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Fabrication and design aspects of high-temperature compact diffusion bonded heat exchangers

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ABSTRACT

The Very High Temperature Reactor (VHTR) using gas-cooled reactor technology is anticipated to be the reactor type for the Next Generation Nuclear Plant (NGNP). In this reactor concept with an indirect power cycle system, a high-temperature and high integrity Intermediate Heat Exchanger (IHX) with high effectiveness is required to efficiently transfer the core thermal output to a secondary fluid for electricity generation, hydrogen production, and/or industrial process heat applications. At present, there is no proven IHX concept for VHTRs. The current Technology Readiness Level (TRL) status issued by NGNP to all components associated with the IHX for reduced nominal reactor outlet temperatures of 750–800 °C is 3 on a 1–10 scale, with 10 indicating complete technological maturity. Among the various potential IHX concepts available, diffusion bonded heat exchangers (henceforth called printed circuit heat exchangers, or PCHEs) appear promising for NGNP applications. The design and fabrication of this key component of NGNP with Alloy 617, a candidate high-temperature structural material for NGNP applications, are the primary focus of this paper.

In the current study, diffusion bonding of Alloy 617 has been demonstrated, although the optimum diffusion bonding process parameters to engineer a quasi interface-free joint are yet to be determined. The PCHE fabrication related processes, i.e., photochemical etching and diffusion bonding are discussed for Alloy 617 plates. In addition, the authors' experiences with these non-conventional machining and joining techniques are discussed. Two PCHEs are fabricated using Alloy 617 plates and are being experimentally investigated for their thermal-hydraulic performance in a High-Temperature Helium Facility (HTHF). The HTHF is primarily of Alloy 800H construction and is designed to facilitate experiments at temperatures and pressures up to 800 °C and 3 MPa, respectively. Furthermore, some preliminary microstructural and mechanical property characterization studies of representative diffusion bonded Alloy 617 specimens are presented. The characterization studies are restricted and less severe from an NGNP perspective but provide sufficient confidence to ensure safe operation of the heat exchangers in the HTHF. The test results are used to determine the design operating conditions for the PCHEs fabricated.

1. Introduction

The Very High Temperature Reactor (VHTR) is a leading candidate for the U.S. Department of Energy's (DOE) Next Generation Nuclear Plant (NGNP) project. The reference VHTR design is a helium-cooled, graphite-moderated, thermal neutron spectrum reactor with core outlet temperatures greater than 900 °C. It is primarily dedicated to efficient cogeneration of electricity and hydrogen or other process heat applications and can be interfaced with commercial applications that utilize high-temperature process heat. An Intermediate Heat Exchanger (IHX) is therefore essential to effectively transfer the heat between the Primary Heat Transport System (PHTS) and the Secondary Heat Transport System (SHTS). It is a major component of the Heat Transport System (HTS) of the NGNP and directly affects the system's overall efficiency. Of all the high-temperature metallic components, the one most likely to be heavily challenged in the NGNP will be the IHX (Idaho National Laboratory, 2009). It should withstand high temperatures for long service duration and must be robust enough to perform its function effectively.

At present, there is no proven high-temperature IHX concept for VHTRs. The current Technology Readiness Level (TRL) status issued by NGNP for all components associated with the IHX for reactor outlet temperatures of 750–800 °C is 3 on a 1–10 scale, with

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10 indicating complete technological maturity (Idaho National Laboratory, 2009). Several candidate IHX designs, such as the shell and tube, plate and fin, printed circuit heat exchanger (PCHE), are being evaluated for NGNP IHX applications. Compared to the shell and tube heat exchangers, compact heat exchangers are characterized by a large surface area density, resulting in reduced space/volume, weight, support structure, and material cost. Among various potential IHX design concepts available, diffusion bonded/printed circuit heat exchangers appear promising for the NGNP applications. PCHEs are compact, efficient, and have high-pressure containment capability, all of which are attractive to the NGNP program. If the IHX is fabricated by diffusion bonding, the bond strength may become the controlling factor for life and it is imperative to develop the optimum diffusion bonding process parameters for high-temperature candidate materials. The design and fabrication of this key component of NGNP are the primary focus of this paper.

In the current study, diffusion bonding of Alloy 617 has been demonstrated, although the optimum process parameters are yet to be completely defined. The PCHE fabrication related processes, i.e., photochemical etching and diffusion bonding are discussed for Alloy 617 plates. In addition, the authors' experiences with these non-conventional machining and joining techniques are discussed in this paper. Two PCHEs were fabricated using Alloy 617 plates and are being experimentally investigated for their thermal-hydraulic performance in a high-temperature helium test facility (HTHF). Detailed microstructural examination and mechanical property characterization of the diffusion bond joint interface is inevitable if diffusion bonding is to be successfully utilized for the fabrication of high-temperature heat exchangers. Some preliminary microstructural and mechanical property characterization studies of representative diffusion bonded Alloy 617 specimens are presented. The characterization studies are less severe from an NGNP perspective but provide sufficient confidence to ensure safe operation of the heat exchangers in the HTHF.

2. High-temperature helium test facility

Fig. 1 shows the schematic and photographs of the high-temperature helium test facility. It has been designed and constructed to facilitate performance testing of heat exchangers at temperatures and pressures up to 800 °C and 3 MPa, respectively. It should be noted that the original design goal of the test facility maximum temperature was 900 °C (Mylavarapu et al., 2009c), which has been reduced due to the reduced reactor outlet temperatures (750–800 °C) in the new DOE VHTR design specifications. The facility has been designed with sufficient flexibility to accommodate testing of heat exchangers with different configurations and other critical components of VHTR, such as valves, instruments, gaskets, and piping, under high-temperature conditions. In designing and constructing the facility, the requirements of ASME B31.3 Process Piping and ASME VIII and IX of the B&PV Code were followed (ASME and ANSI, 2007; ASME, 2007). The facility, however, is not designed and constructed to more restrictive ASME III code. Two counter-flow PCHEs are installed in series in the facility for thermal-hydraulic performance testing under a wide range of operation conditions. Table 1 lists the salient features of the test facility.

The test facility utilizes a gas booster to circulate helium in the test facility piping and components. A 5-gallon surge tank and an inline pressure reducing regulator/valve (PRV) located downstream of the booster help mitigate the pressure fluctuations and ensure a stable helium flow in the test facility. The facility is equipped with pressure transducers for measuring the pressure and differential pressure on both the hot and cold sides of the PCHEs. K-type, Alloy 800H sheathed thermocouple wells are used for measuring the helium temperatures at various locations in the facility. Three venturi type flow meters measure the volumetric flow rates of helium gas flowing through the loop. Additionally, two high-temperature flow meters designed by a commercial vendor are installed in the facility for prototype design testing and cross benchmark of the flow measurements. A turbine-type flow meter installed on the process chilled water-side of the cooler allows monitoring of the flow rate of the process chilled water (PCW). The inlet and exit temperatures of chilled water in the PCW line are measured using precision RTD sensors. This information allows us to estimate the rate of energy removal by the chilled water. All measurement and test equipment have calibration information traceable to NIST standards. Furthermore, this facility adheres to a quality assurance (QA) procedure that is consistent with the QA guidelines provided by the U.S. DOE.

2.1. Thermal-hydraulic experiments in high-temperature helium facility

Performance testing of two counter-flow PCHEs in the test facility is currently in progress at varied operating temperatures, helium pressures, and helium flow rates. To date, the inlet temperature and pressure were varied from 85 to 330 °C/1.0 to 2.7 MPa for the cold side and 208–650 °C/1.0–2.7 MPa for the hot side while the mass flow rate of helium was varied from 15 to 45 kg/h. This range of mass flow rates corresponds to PCHE channel Reynolds number of 900–4200. The data are currently being analyzed and reduced to evaluate the heat transfer and pressure drop characteristics of the heat exchangers.

3. Printed circuit heat exchangers: fabrication and design

3.1. PCHEs as a potential design option for IHX of VHTRs

VHTRs require high-temperature and high efficiency heat exchangers to effectively transfer the heat from primary helium to the secondary fluid (helium or nitrogen/helium mixture). Gas coolants typically have low heat transfer capability due to their low volume-based thermal capacity and thermal conductivity. This necessitates the requirement of a heat transfer surface with a very high surface area density (650–1300 m^2/m^3), i.e., a compact heat transfer surface. Compared to a non-compact heat exchanger, compact heat exchangers such as PCHEs are characterized by a large surface area density, resulting in reduced space, weight, support structure and footprint, energy requirements and cost, as well as an improved process design. Furthermore, due to the nature of the fabrication techniques involved, PCHEs possess high-pressure containment capability and with the right selection of structural materials, they can be designed for high-temperature service applications as well. All these factors have a great influence on the VHTR plant layout and design. Moreover, PCHEs have a sound technology base in that they are being extensively used in demanding non-nuclear applications, albeit at relatively much lower temperatures, such as offshore oil platforms as gas coolers, and compressor after coolers. In light of the above, PCHEs have a tremendous potential to be an excellent choice for IHX.

3.2. PCHE fabrication techniques

The IHX of VHTRs should be able to withstand high service temperatures for long service duration without any structural degradation. The material selection and design of the IHX represent a substantial technical development effort. Among various potential IHX design concepts being considered for VHTRs, PCHEs have the potential to be an excellent design option for the IHX. However,