Assessment of heat exchangers for coupling a high temperature nuclear reactor to hydrogen and biofuels plants

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Abstract

This paper outlines the design problem given to the students of 22.033 and presents four heat exchanger types as candidate designs for the process heat system. Rationale for choosing a heat exchanger and materials concerns are presented and future work is also discussed.

1. Design Problem

The students of 22.033 aim to design a nuclear power plant which will be coupled to hydrogen and biofuels producing facilities by means of high temperature heat exchangers (HXs) [1]. This paper will present and discuss four HX designs that have been selected by the Process Heat team as strong candidates. Materials concerns of prospective HX materials are outlined. Choices of HX configurations and future work are discussed.

2. Process Heat System

A lead cooled reactor with an outlet temperature of 650ºC and a secondary loop of supercritical CO_2 has been chosen by the Core group. The heat provided by the reactor should be transported to the hydrogen and biofuels facilities at minimum temperature and pressure losses. The process heat system will consist of a single high temperature heat exchanger or two heat exchangers in the secondary loop, heat exchangers at the heat storage system, biofuels and hydrogen plants, a heat storage system and piping for transporting the working fluid to the hydrogen and biofuels facility. Also under consideration are heat sink options.

3. Heat Exchanger Designs

The applicability of heat exchanger designs to this system was evaluated based on the feasibility of the heat exchanger technology as well operating temperatures and pressures. Effectiveness, size, heat transfer area per unit volume, working fluid options, heat losses and pressure drops for the various designs were also primary considerations. Of the heat exchanger designs screened, four designs were found to be most promising: Shell and Straight tube heat exchanger, Shell and helical tube heat exchanger, Plate type heat exchanger and Printed Circuit Heat Exchangers (PCHE). Not discussed here are heat pipes and thermosyphons which were also reviewed as potential intermediate heat exchanger designs capable of performing heat transport functions [2]. The principal features of each design are listed in Table 1.

3.1. Shell and straight tube heat Exchanger

These heat exchangers find extensive application in nuclear plants and also as process heat systems and can be designed to be very robust and suitable for special operating conditions such as a radioactive environment. They can be fabricated using Hastelloy, Incoloy, graphite and polymers [4]. The design can be adapted to include fins if one of the working fluids is gaseous and the heat exchanger allows liquid/liquid, gaseous/liquid as well as two phase systems. These heat exchangers are very large due to low heat transfer area per unit volume (~100 m^2/m^3) but allow high operating temperatures (up to 900ºC) and pressures (up to 30 MPa).

3.2. Helical type Heat Exchanger

The shell and helical tube heat exchanger is a variation on the shell and straight tube heat exchanger design and consists of tubes spirally wound and fitted in a shell. Spiral tube geometry provides a higher heat transfer area per unit volume (200 m^2/m^3 compared to 100 m^2/m^3 for straight shell and tube type HXs). This design has been proven by its use in the High Temperature Engineering Test Reactor (HTTR) [5]. Helical type heat exchangers are well suited to gaseous/liquid systems. A disadvantage of this design is the difficulty of cleaning the helical coils [6, 3].

3.3. Plate Type Heat Exchanger

In a plate type heat exchanger, the heat transfer occurs through planar surfaces. Plate type HXs allow counter, cross and parallel flow configurations [7] and can be fabricated from Hastelloy and Ni Alloys. These heat exchangers allow both multi pass and multi stream capabilities and greatest ease of cleaning and maintenance as compared to the other designs reviewed in this paper. There are several

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Table 1: Principal Features of Heat Exchangers (adapted from [3])

HX Type	Compactness	T. Range	Max P.	Multi stream	Multi pass	Cleaning Method
	(m^2/m^3)	(^oC)	(MPa)			
Shell and Tube	~100	~+900	~30	No	Yes	Mechanical, Chemical
Plate	~200	-35 to ~+900	~60	Yes	Yes	Mechanical, Chemical
Helical	~200	~600	2.5	No	No	Mechanical
Printed Circuit	2000 to 5000	-200 to ~+900	~60	Yes	Yes	Chemical

variations on plate type designs and the Bavex plate HX provides the highest operating temperatures (up to 900^{o}C) [3, 6].

3.4. Printed Circuit Heat Exchanger (PCHE)

PCHEs can operate under high temperature (~1000 K) and high pressure conditions. They are typically used in petrochemical, refining, and upstream hydroprocessing industries. PCHEs can incorporate multiple process streams into a singe unit and have low mass/duty ratios of ~0.2t/MW [8]. They are suitable for corrosive environments and have effectivenesses of up to 98%. In a PCHE the fluid flow channels, which are of the order of several millimeters, are chemically etched and the flow can be parallel, cross or counter flow or a combination of all three. Absence of gasket and braze material lowers the probability of leakage [9]. However, there is potential for thermal stresses in the axial direction when there are sharp temperature variations and this design also suffers from low capacity factors due to the need for offline inspection and repairs [10]. Small flow channels could result in fouling problems which would require offline repairs using chemical methods [3]. However, redundant modules may be installed to improve capacity factors of the process heat system during maintenance and repairs. PCHEs have not been used for previously for nuclear applications but are under review as potential HXs for the Next Generation Nuclear Plant [11].

4. Materials concerns

It is imperative that the materials chosen for fabricating heat exchangers for the process heat system are able to withstand operating conditions of high temperatures (up to 900^{o}C) and pressures. Susceptibility of candidate materials to stress corrosion cracking under constant load as well as slow-strain-rate conditions, fracture toughness and crack growth behavior has been studied and literature indicates that Alloy 230 and Alloy 617 are suitable for fabricating high temperature heat exchangers [12]. The operating conditions for the heat exchanger at the hydrogen plant will be more severe due to temperatures higher than the core outlet temperature. Studies indicate that Alloy C-22 and Alloy C-276 because of their high tensile strength and ductility until fracture are suitable heat exchanger materials for heat exchangers operating in or near acidic environments [13]. Future work will require choosing heat exchanger designs and materials for each design.

5. Heat Exchanger Configurations

The heat exchangers may be connected in series or in parallel with the power conversion system. The series configurations will allow extraction of the heat from the supercritical CO_2 at the highest possible temperature but at a power conversion efficiency penalty. A parallel configuration will allow supplying the working fluid at equal temperatures to both the power conversion and process heat systems but each system will receive smaller flow rates of the working fluid. Furthermore, whether connected in series or in parallel with the power conversion system, the HX connected to the CO_2 loop can consist of either a single heat exchanger or a two stage heat exchanger system consisting of a high temperature and a low temperature heat exchanger. A two stage system would reduce costs by eliminating the need for a single large heat exchanger having a long design life but would adversely affect the controllability of the system and increase heat losses [10].

6. Future Work

The choice of heat exchangers, heat exchanger materials and configurations are governed by the working fluid used in the primary cycle and the temperatures, pressures, temperature and pressure drops and flow rates at which process heat will be required at the hydrogen and biofuels plants. Based on these considerations heat exchanger designs and configurations will be chosen from among the four designs discussed in this paper. The heat exchanger design and configuration thus chosen will then be modeled using MATLAB, EES or RELAP5 or a combination of the three and the process heat system will be optimized for this design problem. Future work will also study pressure drops associated with candidate designs.

References

[1] Michael Short. 22.033 syllabus, 2011.

[2] Vivek Utgikar Fred Gunnerson Piyush Sabharwall, Mike Patterson. Phase change heat transfer device for process heat applications. *Nuclear Engineering and Design*, 240:2409–2414, 2010.

[3] Dusan P.Sekulic Ramesh K.Shah. *Fundamentals of Heat Exchanger Design.* John Wiley and Sons, 2003.

[4] M.Takeyama R Tanaka T.Matsuo, M.Ukei. Strengthening of nickel-based superalloys for nuclear heat exchanger applications. *Journal of Nuclear Materials*, 22:1901–1907, 1987.

[5] H.G. Groehn. Thermal hydraulics of helical-type helium/helium intermediate heat exchangers (ihxs) for nuclear process heat applications of high temperature gas-cooled reactors-fundamental research and large scale tests. *Nuclear Engineering and Design*, 126:285–290, 1991.

[6] Michael McKellar Nolan Anderson Piyush Sabharwall, Eung Soo Kim. Process heat exchanger options for fluoride salt high temperature reactor. Technical report, Idaho National Labs, 2011.

[7] Y.Chen S.R. Sherman. Heat exchanger testing requirements and facility needs for the nhi/ngnp project. Technical Report WSRC-STI-2008-00152, 2008.

[8] Heatric tm, 2011. URL `www.heatric.com`.

[9] K.Natesan S.Majumdar, A.Moisseytsev. Assessment of next generation nuclear plant intermediate heat exchanger design. Technical report, Argonne National Laboratory, 2008.

[10] Eung S.Kim Chang H. Oh. Design option of heat exchanger for next generation nuclear plant. Technical report, Idaho National Laboratory, 2008.

[11] Nolan A. Anderson Prashaanth Ravindran, Piyush Sabharwall. Modeling a printed circuit heat exchanger with relap5-3d for the next generation nuclear plant. Technical report, Idaho National Laboratory, 2010.

[12] Anthony E. Hechanova. High temperature heat exchanger project. Technical report, UNLV Research Foundation, 2008.

[13] Narendra Kothapalli Raghunandan Karamcheti Ajit Roy, Lalit Savalia. Mechanical properties and cracking behavior of high-temperature heat-exchanger materials. In *Proceedings of the ASME Pressure Vessels and Piping Conference 2005, Vol 6*, 2005.