HIGH TEMPERATURE HEAT EXCHANGER AND COMPONENT TEST LABORATORY – A GRADED APPROACH

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Introduction

The Next Generation Nuclear Plant (NGNP) Project and the Nuclear Hydrogen Initiative (NHI) are U.S. Department of Energy programs that are responsible for the research, development, and testing of high-temperature gas-cooled nuclear reactor technologies and thermally driven hydrogen production methods. The two programs are related, in that the nuclear reactor will provide high-temperature heat, and the thermally-driven hydrogen plant will consume it. The nuclear reactor is envisioned as a large-scale (500-600 MWth) high-temperature (750-900°C) high-pressure (5-9 MPa) [1] helium-cooled unit that is capable of producing electricity or high-temperature heat. The hydrogen plant is less defined, but a number of methods are currently under investigation by the NHI including High-Temperature Electrolysis [2], the Hybrid Sulfur process[3], and the Sulfur-Iodine process[4]) and lower-temperature alternatives. A high-temperature heat transfer network (HEN) is needed to deliver thermal energy from the nuclear reactor to the hydrogen plant. The combination of a high-temperature gas-cooled nuclear reactor, a HEN, and a downstream user of high-temperature heat such as a nuclear hydrogen plant is known as the NGNP.

Heat exchangers define the HEN, and heat exchanger materials and designs must be identified that operate efficiently and can withstand high operating temperatures and pressures without suffering creep failure. Above 700°C, even high-temperature alloys such as Inconel 617 suffer reduced yield stress and time-to-rupture due to creep. Therefore, effective heat exchanger designs must be developed that minimize stresses, so that failure due to creep can be avoided. In the longer term, substituting ceramics for metals may be a solution, since ceramics have less tendency to creep at higher temperatures, but ceramic heat exchangers are still relatively immature in comparison to metal heat exchangers and are not yet available for nuclear reactor applications.

At the present time, there is no readily accessible laboratory in the U.S. for operating at the high temperatures, pressures, and flow conditions needed to test components for the NGNP HEN. Fortunately, the test equipment and methods are not new and the capabilities needed to perform high temperature heat exchanger testing are not unique. A dedicated testing laboratory could be established, with some investment, at almost any university or national laboratory.

Laboratory-scale static and flow test beds are described that would be capable of measuring leakage rates, fluid flow characteristics, and heat transfer performance at the temperatures and pressures of interest. A graded approach to testing is recommended that would minimize costs at initial stages, while allowing for more accurate measurements at later stages. Initially, once-through test beds that use heated air or steam are suggested to test heat exchanger performance, and the data collected from these tests will be used to calibrate heat exchanger models. Then, one or more closed helium loops can be constructed to more closely measure heat exchanger performance under more representative fluid conditions. Fluid similitude will be used to choose and compare fluid conditions. The test beds must be flexible and should be able to accommodate most lab-scale heat exchangers and other components as long as their input and output manifolds conform to defined dimensions.

Pressure/Leak Testing

A heat exchanger test laboratory must have the capability to perform hydrostatic pressure testing and leak testing capabilities. A hydrostatic pressure test is performed in order to verify that the prototype device can withstand differential pressures in excess of expected operating pressures without excessive deformation or failure. A heat exchanger that is expected to operate with a steady pressure differential (either internally or externally) of 15 psig or greater falls under the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code [5], and the code requires that a hydrostatic test be performed. Such a test would be performed with water or other fluid, and at room temperature. Though the heat exchanger will be expected to operate at elevated temperature, successful completion of a hydrostatic test represents the minimum safety threshold for the component before elevated temperature testing can begin.

Pressure testing should be repeated at the temperatures of interest, though high temperatures will most likely require the use of gaseous fluids to provide the pressure differential, and this will lead to greater energy release at failure. A suggested method for performing this test safely at high temperature is to place the prototype component inside a kiln or furnace within a shielded (but vented) container. The shielded container would provide some protection against shrapnel in case of catastrophic component failure, and the walls of the kiln or furnace would provide back-up protection. The kiln or furnace can also be placed behind a barrier to provide a third layer of protection for the experimenter. The test would be performed by placing the component within the shielded container, heating the component and container within the kiln or furnace until it reaches a steady temperature, and then pressurizing the component for the duration of the test. Figure 1 shows a basic drawing of such a pressure test apparatus.

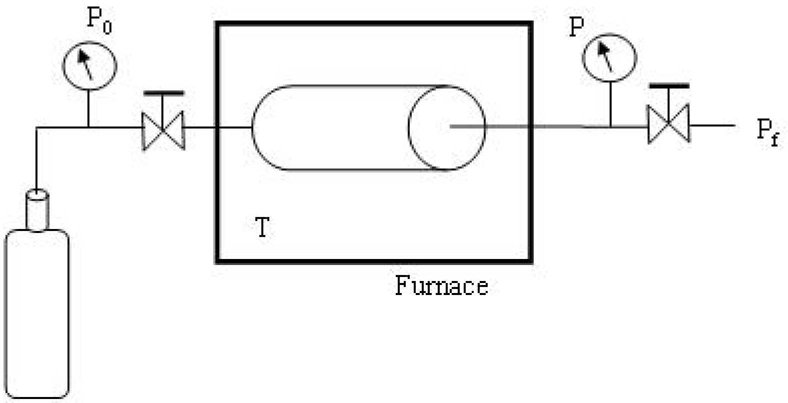

Figure 1: Simplified high-pressure test and leak test apparatus.

Beyond pressure testing, leak testing should be performed at the temperatures and pressure of interest in order to quantify detectable leakage rates from the inside to the outside of the prototype component, and, in the case of heat exchangers, to quantify detectable leakage rates between the hot and cold channels. Leakage rate testing is performed by pressurizing the component at an equilibrium temperature, and then measuring the decay in pressure. A steady-state leakage rate can be deduced from the test conditions and the measured decay rate [6], and the individual leakage rates of a heat exchanger (hot side external, cold side external, cross leakage) can be measured by pressurizing just the hot side of the HX, just the cold side of the HX, and then both sides at the same pressure in order to differentiate between external leakage and cross-heat exchanger leakage [7]. For added accuracy, the leakage tests are performed at different temperatures to more closely match the average temperatures of the hot and cold sides of the heat exchanger.

Beyond leak testing, the proposed leak testing apparatus could be used for performing cyclic pressurization if automatic pressure controls were installed. Such testing is useful if it is desired to determine whether a design or prototype is subject to deleterious effects from mechanical fatigue.

Once-Through Flow Testing

Concerning the NGNP, the most accurate heat exchanger testing would be performed at the conditions and with the fluids of interest. That is, testing would be performed at high-temperature and pressure, and by using helium as the chosen heat transfer fluid. Since Grade-A helium sells for approximately \$3.24 to \$3.79/m^3 (2007 \$) [8], closed heat transfer loops would be needed to conserve helium. Closed loops require the use of helium compressors and other control systems, so that the overall cost of the test bed would be relatively expensive.

The point of initial lab-scale tests, however, is to measure performance data in order to validate heat exchanger models, and exact replication of the fluid conditions of interest is less important. As long as good instrumentation is used and proper testing procedures are adopted, the heat exchanger models can be validated against the tested fluid conditions, assuming that the models are applicable to both helium and non-helium fluids. It is suggested that air and/or steam be used as heat transfer fluids, and that an open flow systems that rely on pressurized sources be used to create the fluid flow conditions of interest rather than compressors. Air and water are freely available in nearly any laboratory at much less cost per unit volume than helium.

Figure 2 shows a schematic of a basic open flow system that uses compressed air as the heat transfer fluid. In the figure, compressed air is supplied from cylinders or from tanks that can be maintained at a defined pressure using air compressors and pressurestats. Gas boosters may also be used to reach higher pressures. Regulators are used to establish the system pressure, and back-pressure regulators are used to adjust the downstream pressure in order to "dial-in" the differential pressure across the heat exchanger, which can vary between zero (no-flow condition) and the difference between the regulated pressure and atmospheric pressure (full-flow condition). In-line heaters are used to increase the temperature of the air from near room temperature to high-temperature, and coolers are used to cool the gas exiting the heat exchanger down to a low enough temperature that it does not damage the valves and back-pressure regulators downstream. Sensors are installed that can measure the temperature, pressure, and flow-rate of the air before and after the heat exchanger, so that heat exchanger performance, pressure drop, friction factors, and other relevant information can be calculated. For a laboratory-scale system, the heaters may be electrically driven, and examples of in-line heaters capable of heating air to 700°C at 150 psig are shown in Figure 3. If steam is used instead of air, a lab-scale steam boiler or laboratory steam source can be substituted for one of the high-pressure air tanks. Multiple heat exchangers and other components could be tested with such a test bed as long as the gas input and output manifolds for the test article are manufactured to conform to the standard sizes and configurations established for the test bed. A co-current arrangement of flows is shown, but the inlet and outlet piping should be arranged to allow for co-current, cross-current, and counter-current flow.

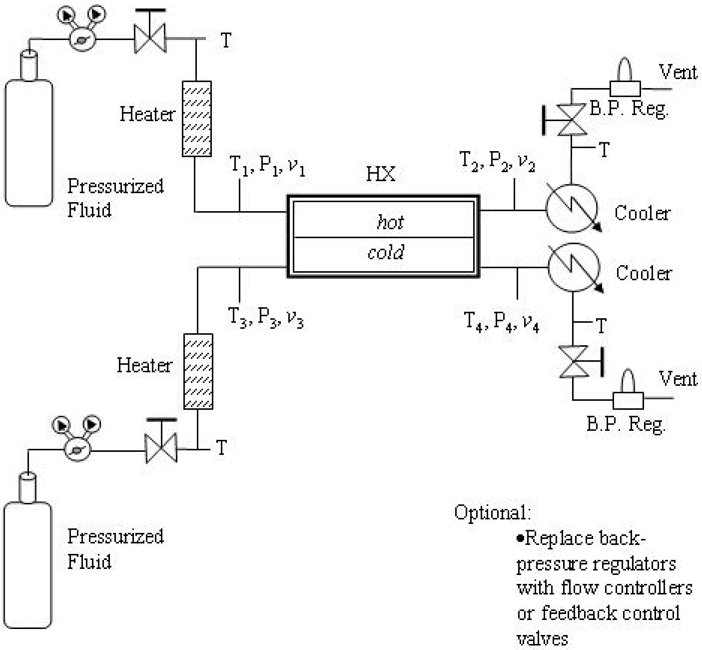

Figure 2: Once-through heat exchanger test apparatus.

Figure 3: In-line air heaters operate up to 700°C and 120 psig (Heat Torch$^{\mathrm{TM}}$200 by Farnum Custom Products, Inc.).

Partially Closed Loop

At a later stage of testing, one of the once-through air paths can be replaced with a closed helium loop to more closely approach the test conditions of interest. A schematic of a partially closed heat exchanger test bed is shown in Figure 4.

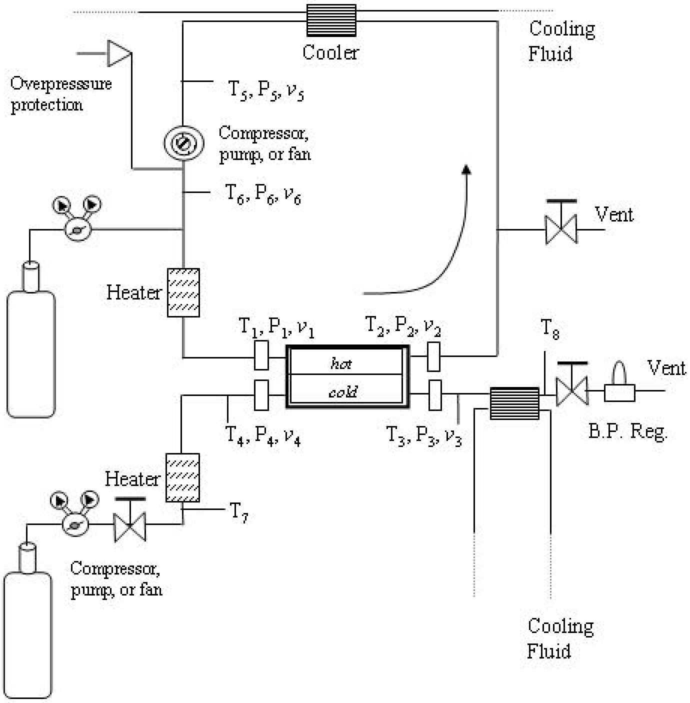

Figure 4: Partially closed heat exchanger test apparatus.

In Figure 4, the close loop is connected to a pressurized helium source, and a compressor is used to move the helium through the loop. Because there are few (inexpensive) compressors that can operate at temperatures as high as 800-900°C, a cooler and heater may be installed before and after the compressor to reduce the operating temperature to the compressor. Adding a cooler and heater to the loop reduces the thermal efficiency of the loop, but thermal efficiency is not the point of the test bed, and its purpose is to create fluid flow conditions that are suitable for a particular heat exchanger or component test. In addition to the compressor, temperature, pressure, and flow rate instrumentation is provided in all sections of the loop in order to monitor fluid flow conditions. A co-current arrangement of flows is shown, but the inlet and outlet piping should be arranged to allow for co-current, cross-current, and counter-current flow.

Two Closed Loops

The next level of sophistication of the heat exchanger test apparatus occurs when both once-through loops are replaced with closed helium loops. Such a configuration is shown in Figure 5. The second closed loop is a replicant of the first closed loop, and the two loops are operated independently. Helium is supplied batch-wise to the loops, and is only released from the loops when it is necessary to reduce system pressures for a test, or to remove or install a test article or other device in the apparatus. A co-current arrangement of flows is shown, but the inlet and outlet piping should be arranged to allow for co-current, cross-current, and counter-current flow.

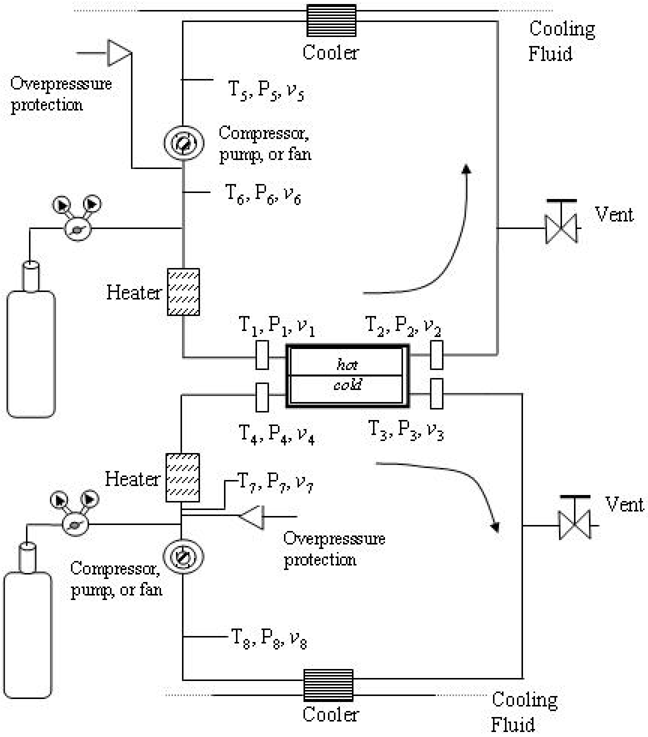

Figure 5: Fully closed heat exchanger test apparatus.

Similitude

The fluid and heat transfer properties of air and steam are different than high pressure helium at a given temperature and pressure, but the conditions of the experiments with air or steam can be changed to correspond to fluid conditions that are similar to or at least approaching what would have been realized had hot high-pressure helium been used instead. Though the individual properties of fluids will differ (density, viscosity, thermal conductivity, etc.), different fluids will behave in similar ways when certain dimensionless combinations of their fluid properties and the system geometries are similar. This similarity is called similitude [9]. In fluid and heat transfer systems, similarity is indicated by matching dimensionless numbers - Reynolds number (Re), Prandtl number (Pr), Graetz number (Gz), Stanton number (St), Nusselt number (Nu), and others. Testing of devices under similar conditions has been discussed by Kline [10], Bardet and Peterson [11], and Ingersoll et al. [12]. The Re, Pr, and Nu are related to each other through the Gz and St numbers (see Equations 1 and 2).

$$\mathrm{Gz} = \frac{\pi}{4}\mathrm{RePr}\frac{D}{L} \tag{1}$$

$$\mathrm{St} = \frac{\mathrm{Nu}}{\mathrm{RePr}} \tag{2}$$

In Equation 1, the parameters D and L are the diameter and length of the flow channel. Depending upon whether the flow conditions are laminar or turbulent, there are a number of correlations that use the Re, Pr, Gz, or St to calculate the Nu and, as a result, the heat transfer film coefficient. Texts on heat transfer should be consulted in order to determine which correlations are applicable to the test conditions of interest (e.g., laminar flow, turbulent flow, tubular versus planer geometries, etc.).

Next Steps

A high-temperature leak testing apparatus has been described, and concepts for once-through and close loop heat exchanger test beds have been offered that may be constructed at reduced capital cost in comparison to building a fully closed, pressurized, heated test facility for laboratory-scale heat exchangers and other components for the NGNP Project. Certainly, closed loops will be needed to advance the technological readiness of prototype heat exchangers, but the initial stages when technical risk is high, it is beneficial to have access to a relatively inexpensive test bed that can be used to screen heat exchanger concepts and to perform initial model validation under test conditions that are more easy to reach with simple equipment. Later, as hands-on experience grows and heat exchanger designs mature, the investment in closed loops can be made with less risk of failure due to component failure, poor heat exchanger design, and operator inexperience. It is recommended that such test systems be considered as stepping stones to larger and more complicated facilities that would, in time, be capable of providing test conditions approaching those of the projected nuclear plant design.

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