Modeling of Integrated Cryocooling Systems to Improve Resiliency of Superconducting Power Grids on Electric Transport Systems

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ABSTRACT

Conceptual designs of a heat exchanger to provide cryogen circulation at multiple temperatures using variable cooling sources including liquid hydrogen, liquid oxygen, and cryocoolers are proposed for integrated cryogenic systems of electric transport platforms. Cryogenic circulation systems are needed for superconducting and other power devices on electric aircraft and ships. Power devices operate at a broad range of conditions including operating temperature, heat load, and efficiency. Motivated by these needs, a graded heat exchanger that can support cryogen circulation at multiple temperature ranges was designed to integrate a heat exchanger with a cold core at the center cooled by a liquid cryogen or a cryocooler. The outer modules of the heat exchanger stay at warmer temperatures as the cooling power from the central core gets transferred to the outer layers that support cooling a gaseous cryogen of the closed loop circulation system. As an exploratory effort of the concept of the graded heat exchanger, 2-D axisymmetric finite element models (FEM) and simulations were performed for a single module of a screen and porous material for various cooling power and porosities. Results show the feasibility of the graded heat exchanger without a significant pressure drop. More in-depth simulations for the detailed design are needed to realize efficient designs suitable for easier fabrication using advanced machining techniques.

INTRODUCTION

For large electric transportation applications, high temperature superconducting (HTS) power devices provide a solution to the gravimetric and volumetric power density constraints of the electrical power system. One of the challenges associated with HTS technology is the need for cryogenic temperature and the associated cryogenic infrastructure. For electric transportation applications, HTS generators (20-30 K), motors (40-60 K), and cables (50-80 K) are required to operate with high efficiency, reliability, and resiliency to ensure the safe and continued operation of the power system [1]. Electrically, HTS power systems for electric aircraft and ships are similar although the needed cryogenic infrastructure for the two platforms differs significantly. For electric aircraft, liquid hydrogen is being explored as a fuel source to enable zero emission through combustion in either HTS generators or fuel cells [2]. For either device, the hydrogen needs to be at or slightly above room temperature to be used as a fuel source. Storing hydrogen as a liquid (~20 – 25 K) provides a higher energy density solution whilst also allowing the inherent cryogenic cooling to be exploited as part of the thermal management system for the electrical power system. For the thermal systems, the availability of liquid hydrogen (LH2) eliminates the need for cryocoolers onboard the

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aircraft but presents additional challenges in the design of heat exchangers for heat transfer from the electrical devices. The design of the heat exchangers must account for the limited quantity of hydrogen on board the aircraft as well as the fluctuation in heat loads of the power systems. During takeoff, the power demands of the aircraft are approximately double the cruise stage [3]. Also, the heat exchangers must be able to operate with a separate cryogenic circulation medium such as helium gas when the aircraft is on the ground for extended periods due to the large heat capacity of the system which would require several hours for thermal equilibrium to be established.

For electric ships, a closed loop helium gas (GHe) circulation system is utilized for the HTS power devices. GHe is preferred over liquid nitrogen (LN2) due to the larger operating temperature range that enables a single cryogen to serve the HTS generators, motors, and cables [4]. GHe also presents a lower asphyxiation hazard in a confined space compared to LN2. The electrical power system for shipboard applications is at ~100 MW that requires multiple HTS generators, motors, and cables. To ensure a power dense solution, optimization of the cryogenic infrastructure needs to be performed. It is necessary to develop an integrated cooling of these HTS devices without reducing the overall efficiency, resiliency, and redundancy of the power system. Previously, we investigated how the sizing of cryocoolers for an HTS cable network can influence the availability of the electrical power system equipped with cryocoolers [5]. It was observed that multiple smaller cryocoolers were advantageous compared to fewer larger cryocoolers. The thermal infrastructure proposed in the study did not have a heat exchanger which could be utilized to decouple the HTS cables from the cryocoolers. The addition of a versatile graded heat exchanger allows for greater versatility of the thermal system to achieve the targeted operating temperature of the HTS devices whilst also offering a potential solution to add thermal battery storage to mitigate a failure of a cryocooler.

This paper discusses the need for versatile heat exchanger designs for electric transport applications to maximize the efficiency of system-level thermal management and ensure the resiliency of the power system against cryogenic system failures. The heat exchanger designs need to be compatible with different cryogens as well as to ensure the desired operating temperature requirement of each HTS device is met. The paper provides an overview of the thermal design constraints for both electrical aircraft and ships. The overview discusses the design requirements for the primary and secondary cooling loops of the heat exchanger along with anticipated heat loads and operating temperature ranges of the devices within the electrical system. A novel heat exchanger design is discussed and finite element analysis was performed to determine its feasibility for large electric transport applications.

CRYOGENIC THERMAL SYSTEM REQUIREMENTS FOR LARGE SCALE ELECTRIC TRANSPORT PLATFORMS

The thermal system requirements for electric transport systems depend on both device- and system-level topologies selected. This is an active area of research with multiple solutions being considered. To provide context to the potential benefits of versatile heat exchanges as part of the integrated cryogenic system for HTS power systems, notional electric power systems of aircraft and electric ships are examined.

Integrated Cryogenic System

An integrated cryogenic system offers several advantages over individual and distributed cooling systems due to the requirements of various operating temperatures for multiple devices. By chaining multiple devices into one cooling system, overall efficiency can be significantly improved, and the cooling structure can be simplified with a flexible design of piping. For instance, wide operating temperature range can be achieved by connecting cryogen flow directly from cryocooler or exit of other devices in parallel and/or in series as shown in Figure 1.

Flow control of the cryogen to satisfy the cooling requirement of each device depending on the operating conditions and stages of the mission is crucial in designing thermal management at the system level. Innately, the system requires a high cooling capacity obtained by a large cryocooler or liquid cryogen and a large flow rate of cryogen throughout the system. The primary cryogenic loop of the circulation system might need additional cooling power directly from the cryocooler when the device operated at higher power levels or additional resiliency is needed. In contrast, residual cooling power available after

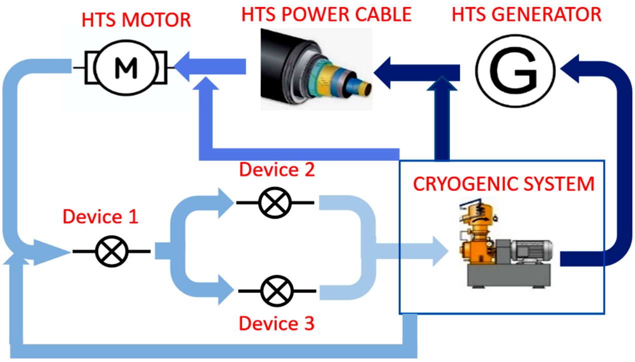

Figure 1. Conceptual integrated cryogenic system of multiple HTS power devices

cooling a device might not be needed for the next devices in the main circulation loop. Flow control on each device can be achieved based on the temperatures and flow rates of available cryogens in the thermal system to keep the inlet temperature of the cooling loop of each device. As thermal management involving heat exchangers generally performs more efficiently at a higher temperature, the cryogen temperatures in the parallel lines do not need to be always the lowest temperature of the whole system. Therefore, the most cost-effective cooling scheme needs to provide the cryogen at the required inlet temperature for each device.

Electric Aircraft

Large electric aircraft are expected to have a power rating of ~40-50 MW and utilize a turbo-electric distributed propulsion (TeDP) [6]. This allows for the decoupling of the generators and motors and positions them in their ideal locations on the aircraft. The generators and motors are connected electrically via power electronic devices and a cable network. The required generation can also be achieved by utilizing fuel cells in combination with the generators. LH2 is intended to be utilized as both a cryogen and fuel source for the aircraft. The quantity of hydrogen onboard is based on the fuel requirement requiring highly efficient designs of both electrical and thermal components. Given the primary purpose of hydrogen is to serve as fuel, the path taken by the hydrogen between the storage tank and combustion should be minimized to reduce the potential of leak/failure of the combustion system. Hydrogen coming into direct contact with electrical devices is also not preferred due to combustion hazards in the event of an electrical arc, hydrogen embrittlement, and the reduced dielectric strength of hydrogen gas when operated at low pressure and flow rates. These constraints require heat exchangers that couple the hydrogen source on the primary side and a different working cryogen on the secondary side. For the HTS motors, generators, and cables, high pressure GHe should provide the required cooling power at the desired temperatures of the devices. For other power devices such as the power electronics and fuel cells which operate at a temperature close to room temperature, it is possible to utilize a traditional coolant for the secondary side of these cooling loops. It is also necessary that the heat exchanger be coupled to a different cooling source besides the hydrogen from the aircraft storage tanks. Given the open loop configuration of the cooling source, it would not be appropriate to operate while on the ground for extended periods. It would be beneficial for cooling to be provided by a closed loop GHe circulation system while the aircraft is on the ground. A GHe circulation system will cool each device to its operating temperature before takeoff due to the large time constant associated with the thermal aspects. The size of the GHe circulation system can also be reduced as during low/no load conditions the heat load being caused by the electrical device is minimal [7]. Figure 2 provides a notional schematic of the heat exchanger design and its interaction with the components on the aircraft. Figure 1 shows multiple cooling loops that exist in parallel for the electrical devices. Parallel configurations are preferred to series configurations to ensure that a failure of the cryogenic section minimizes the number of electrical devices affected.

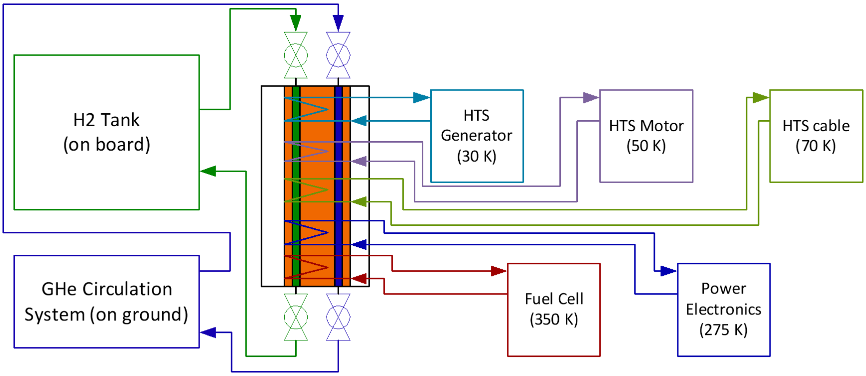

Figure 2. A schematic of the thermal system of a notional power system of an aircraft.

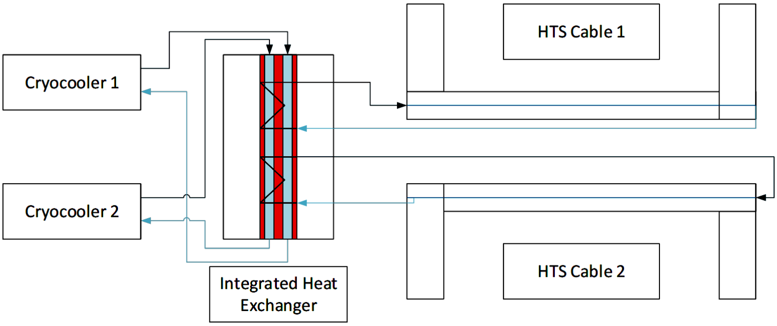

Figure 3. A schematic of integrated thermal system of power system of a notional electric ship.

Electric Ships

For electric ships, the cooling for the HTS devices is provided by a closed loop GHe circulation system. GHe enables the operating temperatures for HTS generators, motors, and cables to be met, however, it requires the use of cryocoolers adding to the size and weight of the overall system. Our research focused on understanding the resiliency required for the cryogenic system to ensure the continued operation of the power system in the event of failure within the HTS cable network [8-9]. One of the drawbacks of utilizing a large capacity cryogenic system is that the failure of the cryogenic device has the potential to affect a major part of the electrical system. The ability to add thermal battery storage as part of the cryogenic system provides a buffer in the event of a cryocooler failure which gives the electrical system sufficient time to respond. An integrated heat exchanger also enables sharing of cooling loads easily across multiple cryocoolers which enables maintenance to be performed and cooling loads to be adjusted between devices based on their operating conditions. Figure 3 depicts a schematic of an integrated heat exchanger as part of the thermal system of a notional electric ship.

A GRADED HEAT EXCHANGER

Conceptual Design of Graded Heat Exchanger

Efficient thermal systems can only be achieved if each device is served with cryogen at the appropriate operating temperature. In electric aircraft, LH2 is being explored as a fuel as well as a cryogenic cooling source before transforming into a combustible gas state. In electric ships, large cryocoolers are used as a cooling source. With the similarity of the two platforms' design of an integrated thermal system with high efficiency and resiliency, a graded heat exchanger is explored as shown in Figure 4. The graded heat exchanger transfers the cooling power of either LH2 or cryocoolers to gaseous cryogen flow at multiple desired temperature range with the desired flowrate as needed. The graded heat exchanger consists of a

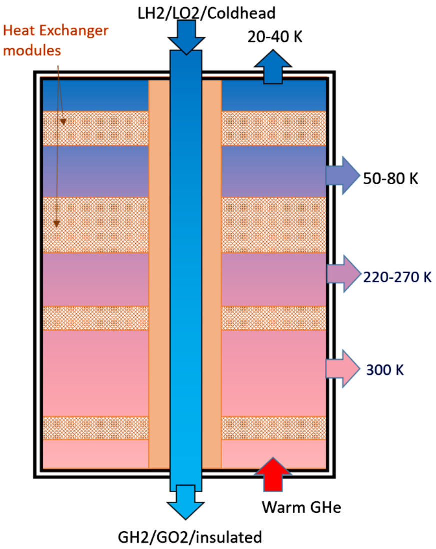

Figure 4. Schematic of conceptual graded heat exchanger.

cold core at the center surrounded by a cryogen such as GHe flow that is cooled by passing through the heat exchanger modules. The cold core is cooled by LH2, cryocoolers, or other liquid cryogens. The heat exchanger module design allows flexibility and interchangeable parts based on the heat loads of the electrical devices to deliver GHe at the desired temperature. As warm GHe counter-flows with the cold source flow and passes through the conductively cooled heat exchanger modules, the temperature of GHe decreases. Graded design modules can lower the GHe temperature as desired. Also, the cold core and heat exchanger modules add stability and resiliency to the system since their heat capacity acts as a thermal battery when the cooling sources fail.

The graded heat exchanger is versatile enough to fit various thermal applications of electric transportation. As shown in Figure 5, the modular design of the graded heat exchanger enables its structure to have a selected temperature regime of a particular temperature of the cryogen. The case shown in 5(a) allows a

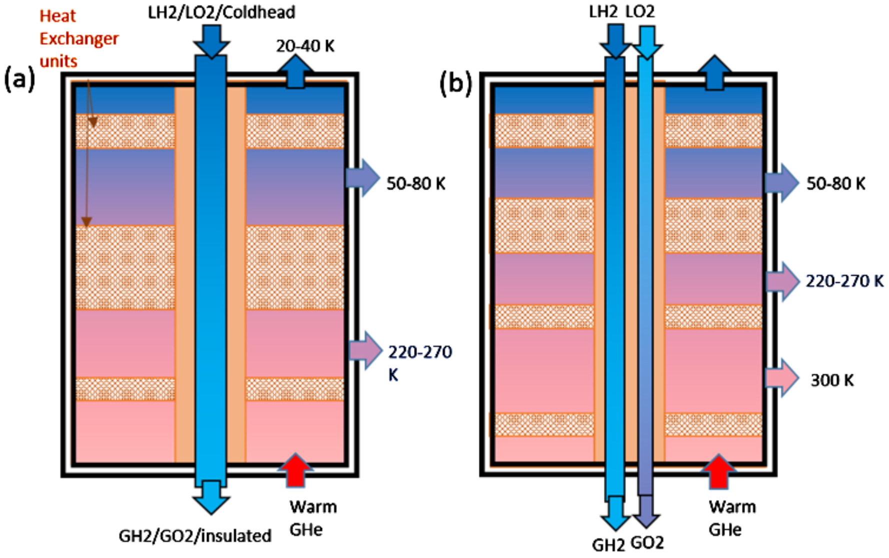

Figure 5. Potential configurations of versatile graded heat exchanger concept.

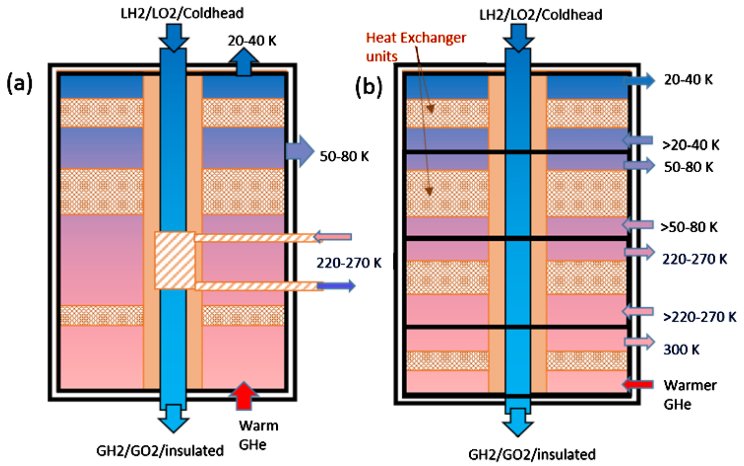

Figure 6. Additional potential configurations of versatile graded heat exchanger concept.

room temperature cooling medium for such as water-cooled or air-cooled power electronics. The GHe at 300 K would not need the first modular cooling section. For the cases shown in 5(b), when multiple cooling sources such as LH2 and LO2 are available, the cold core can have multiple paths for the liquid cryogens.

In Figure 6(a), where cryogens other than GHe are used, the module can have a separate sub-heat exchanger directly attached to the cold core. In the case of Figure 6(b), the GHe circulation system can have and separate temperature control, separate chambers insulated from one another but still share the same cooling source at the core.

The crucial component of the graded heat exchanger is the heat exchanger module that transfers cooling power from the center cold core to the path of GHe around the core. It is expected that the thickness of the heat exchanger unit is related to the temperature and pressure drops across the module. A well-designed module maximizes the temperature drop but minimizes the pressure drop. As the opening of the GHe path in the module increases, the pressure drop decreases, and less cooling power is transferred to the GHe path. Therefore, the optimum design that minimizes the pressure drop and maximizes the heat transfer is crucial for the graded heat exchanger. To find the optimal values for the parameters of pressure drop and cooling efficiency including the geometry of the heat exchanger module, cooling power, cross-section available for of GHe path, and pressure and temperature of inlet GHe, preliminary simulations conducted using COMSOL as discussed in the next section.

Preliminary Results of the Models of the Graded Heat Exchanger Module

For simplicity of the parametric study on the performance of the heat exchanger module, a single module in a 2-D axisymmetric model with a cold core of constant cooling power (simulating conductive cooling by cryocooler) is modeled using COMSOL. Figure 7 shows the domain of the simulation that consists of a cold core, cooling module, and helium flow enclosed by an insulated cylinder. A 100 mm diameter cold core at the center has a heat sink surface on the top end, insulated on the bottom, and an annulus outer diameter of 135 mm is attached to the cold core to allow GHe to flow through the module. GHe enters at the bottom at a constant upward velocity and exits at the top as cooled while passing through the module.

The first module geometry selected is a screen with constant temperature as shown in Figure 7. GHe at 80 K and 2MPa enters, cooled, and exits at about 70 K after passing through the screen at 50 K with a 0.5 opening ratio. The pressure drop across the screen is small in this case. Although the cooling power transfer from the cold core to the screen is not considered in this heat exchanger structure, it suggests that a well-designed screen works effectively to cool GHe at the cryogenic flow conditions.

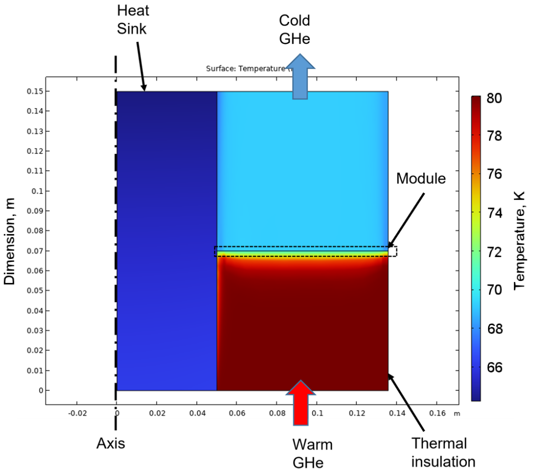

Figure 7. Domain of 2D axisymmetric heat exchanger unit with a screen module simulated on COMSOL

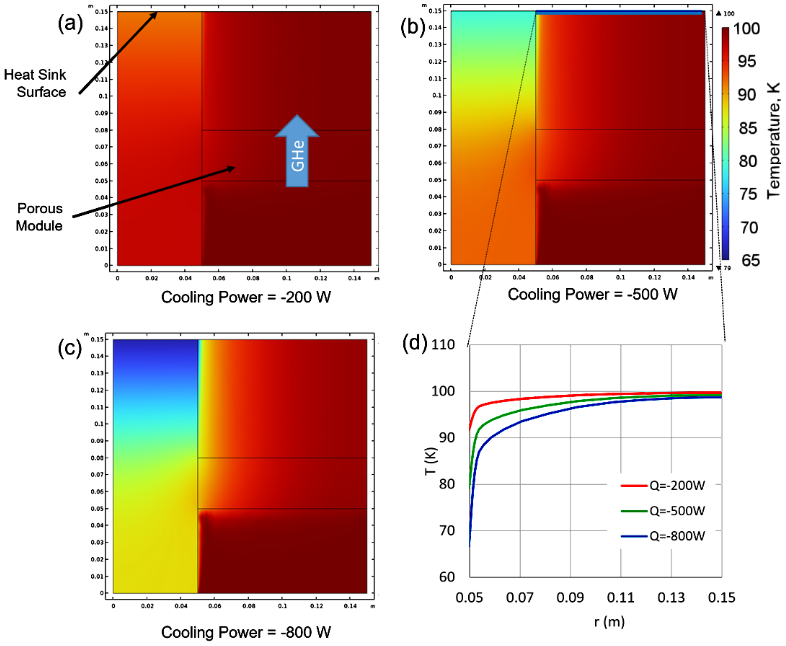

Figure 8. Temperature maps of the 2D axisymmetric heat exchanger with a porous copper module. For (a)-(c), various cooling powers provided, and (d) exit temperature of GHe.

The heat exchanger module discussed in the next section uses a porous copper structure, as shown in Figure 8. The porous copper module with 0.5 porosity, 150 mm outer diameter, and 30 mm thick is attached to the center core to convey the cooling power from the core to GHe. The cooling power at the top surface of the cold core varies from (a) -200, (b) -500, and (c) -800 W, respectively, GHe flow rate of 20 g/s, 100 K, and 2 MPa at the inlet passes through the heat exchanger module and gets cooled. Figure 8 (d) shows the exit temperature along the radius at the exit. The temperature drop across the module is proportional to the cooling power provided and the effectiveness of heat transfer to the module. As more cooling power is provided, the exit temperature decreases but especially near the cold core, which suggests the additional flow path control and modification of module geometry to better convey the cooling power to the module from the cold core.

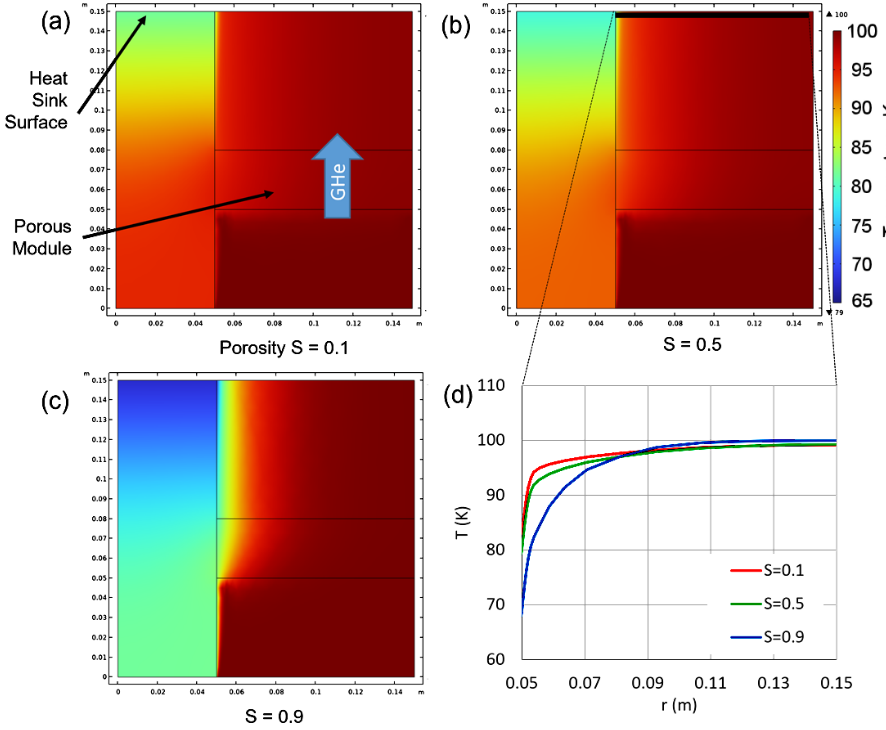

Figure 9. Temperature maps of the 2D axisymmetric heat exchanger with a porous copper module. (a)-(c) show the results of various porosities (S), and (d) exit temperature of GHe.

For the same porous module, the temperature drop for various porosity values is studied, as shown in Figure 9. For porosity S of 0.1, 0.5, and 0.9 at a given cooling power of -500 W at the heat sink surface, the temperature change of GHe at the inlet of 20 g/s, 100 K, and 2 MPa is studied. As expected, the temperature drop is larger when GHe passes through the higher porosity module that has more contact surface of the copper module resulting in a lower temperature at the exit. Large porosity values, however, allow a larger temperature gradient radially, which also suggests the need for additional investigations for optimal flow in the module design for better efficiency of the modular heat exchanger. In all the cases, the pressure drop is minimal, less than 1% of inlet pressure (0.2 MPa) even for the smallest porosity (S=0.1).

Further design considerations are needed to improve the transfer of cooling power to the module and flow path control for better mixing since this module is stacked for better cooling. Better cooling power transfer from the cold core to the module can be achieved by adding spokes in the flow path of the module. This also helps the structural stability of the module. For multiple stacks of the modules, better mixing of inner flow and outer flow is essential. To achieve uniformity, other considerations in flow control such as fins or more complicated inner structure of the module will have to be adopted. A test-scale experiment using multiple copper modules that can be manufactured using copper 3D printing is being planned and experimental results will be compared with the simulation in the near future.

CONCLUSION

A graded heat exchanger was investigated to serve HTS power devices operating at different temperature ranges. A segment of the graded heat exchanger module has been studied using screen structure and porous copper module. The temperature drop through the module shows promising results but also suggests the need for further research on heat exchanger module structure development for improved cooling efficiency and flow uniformity.

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