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Study on the Application of Bayonet Tube Steam Generators to Molten Salt Reactors

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1. Introduction

Molten Salt Reactors (MSRs) have garnered significant attention in recent years due to their potential to revolutionize nuclear energy production. These reactors offer several advantages over traditional light water reactors, including enhanced safety features and improved efficiency. Unlike conventional solid-fuel reactors, MSRs operate with liquid nuclear fuel, allowing for continuous refueling, improved fuel utilization, and passive safety mechanisms. Historically, the Molten-Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory demonstrated the feasibility of MSR technology. The MSRE, which operated from 1965 to 1969, was designed to test the neutronics of a thorium breeder reactor and showcased the potential for high-efficiency heat engines [2].

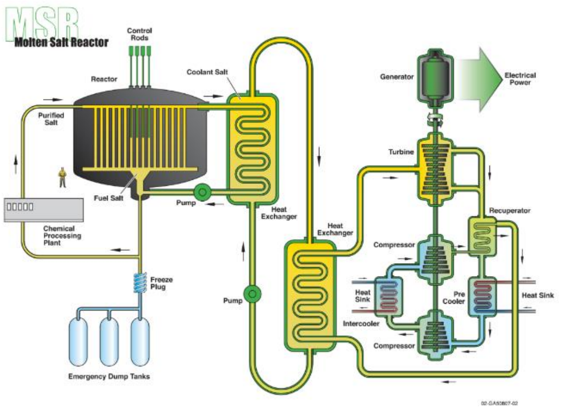

Fig. 1. Molten salt reactor schematic diagram [1]

However, one of the key challenges in MSR design is the efficient transfer of heat from the high-temperature molten salt to the power conversion system, which necessitates innovative steam generator designs, particularly given the high freezing temperatures of molten salts. Because the evaporator section is decoupled from the salt, and if freezing does occur it is limited to the outside of tubes, the bayonet design is intrinsically more tolerant. In addition, the steam generator must withstand significantly higher temperatures than those in conventional pressurized water reactors (PWRs). This requires careful engineering to ensure resistance to fatigue failure while maintaining a compact design. Additionally, steam generators must be designed to allow for in-service inspection (ISI), which has led most MSR developers and research institutions to consider helical tube steam generators as the most promising design. However, historically, Oak Ridge National Laboratory (ORNL) proposed a Bayonet tube steam generator that could better leverage the high-temperature characteristics of molten salt reactors [3][4].

The Bayonet design features a once-through, vertical concentric tube configuration, where feedwater enters through an inner tube, evaporates, and subsequently flows downward through an annulus to receive additional superheat before exiting as high-quality steam. This design inherently minimizes thermal stresses and flow instabilities while providing a buffer between the high-temperature molten salt and the lower-temperature water, mitigating issues such as salt freezing and thermal shock

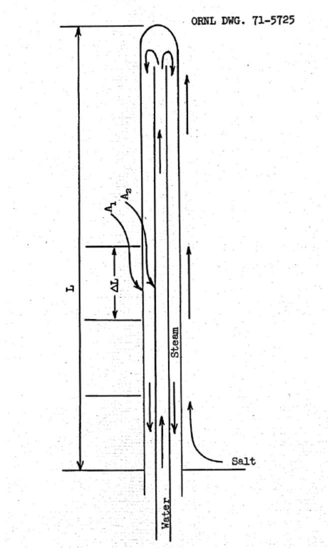

Fig. 2. Diagram of Bayonet Tube for Steam Generator [3]

In the past, due to limited computational power, the analysis of steam generators relied on several simplifying assumptions, such as maintaining a constant heat transfer coefficient in specific regions. Consequently, this study aims to develop a more accurate design for Bayonet steam generators under various conditions by implementing a newly developed computational code. To achieve this, the KAIST-HXD code, originally developed for analyzing sCO_2 heat exchangers, was enhanced with additional functionalities [5]. The bayonet tube steam generator is significantly influenced by the length required for boiling, which can greatly affect the steam generator design. Therefore, using the modified code, steam generator for molten salt reactors were designed for steam conditions at 6MPa, 10MPa, and 15MPa, respectively, and the results were compared.

2. Methods

2.1. Bayonet Tube Steam Generator

The bayonet tube consists of a dual-tube structure, where the fluid flows upward through the central tube, absorbing heat from the surrounding annular tube, and then downward through the annular region, receiving heat from the external hot side while simultaneously transferring heat inward to the central tube. Although bayonet tubes exhibit lower power density compared to other highly compact heat exchangers, the steam serves as a thermal buffer between water and molten salt, offering two significant advantages. Firstly, on the molten salt side, direct heat exchange with feedwater through the wall is avoided, significantly reducing issues associated with molten salt solidification compared to conventional steam generators. Secondly, on the water side, the wall temperature increase near dry-out conditions is significantly reduced due to the absence of direct heat transfer with high-temperature molten salt.

In conventional pressurized water reactor (PWR)-based steam generators, the maximum temperature difference between the hot and cold sides typically does not exceed 150°C, thus limiting the impact of dry-out. However, for molten salt reactor steam generators, the maximum temperature difference can approach 300°C, making fatigue failure due to frequent dry-out induced thermal cycling a critical issue affecting component longevity. In typical once-through steam generators under these conditions, the wall temperature variation around dry-out can reach approximately 200°C. In contrast, bayonet tubes limit this temperature variation to within 50°C, substantially reducing the risk of fatigue-induced damage.

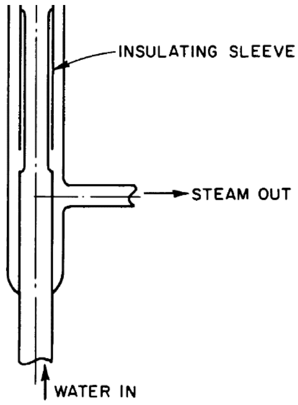

Fig. 3. Insulating Sleeve designed from ORNL [4]

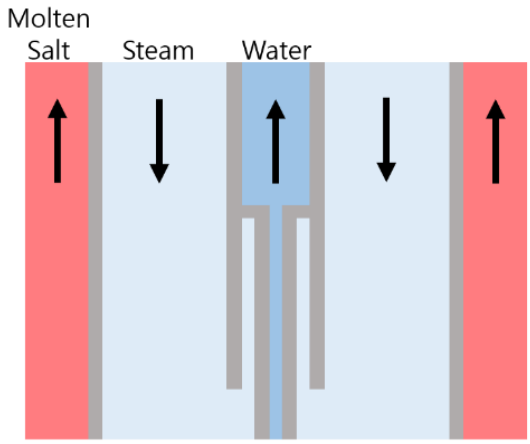

Fig. 4. Original Insulating Sleeve Diagram

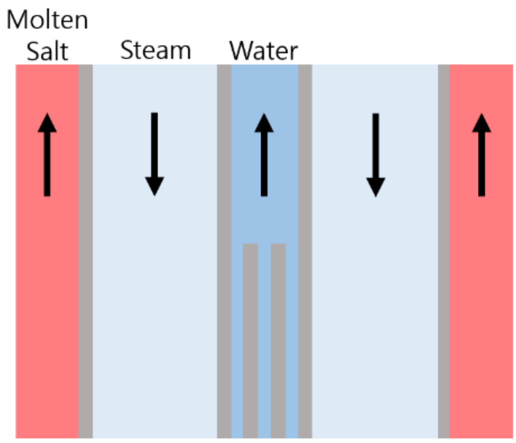

Fig. 5. Modified Insulating tube Diagram

Due to the geometric characteristics of bayonet tubes, there is an inherent limitation in achieving significant superheat temperature increases without dedicated insulation sections. Oak Ridge National Laboratory (ORNL) previously addressed this by adding an external tube around the central tube to convert convection effects into conduction, effectively mimicking insulation. In this study, considering manufacturability and the need for orificing at the inlet to each bayonet, insulation tubes were placed inside the central tube. Computational analysis was performed by reducing the flow area and solving the conduction equations between the insulating tube and central tube wall, thereby simulating the insulation effect realistically while using the KAIST-HXD code.

2.2. KAIST-HXD

The original KAIST-HXD code is a heat exchanger design code developed at KAIST based on MATLAB. It divides the entire heat exchanger into multiple nodes and calculates heat transfer and pressure drop for each node [5][6].

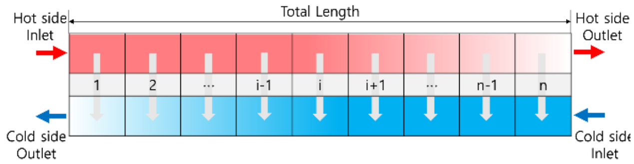

Fig.6. Original KAIST-HXD nodalization

The original KAIST-HXD was improved to analyze the Bayonet tube steam generator. Specifically, to enable the use of a steam system on the cold side, heat transfer and pressure drop models related to two-phase water flow were incorporated into the code. Most of these models were adapted from TRACE V5.0, a widely used code in the field of thermal hydraulic analysis.

Table.1. KAIST-HXD Heat transfer correlations

Single-phase	Water	Gnielinski
	Steam	Gnielinski
Two-phase	ONB	$T_{ONB} = T_{sat}$
	CHF	CHF lookup table 2006
	Void fraction	Lockhart-Martinelli
	Others	Same as TRACE

Table.2. KAIST-HXD frictional factor correlations

Single-phase	Churchill
Two-phase	Same as TRACE

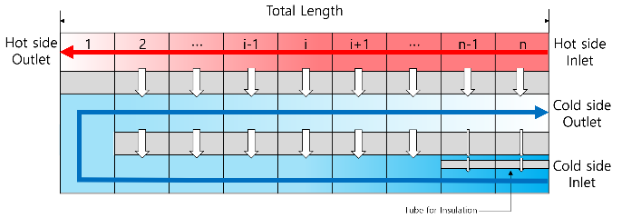

Fig.7. Modified KAIST-HXD nodalization

Moreover, the code structure for the nodes and calculations has been modified. In the case of the previous HXD, the convergence of wall temperatures through iterations at each node did not present significant issues in determining the overall length of the heat exchanger. However, for the Bayonet tube, when convergence is initiated from the Cold Side Inlet, problems arise if the temperature and pressure values do not precisely match at the transition from the center tube to the annular tube. This mismatch results in an improperly designed heat exchanger with incorrect energy balance.

Therefore, the improved code was modified to converge from the Hot Side Outlet to the Hot Side Inlet. Additionally, since both the heat exchange between salt and steam and the heat exchange between steam and water must be simultaneously analyzed, the overall node structure was updated to simulate a 3-way heat exchanger. Regarding the Insulation part mentioned earlier, additional input data related to the Insulation tube have been incorporated so that only the conduction equation can be solved between the Insulation tube and the Center tube.

In the analysis of heat exchangers or steam generators, established codes such as MARS-KS and RELAP5 are often employed. However, when investigating novel fluids like solar salts or chloride salts, incorporating their thermophysical properties into these legacy codes can be challenging and time-consuming. In contrast, KAIST-HXD code is designed for greater flexibility and modularity. It allows seamless integration with property databases such as REFPROP, enabling the user to simulate a wide range of working fluids without significant code modification. Furthermore, the code structure supports easy substitution and testing of different heat transfer and pressure drop models, which is particularly beneficial for rapid sensitivity analyses and optimization. These capabilities, combined with a significantly faster runtime compared to large-scale system codes, make our approach especially suitable for optimization studies of heat exchanger design. The code is currently under active development, with planned expansions to support more complex geometries such as helical tubes, enhancing its applicability to compact, high-performance systems.

2.3. Input data for KAIST-HXD

For the analysis of the bayonet steam generator, input data must be prepared, including details about the type of salt, its physical properties, steam temperature and pressure conditions, and wall material properties. The temperatures and pressures for the hot and cold sides were set to the typical temperature and pressure ranges for MSRs. To assess the impact of pressure, water pressure was varied at 6 MPa, 10 MPa, and 15 MPa, and designs were developed for each pressure.

The geometry was selected with an outer diameter for the tubes that is feasible for ISI, and the tube thickness was chosen based on a simple analysis to withstand high pressure differentials between the steam and the salt. The heat exchanger length was set at 3.5 meters, with insulation length constituting 15% of the total length. For each pressure, the flow rates on the hot and cold sides were adjusted and the design was optimized accordingly. The entire heat exchanger was analyzed by dividing length into 300 meshes.

The design objectives were:
- A temperature difference of no more than 80°C on the salt side
- A pressure drop of no more than 100 kPa on the salt side
- A superheated steam outlet temperature of at least 490°C.

The input data used in the code is summarized in Table 3

Table.3. Input data for KAIST-HXD (Bayonet tube)

Cold side	
Working fluid	Water
Pressure	6, 10, 15 MPa
Temperature	T(steam) > 490 °C
Hot side	
Working fluid	Solar Salt
Pressure	1 – 3 bar
Temperature	470 – 550 °C
Geometry	
Outer tube	1/2 inch, 17 BWG
Center tube	1/4 inch, 18 BWG
Insulation tube	1/8 inch, 20 BWG
Pitch	15.24 mm
Tube length	3.5m
Inflation length	0.53 m (15%)

3. Results

Figures 8, 9, and 10 illustrate the temperature distributions of the Bayonet Tube steam generators designed at 6 MPa, 10 MPa, and 15 MPa, respectively, using the in-house developed KAIST-HXD code. Tables 4, 5, and 6 summarize the thermal-hydraulic inlet and outlet conditions of each steam generator designed under the corresponding pressures, also obtained through the KAIST-HXD code. The meaning of each line and the detailed calculation procedure are described in Section 3.4, Results Summary.

3.1. Steam Pressure: 6MPa

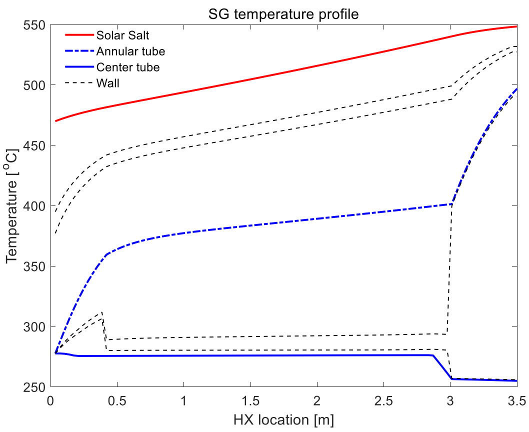

Fig.8. Designed Bayonet Tube Steam Generator Temperature (6MPa)

Table.4. Bayonet Tube Steam Generator Design Values (6MPa)

Cold side	
Inlet Temperature	255.04 °C
Outlet Temperature	496.97 °C
Mass flow rate / tube	0.005 kg/s
Total Pressure Drop	112.52 kPa
Hot side	
Inlet Temperature	548.46 °C
Outlet Temperature	470.0 °C
Mass flow rate / tube	0.095 kg/s
Total Pressure Drop	63.6 kPa
Steam Generator Information	
Power Density	14.18 MW/m^3

3.2. Steam Pressure: 10MPa

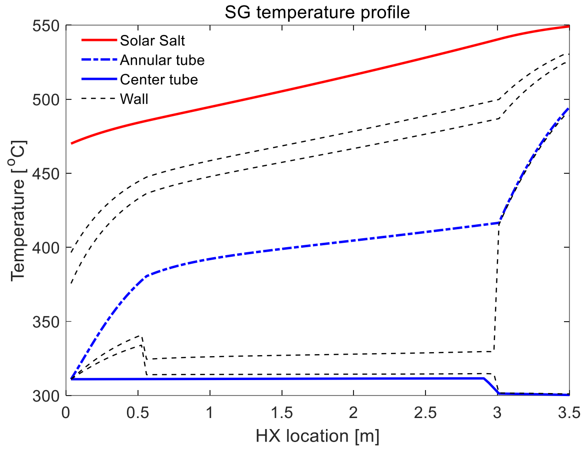

Fig.9. Designed Bayonet Tube Steam Generator Temperature (10MPa)

Table.5. Bayonet Tube Steam Generator Design Values (10MPa)

Cold side	
Inlet Temperature	300.34 °C
Outlet Temperature	494.60 °C
Mass flow rate / tube	0.0068 kg/s
Total Pressure Drop	117.46 kPa
Hot side	
Inlet Temperature	549.14 °C
Outlet Temperature	470.0 °C
Mass flow rate / tube	0.112 kg/s
Total Pressure Drop	64.78 kPa
Steam Generator Information	
Power Density	16.87 MW/m^3

3.3. Steam Pressure: 15MPa

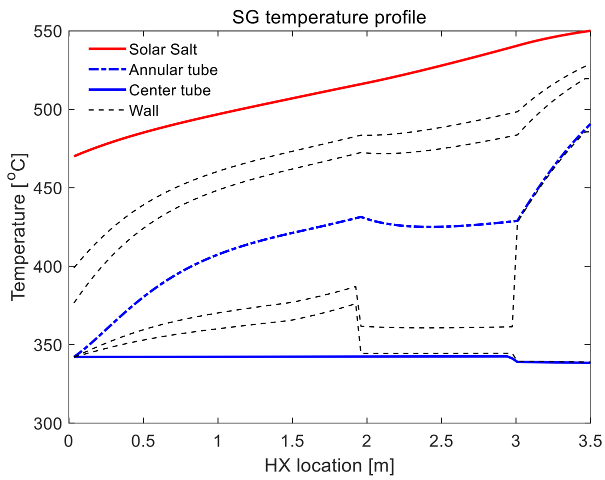

Fig.9. Designed Bayonet Tube Steam Generator Temperature (15MPa)

Table.6. Bayonet Tube Steam Generator Design Values (15MPa)

Cold side	
Inlet Temperature	338.39 °C
Outlet Temperature	490.60 °C
Mass flow rate / tube	0.009 kg/s
Total Pressure Drop	118.79 kPa
Hot side	
Inlet Temperature	549.98 °C
Outlet Temperature	470.0 °C
Mass flow rate / tube	0.124 kg/s
Total Pressure Drop	65.67 kPa
Steam Generator Information	
Power Density	18.87 MW/m^3

3.4. Results Summary

In each graph, the red line represents the temperature of the salt, while the black dashed line represents the surface temperature of each wall. The blue solid line represents the temperature of the water boiling as it rises along the central tube, and the blue dashed line represents the temperature of the steam heating as it descends through the annular tube.

The analysis was iterated by sequentially checking the pressure drop of salt, temperature drop of salt, and steam temperature within the limited length of the heat exchanger. The tubes that yielded the highest power density within the target range were chosen as the final optimized design.

The analysis results show that the Reynolds number for water in the steam generator ranged from about 15,000 to 27,000, and for steam, it ranged from 15,000 to 41,000. These values are lower than those for typical once-through steam generators, as the water needs to boil completely in the central tube, resulting in flow constraints within the limited length. Despite relatively low flow rates, a Power Density of 14-19 $\mathrm{MW/m^3}$ was achieved, which is higher than the 4.8 $\mathrm{MW/m^3}$ of the SMART Helical steam generator [7]. While the temperature difference between the hot and cold sides is larger than that of pressurized water reactors (PWRs), enabling a higher power density, the comparison of total power capacity confirms that MSR steam generators, even with bayonet tube designs, can be fabricated in a practical size.

Moreover, in conventional once-through steam generators, the hot-side working fluid often enters from the top and exits from the bottom. Attempts were made to reverse the flow direction in the Bayonet tube steam generator, but it was found that this resulted in a limitation in maximizing the steam temperature at the outlet. Therefore, it was concluded that the current flow direction is optimal for improving overall reactor efficiency.

The key insight from the design process was that as the target exit steam pressure increases, the difference in latent heat of vaporization decreases. This results in a reduced amount of heat required for boiling within the constrained length, allowing for an increased flow rate and a higher power density. Additionally, it was confirmed that the temperature difference across the internal wall of the center tube before and after dry-out remained within 50°C for all three pressure levels, verifying that the Bayonet tube design is favorable for minimizing thermal fatigue in the steam generator.

3. Conclusions and Future Works

This study aimed to evaluate the feasibility of applying Bayonet Tube steam generators in molten salt reactors (MSRs) by modifying the KAIST-HXD code and developing a design methodology for heat exchanger design. For a fixed geometry, the steam generator design was completed by varying the flow rates of the hot and cold sides at steam pressures of 6 MPa, 10 MPa, and 15 MPa.

The analysis showed that as the target steam pressure increased, the required boiling length decreased, allowing for higher mass flow rates and, consequently, higher power densities. Based on the calculated power density, it was confirmed that the Bayonet Tube steam generator is sufficiently applicable to MSRs and can be constructed in a practical size. Additionally, the Bayonet Tube structure reduced the wall temperature difference before and after dry-out, which is beneficial in preventing thermal fatigue.

Since the analysis was conducted with a fixed geometry that could withstand the differential pressure, it cannot be claimed that a full sensitivity evaluation for all variables was performed. By adjusting the total length of the heat exchanger and insulation length within the desired settings, a steam generator with even higher power density could likely be designed. Future work will involve performing various sensitivity evaluations by varying parameters such as length, insulation length, and P/D ratio.

ACKNOWLEDGEMENT

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