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DIFFUSION BONDED HYDROGEN PRE-COOLER PRESSURE FATIGUE

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ABSTRACT

Diffusion bonded heat exchangers, also known as printed circuit heat exchangers (PCHEs), have numerous benefits over traditional shell and tube heat exchangers including high pressure containment, a compact size with 1000 to 5000 m^2 of surface area per unit volume, and lower costs. One emerging application is in hydrogen vehicle fueling stations as a pre-cooler where the hydrogen is cooled at pressures up to 875 bar. These pre-coolers must be able to withstand pressure cycling over 10^5 cycles during the fueling station lifetime without degradation of their pressure boundary that could result in leakage of hydrogen.

This work presents details on a pressure fatigue validation test of a diffusion bonded pre-cooler using water to 10^5 cycles. In addition to monitoring for pressure decay, helium leak checks were performed every 10^4 cycles on the unit to assess the risk and extent of any fatigue crack propagation not easily observed from the pressure signal. The pressure conditions follow the standards outlined in SAE J2601 for maximum ramp rate and maximum filling pressure. A complimentary numerical mechanical model was developed to assess the magnitude and location of internal stresses in the complete pre-cooler geometry which may limit fatigue life and guide destructive examination after testing.

Keywords: Heat Exchangers, Diffusion Bonding, PCHE

1. INTRODUCTION

Diffusion bonded heat exchangers were originally developed at Sydney University in 1980 [1] and have since been under active development by several heat exchanger original equipment manufacturers. These devices are formed by chemically etching flat plates to create flow channel patterns for one or more fluid streams, stacking them, and diffusion bonding them together to create a block with the material strength throughout as required under the ASME Boiler and Pressure Vessel (BPV) Code [2]. A photochemical etching process is used to form flow channels in these heat exchangers in a similar process to that used to created integrated circuits leading to the commonly-used term of “printed circuit heat exchanger” or PCHE, though the similarity to printed circuit boards ends there.

Compact heat exchangers (CHXs) more generally have led to significant advancements in process intensification through numerous industries [3]. Reducing the characteristic diameter of the flow channels within a heat exchanger increases the surface area per unit volume or ‘compactness’ of the heat exchanger, the internal heat transfer coefficients of the fluids within the heat exchanger, and the pressure containment capability of the channels [4]. These benefits can dramatically reduce the size required for heat exchange with corresponding benefits in system integration and fluid inventory with prices typically half that of comparable high pressure stainless steel shell and tube heat exchangers [5]. The advancement of CHX technology has been particularly beneficial for a variety of refrigeration applications as plate and frame heat exchangers (PHE) largely replaced shell and tube units and were subsequently replaced by plate-fin heat exchangers (PFHEs). However, both previous heat exchanger types are limited to applications involving design pressures less than 130 bar (13 MPa).

Diffusion bonded compact heat exchangers are the next logical step toward process intensification of high-pressure applications including hydrogen filling station precooling, intercooling, and aftercooling with design pressures around 1000 bar (100 MPa) and temperatures ranging from -50 °C to 180 °C. Previous work by Heatric™ developed a diffusion bonding qualification procedure adopted in the ASME BPV Code [6], but very little information is available on the reliability of PCHEs under failure modes other than static burst testing.

An early meeting at the Massachusetts Institute of Technology (MIT) with representatives from Heatric™ was summarized by Gezelius [7] and suggested that PCHEs were “essentially immune to [pressure] transients” with internal tests to twice the design pressure surviving to $5x10^6$ cycles without signs of failure. Previous work by Kobe Steel [8] is consistent with this statement and presents results for two PCHEs designed

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for hydrogen filling station applications surviving to 10^5 cycles in water and $7x10^4$ cycles in hydrogen.

While these publications provide some confidence in the reliability of PCHEs, neither demonstrates the specific failure mode of a unit under pressure fatigue or validates this lifetime to design expectations. To achieve these aims Sandia National Laboratories has partnered with Vacuum Process Engineering to demonstrate the fatigue life of a hydrogen pre-cooler PCHE and eventually confirm the lifetime and failure mode of this unit under relevant transient conditions.

2. METHODOLOGY

This work involves complementary experimental and simulation investigations to gain greater confidence in Hydrogen Pre-cooler (H2PC™) mechanical performance under high cycle fatigue.

2.1 Hydrogen Pre-cooler Design

Hydrogen pre-coolers are used for cooling a high-pressure hydrogen stream from a typical 40 °C inlet to about -40 °C using refrigerants such as Syltherm XLT, Dynalen HC-50, CO_2 and others. These are plate type heat exchangers that use chemically etched plates, which are diffusion bonded together to provide high mechanical integrity pressure containment. Diffusion bonding is a solid-state joining process with strength through the bond-line equal to parent metal strength, making them highly suitable for the high pressure requirements of hydrogen pre-coolers. Fluid flow channels are made using chemical etching to provide flexibility in design layouts with superior ability to balance pressure drop and heat transfer.

The H2PC™ mechanical design follows the design by formula rules of ASME Section VIII, Division 1. Design and construction of diffusion bonded microchannel heat exchangers are permitted and directed by mandatory Appendix 42 of the same code. As per the appendix, the internal pressure stresses and design are guided by the Appendix 13 rules [6], [9]. Based on previous comparisons made between stresses from the Div. 1 design by formula rules and finite element analysis of core channels, the allowable stresses values obtained from ASME Section IID are limited to the lower strength values of SS316L, despite constructing the pre-cooler from SS316/316L dual certifiable material with the chemistry of SS316L but the strength of SS316. Designing for lower strength values while manufacturing with higher strength material provides an additional safety factor beyond what is accounted for in the BPVC.

Specific geometry details related to the integral porting and manifolding into the heat exchanger along with the specific diffusion bonding procedure used (times, temperatures, etc.) are proprietary trade secrets and cannot be included in this work, but the geometry of the channels is similar between manufacturers and largely prescribed by ASME BPVC Section VIII Division 1 Appendix 13 [6]. Therefore while these test results are specific to the current heat exchanger they do provide confidence in the mechanical integrity of the heat exchanger channels used in all diffusion bonded heat exchangers. Care must still be taken to analyze and test new header and manifold designs as these can greatly impact mechanical integrity [10], [11].

Helium leak tests are also conducted as part of quality assurance practices with an industrial accepted maximum leak rate criterion of 10^{-7} cc/sec. The pre-cooler under test had an actual leak measurement of 10^{-9} cc/sec. Hydrostatic pressure tests with a test pressure to design pressure ratio of 1.43 is applied to further ensure product integrity.

The pre-cooler under test is shown in Figure 1 and has a high-pressure circuit MAWP of 1000 barg at 65°C and a MDMT of -65°C at 1000 barg. The outer dimensions of the diffusion bonded core are 11.0 inches (280 mm) long, 6.10 inches (155 mm) wide, and 6.89 inches (175 mm) high. Its design weight dry is 79.8 lbs (36.2 kg). This heat exchanger is a full-scale unit that can be used in a hydrogen vehicle fueling station and is notably smaller than existing designs for the same conditions. Although it is typically oriented with the larger coolant nozzles horizontal, this unit is oriented vertically to aid in air venting and water draining.

FIGURE 1: Hydrogen Pre-cooler under test.

2.2 Pressure Fatigue Experiment

A new experimental capability was developed at Sandia National Laboratories named the Pressure Vessel Test Rig (PVTR). Its purpose is to test pressure vessels in overpressure and pressure fatigue conditions and uses water to reduce hazards associated with ruptured vessels. It consists of a customized shipping container that acts as secondary containment for test articles, a customized pressure test cart that can be electrically controlled, and a digital data acquisition and control system as shown in Figure 2. A helium leak detector is moved in to the chamber when used but not shown in this image. The system was used previously for burst testing of PCHE semi-circular external headers for validation of the ASME Boiler and Pressure Vessel Code and finite element simulations [12].

FIGURE 2: Pressure Vessel Test Rig in secondary containment with pressure cart on front left, electrical enclosure rear left, and test stand and H2PC™ on right

The customized pressure cart was designed and fabricated by H. Lorimer Corporation and can provide a controllable pressure between 500 and 60,000 psi. It has both high and low pressure systems that are pressurized with Maximator air-driven water pumps. Each system has an air pressure regulator and several valves for isolation and dumping. The cart can be operated locally with manual controls or remotely with standard electrical inputs. For operations where rupture is possible, it is operated remotely through a National Instruments data acquisition system with an embedded controller. This is a reliable control system that has deterministic and repeatable behavior for safe, unmanned operation.

The data acquisition and control system was programmed in LabVIEW and enabled both manned and unmanned operation. For unmanned operation, many safety features were implemented that safely shutdown the system in the event of overpressure, underpressure caused by a leak or lack of supply water or air, and rapid depressurization. Pressure cycling can be customized with the number of cycles, initial and final pressure, ramp time, and a hold time. Closed-loop PID control was implemented to adjust for changes in the system behavior that were observed. The program records data at a nominal 1 Hz rate to a local computer.

Pre-cooler health is monitored continuously for large failures by pressure rate calculations in the control software as well as occasionally for micro-cracks with helium leak detection. Helium leak detection is performed at regular intervals of 10k cycles (approximately monthly) and follows industrial best practices. A Varian 959 MacroTorr mass spectrometer helium leak detector is used with a leak measurement range of 10^{-8}atm cc/sec.

Prior to testing, the H2PC™ is dried by draining, purging with heated nitrogen, and pumped under roughing vacuum until all the water is removed. The leak detector is calibrated prior to every test with a new calibrated leak reference at $1.3x10^{-7}$ atm cc/sec (roughly 4 atm cc/year) near the middle of the leak detector measurement range. During the test, the H2PC™ high pressure hydrogen side is connected to the detector, put under vacuum, and helium is flooded through the low pressure circuit as well as introduced to all external surfaces with a helium gun. This allows for detection of micro-cracks between the high pressure side and any other area.

The goal of the experiment is to validate the H2PC™ mechanical integrity when subject to 10^5 cycles between atmospheric pressure and the maximum pressure it may see in service. The maximum pressure was conservatively chosen as the maximum fill pressure possible of 12,700 psi (87.5 MPa) as specified in the Society of Automotive Engineers (SAE) J2601 standard for fueling of light duty vehicles [13]. The pressure ramp rate on the H2PC™ was set to follow the maximum pressurization rate of 3480 psi/min (24 MPa/min). The ramp time was therefore 218.8 seconds (3.6 minutes). The SAE J2601 standard was used as the hydrogen pre-cooler under test is meant to cool the hydrogen stream in fueling stations before it enters the vehicle and will be subject to the conditions outlined.

2.3 Finite Element Simulation

Simulations can provide insight into internal stress states and may provide a link to estimate fatigue life in connection with stress-fatigue diagrams for common metals. Simulations were performed predicting the distribution of stress throughout the H2PC™ using Sierra Solid Mechanics [14]. The domain consisted of a rectangular prism representative of the full H2PC™ design yet containing only one repeat unit (B-A-B) in addition to each flow side's respective headers. We discretized this domain into 133 million quadratic tetrahedral elements, with higher resolution near pressure surfaces and larger elements towards the outer boundaries as shown in Figure 3. The cold side channels and headers were subjected to a static 3.5 MPa load while the hot side had 87.5 MPa applied. A Young's modulus of 200 GPa and Poisson's ratio of 0.265 were used for the stainless steel. The stress model used was linear elastic.

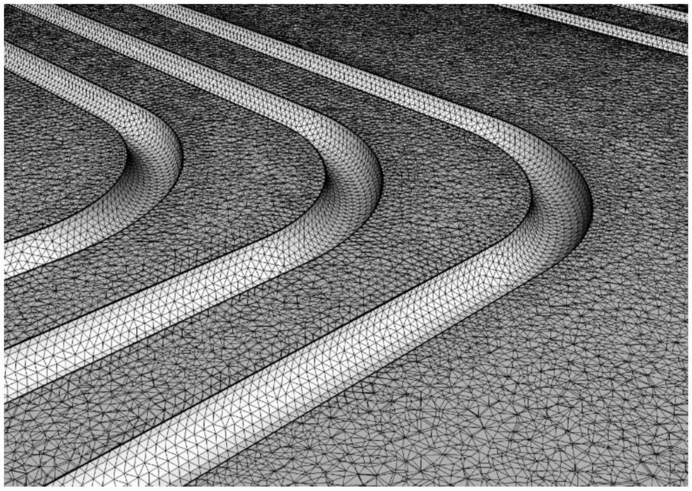

FIGURE 3: Tetrahedral mesh shown in area of high pressure channels

3. RESULTS AND DISCUSSION

The results include pressure fatigue conditions, leak check results, and simulation predictions of stress that may be useful in fatigue predictions.

3.1 Pressure Fatigue Experiment

The pressure cycling in the experiment was controlled as tightly as possible with the moderate variations in pump behavior over time. To be conservative and ensure that nearly all cycles reach the target pressure, the target pressure and ramp time settings were slightly increased. A plot of the raw pressure measurements for the first 10^5 cycles is shown in Figure 4 as a function of cycle time in addition to the maximum ramp rate specified in SAE J2601, the target pressure of 12,700 psi (875 bar), and the ramp time. The slope on the measured pressures is slightly higher than the maximum for conservatism. There is greater variability at the early stages of the pressure ramp due to pump friction causing a variable starting time. But overall, the ramps follow the expected trend.

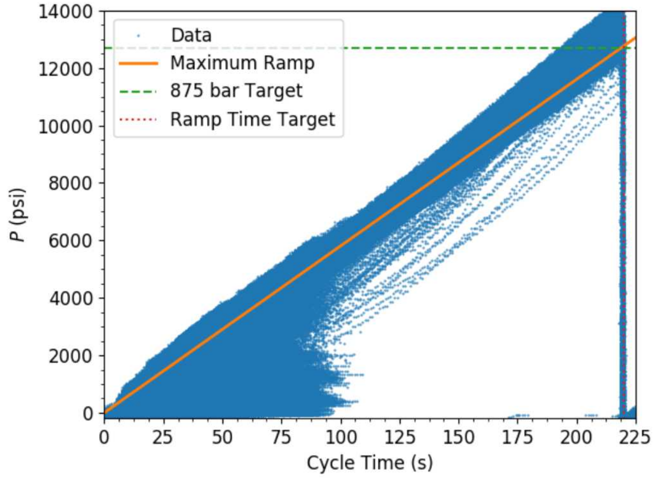

FIGURE 4: Pressure data for the first 10^5 cycles

The raw pressure data were processed further for data reduction and statistical information. Data were interpolated onto a common sampling period of 1 Hz to compensate for slight recording rate variability. They were then ensemble averaged so every pressure at each cycle time was averaged individually. The results are shown in Figure 5 with the targets described before in addition to the 97.5% and 2.5% ranges that bound the central 95% of measurements. Except for the first ~30 seconds, most of the pressure was aligned with the desired ramp.

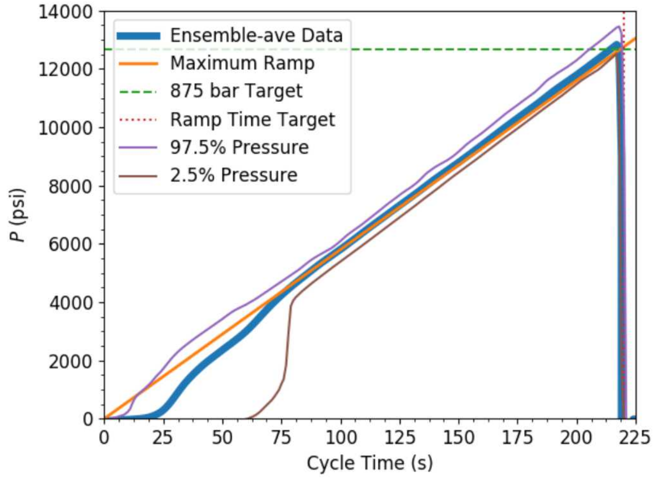

FIGURE 5: Ensemble averaged pressure data for the first 10^5 cycles

The maximum pressure in each cycle is a good indicator of imposed conditions. These are shown in the histogram of Figure 6 and show that the large majority of maximum pressures were above the 875 bar target. In the first 10^5 cycles, the average maximum cycle pressure is 12,914 psi (890.4 bar) and 92.5% met or exceeded the target.

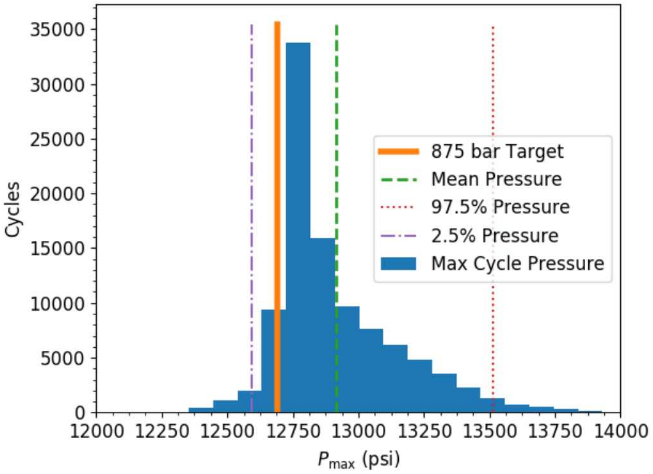

FIGURE 6: Histogram of maximum cycle pressures for the first 10^5 cycles

To date the experiment has reached 10^5 cycles with leak checks performed before testing and every 10^4 cycles. The H2PC™ has had no detectable leak at any point of the process, both at VPE before shipping and at Sandia Labs. The excellent mechanical performance in one of the longest pressure fatigue tests of any PCHE is a great demonstration of the safety and reliability of diffusion bonded heat exchangers, a validation of the pressure safety design, and builds confidence in sound manufacturing and quality control processes.

3.2 Finite Element Simulations

The finite element simulations were used to identify locations of high stress and quantify their magnitude. Some of the highest resulting stresses were in the apparent stress concentrator regions on the high pressure circuit where the semi-circular channel ridges are bonded to the next sheet as shown in Figure 7 with von Mises stress highest at the pressure boundaries. Consequently, stress magnitudes were averaged over these faces with a result of 118 MPa (1180 bar) on the high-pressure circuit and much lower on the low pressure circuit. Note that the predicted stress values over 1.5 time the code allowable $(1.5x138\text{ MPa} = 207\text{ MPa})$ are shown in green and represent only a small portion of the elements. These regions are neglected under ASME Section VIII Division 1 design-by-rule requirements, but in practice these regions of high stress concentration would experience local plastic deformation based on the ductile behavior of the bonded material leading to stresses below ASME allowable limits under design-by-analysis requirements in Section VIII Division 2. Therefore, the cross-sectional average stress will remain below the code allowable stress after initial plastic deformation occurs.

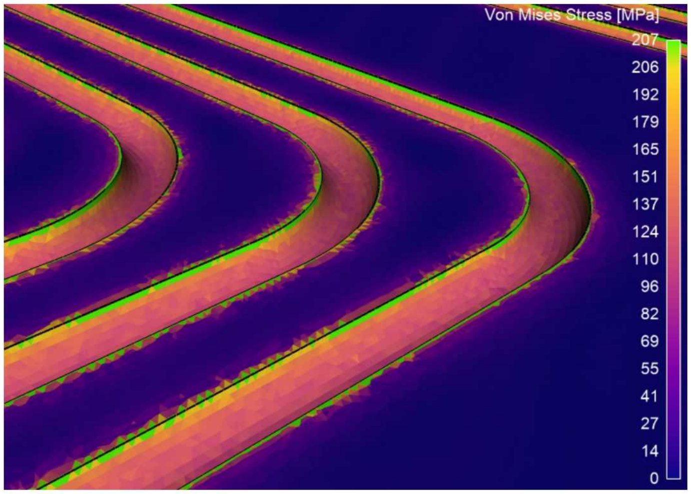

FIGURE 7: von-Mises stress in the high-pressure hydrogen channels

To build confidence in the simulation predictions, a study was performed on the relation of predicted von Mises stress error and mesh resolution. Figure 8 shows the results of the study on four different quantities with five levels of mesh refinement. Because the base mesh was already large, only local refinement near pressure boundaries was used, though this refinement is likely to be the most effective and have a direct impact on the quantities tracked. The results show at least second order convergence as expected, suggesting that the mechanical model and its implementation are free from sizeable errors.

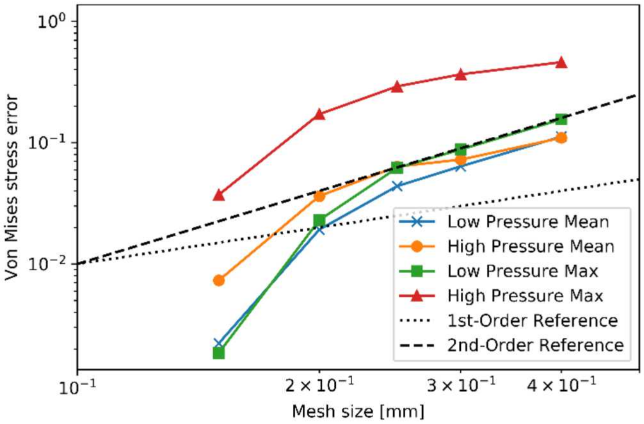

FIGURE 8. Solution verification study results showing consistent reduction in error with increased mesh resolution on all quantities

4. CONCLUSION

This work has presented our progress toward establishing the lifetime and failure mode of a PCHE designed to be used as a hydrogen filling station pre-cooler. To date we have completed 10^5 pressure cycles from ambient pressure to 875 bar with over 92.5% of the cycles exceeding this target pressure using water. No signs of pressure decay or leakage have been detected and helium leak tests conducted every 10^4 cycles have shown no detectable increase in the helium leak rate with a measured rate well below the industrial standard level of 10^{-7} cc/sec. This milestone has already satisfied requirements from hydrogen filling station systems integrators.

In addition to this experimental work, complementary computational simulations have been performed to predict the stresses within the H2PC™ and identify likely failure locations. High stresses have been observed near stress concentrations within the unit that are expected to plastically deform to the yield stress without causing failure, but near-header pressure still suggest this to be the most likely failure location.

The experiment reached 10^5 pressure cycles at the end of March 2020 at the maximum SAE-J2601 pressurization rate. The next step is to increase the pressure ramp rate by a factor of 5-8x depending on the capability of the compressor and continue testing to at least 3×10^5 cycles by July of 2020.

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