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Size Optimization of KAIST Micro Modular Reactor (KAIST-MMR) for Marine Propulsion

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1. Introduction

Marine transportation consumes one-third of trade-related fossil fuels. The resulting greenhouse gases account for 3.3% of global carbon dioxide emissions for now and it is projected to increase up to 17% in 2050. Due to this reason, the International Maritime Organization (IMO) developed regulations for reducing greenhouse gas emissions for shipping industry to drastically cut carbon emission.

The KAIST-MMR, which is a micro modular reactor designed by KAIST, is a power system integrating an sCO_2 cycle and a reactor core into one module. This design made the KAIST-MMR to have size and mass that could be suitable for ship propulsion. Kim's research showed that KAIST-MMR is a feasible option for a 1000TEU container ship [1].

In this study, two strategies for optimizing the mass of KAIST-MMR are presented so that it can be used for the propulsion of ships. First, an air-cooled cooler is changed to a water-cooled cooler. Second, by using the MARS code developed by KAERI, the mass of the decay heat removal system is optimized. The mass of KAIST-MMR for marine propulsion changed from these two major changes, and the total mass is compared with the current marine diesel engine.

2. Methods and Results

2.1 Water-cooled Precooler Design

Since the KAIST-MMR is designed for land-based operation for supplying electricity to isolated grid, the precooler and the decay heat removal system (DHRS) operate with air cooling. However, sufficient seawater supply is always possible in marine propulsion systems. Therefore, the design of the precooler and DHRS can be changed from air-cooling to water-cooling. By using water, the mass of the precooler and DHRS can be reduced due to better heat transfer capability of water than air. This is positive for a marine propulsion system.

The design parameters of the system based on KAIST-MMR are shown in Table 1. With this condition, KAIST-HXD (Heat eXchanger Design) code, based on a 1D finite different method, was used for precooler design. The designed precooler results and original air-cooled precooler data are shown in Table 2. For the PCHE flow path, a zigzag flow path of 32.5 degrees was used. The mass of the precooler was estimated using the density of SS-316 steel.

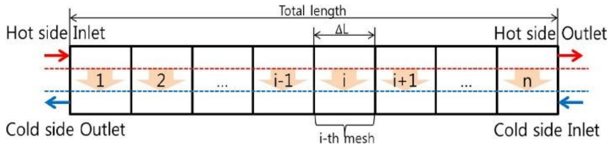

Fig 1. KAIST-HXD Node Structure [2]

Table 1. Fixed value for the Precooler Design

Fixed value			
Hot side inlet T (°C)	157.79	Hot side inlet P (MPa)	8.091
Hot side outlet T (°C)	60.0	Hot side outlet P (MPa)	8.001
Cold side inlet T (°C)	30.0	Cold side inlet P (MPa)	0.4
Hot side pressure drops (kPa)	90	Hot side mass flow rate (kg/s)	180

Table 2. Precooler Design results

Coolant	Water	Air [3]
Number of hot side channel	108000	80000
Number of cold side channel	108000	80000
Hot channel diameter (mm)	2.0	1.9
Cold channel diameter (mm)	2.0	1.9
Plate thickness (mm)	1.0	1.0
Gap between channels (mm)	1.0	1.0
Length of precooler (m)	0.307	0.670
Cold side coolant mass flow rate (kg/s)	120.0	126.0
Volume of precooler (m^3)	0.151	0.309
Mass of precooler (kg)	1207.0	2472.0

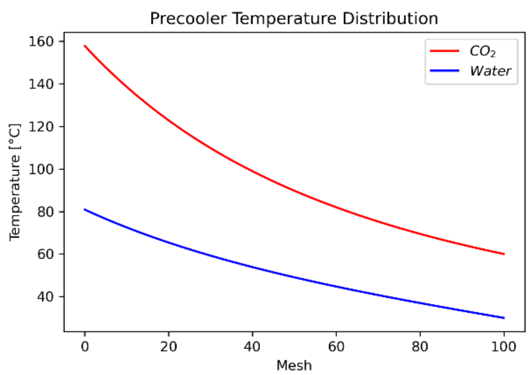

Fig 2. Precooler Temperature Distribution

The redesigned water-cooled precooler has the same performance as the existing KAIST-MMR's air-cooled precooler but has half the mass and volume [3].

2.2 Decay Heat Removal System (DHRS) Design

The decay heat removal system (DHRS) is a safety system that serves to remove decay heat of a nuclear reactor for normal shutdown as well as accident conditions. To improve safety in case of emergency, DHRS is designed to operate passively and does not have active components.

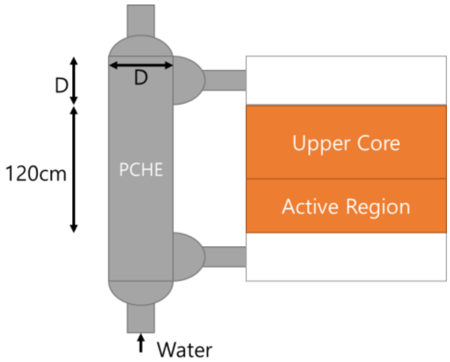

Fig 3. Schematic Diagram of DHRS

DHRS consists of a flow path that bypasses the reactor coolant system, a flow path that draws seawater to cool the heat, and a PCHE between the two flow paths. Considering redundancy, DHRS is installed in two systems. To design the PCHE between these two flow paths, simulations were performed for both normal shutdown and LOCA using MARS, a system analysis code developed by KAERI.

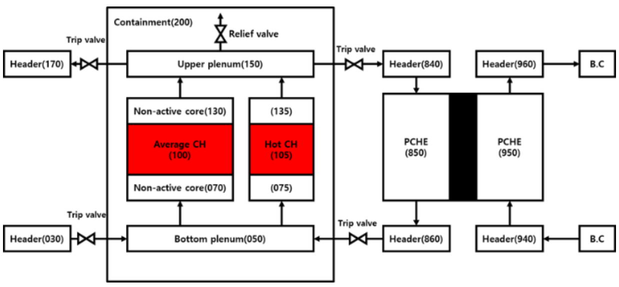

Fig 4. MARS Simulation Node Structure

For the simulation, the reactor and DHRS were simulated with MARS code and modeled with nodes as shown in Figure 4. As for the operation of DHRS, the valve is operated when the reactor is tripped, the core is separated from the power conversion system, and the valve connected to the DHRS is opened to operate the DHRS. In the DHRS design process, the safety criteria in Table 3 are considered.

Table 3. Safety Criteria

Safety Parameters	Safety Criteria
Maximum containment pressure (MPa)	10
Cladding melting point (K)	1773.15
Fuel melting point (K)	2623.15
CO_2 temperature (K)	970

The channel and shape of PCHE were configured as shown in Figure 5 and Table 4. With the shape and total length of PCHE fixed, the diameter of the semi-cylindrical PCHE header is changed, and the diameter that safely removes decay heat during normal and emergency shutdown modes was obtained using MARS code. As a result of MARS code simulation, the heat was stably removed when D=0.4 m and the water flow rate is 15 kg/s. MARS code simulation results are shown in Figures 6 and 7.

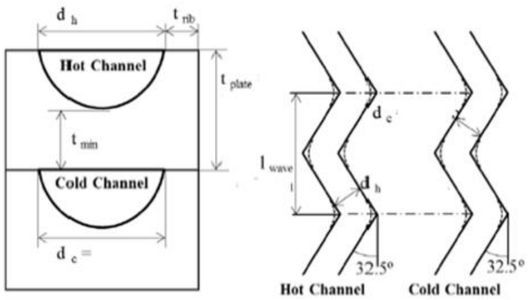

Fig 5. PCHE Channel Profile

Table 4. PCHE Geometry Information

Type	Zigzag channel PCHE
Material	SS316
Hot channel diameter (mm)	2
Cold channel diameter (mm)	2
Plate thickness (mm)	1
Gap between channels (mm)	1.3
Length of PCHE (m)	0.12

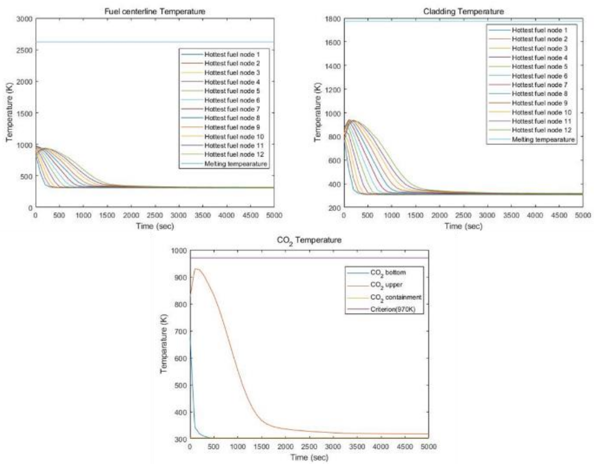

Fig 6. Normal Shutdown

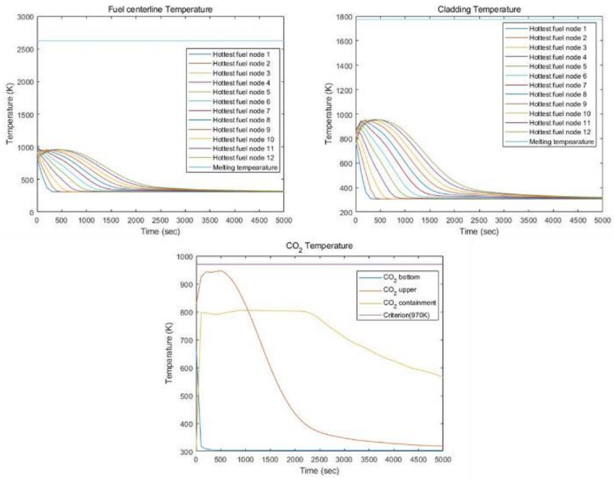

Fig 7. LOCA Shutdown

From Figures 6 and 7, it can be confirmed that the PCHE of the given design satisfies the safety criteria for both normal and emergency shutdown cases. The PCHE volume obtained from the header diameter that satisfies the given PCHE geometry information and MARS simulation is $0.23m^3$.

The mass of one DHRS is 1,840 kg excluding the header. To add header mass, the header thickness is calculated with ASME BPVC (Boiler and Pressure Vessel Code) division 8, and the thickness of the header becomes 44mm. Adding the mass of the header and taking redundancy into account, the total mass of DHRS is 5854 kg.

2.3 Containment Design

In case of loss of coolant accident, the countermeasure is to isolate the core from the power generation system with a valve and removing heat through DHRS. Therefore, in the event of a rupture accident, CO_2 leaks from the core to the containment, increasing the containment pressure. Figure 8 shows the results of calculating the pressure changes of containment and core during LOCA using MARS simulation. In the event of an accident, it can be confirmed that the maximum containment pressure is 9.65 MPa, which is lower than the existing design limit of 10 MPa.

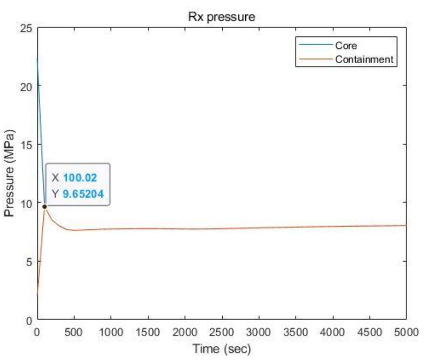

Fig 8. LOCA Pressure

2.4 Comparison with Diesel Engine

Due to the design change, the total mass of the KAIST-MMR was reduced from 154 tons to 138.8 tons [4]. Currently, the main propulsion power of ships is a diesel engine. The dimensions and mass of a 10MW marine diesel engine with the same output as the KAIST MMR are as follows. The Wärtsilä 9L46F’s dimensions are 11m in length and 5m in height, and its weight is 140 tons. [5] For Hyundai 20H32/40V’s case, is 13m in length and 4.8m in height, and its weight is 153.5 tons. [6]

In other words, KAIST-MMR succeeded in achieving a comparable mass with conventional marine diesel engines due to mass reduction of 15.2 tons. In addition, the mass advantage of KAIST-MMR is greater because KAIST-MMR includes the weight of fuel, whereas marine diesel engines do not include the weight of diesel fuel necessary.

3. Conclusions

The mass of KAIST-MMR was optimized to be competitive with conventional marine propulsion diesel engine. KAIST-HXD and MARS codes were mainly used for the process. Compared to the existing KAIST-MMR land-base design, the total mass was reduced by 15.2 tons due to the optimized precooler and DHRS. The reduced mass of the KAIST-MMR is 138.8 tons, and there are sufficient advantages compared to the diesel engine, which weighs 140 tons, excluding the fuel weight. In order to further optimize for marine propulsion nuclear system, it is possible to cool below the minimum temperature of KAIST-MMR with sea water cooling. Further research on cycle redesign will be commenced in the future

ACKNOWLEDGEMENT

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