AESE Library Developed in OpenModelica: Simulation and Research for Nuclear Power Systems

MODPROD & OpenModelica workshops 2025

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目录CONTENTS

1. Introduction and Concept

☐ Feasibility foundation

- Complex **multi-domain coupled** nuclear energy system models are suitable for visual modeling based on the **Modelica** language.

- **OpenModelica** can simulate steady-state and transient behaviors of nuclear systems, focusing on **nuclear**, **working fluid properties**, **thermo-hydraulics**, and **dynamic control**.

Feasibility Foundation

The Basic Characteristics of the Modelica

Object oriented, equation based unified physical system modeling language

Inheritable and reusable	multi-domain modeling	Relatively realistic visual system network

OpenModelica

- Open-Source Modelica Language Editor

Advanced Energy Systems Engineering

- Self-developed Component Model Library
- For Nuclear Power Systems
- For Advanced Energy Systems

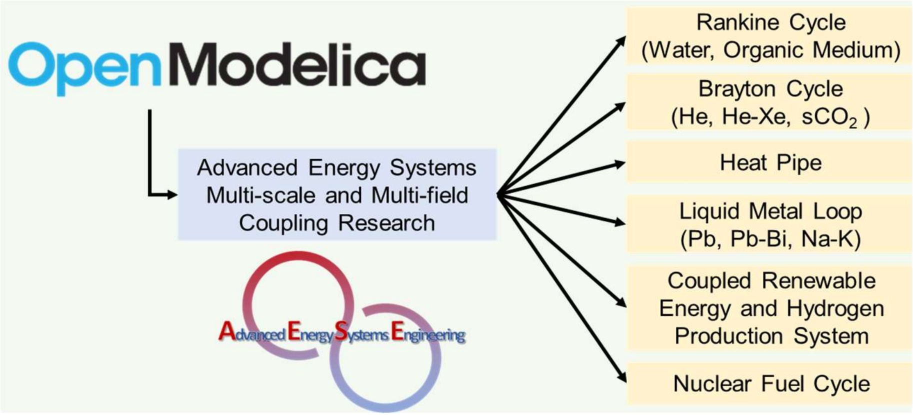
Advanced Energy Systems Engineering (AESE)

Introduction and Concept
AESE

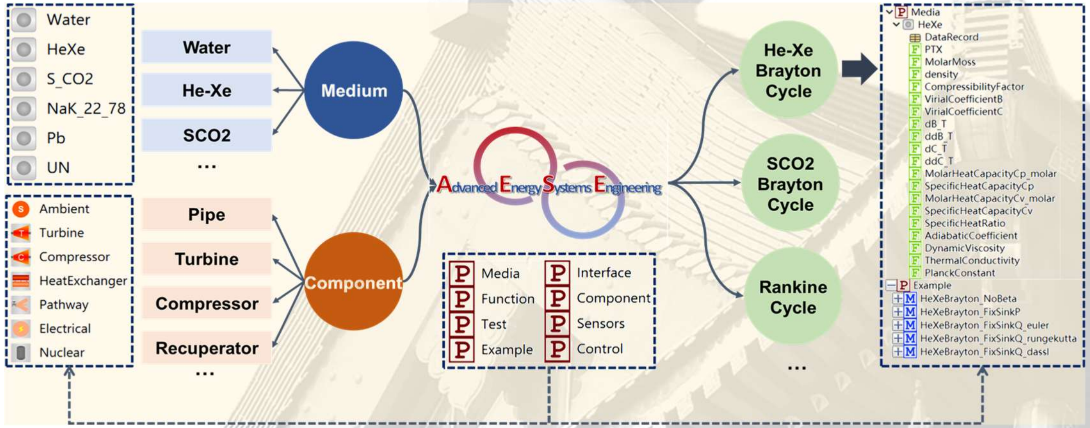
☐ Research framework

- Compared to specialized nuclear engineering simulation software like RELAP5 for water cycles, the Modelica-based AESE library aims to not only support **traditional water cycle verification** and simulation but also facilitate **development and research on new reactors and energy systems**.

Application Framework

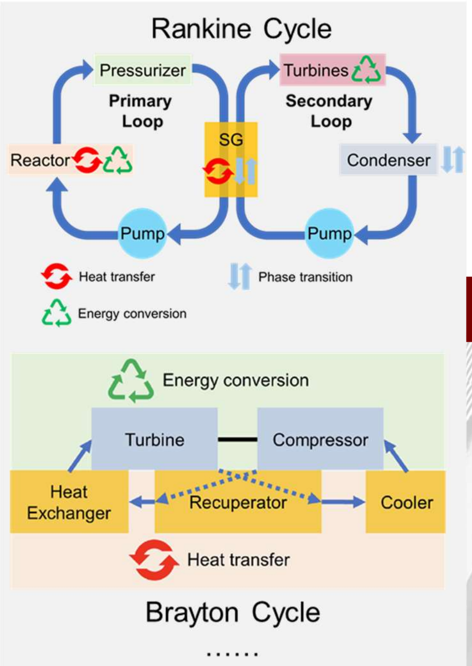


Dynamic Energy Conversion System in the AESE Library

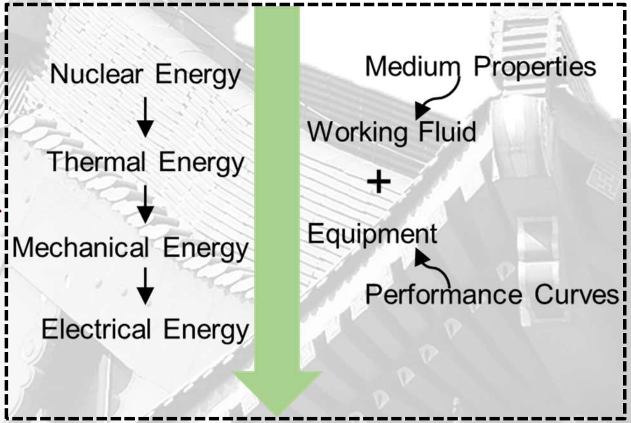


Modeling Concept

- The goal of a nuclear power system is to **convert nuclear energy into electricity**, with **thermal and mechanical energy conversion** through **working fluids and equipment** as the essential process of the dynamic energy conversion system, while the static energy conversion system also has its essential process.
- The advantage of Modelica and the modeling philosophy of the AESE library lie in capturing **essential processes**, modularizing them, and further refining or expanding based on reusable modules.
- The simulation of the **system model** can further drive **backend applications** such as object design optimization and intelligent operation.



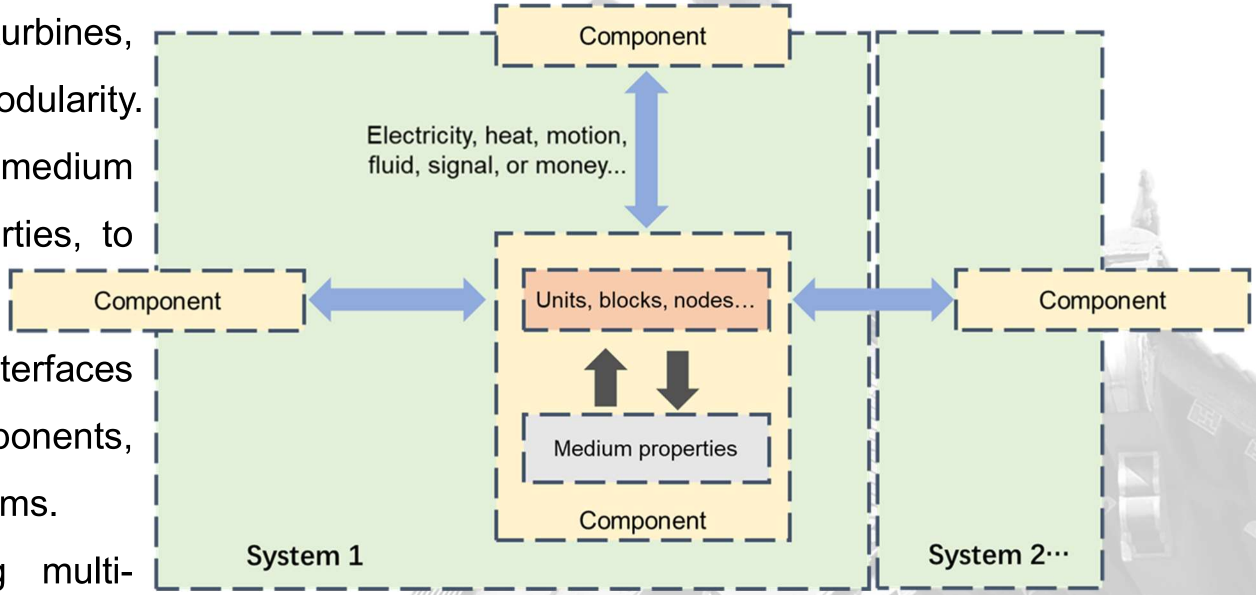
Dynamic Energy Conversion System



Unified Basic Elements

Modeling Concept

- **Component-based Modeling**: Decomposing the system into reusable components like turbines, compressors, and pipes for flexibility and modularity.
- **Medium Property Definition**: Defining medium properties, such as thermodynamic properties, to describe system behavior.
- **Interface Considerations**: Customizing interfaces based on information flow between components, involving multiple domains in complex systems.
- **Multi-level System Design**: Simulating multi-domain energy systems through interconnected components and systems.

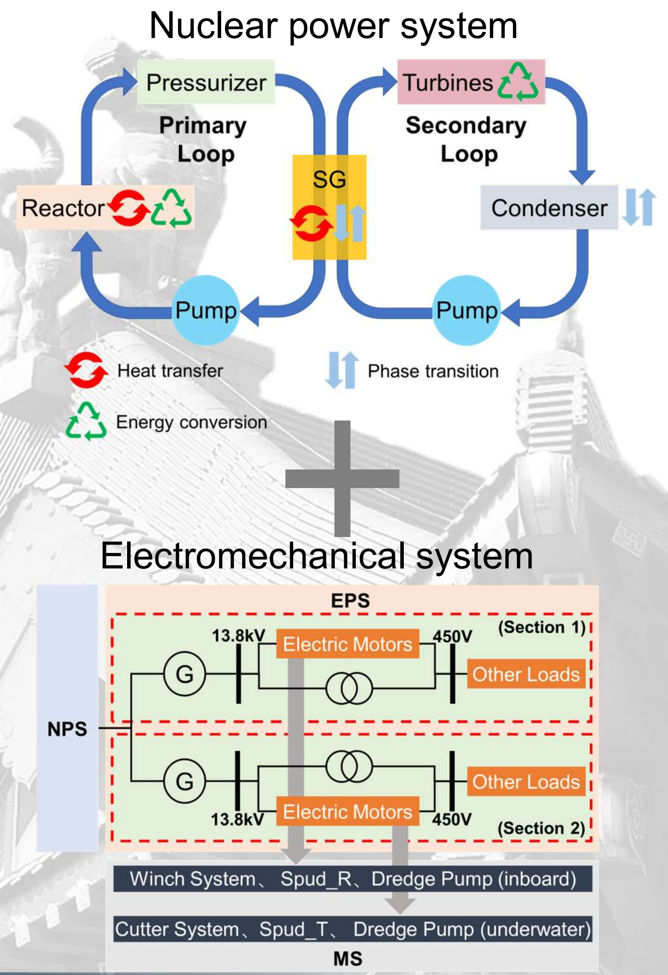


2. Modeling and Simulation

Modeling and Simulation
Nuclear Power Engineering Ship (NPES)

☐ Objectives and Research Content

- NPES is a large and complex system.
- Develop a **basic flow network model** based on the **ThermoPower** library.
  - ➢ The steam generator component was further supplemented, the original power interface enriched, and calculations for voltage and frequency included.
- Further supplementation based on **AESE** includes models:
  - ➢ A **point reactor kinetic model** has been developed.
  - ➢ A range of **power grid components**, such as transformers, switches, and motors, has been integrated.
  - ➢ Large **mechanical equipment components** for various functions have also been assembled.

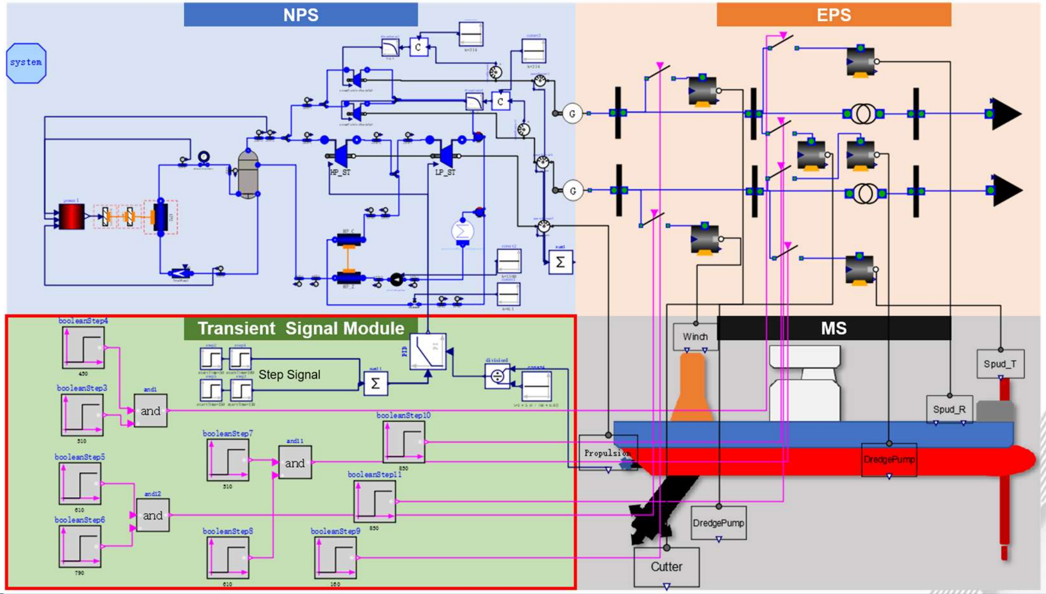


Modeling and Simulation

Nuclear Power Engineering Ship (NPES)

☐ System model of NPES

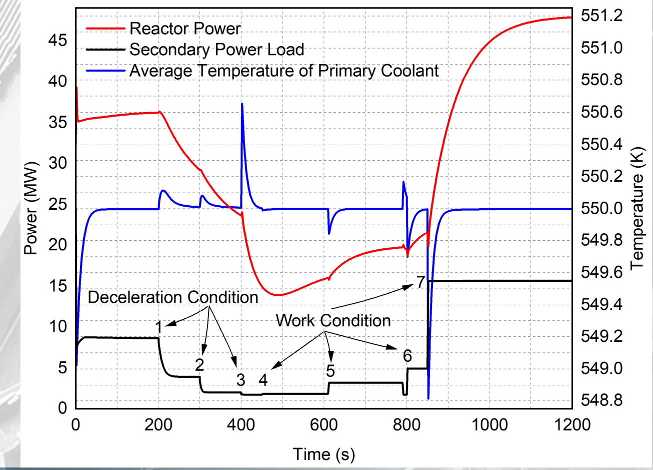
- A full-system visualization model has been established, with the nuclear power and electromechanical systems **consistent with the actual topology**.
- **Steady-state validation** and **transient simulation** of the full-system model have also been conducted.



Steady-state validation

Parameter	Reference	Result	Error
Reactor thermal power (MW)	36	35.81	0.52%
Temperature of SG primary side inlet (K)	558.15	555.18	0.53%
Temperature of SG primary side outlet (K)	544.15	544.82	0.12%
Pressure of SG secondary side (MPa)	3.9	3.72	4.61%
Feedwater temperature of SG secondary side (K)	433.15	431.28	0.43%
Steam temperature of SG secondary side (K)	524.15	519.19	0.95%
Steam output of SG (kg/s)	17	17.31	1.82%
Mechanical power output of steam turbine (MW)	7.35	7.38	0.41%

Transient simulation

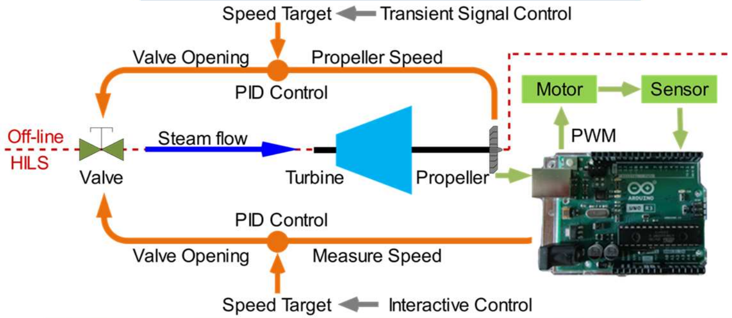


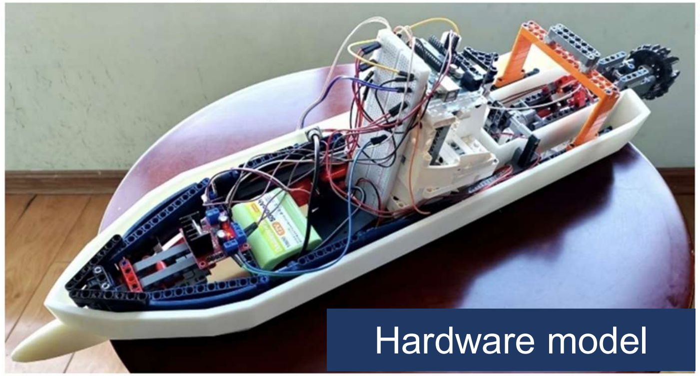
Modeling and Simulation
Nuclear Power Engineering Ship (NPES)

□ Hardware-in-the-loop simulation model of NPES (AESE + ThermoPower + Modelica_Embedded)

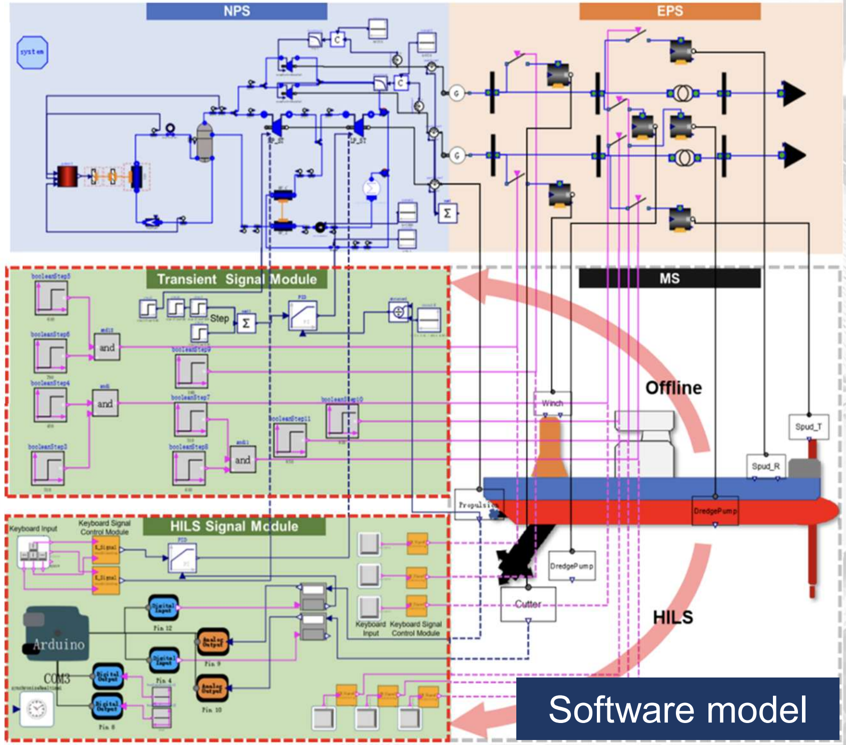
- To verify and test the control system, a **hardware-in-the-loop simulation** platform was built for exploration. A simulation framework **combining virtual and physical models for NPES** has been established.

Theoretical framework

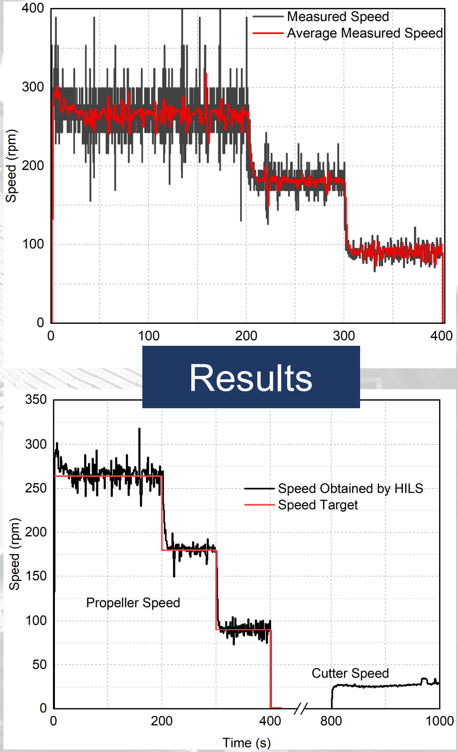




Hardware model



Software model



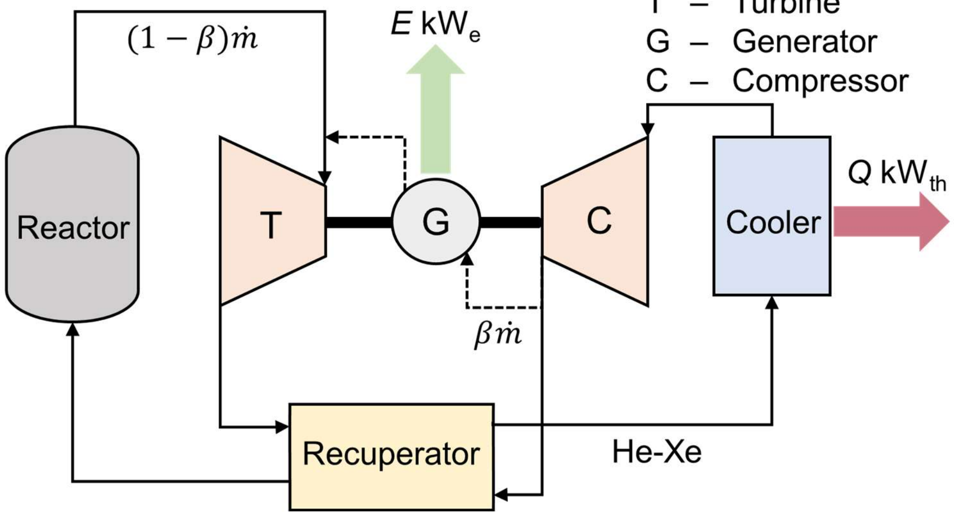
Results

Modeling and Simulation
He-Xe Closed-Brayton-Cycle (CBC) System

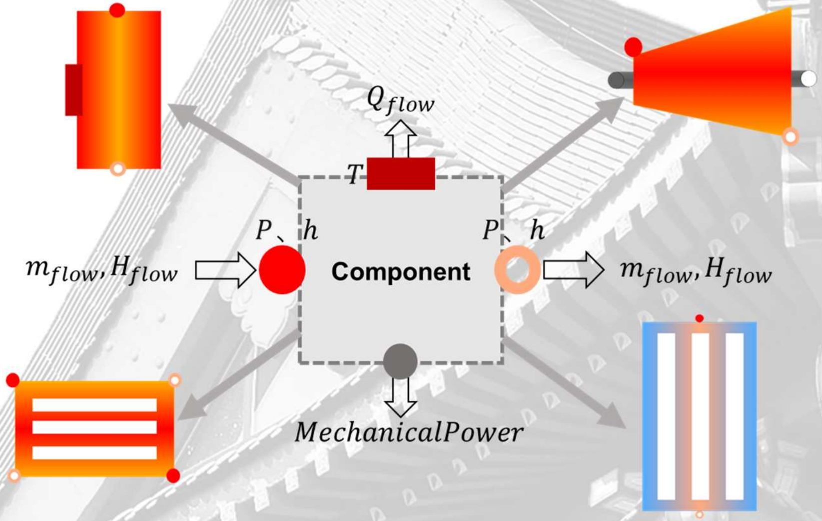
Objectives and Research Content

- Adding a certain proportion of xenon to helium can **improve the system's performance** while **reducing the size** of the equipment.
- The helium and xenon (He-Xe) mixture is **outside the ideal gas range**, and the elemental gas mixture provided by **MSL** can no longer meet the computational requirements.

System theoretical framework



Basic Brayton cycle components in AESE



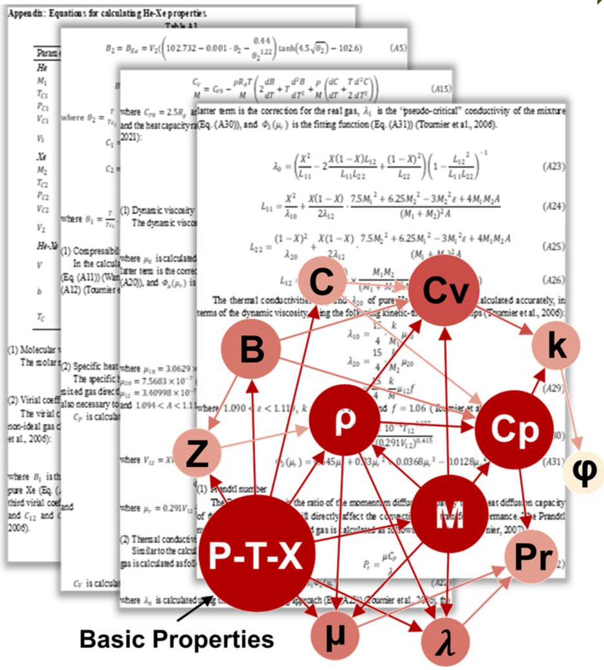
Modeling and Simulation

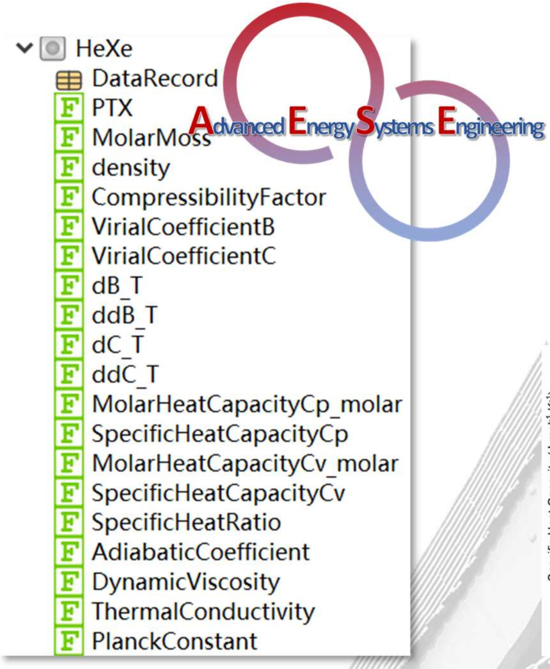
He-Xe Closed-Brayton-Cycle (CBC) System

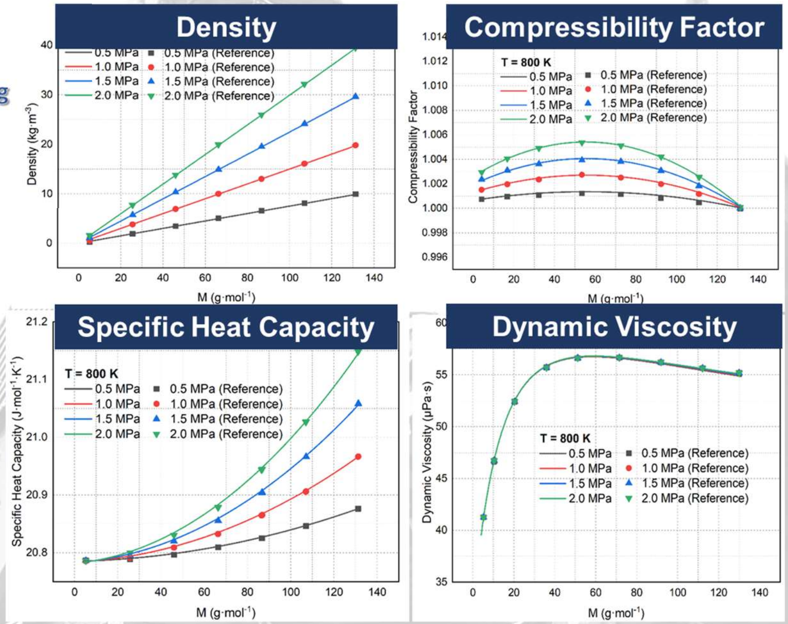
☐ Properties of He-Xe mixed gas

- Based on the **theoretical method** proposed by Tournier, El-Genk, and others, a **He-Xe mixed gas property calculation package** has been developed in the AESE library using Modelica.

Computational theory → Medium property library → Some validation results





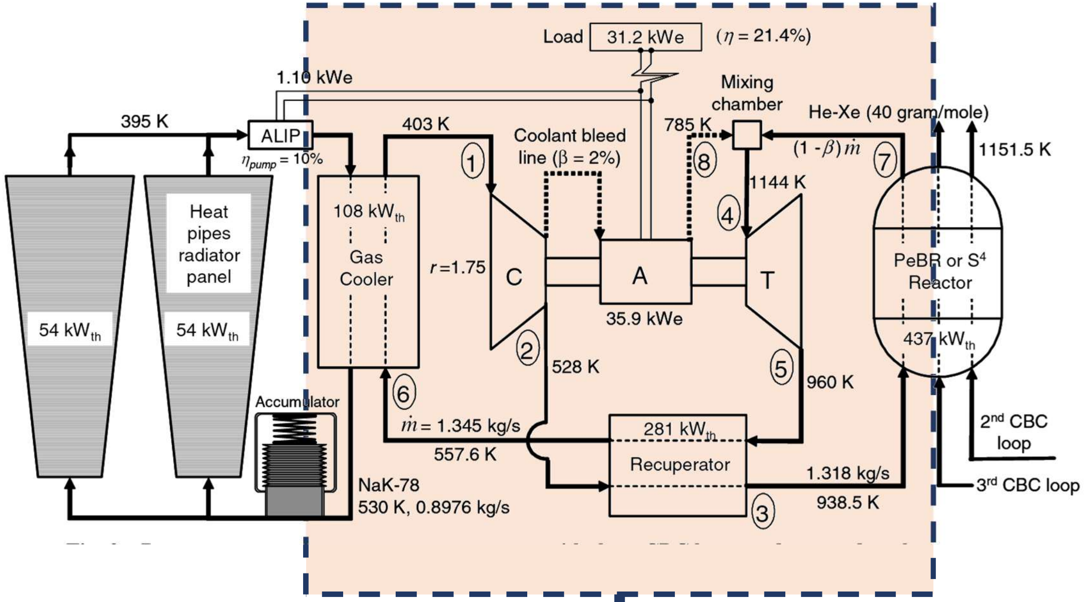


Modeling and Simulation
He-Xe Closed-Brayton-Cycle (CBC) System

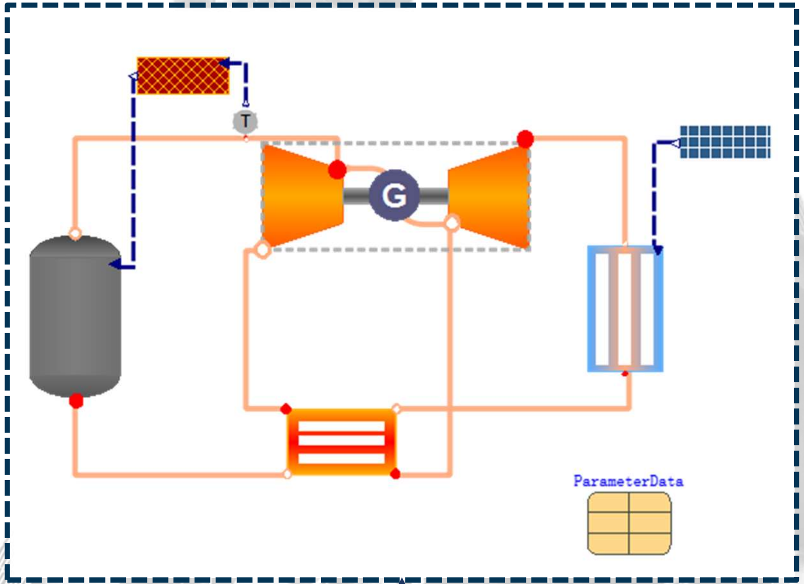
☐ System model of He-Xe CBC system

- A He-Xe CBC system model has been established in AESE based on the reference system topology.

Reference



System Modeling Based on AESE



Modeling and Simulation
He-Xe Closed-Brayton-Cycle (CBC) System

☐ Simulation result validation of the He-Xe CBC system

- After steady-state simulation validation, the error of the system model is within **3%**.

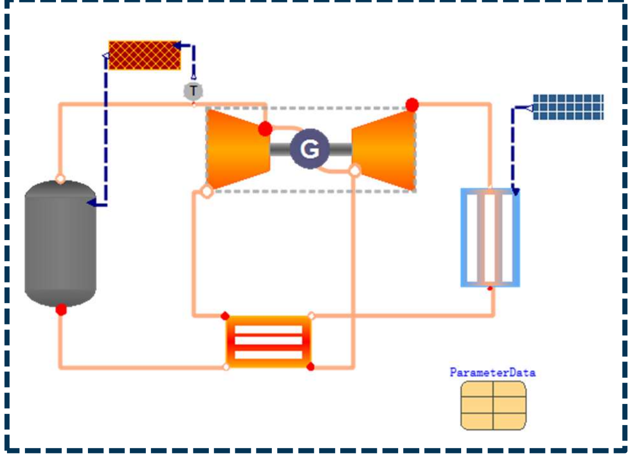
Parameter	Reference	Simulation	Relative Error (%)
System			
Reactor thermal power (kW)	145.7	141.615	2.80
Cooler cooling power (kW)	108	109.624	1.50
Molar fraction of He in He-Xe	0.72	0.72	/
Mass flow rate ($kg \cdot s^{-1}$)	1.345	1.317	2.08
Highest cycle pressure (bar)	20	20	/
Cycle electric power (kW)	30.1	29.39	2.36
Bleed-line fraction β	0.02	0.02	/
Alternator (electrical) efficiency	0.9	0.92	2.22
Shaft mechanical efficiency	0.867	0.88	1.48
Reactor			
Inlet temperature (K)	938.5	944.172	0.60
Exit temperature (K)	1151.5	1153.22	0.15
Pressure-loss ratio ΔP/P	2.7%	2.65%	1.85
Turbine			
Inlet temperature (K)	1144	1144.44	0.04
Exit temperature (K)	960	966.66	0.69
Polytropic efficiency	0.875	0.875	/
Aerodynamic load	0.886	0.867	2.14

Parameter	Reference	Simulation	Relative Error (%)
Recuperator			
(Hot leg) Inlet temperature (K)	960	966.66	0.69
(Hot leg) Exit temperature (K)	557.6	559.65	0.37
(Cold leg) Inlet temperature (K)	528	528.25	0.05
(Cold leg) Exit temperature (K)	938.5	944.17	0.60
(Hot leg) Pressure-loss ratio ΔP/P	1.5%	1.51%	0.67
(Cold leg) Pressure-loss ratio ΔP/P	0.6%	0.602%	0.33
Effectiveness	0.95	0.952	0.21
Cooler			
Inlet temperature (K)	557.6	560.89	0.59
Exit temperature (K)	403	403	/
Pressure-loss ratio ΔP/P	1.0%	1.01%	1.00
Compressor			
Inlet temperature (K)	403	403	/
Exit temperature (K)	528	528.254	0.05
Pressure ratio	1.75	1.75	/
Polytropic efficiency	0.83	0.83	/
Aerodynamic load	0.71	0.723	1.80

Modeling and Simulation
He-Xe Closed-Brayton-Cycle (CBC) System

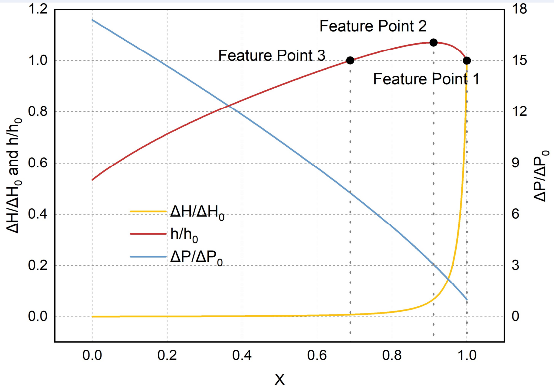
Performance of the He-Xe CBC system

- The He-Xe CBC system has many **design optimization aspects**, such as gas composition ratio and compressor pressure ratio.
- Calculations under various design parameters can be performed using the **system simulation** to explore their impact on system performance.

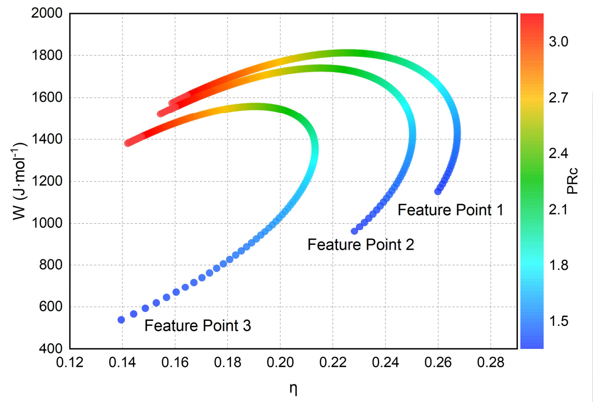


Impact of various parameters on system performance

Relative heat transfer coefficient
Relative pressure loss coefficient
Compressor relative enthalpy rise



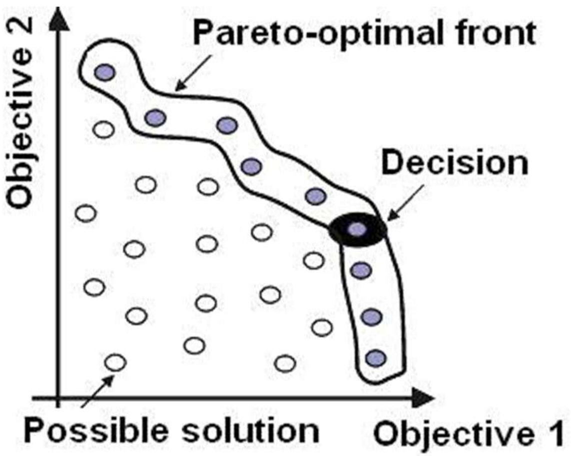
System efficiency
Specific work

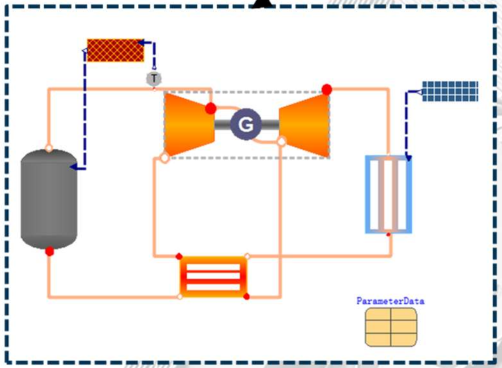


Multi-objective optimization

- To further investigate the impact of parameters on the system and obtain **relatively optimal designs**, we also **coupled OpenModelica with Python algorithms** to perform **multi-objective optimization** of the system.

  - **Multi-objective optimization** involves solving problems with **multiple conflicting objectives**.
  - **NSGA-II** is a popular multi-objective optimization algorithm that finds a set of Pareto-optimal solutions by ranking them based on dominance and diversity, ensuring a well-distributed solution set.



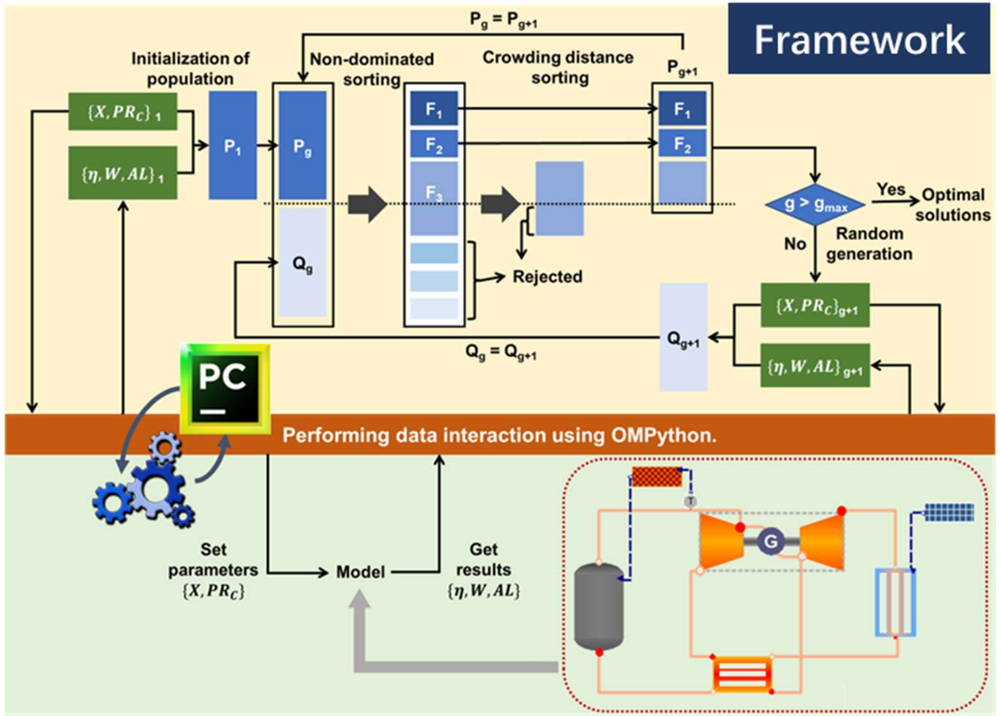


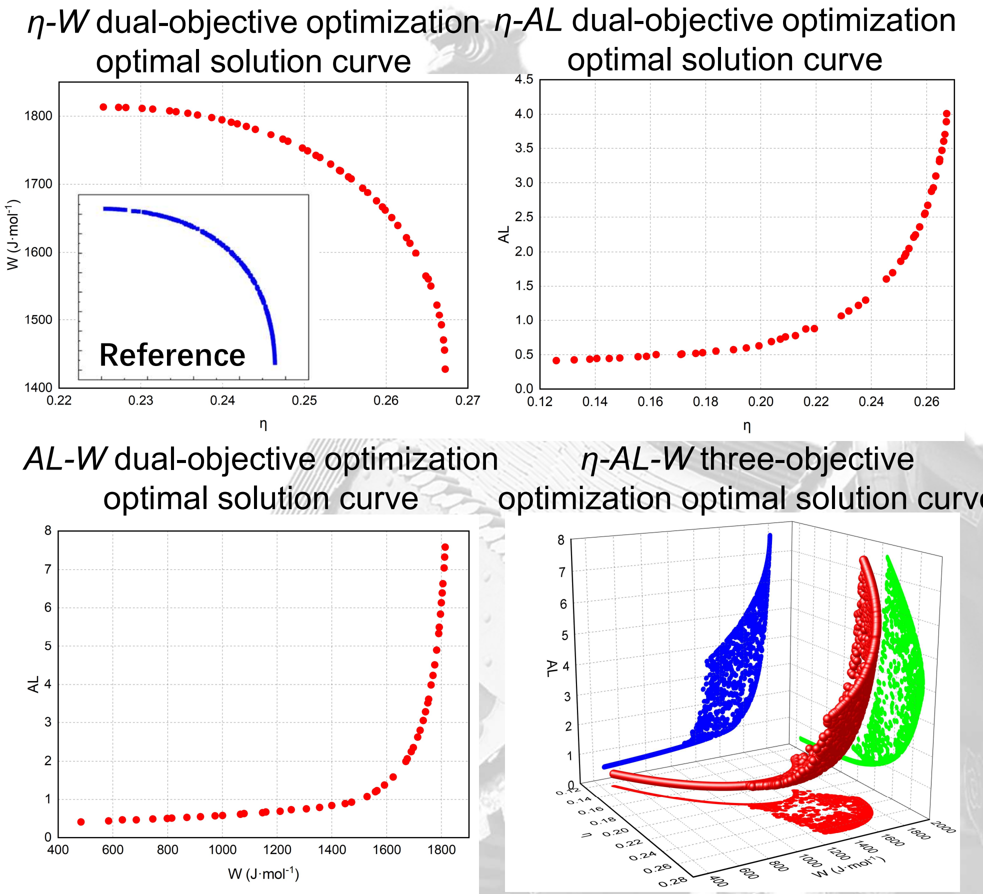
More efficient,
more compact,
more flexible,
lighter, and safer...

Non-dominated Sorting Genetic Algorithm II **(NSGA-II)**

Multi-objective optimization

- A model-driven multi-objective optimization framework has been established based on AESE and **OMPython**.





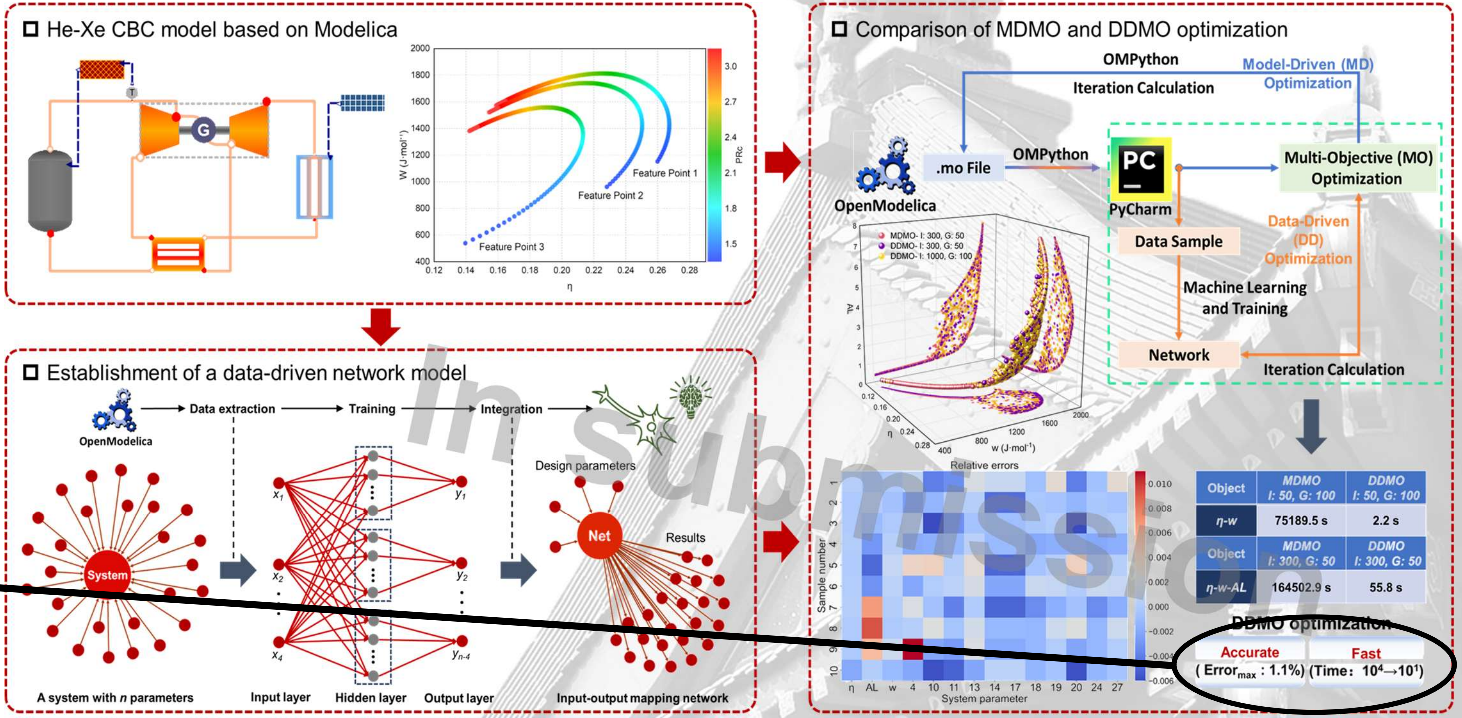
η-system efficiency, *W*- Specific work, *AL*- Aerodynamic load

Zhang, A., Wang, X., 2024. Development of Modelica-based one-dimensional thermodynamic cycle library and its application in simulation and multi-objective optimization of a He–Xe closed-Brayton-cycle system. Progress in Nuclear Energy 172, 105205.

Modeling and Simulation
He-Xe Closed-Brayton-Cycle (CBC) System

Data-Driven multi-objective optimization

- **Traditional model-driven multi-objective optimization** requires **a large amount of model computation time**;
- To **accelerate** the optimization process, **system identification** was leveraged, and **neural networks** were used to speed up the optimization process.
- **Data-driven approaches** can **ensure accuracy** while further accelerating the optimization process (**×1000**).



Accurate
(Error$_{max}$: 1.1%)

Fast
(Time: $10^4 \rightarrow 10^1$)

Research on Other Systems

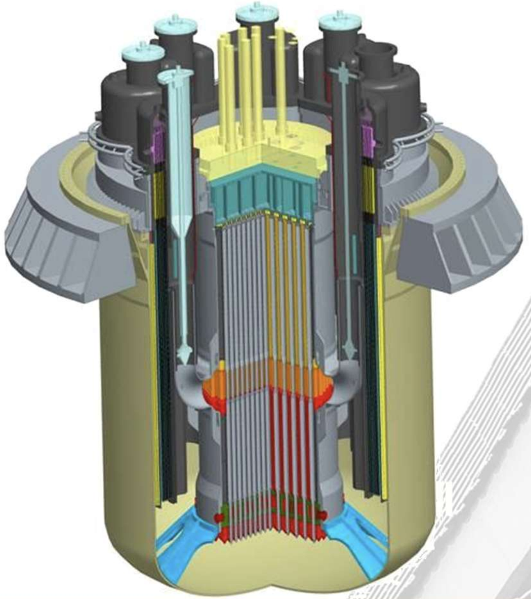
☐ Lead-cooled Fast Reactor

- As one of the fourth-generation nuclear energy systems, the lead-cooled fast reactor requires **rapid modeling**, **safety analysis**, and **multi-domain coupling calculations**.
- Utilizing the modeling advantages of the Modelica language can integrate these aspects, thus better facilitating the engineering design of nuclear energy systems.

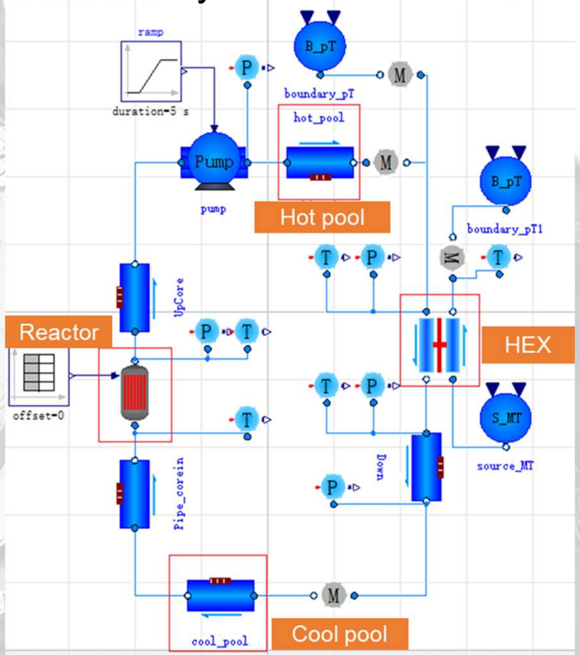
➢ The **lead coolant properties** were established using the **MSL**'s **incompressible fluid framework**.

➢ A loop model with **detailed design parameters** was validated based on published literature.

ALFRED



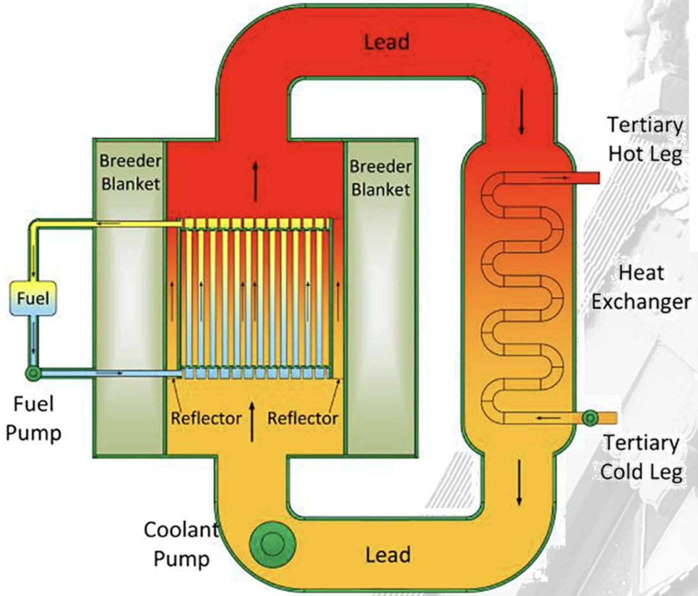
System Model

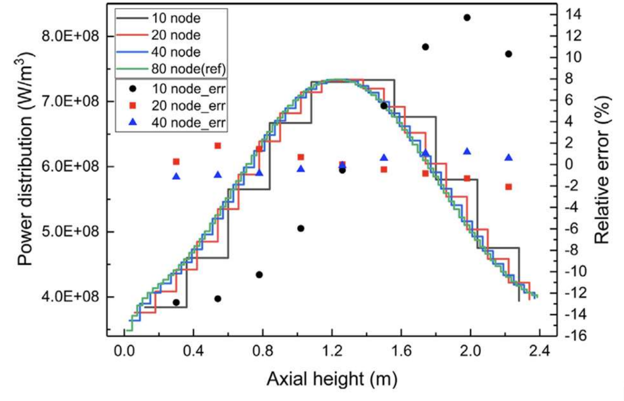


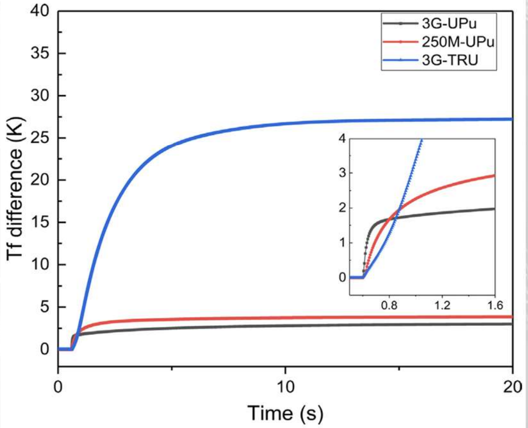
☐ Dual-Fluid Reactor（DFR）

- The Modelica is used to solve one-dimensional coupled equations of the DFR system.
- A model with **three one-dimensional loops** coupled to **point-kinetic neutron dynamics** is constructed using **heat balance equations** to investigate system responses to boundary condition changes.
- This case demonstrates the potential of using the Modelica language for **innovative nuclear energy system** design and research.

Working principal of the DFR





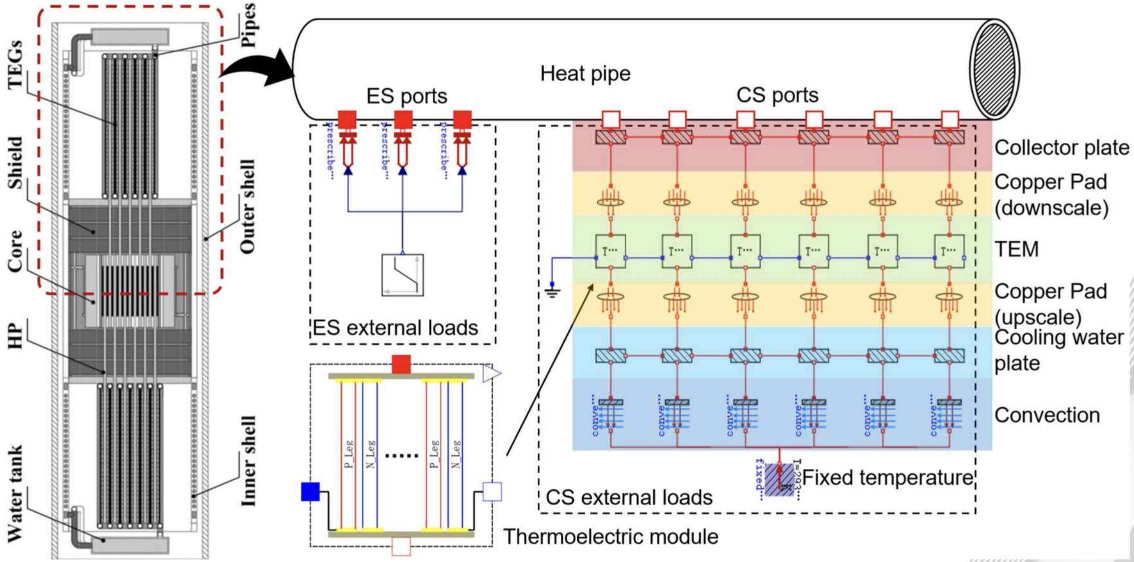


Modeling and Simulation

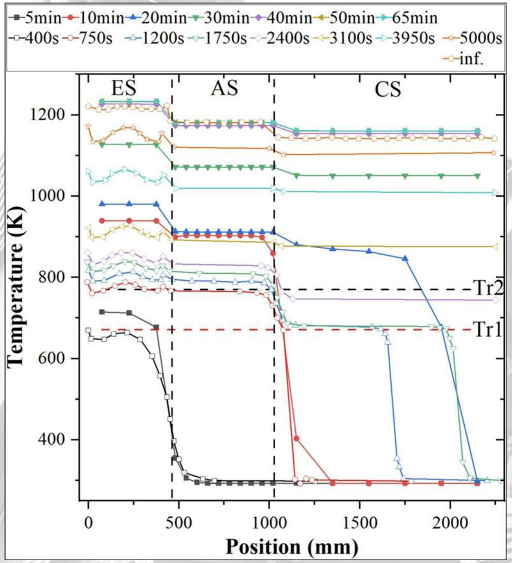
Research on Other Systems

☐ Heat Pipe

- Innovative models for high-temperature alkali heat pipes and their coupling with thermoelectric generators were developed using Modelica, integrating **2D heat conduction** and **1D pressure equations** for accurate dynamics.
- This case provides insights for optimizing heat pipe thermoelectric generator systems and advancing thermoelectric conversion technology.



Two-dimensional layout of the NUSTER-100 (left) and the established model of a single heat pipe and its loads (right).



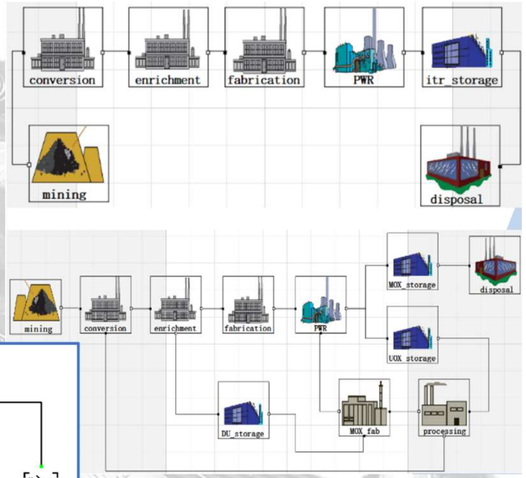
Wall temperature distributions in the frozen state start-up

Duan, L., Cammi, A., Wang, X., 2025. Object-Oriented modeling and simulation of heat pipe thermoelectric generator systems and its Application. Applied Thermal Engineering 125456.

Modeling and Simulation
Research on Other Systems

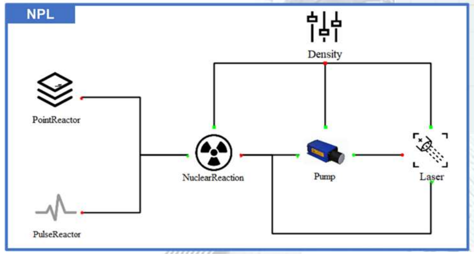
◻ Nuclear fuel cycle scenario analysis and optimization

- Forecast the future trends of nuclear power based on current reactor types.
- Develop an object-oriented dynamic nuclear fuel cycle system.
- Simulate various nuclear fuel cycle scenarios and their components.



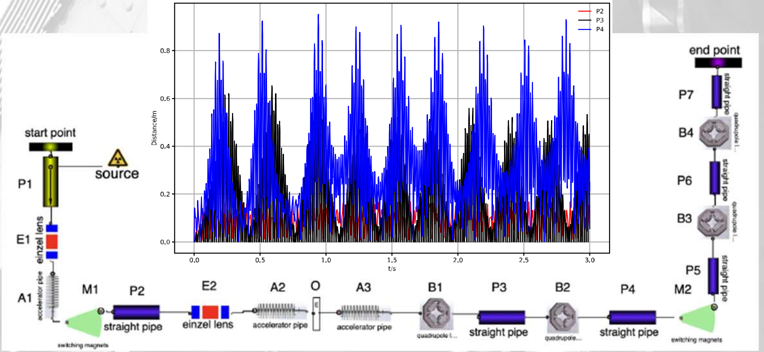
◻ One-Dimensional Nuclear Pumped Laser System

- Simulation of He-Xe and He-Ar-Xe Laser Systems.
- Combine with pulse reactors to achieve transient response.
- Integrate with IECT to achieve thrust output.



◻ Modeling of Accelerator Systems

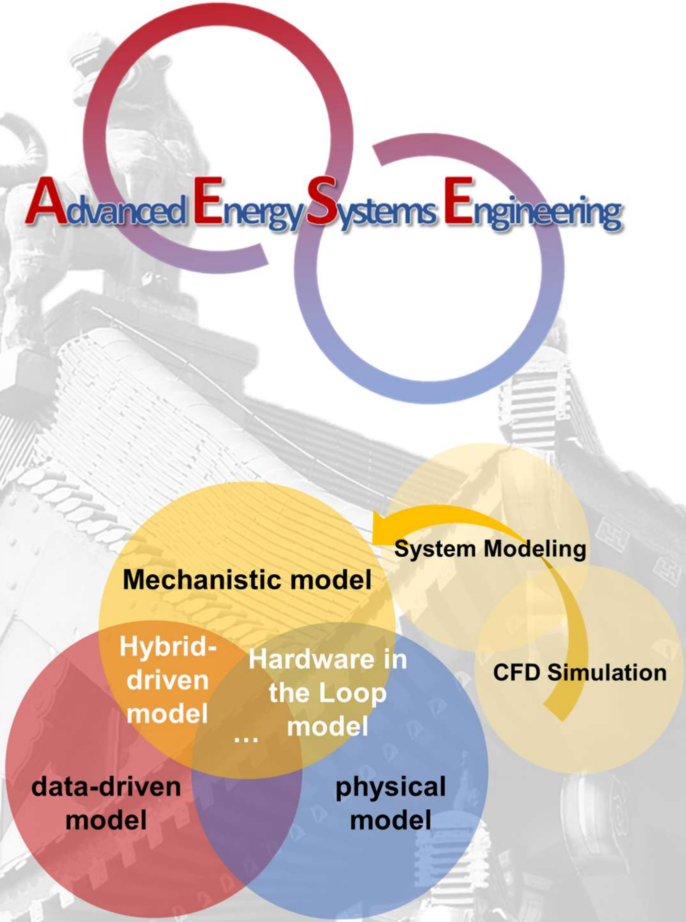
- Simulate the TASHEU accelerator system of Harbin Engineering University.
- Achieve full-process simulation of a single charged particle.



3. Conclusions

Conclusions

- **Modelica-based Modeling in OpenModelica:** Allows for modeling across multiple disciplines (electromechanics, thermodynamics, fluids, signals) to form components or system models, with advantages in simulating **multi-domain coupled nuclear energy systems**.
- **AESE Library:** Developed using Modelica, AESE aims to support traditional water cycle system simulations as well as the development and research of **new reactor and energy systems**. Based on the development of the AESE model, we also focus on the further applications of the model, such as **hardware-in-the-loop simulation** and system **multi-objective optimization**.
- The focus of the upcoming work will also be on the coupling analysis across **various dimensions**, including the system model and data, intelligent algorithms, and CFD and other three-dimensional computational programs.



4. About US

An Overview of Our Research Group

Basic Information

☐ Members

- There are 5 teachers, 4 doctoral students, 15 master students, and 10 international students

Asso. Prof. **Xiang WANG**
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PhD in Nuc. Eng. (TUM).
Neutronics, CFD, system analysis, multi-physics coupling, nuclear technology application.

Prof. **Daqing WEI**
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PhD in Mat. Sci. (HIT). **Nuclear material, irradiation damag, ceramic surface modification of metallic materials.**

Asso. Prof. **Qingyu WANG**
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PhD in Nuc. Sci. & Tec. (HEU).
Irradiation effects, multi-scale simulation and analysis.

Asso. Prof. **Tian ZHANG**
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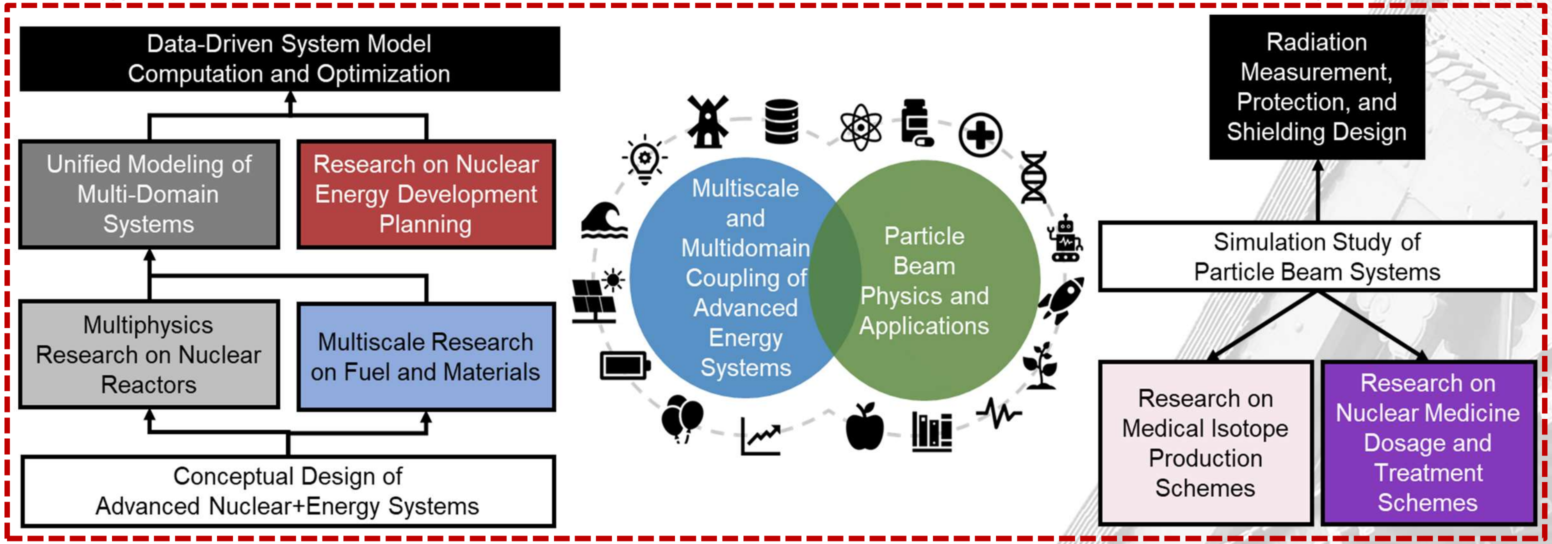
PhD in Reactor Safety (RWTH).
Reactor safety, fuel performance, design of accelerator target systems, isotope yield analysis.

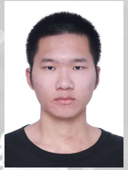
Asso. Prof. **Yongchang LI**
lyc2012@hrbeu.edu.cn
PhD in Mat. Sci. & Eng. (TAMU).
Ion accelerator applications, radiation damage, nuclear technology analysis.



Ao Zhang
system analysis and control, HILS, machine learning.

Gengzuo Liu
Radiation, accelerator operation, nuclear medicine.

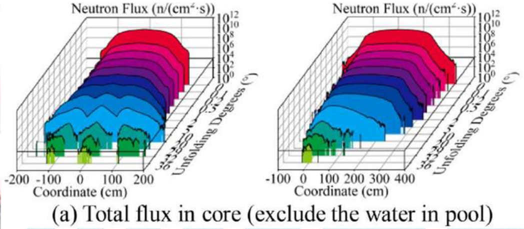
Wenlan Ou
TH analysis, liquid metal coolant, multi-physics coupling analysis of liquid fuel.

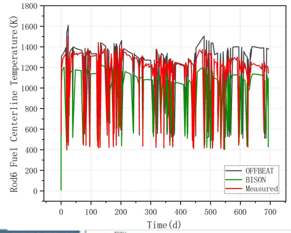


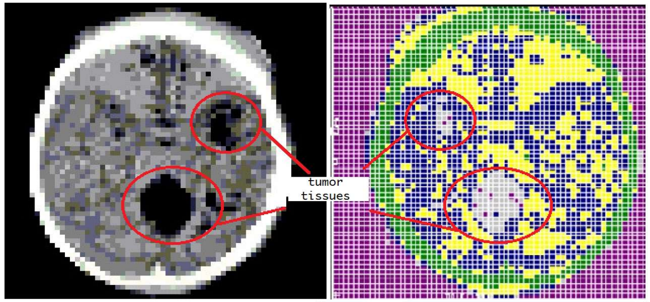
Zihao Liu
Reactor physics, PDE solving & approximation.

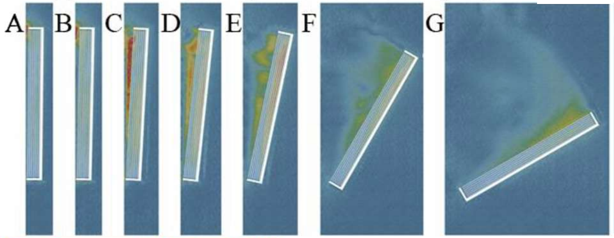
An Overview of Our Research Group

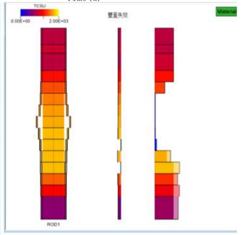
Basic Information

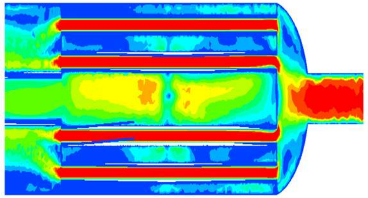


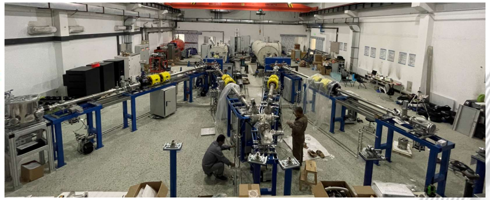


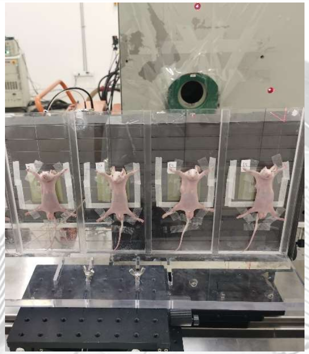


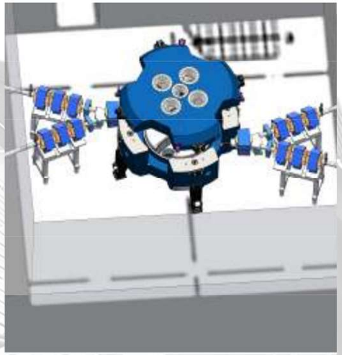












Welcome to Harbin, China,
to exchange and cooperate with us!

感谢您的关注！

Thank you for your attention!