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HIGH TEMPERATURE HEAT EXCHANGERS FOR NUCLEAR APPLICATIONS

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ABSTRACT

Many nuclear engineering applications, current and future, require heat exchangers operating at high temperatures. The operating conditions and performance requirements of these heat exchangers present special design challenges. This paper considers these challenges with respect to a simple heat exchanger design manufactured of a novel carbon material. Heat transfer and effectiveness calculations are performed for several parametric studies regarding heat exchanger parameters. These results are used to better understand the design challenges of high temperature heat exchangers as well as provide a starting point for future optimization work on more complex heat exchanger designs.

NOMENCLATURE

Temperature	T (K)
Pressure	p (Pa)
Density	ρ (kg/m^3)
Specific Heat	c_p (J/kg·K)
Thermal Conductivity	k (W/m·K)
Viscosity	μ (N·s/m^2)
Velocity	v (m/s)
Volumetric Flow Rate	Q (m^3/s)
Mass Flow Rate	$\dot{m}$ (kg/s)
Heat Transfer Rate	q (W)
Heat Flux	q” (W/m^2)
Effectiveness	ε (%)
Length	l (m)
Cross Sectional Area	A (m^2)
Volume	V (m^3)
Channel Radius	r (m)

Subscripts

Inlet	i
Outlet	o
Hot Fluid	h
Cold Fluid	c
Structural Material	s

INTRODUCTION

The capability to generate energy at high temperatures will enable high-efficiency electricity production as well as facilitate currently developing technologies such as large scale hydrogen production. Design of several of the next generation nuclear reactors has commenced with this in mind. In fact, the Very High Temperature Reactor (VHTR) will operate at temperatures in the range 900°C - 1000°C [1].

The nuclear community must have the ability to support high temperature conditions prior to implementation of high temperature reactors. This requirement extends beyond the nuclear reactor to reactor powered processes as well devices that couple processes to reactors. High temperature heat exchangers (HTHX) represent a key technology in accomplishing this goal.

In nuclear reactor systems, regardless of operating temperature, an intermediate heat exchanger couples the reactor to a specific process or processes through a series of fluid loops (Figure 1). This design isolates the nuclear reactor to prevent nuclear contamination as well as provides a means of regulating energy delivery to the process. The design requirements of the HTHX and connecting fluid loops depend on the reactor type and process requirements. This paper investigates these requirements and subsequent considerations to form a basis on which to begin the HTHX design.

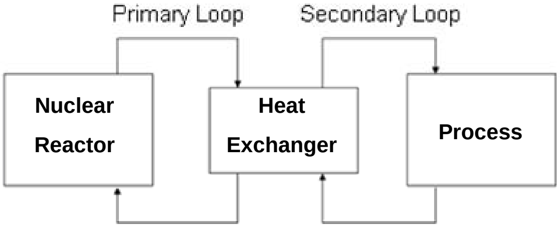

Figure 1. NUCLEAR REACTOR SYSTEM

Novel high temperature materials necessitate a re-evaluation of heat exchanger design practices. Improved designs will take advantage of the superior high temperature properties of these materials. However, designs must also reflect manufacturing limitations. This paper will present a model definition and results from a number of parametric analyses regarding a heat exchanger design made from amorphous carbon.

HIGH TEMPERATURE NUCLEAR APPLICATIONS

HTHX design requires an understanding of operating conditions and performance requirements. A review of high temperature nuclear reactor applications will provide this information. Applications include, among others: electricity generation, coal gasification, and hydrogen production.

The Nuclear Energy Research Initiative (NERI) has placed nuclear hydrogen production among its top research goals [2]. This paper will focus HTHX design on the conditions and requirements surrounding this process.

Common means of producing hydrogen, gasification and electrolysis, suffer from contamination and low efficiency problems, respectively [3]. A thermochemical cycle coupled directly to a nuclear reactor represents the most promising means for future large scale hydrogen production [3]. A review of the existing thermochemical cycles suggests that the sulfur-iodine process is the most promising [3]. The following reactions define this process (the temperature at which the reaction occurs is listed to the right of the reaction):

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (120°C)$$
$$H_2SO_4 \rightarrow H_2O + SO_2 + \tfrac{1}{2}O_2 \quad (850°C)$$
$$2HI \rightarrow H_2 + I_2 \quad (450°C)$$

Once started, only energy and water remain as required inputs to maintain hydrogen production. The process recycles the other reactants. The general layout for a sulfur-iodine hydrogen production process coupled to a nuclear reactor (shown with helium loops) is shown in Figure 2.

General Atomics has developed a hydrogen production plant based on the sulfur-iodine thermochemical process coupled to a H2-MHR (hydrogen producing modular helium reactor) [4]. The HTHX operating conditions are shown in Table 1.

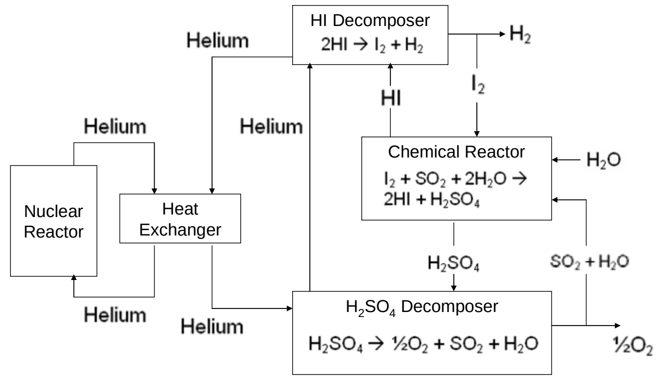

Figure 2. SCHEMATIC FOR A HYDROGEN PRODUCTION PLANT [4]

Table 1. HTHX OPERATING CONDITIONS [4]

Condition	Value
$T_{h,i}$	1000°C
$T_{h,o}$	636°C
$p_{h,i}$	7.0 MPa
$T_{c,i}$	450°C
$T_{c,o}$	975°C
$p_{c,i}$	7.1 MPa

HTHX MATERIALS SELECTION

Working Fluids

Working fluids serve as the energy transport medium throughout the reactor/process system. Having adequate thermal properties to support required heat transfer is the most important criterion in selection. Additionally, working fluids must be safe, compatible with structural materials, and conducive to minimizing design complexity.

Helium, molten salts, and liquid metals represent the three most promising high temperature coolants for both the primary and secondary loops [5]. At present, high temperature helium cooled reactors have the highest level of maturity. Therefore, the model presented in this paper will use helium as the working fluid in both the primary and secondary loops.

Structural Materials

Structural materials for HTHX systems must retain their strength at high temperatures in order to withstand stresses induced from fluid loop pressure differences, continuous and transient thermal conditions, and loads imposed through fluid flow. Historically, high temperature systems have used high nickel content alloys such as Hastelloy and Waspalloy. These materials provide compatibility with working fluids up to 750°C [6], well below the 1000°C upper temperature limit of the VHTR.

Alternatives include advanced ceramics which retain strength at elevated operating temperatures and have excellent thermal shock and corrosion resistances. Novel carbon forms represent one such advanced material and will have the ability to survive at temperatures in excess of 1000°C. The model presented in this paper will use material properties based on test results regarding cellulose derived amorphous carbon [7].

NUMERICAL MODELING

The modeling presented here will focus on optimization of heat exchanger design parameters with respect to heat transfer rate and effectiveness (two of many heat exchanger performance criteria). Note that, while both of these criteria represent significant means of rating heat exchanger designs, one may play a more important role than the other depending on the requirements of the application. This becomes relevant regarding designs that adversely affect one criterion while favorably affecting the other.

A base model will be defined and used to perform parametric analyses relating to: channel radius, channel spacing, channel length, and flow-rate.

The analyses presented here do not require a full scale-up to actual heat exchanger dimensions in order to provide informative results. The model will characterize a unit cell representative of the heat exchanger matrix. These analyses will not yield pressure drop data or focus on pressure drop minimization. Future work will include fluid flow modeling to account for this information.

Model Definition

A block of amorphous carbon with parallel channels of circular cross section for the two fluid flows (hot and cold) represents the simplest heat exchanger design. A two-dimensional cross section of this geometry is illustrated in Figure 3.

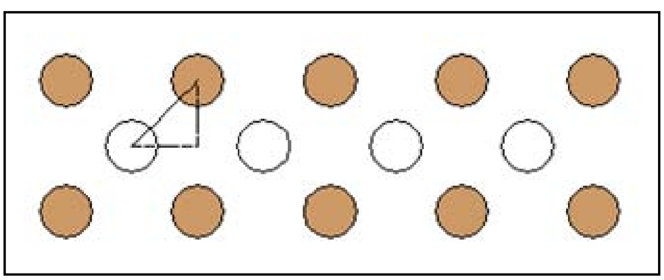

Figure 3. CROSS SECTION OF THE HEAT EXCHANGER MATRIX WITH CIRCULAR FLOW CHANNELS

The open circles represent one working fluid (hot) while the shaded circles represent the second working fluid (cold). The unit cell used for models, simplified through symmetry, is shown by the outlined triangle in Figure 3 and shown as a three-dimensional segment in Figure 4.

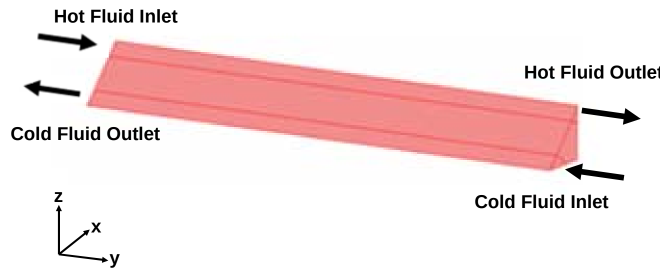

Figure 4. REPRESENTATIVE MODEL GEOMETRY BASED ON SYMMETRY (ARROWS INDICATE FLOW DIRECTION)

Equations 1 and 2 define the governing energy equation for the solid and liquid domains, respectively. The governing equation for the liquid domains has a term added to account for convective heat transfer. The subscript "x" in equation 2 (as well as in equations 8 and 10) denotes either c or h for cold and hot fluids, respectively. The analysis will solve the three equations simultaneously.

$$\nabla \cdot (-k_s \nabla T_s) = 0 \tag{1}$$

$$\nabla \cdot (-k_x \nabla T_x) = -\rho_x c_{p,x} v \cdot \nabla T_x \tag{2}$$

Operating conditions from Table 1 will define the temperature boundary conditions at the hot and cold fluid inlets. Equations 3 through 6 define the boundary conditions for the hot inlet, hot outlet, cold inlet, and cold outlet boundaries, respectively. Equations 4 and 6 dictate that all of the energy leaving the system at the fluid outlet boundaries does so through convection only. Equation 7 defines the boundary condition for the two solid end boundaries (insulation) as well as all of the external boundaries along the length of the heat exchanger in order to impose symmetry.

$$T_{h,i} = 1273.15\text{K} \tag{3}$$

$$q \cdot n = \left(\rho_h c_{p,h} v T_h\right) \cdot n; n \cdot \left(-k_h \nabla T_h\right) = 0 \tag{4}$$

$$T_{c,i} = 723.15\text{K} \tag{5}$$

$$q \cdot n = \left(\rho_c c_{p,c} v T_c\right) \cdot n; n \cdot \left(-k_c \nabla T_c\right) = 0 \tag{6}$$

$$n \cdot (-k_s \nabla T_s) = 0 \tag{7}$$

The two interface boundaries between the solid and the hot and cold fluid flows have a heat flux continuity boundary condition as defined by equation 8.

$$
\begin{aligned}
&-n \cdot (-k_x \nabla T_x + \rho_x c_{p,x} v T_x) \\
&-n \cdot (-k_s \nabla T_s) = 0
\end{aligned} \tag{8}
$$

Flow through both fluid channels is laminar with a fully developed parabolic profile. Volumetric flow-rate for both hot and cold fluids is 7.362 x 10^{-6} m^3/s. The flow orientation is counter-flow as shown in Figure 4. Dimensions of the base model are shown in Table 2. Helium and structural material properties are shown in Table 3. Note that hot and cold fluid properties are based on the hot and cold inlet temperatures.

Table 2. BASE MODEL DIMENSIONS

Dimension	Value (m)
Hot Channel Radius	0.0025
Cold Channel Radius	0.0025
Channel Length	.5
Center to Center Horizontal Distance between Hot Channels	0.015
Center to Center Horizontal Distance between Cold Channels	0.015
Center to Center Distance Between Hot and Cold Channels	0.0106

Table 3. HELIUM AND STRUCTURAL MATERIAL PROPERTIES [6] [7]

Property	Value
k_h	0.483 W/mK
k_c	0.441 W/mK
$c_{p,h}$	3,123 J/kgK
$c_{p,c}$	3,123 J/kgK
ρ_h	5.226 kg/m^3
ρ_c	5.633 kg/m^3
k_s	1.440 W/mK
$c_{p,s}$	2,272 J/kgK
ρ_s	3,200 kg/m^3

Effectiveness Calculations

The analyses presented here will use heat transfer rate and heat exchanger effectiveness as quantitative measures of heat exchanger performance. Equation 9 defines the effectiveness of a heat exchanger where q_{max} refers to the theoretical maximum heat transfer rate based on the difference between the hot and cold inlet temperatures. Equations 10 and 11 define q and q_{max}, respectively [9]:

$$\varepsilon = \frac{q}{q_{max}} \tag{9}$$

$$q = \rho_x v A c_{p,x} (T_{x,o} - T_{x,i}) \tag{10}$$

$$q_{max} = \rho_h v A c_{p,h} \left(T_{h,i} - T_{c,i}\right) \tag{11}$$

Equation 11 uses the minimum values for the mass flow rate and specific heat terms with respect to the hot and cold fluids; for this application, the hot fluid. [9].

ANALYSES AND RESULTS

Influence of Channel Radius

This analysis will determine the effect of channel radius on the effectiveness and the heat transfer rate of the heat exchanger. The flow-rate is kept constant between the calculations by varying the radius. Note that, the center to center distance between the channels is kept the same.

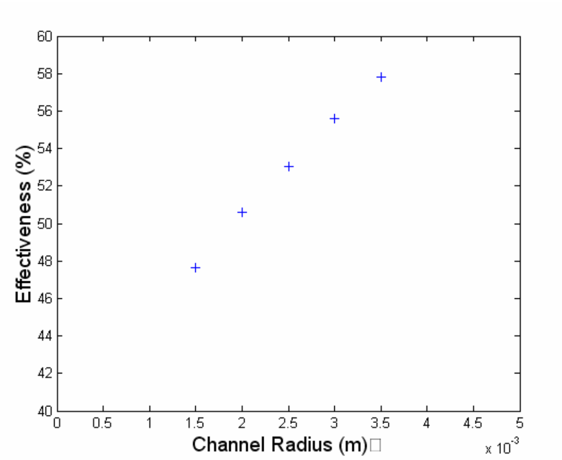

Figure 5. HTHX EFFECTIVENESS VS. CHANNEL RADIUS

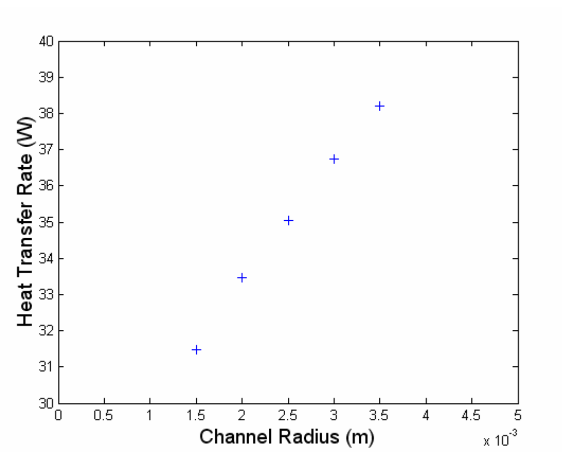

Figure 6. HEAT TRANSFER RATE VS. CHANNEL RADIUS

Figure 5 shows a linear increase in effectiveness with respect to channel radius. Figure 6 shows a linear increase in heat transfer rate with respect to channel radius. The increase is due to the enlargement of the heat transfer surface area.

A more realistic analysis would involve changing the radius while keeping the edge to edge distance between the channels constant. Further work will investigate this effect.

Influence of Channel Spacing

This analysis will investigate the effect of channel spacing on the effectiveness and the heat transfer rate of the heat exchanger. Calculations are performed for two cases, A and B, as shown in Figure 7. The open circles represent one working fluid (hot) while the shaded circles represent the second working fluid (cold). Note that the center to center distance between the hot and cold channels remains the same between the two cases. The results in Table 4 show that Case A has both increased heat transfer rate and effectiveness with respect to Case B.

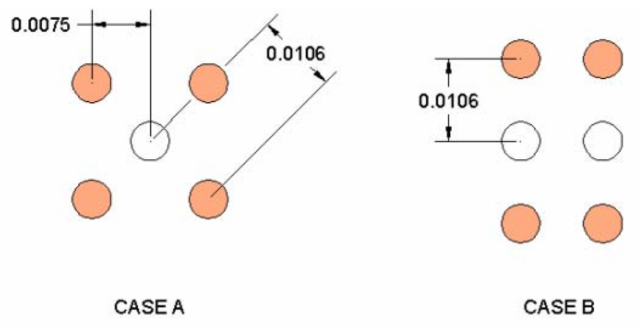

Figure 7. HEAT EXCHANGER CHANNEL CONFIGURATION (ALL DIMENSIONS IN METERS)

Table 4. CHANNEL SPACING ANALYSIS RESULTS

Case	q_{max} (W)	ΔT_h (K)	q (W)	Effectiveness (%)
A	66.1	291.7	35.1	53.1
B	132.2	217.8	52.3	39.6

Influence of Channel Length

This analysis will determine the extent of channel length on the effectiveness and the heat transfer rate of the heat exchanger.

Figure 8 shows an increase in effectiveness with respect to channel length. Figure 9 shows an increase in heat transfer rate with respect to channel length.

Note that longer channel lengths increase pressure drop as well as increase material and manufacturing costs. Future work will investigate the extent of the pressure drop.

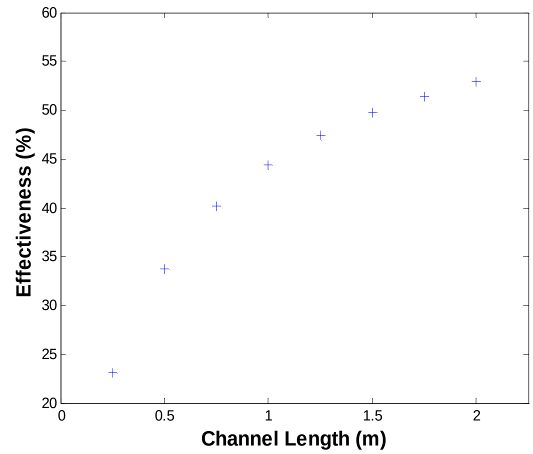

Figure 8. HTHX EFFECTIVENESS VS. CHANNEL LENGTH

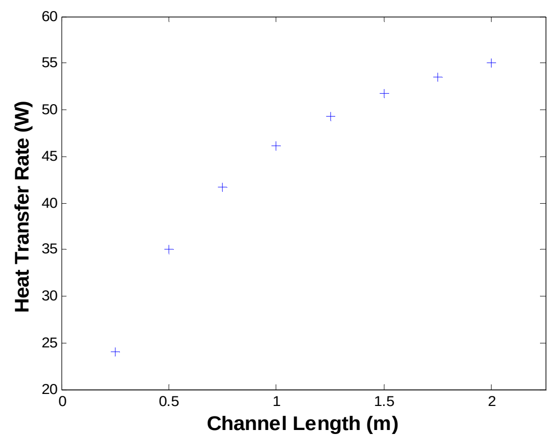

Figure 9. HEAT TRANSFER RATE VS. CHANNEL LENGTH

Influence of Flow-rate

This analysis will investigate the effect of volumetric flow rate on the effectiveness and the heat transfer rate of the heat exchanger.

The results in Figures 10 show that effectiveness decreases with increased flow-rate. The results in Figure 11 show that heat transfer rate increases with flow-rate. The decrease in effectiveness arises from q_{max} increasing at a faster rate than q with respect to increasing the volumetric flow rate.

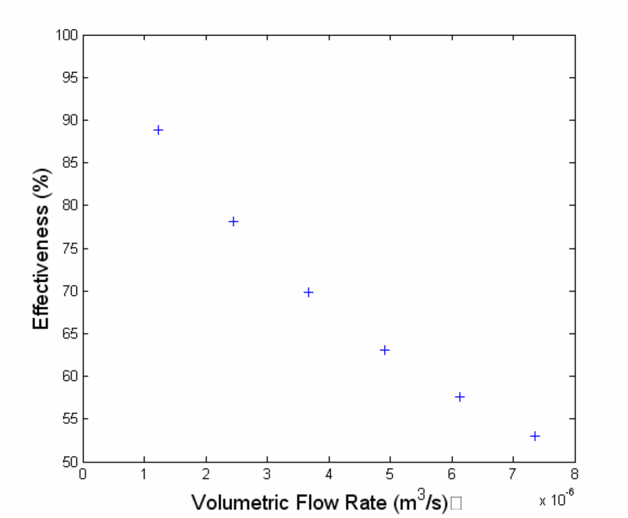

Figure 10. HTHX EFFECTIVENESS VS. VOLUMETRIC FLOW-RATE

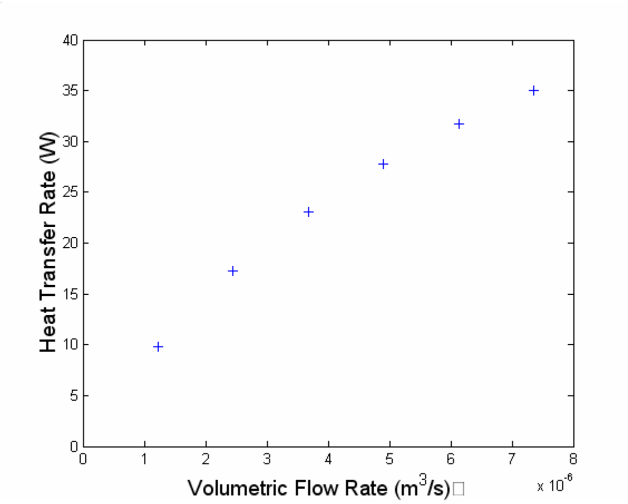

Figure 11. HEAT TRANSFER VS. VOLUMETRIC FLOW-RATE

CONCLUSION

A review of high temperature nuclear applications leads to the definition of HTHX operating conditions and performance requirements. This information provides a starting point for design optimization.

Design optimization begins with the simplest possible heat exchange design: a block with circular channels for fluid flow. A number of calculations investigated the influence of channel radius, channel spacing, channel length, and flow-rate on heat transfer rate and heat exchanger effectiveness. The data gathered from these analyses provides a basis for more complex modeling and optimization methods.

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