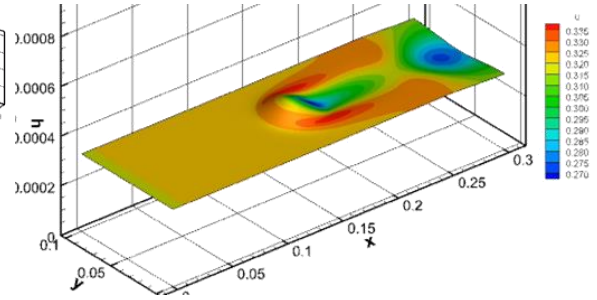


Flow direction



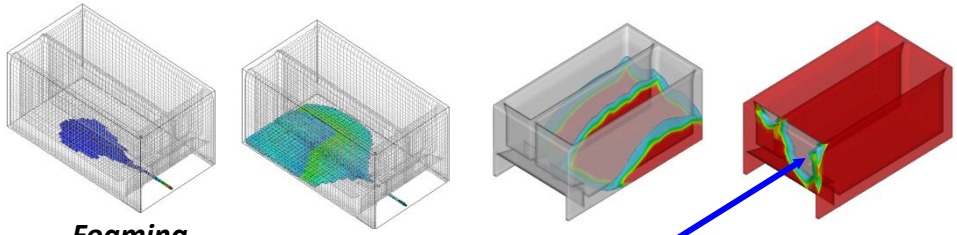
New code development for film flow analysis



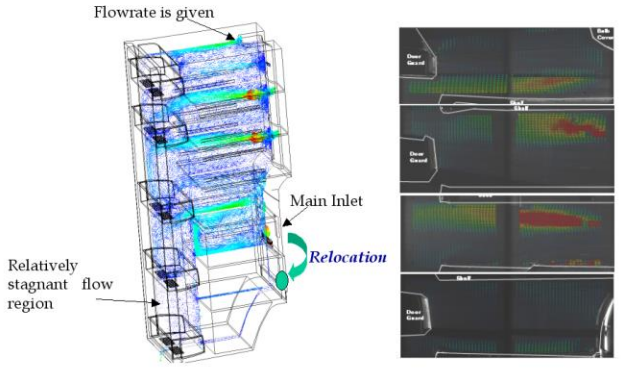


Experiences in industry

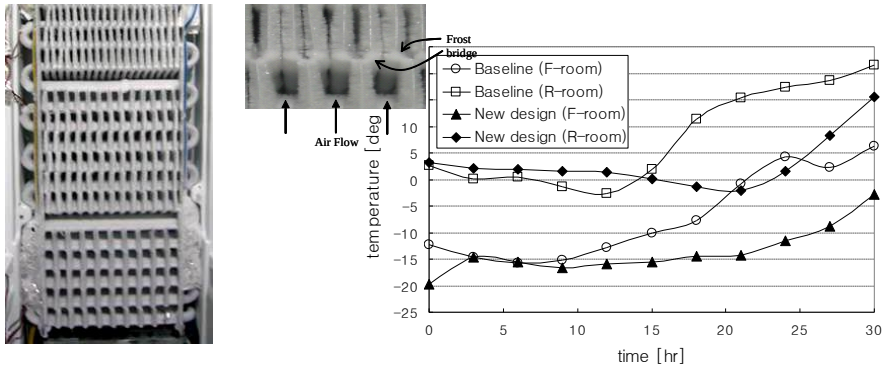
•PU foam-filling process for refrigerator



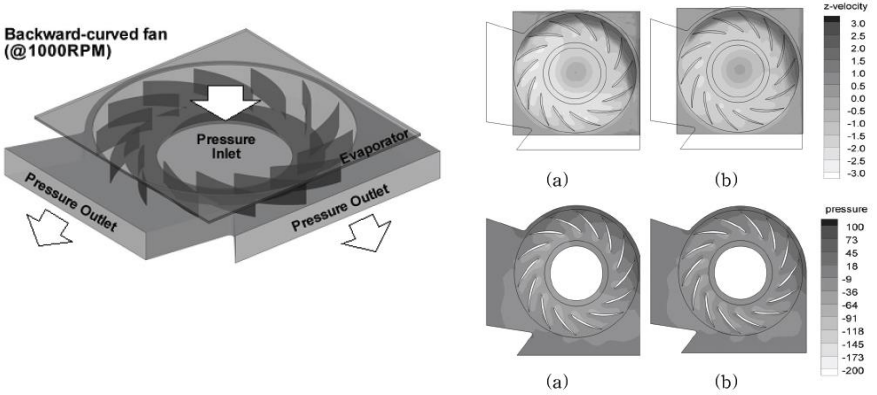
•Even cooling



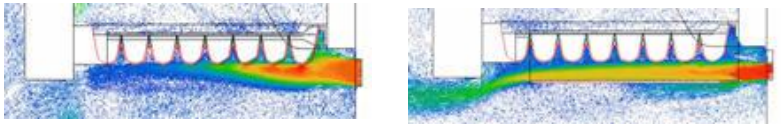
•Frosting in an evaporator



•Fluid machinery



•Solidification(freezing)



- Thermal management technology
- Advanced numerical model for aero-thermal system
- CFD for multi-phase flow
- **Research programs**

Research programs

Rolls-Royce®

Technology Centre in Thermal Management

LG University Future Research Center in Thermal Design

KETEP

Technology Development of Gas Turbine Blade Reengineering Specialized for Domestic Operating Environment

NRF National Research Foundation of Korea

Development of a non-iterative thermal-fluidic topology optimization technique based on the machine learning

국방과학연구소 Agency for Defense Development

UTRC

The UAV Gas Turbine Research Center

RIST 재단법인 포항산업과학연구원 Research Institute of Industrial Science & Technology

Development of Analysis Techniques for the Thermal-Management of Na-$NiCl_2$ Battery ESS

DSME

Research of phase change transient analysis for the heat transfer performance and temperature distribution in BAHE

Publications in 3 years (SCI-E)

[01] F.K. Kholi, H. Kallath, A. Mucci, M.Y. Ha, J. Chatwynd-Chatwin, and **J.K. Min***, "Experimental study of effects of wicks and boundary conditions on thermal performance of heat pipes," Journal of Mechanical Science and Technology, 36(1), pp. 417-432, 2022.

[02] F.K. Kholi, H. Kallath, A. Mucci, M.Y. Ha, J. Chatwynd-Chatwin, and **J.K. Min***, "Experimental study of the effect of geometrical length to diameter ratios and heater orientations on sintered-based heat pipes thermal behavior," International Communications in Heat and Mass Transfer, 129, 105734, 2021.

[03] F.K. Kholi, J. Park, K. Lee, M.Y. Ha, M. Klingsporn, J. Chatwynd-Chatwin, S.Y. Yoon*, and **J.K. Min***, "Experimental and numerical analysis of the transient behavior of the oil de-congealing process in an aero fuel-cooled oil cooler under low-temperature conditions," Journal of Engineering for Gas Turbines and Power-Transactions of the ASME, 143, 091027-1 - 091027-17, 2021.

[04] J.S. Lee, M.Y. Ha, and **J.K. Min***, "Numerical study on the mixed convection around inclined-pin fins on a heated plate in vertical channels with various bypass ratios," Case Studies in Thermal Engineering, 27, 101310-1 - 101310-16, 2021.

[05] F.K. Kholi, H. Kallath, A. Mucci, M.Y. Ha, J. Chatwynd-Chatwin, and **J.K. Min***, "Experimental investigation of the effects of inclinations and wicks on the thermal behavior of heat pipes for improved thermal applications," Case Studies in Thermal Engineering, 26, 100997-1 - 100997-15, 2021.

[06] J.S. Lee, M.Y. Ha, and **J.K. Min***, "A topology optimization based design of a liquid-cooled heat sink with cylindrical pin fins having varying pitch," International Journal of Heat and Mass Transfer, 172,121172-1 - 121172-18, 2021.

[07] H.J. Hwang, J. Park, and **J.K. Min***, "A numerical study on the flow control characteristics of a cavitating venturi with one- and two-stage diffusers," Journal of Mechanical Science and Technology, 35(4), pp. 1463-1472, 2021.

[08] H. Kallath, F.K. Kholi, Q. Jin, M.Y. Ha, S.H. Park, H. Kim, J. Chatwynd-Chatwin, and **J.K. Min***, "Numerical study of the flow uniformity inside the high-pressure side manifolds of a cooled cooling air heat exchanger," Applied Thermal Engineering, 189, pp. 116645-1-116645-14, 2021.

[09] H. Kallath, F.K. Kholi, M.Y. Ha, and **J.K. Min***, "A Multi-Objective Airfoil Shape Optimization Study using Mesh Morphing and Response Surface Method," Journal of Mechanical Science and Technology, 35(3), pp. 1075-1086, 2021.

[10] A. Mucci, F.K. Kholi, J. Chatwynd-Chatwin, M.Y. Ha, and **J.K. Min***, "Numerical investigation of flow instability and heat transfer characteristics inside pulsating heat pipes with different numbers of turns," International Journal of Heat and Mass Transfer, 169,120934-1 - 120934-18, 2021.

[11] J. Park, M.Y. Ha*, M. Klingsporn, J. Chatwynd-Chatwin, and **J.K. Min***, "An improved numerical analysis of the transient oil de-congealing process in a heat exchanger under low temperature conditions," Journal of Mechanical Science and Technology, 35(1), pp. 391-406, 2021.

[12] A. Mucci, F.K. Kholi, M.Y. Ha, **J.K. Min***, P. Beecroft, and J. Chetwynd-Chatwin, "Transient performance analysis of an aero gas turbine Cooled Cooling Air Heat Exchanger," Journal of Engineering for Gas Turbines and Power-Transactions of the ASME, 142, 111014-1 - 111014-15, 2020.

[13] J.S. Lee, M.Y. Ha, and **J.K. Min***, "A finite-volume based topology optimization procedure for an aero-thermal system with a simplified sensitivity analysis method," International Journal of Heat and Mass Transfer, 163, 120524, 2020.

[14] M. Shim, M.Y. Ha, and **J.K. Min***, "A numerical study of the mixed convection around slanted-pin fins on a hot plate in vertical and inclined channels," International Communications in Heat and Mass Transfer, 118, 104878, 2020.

[15] H. Kallath, F.K. Kholi, M.Y. Ha, and **J.K. Min***, "Computational study on the aerodynamics of a surface-heated wing for thermal management," AIAA Journal, 58(10), pp. 4339-4356, 2020.

[16] F.K. Kholi, A. Mucci, H. Kallath, M.Y. Ha, J. Chetwynd-Chatwin, and **J.K. Min***, "An improved correlation to predict the heat transfer in pulsating heat pipes over increased range of fluid-filling ratios and operating inclinations," Journal of Mechanical Science and Technology, 34(6), pp. 2637-2646, 2020.

Further thoughts

- Advanced numerical modeling for thermal management tech for extreme operating condition
- Keywords
  - HPHT, Cryogenic, Transient
  - Highly efficient system
  - Ultra compactness (novel shape)
  - Safety + Life, reliability, durability
  - Market pressure : Better, Cheaper, Faster
- Potential of CFD
  - The use of CFD is wide-spreading across all fields (engineering, environment, medicine, sports etc.).
  - The market for commercial CFD-software has been steadily growing – 13-15 % per year.
  - More potential users are educated in CFD.
  - Computing power is increasing –DNS and LES are becoming possible for more complex flows.
  - High-fidelity simulations (10-100 billions of grid points, or more) will provide better data.
  - Full-scale, full-system analysis will become common.
- Strategy: New definition of “Multi-”
  - Multi-physics: structural, reliability, life, material, chemical etc.
  - Ready for the high-performance computing as well as the Multi-fidelity approach.
  - Intelligent Multi-objective design with strong background of fundamental design theory.
  - Multi-phase CFD: still long way to go.

Members

Junseok Lee, Ph.D. (Post-doc)

Research:
Topology optimization for aero-thermal application
Numerical study for heat sink under the mixed convection

Jae Sung Yang (Ph.D. candidate)

Research:
Topology optimization for aero-thermal application
OpenFOAM / Nek5000 code development
Battery thermal management

Jung Tae Kim (Master's student)

Research:
Optimization of fluid machinery
Phase change analysis for heat exchanger

Jeonghoon Heo (Master's student)

Research:
Gas turbine casing cooling
Suction flow in gas turbine casing

Yeon Dong Ryu (Master's student)

Research:
Valve analysis

Myoung Hun Han (Master's student)

Research:
Condensation

Seongho Park (Undergraduate intern)

Research:
Assistance for CFD analysis and Experiment

Alumni

	**Hariharan Kallath, Ph.D.** Collins Aerospace (Ireland)
	**Foster Kwame Kholi, Ph.D.** Hylium industrial Inc. (Korea)
	**Alberto Mucci, Ph.D.** Whittle laboratory, University of Cambridge (United Kingdom)

	**Hyo Jae Son, Master** LG electronics (Korea)
	**Namgyoung Lee, Master** Current affiliation:
	**Minbo Shim, Master** Agency for Defense Development (Korea)
	Yeong Woong Oh, Master Hyoseong electric co. LTD (Korea)

Thank you!