NATURAL CIRCULATION MODEL AND PERFORMANCE ANALYSES OF "SLIMM"- A SMALL, MODULAR SODIUM-COOLED REACTOR

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ABSTRACT

The sodium-cooled, Scalable LIquid Metal cooled small Modular (SLIMM) reactor, developed at the University of New Mexico, can generate 10 to 100 MW_{th} without refueling for many years. At 100 MW_{th}, the operation life estimate is ~ 5.8 full power year (FPY) and as much as 33.3 FPY when operating at 20 MW_{th}. Natural circulation of liquid sodium cools the reactor core during nominal operation and after shutdown, with the aid of an in-vessel chimney (2-8 m tall) and a helically coiled tubes Na/Na heat exchanger (HEX) that serves as the in-vessel heat sink. The liquid sodium enters the core at 610 K, and exits at ≤ 820 K. At these temperatures, sodium corrosion of the HT-9 steel for the UN fuel rods cladding, the core structure, and the reactor vessel is not a concern. Developed is a natural circulation model to simulate the performance of the SLIMM reactor during nominal, steady-state operation. The model solves the coupled momentum and energy balance equations for the in-vessel circulating liquid sodium and the Na/Na heat exchanger. It calculates the total flow rate and exit temperature of the circulating liquid sodium through the core as functions of the reactor thermal power, the chimney height, and the HEX design (total height, number and dimensions of the concentric helical coils, and the coils tube diameter and pitches).

KEYWORDS
Helically coiled tubes heat exchanger, SLIMM small modular reactor, natural circulation model, passive operation, liquid sodium, UN fuel, and HT-9 steel

1. INTRODUCTION

Small Modular Reactors (SMRs) are those capable of providing ≤ 300 MW_e of electricity generation [1]. Concepts that include water-cooled, gas-cooled and liquid metals cooled reactors are at various stages of development [1-5]. Some are compact for factory-fabrication and transportation by trucks, rail, or barges to the plant site and /or cooled by natural circulation during nominal operation and after shutdown [1, 3, 5]. The SMR designs offer many passive safety features, and some have long operation lives (> 3-5yrs) without refueling.

The sodium-cooled, Scalable LIquid Metal cooled small Modular (SLIMM) reactor concept, developed at the University of New Mexico's Institute for Space and Nuclear Power Studies [6-8], can generate 10-100 MW_{th} continuously without refueling for extended periods. At 100 MW_{th}, the SLIMM reactor operation life is ~ 5.8 full power year (FPY) and as much as 33.3 FPY when operating at 20 MW_{th} [8]. Natural circulation of liquid sodium cools the reactor core during nominal operation and after shutdown, with the aid of an in-vessel tall (2-8 m) chimney and a helically coiled tubes Na/Na heat exchanger (HEX) that serves as the in-vessel heat sink (Figs. 1 and 2). The HEX design as well as the height of the chimney affect the operation parameters of the SLIMM reactor. Thus, this work presents a thermal hydraulics and natural circulation

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model developed for investigating the performance of the SLIMM reactor during nominal steady state operation.

The model calculates the circulation rate of the in-vessel liquid sodium, $\dot{m}$, and exit temperature in the core, T_{ex}, as functions of the reactor thermal power, P_{Rx}, the height of the in-vessel chimney, H_{Ch}, and the design of the in-vessel HEX. The placement of the HEX at the top of the downcomer (Fig. 2) maximizes the static pressure head for passively circulating the in-vessel liquid sodium. The varied HEX design parameters are the number (n_{co}), diameter (D) and pitches (p) of the concentric helical coils, the coils tube diameter (d_t), the total height and the temperature pinch, ΔT_{pinch}, between the in-vessel circulating liquid sodium and the secondary sodium flowing through the HEX coils (Fig. 3a).

The performed analyses using the developed natural circulation model ascertain that the height of the Na/Na heat exchanger, H_{HEX} is at least one meter shorter than of the in-vessel chimney (Fig. 2) as well as the in-vessel circulating liquid sodium enters and exits the reactor core at 610 K and $\leq$ 820 K, respectively. At these temperatures, sodium corrosion of the HT-9 steel for the UN fuel rods cladding, the core structure, and the reactor vessel is not a concern. This paper investigates the effects of changing P_{Rx}, H_{Ch}, and the design of the in-vessel Na/Na HEX (Fig. 2) on the SLIMM reactor performance during nominal steady state operation, including the circulating rate of the in-vessel liquid sodium and T_{ex} and the in-vessel pressure losses.

2. SLIMM Reactor Design

The SLIMM reactor can operate at 10 to 100 MW_{th}, with the same core design, by simply varying the height of the in-vessel chimney, H_{Ch}, and the design of the in-vessel helically coiled tubes Na/Na HEX [6-8]. The SLIMM reactor would be fabricated, assembled and sealed at the factory, and then shipped to the construction site by rail, a heavy truck or a barge. The reactor would be installed below ground to avoid impact by missiles or aircraft, and mounted on seismic insulation bearings to resist earthquakes [8].

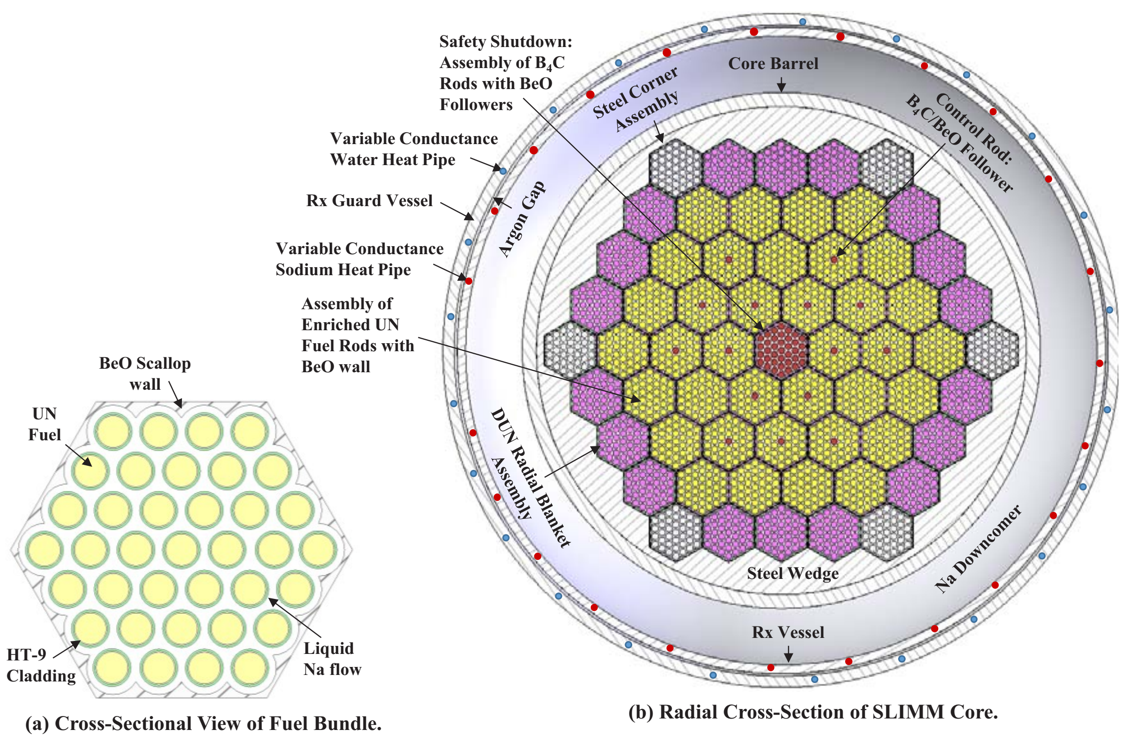

Figure 1. Cross-Sectional Views of SLIMM Reactor Core and UN Fuel Bundle [6-8].

Both the HT-9 primary and guard vessels of the SLIMM reactor are made of two sections (Fig. 2). The lower section houses the reactor core and in-vessel control and the upper section houses the chimney and the Na/Na helically coiled tubes HEX. The heights of the chimney, the HEX and the upper section of the primary and guard vessels depend on the reactor nominal thermal power, P_{Rx}. [8]

The SLIMM reactor operates fully passive, except for the in-vessel control drives, and uses UN fuel with an enrichment < 18% [6-8]. The reactor core (Fig. 1) takes advantage of the high metal-atom ratio, high melting point and high thermal conductivity of the UN fuel [9] and uses HT-9 steel for the UN fuel rods cladding, reactor primary and guard vessels and the core structure (Figs. 1 and 2). The high thermal conductivity of UN [9] keeps the fuel temperature during nominal reactor operation below 1400 K, depending on P_{Rx}. At such a low temperature, fuel swelling and fission gas release are non-issues [10]. In addition to its compatibility with the HT-9 steel and liquid sodium, UN has a high volumetric heat capacity for enhanced safety [8].

The fuel rods in the driver core are bundled in a triangular lattice with a Pitch-to-Diameter (P/d) ratio of 1.2 in 36 hexagonal assemblies. The scalloped BeO walls of the shrouds for the assemblies (Fig. 1a) [6-8] ensures equal flow area for all fuel rods in the assemblies (Fig. 1a). The BeO low parasitic neutron absorption and the production of fast neutrons by the (n, 2n) and (γ, n) reactions in the Beryllium, increase the hot-clean reactivity by several dollars [7, 8]. Such increase in reactivity prolongs the operation life of the SLIMM reactor without increasing the UN fuel enrichment.

Each fuel assembly in the driver core is loaded with 37, 2.357 cm diameter UN rods clad in HT-9 steel (Fig. 1a). Sodium fills the radial gap between the UN pellets and the HT-9 steel cladding. The driver core's 36 fuel assemblies are arranged in 3 concentric rings; 6 in the first, 12 in the second and 18 in the third ring (Fig. 1b). A radial blanket (the 4th ring in Fig. 1b) that consists of 18 assemblies surrounds the driver core; twelve assemblies are loaded with HT-9 clad DUN rods, and six corner assemblies loaded with HT-9 steel rods. The radial blanket assemblies have HT-9 shrouds with scalloped walls. In addition, HT-9 wedges fill the space between the radial blanket and the 10 cm-thick HT-9 core barrel (Fig. 1b) [6-8].

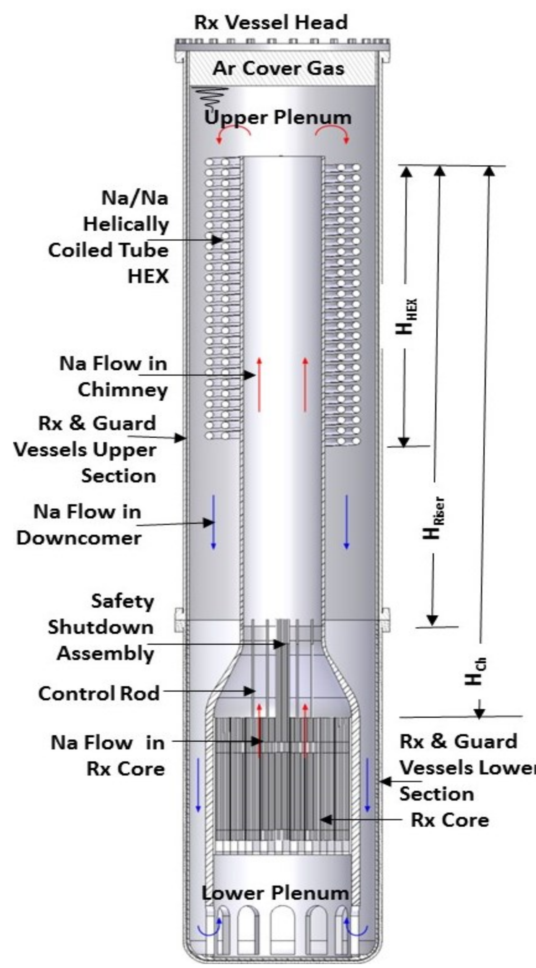

Figure 2. SLIMM Reactor Longitudinal Cross-Section [6-8].

Natural circulation of the in-vessel liquid sodium (Fig. 2) cools the reactor core during nominal operation and after shutdown, with the aid of an in-vessel tall chimney and a helically coiled tube Na/Na HEX (Fig. 2). The difference between the static heads of the liquid sodium in the downcomer and that in the core and the chimney circulates the liquid sodium coolant through the core (Fig. 2). The liquid sodium transports the fission heat generated in the reactor core to the HEX, which serves as the in-vessel heat sink. The cooled sodium exiting the HEX at 610 K flows through the downcomer to the lower plenum, before entering the reactor core (Fig. 2).

The temperature pinch (Fig. 3a) between the in-vessel circulating liquid sodium and the secondary sodium flowing through the HEX coils, the diameter and the number of the concentric helical coils in the HEX, and the coils tube diameter and pitches (Fig. 3b) affect the flow rate and temperature of the liquid sodium exiting the reactor core. The number of the HEX coils, n_{co}, varies from 6 to 14, depending on the P_{Rx}, d_t, and H_{Ch}. Increasing n_{co} increases the heat transfer area and decreases the height of the HEX, which decreases the friction pressure losses. Conversely, increasing n_{co} decreases the flow area of the circulating liquid sodium between the HEX coils, which increases pressure losses. Thus, depending on the values of P_{Rx} and H_{ch}, the net effect of increasing n_{co} would be to either increase or decrease the liquid sodium flow rate and exit temperature in the reactor core. The developed natural circulation and thermal-hydraulics model, described in the following section, is used to qualify the effect of the HEX design, among other things, on the performance of the SLIMM reactor during steady state operation.

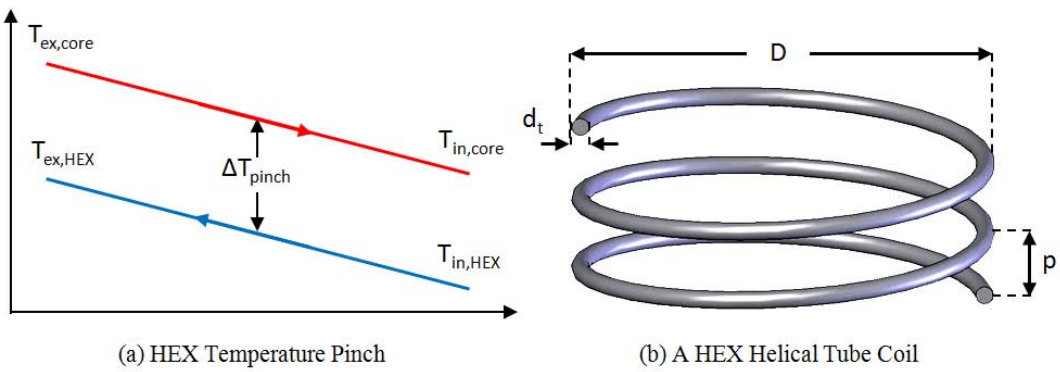

Figure 3. The HEX Temperature Pinch and a Helically Coiled Tube.

3. Natural Circulation and Thermal-Hydraulics Model for SLIMM Reactor

The developed 1-D, model is for simulating the cooling the SLIMM reactor core with natural circulation of liquid sodium during nominal operation and after shutdown, with the aid of the in-vessel tall chimney and the helically coiled tubes heat exchanger (Fig. 2). For a constant core inlet temperature, T_{in} = 610 K, the model calculates the total sodium flow rate and exit temperature in the core as functions of the chimney height and the design of the HEX (Fig. 2). At the above inlet and exit temperatures, corrosion of the HT-9 fuel rod cladding and core structure with liquid sodium is negligible [11].

The natural circulation model solves the coupled overall momentum and energy balance equations for the in-vessel liquid sodium and reactor core. The liquid sodium flow traverses the reactor core, chimney, the upper plenum, the coiled tube heat exchanger, the downcomer, and the lower plenum (Fig. 2). The overall energy balance equation for the reactor core equates the rate of heat generation by fission, P_{Rx}, to that removed by the circulating liquid sodium through the core, as:

$$P_{Rx} = \dot{m}\,\bar{C}_p(T_{ex} - T_{in}) \qquad (1)$$

On the right hand side of this equation, the mass flow rate of liquid sodium through the core, $\dot{m}$, and T_{ex} are determined from the coupled solution of the overall momentum balance equation for the in-vessel circulating liquid sodium (Eq. 2). At steady state, the reactor thermal power also equals that removed from the in-vessel circulating sodium in the helically coiled tubes heat exchanger (Fig. 2). The overall momentum balance equation for the circulating liquid sodium in the reactor vessel equates the net driving static pressure head to the total friction pressure losses along the in-vessel flow path of liquid sodium (the core, chimney, upper plenum, HEX, downcomer, and the lower plenum), thus:

$$\Delta P_d - \sum \Delta P_L = 0 \tag{2}$$

The net driving pressure head in Eq. (2), ΔP_d, is given as:

$$\Delta P_d = \{(\rho_{in} - \rho_{ex})H_{Ch} + (\rho_{in} - \bar{\rho}_C)H_C - (\rho_{in} - \bar{\rho}_C)H_{HEX}\}g \tag{3}$$

The total pressure losses in equation (2), $\sum \Delta P_L$, are the sum of those experienced by the circulating liquid sodium in the reactor core, the chimney, the HEX, and the downcomer, as well as those due various flow contractions and expansions (Fig. 2). These losses are expressed as:

$$\sum \Delta P_L = \Delta P_C + \Delta P_{Ch} + \Delta P_{HEX} + \Delta P_{dc} + \sum \Delta P_{exp} + \sum \Delta P_{con} \tag{4}$$

Each term in equation (4) depends upon the dimensions of and the liquid sodium average temperatures in the various regions of the reactor [8, 12]. All dimensions of the SLIMM reactor are known, except for the height of the chimney and the design and height of the HEX, which are varied in the model. The height of the heat exchanger, H_{HEX}, depends on the number and diameters of the concentric helical coils, the coils tube diameter and pitches as well as the in-vessel sodium's total flow rate and T_{ex} in the reactor core, which depend on P_{Rx} and H_{Ch}. The height of the heat exchanger, $H_{HEX,}$ is shorter than H_{ch}, by at least one meter. Figure 4 presents a sketch of a Na/Na HEX of six concentric helical coils of the same tube diameter, but different tube lengths and pitches.

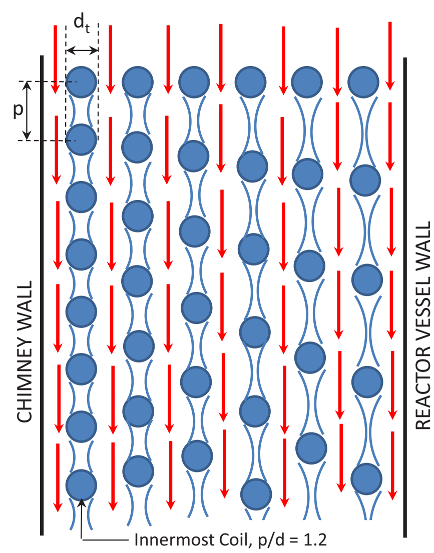

Figure 4. In-Vessel Sodium Flow Between Six Concentric Helical Coils Heat Exchanger.

The input to the developed natural circulation model includes n_{co}, d_t and the pitch of the inner most coil for the HEX, P_{Rx} and H_{Ch}. Then, the lengths and pitches of the heat exchanger coils, the equivalent hydraulic diameter for the HEX, D_e, the height, $H_{HEX,}$ and the pressure losses for the heat exchanger, ΔP_{HEX}, are calculated from solving the heat exchanger's energy balance (Eq. (5)) and momentum balance equations (Eq. (6)):

$$\sum_{i=1}^{n_{co}} P_{co,i} = P_{Rx} \,. \tag{5}$$

$$\Delta P_{HEX} = \Delta P_{HEX,i} = \Delta P_{HEX,1} = \Delta P_{HEX,2} = \cdots = \Delta P_{HEX,n_{co}} \,, \tag{6}$$

Equation (5) states that the sum of the thermal power removed from the circulating liquid sodium through the heat exchanger to the secondary sodium flowing through all the heat exchanger coils equal that generated in the reactor core. Equation (6) states that the friction pressure losses across each of the heat exchanger coils are equal to the total pressure losses across the HEX. Although the total length of the tubes and the pitches of the coils are different, the heights of the helical coils in the heat exchanger are the same and equal to that of the heat exchanger, H_{HEX}. The coupled solution of Equations (5) and (6), in conjunction with Equation (1) – (4), is subject to the following assumptions and requirements:

(a) The external pressure losses across each of the helical coils in the heat exchanger are the same and equal the total pressure losses across the heat exchanger. Therefore, the lateral spacing between the helical coils in the heat exchanger is such that the equivalent hydraulic diameter, D_e, and the liquid sodium mass flux, G_{HEX}, in the passages between the coils are the same. However, the total flow rate of liquid sodium through the heat exchanger is the same as that circulating through the reactor core during steady state operation.

(b) Model the heat exchanger as comprised of concentric annuli separated by solid, smooth walls of the same thickness as the diameter of the coils tube (e.g., Fig. 4). Thus, the HEX model neglects cross flow and the surface curvature of the coils. This simplifying approach underestimates the pressure losses in the heat exchanger, which are a small fraction of the total losses in the SLIMM reactor for the in-vessel sodium circulation. Detailed, 3-D Computational Fluid Dynamic (CFD) analysis is currently underway for accurately determining the actual pressure losses and developing a correlation for the SLIMM helically coiled tubes heat exchanger. Nonetheless, this simplifying assumption makes it possible to use the following formulation [13] of Darcy equation [14] for estimating the friction pressure losses across the heat exchanger, ΔP_{HEX}, as:

$$\Delta P_{HEX} = (a/2)\left(H_{HEX}/D_e^{1+b}\right)\left(\bar{\mu}^b/\bar{\rho}\right)G_{HEX}^{2-b} \tag{7}$$

In this equation, the values of the coefficient "a" and the exponent "b" depend on the values of Reynolds number in the heat exchanger concentric annuli [12, 13]. The average dynamic viscosity, $\bar{\mu}$, and density, $\bar{\rho}$, of the in-vessel liquid sodium flowing through the heat exchanger are evaluated at the arithmetic average sodium temperature in the heat exchanger. This temperature is the same as in the reactor core $((T_{in} + T_{ex})/2)$.

(c) Neglect heat losses across the chimney and the core barrel walls to the liquid sodium flowing in the HEX and the downcomer. The side heat losses from the core to the sodium in the downcomer are relatively small. This is because the rate of heat generation by fast neutron fission in the DUN radial reflector assembles (Fig. 1) is small (a few percentage of the reactor total) [8]. Furthermore, the relatively low thermal conductivity of the HT-9 steel wedges (Fig. 1) and the core barrel wall minimize side heat loss from the core. The side heat losses through the wall of the chimney to the liquid sodium flow through the heat exchanger would decrease the inlet, but not the average temperature of the in-vessel liquid sodium in the heat exchanger. Thus, this assumption would slightly affect the calculated flow rate of the in-vessel liquid sodium and its temperature exiting the reactor core.

(d) Although the total lengths and pitches of the heat exchanger coils are different, the internal pressure losses due to the secondary liquid sodium flow inside the coils are equal, thus:

$$\Delta P_{s,i} = \Delta P_{s,1} = \Delta P_{s,2} = \cdots = \Delta P_{s,n_{co}}, \tag{8}$$

Because the total height of the coiled tubes in the heat exchanger should be the same and equal to H_{HEX}, the coil pitch (Fig 3b) increases with radial distance, from the inner most coil near the chimney to the outermost coils near the reactor vessel wall in the downcomer (Fig. 4).

(e) The heat transfer coefficient for the in-vessel liquid sodium flow and the secondary sodium flow inside the heat exchanger coils is determined using a recently developed correlation for alkali metals flow in uniformly heated tubes [15], as:

$$\mathrm{Nu} = 5.6 + 0.13\ \mathrm{Pe}^{0.863} \tag{9}$$

The solution of the coupled equations (5) – (9), in conjunction with equations (1)-(4), assumes a temperature pinch, ΔT_{pinch} = 50 K, between the in-vessel liquid sodium and the secondary sodium flowing inside the heat exchanger coils (Fig 3a) and a P/d ratio of 1.2 for the innermost HEX coil (Fig. 4). The solution calculates the in-vessel sodium flow rate and exit temperature in the core and the HEX height as functions of P_{Rx} and H_{Ch}. In addition, the solution calculates the HEX coils diameters, lengths and pitches, the HEX equivalent hydraulic diameter, D_e, the liquid sodium mass flux through the HEX, and the thermal power removed by each of HEX coils, as functions of n_{co} and d_t. The lengths of the various heat exchanger coils are determined based on the needed surface area for heat transfer from the in-vessel liquid sodium flow to the counter current flow of the secondary liquid sodium inside the coils (Fig. 3a). This is subject to having the same internal pressure losses and inlet and exit temperatures of the secondary liquid sodium flow through the coils. The solution accounts for the changes in the properties of liquid sodium with temperature throughout the reactor vessel. The details of the HEX design, governing equations, and solution methodology are the subject of a future publication.

An iterative approach in the MATLAB commercial software [16] solves the coupled Equations (1)-(9). This approach used a 'while loop' to iterate through a vast number of values and matrices until the difference between the static driving pressure head and the total pressure losses in Equation (2) converge to within 0.001 Pa and the estimates of the reactor exit temperature converge to within 0.005 K. Although not unique to MATLAB, the iterative solver is beneficial and efficient for performing the calculations that covered a wide range of parameters. MATLAB operates primarily on whole matrices and arrays [17] and uses highly optimized libraries, specifically for matrix operations, which were useful for our system of equations in the developed in-vessel natural circulation model.

The following section presents the calculated operation parameters of the SLIMM reactor and the results of effects of the various HEX design parameters on the flow rate and temperature of the liquid sodium exiting the reactor core as functions of the chimney height and the reactor thermal power.

4. RESULTS AND DISCUSSION

Parametric analyses of the SLIMM reactor during nominal operation are performed using the developed thermal-hydraulics and natural circulation model. The ranges of the various parameters used in the analyses are listed in Table I. In this table, the values for the reactor base design are marked with an asterisk (*). The analyses varied the various parameters in Table I, one at a time, within the indicated ranges. The effect of the various parameters on the calculated performance of the base reactor design are presented and discussed in this section.

4.1. SLIMM Reactor Performance Surface

Figure 5 presents a performance surface for the SLIMM reactor. It is comprised of a grid of curves indicating the different reactor thermal powers and intersecting curves indicating different chimney heights. For a given reactor thermal power and a chimney height, this figure provides the total mass flow rate and the corresponding exit temperature of the liquid sodium in the reactor core. The results in Fig. 5 are for the base case parameters in Table I with 10 concentric HEX coils and a coils tube outer diameter, d_t = 3.5 cm. The performance surface in Fig. 5 is bounded by a vertical line of the highest sodium exit temperature allowed, 820 K, and another inclined line

Table I. SLIMM Analyses Parameters.

PARAMETER	RANGE
H_{Ch} (m)	2 – 8*
P_{Rx} (MW_{th})	10 – 100*
n_{co}	6 – 10* – 14
d_t (cm)	1.5 – 3.5* – 8
Inner coil (p/d_t)	1.2* – 4.8
ΔT_{pinch} (K)	30 – 50* – 80
δ_w (mm)	2*
T_{in} (K)	610*

** Indicate Base Case Design*

corresponding to having $H_{HEX} = (H_{Ch} - 1.0\ m)$. The crossed square symbol in Fig. 5 indicates the liquid sodium flow rate and T_{ex} for the SLIMM reactor base design ($P_{Rx} = 100\ MW_{th}$ and $H_{Ch} = 8$ m (Table I)).

The results in Fig. 5 show that increasing H_{ch} increases the liquid sodium total flow rate and decreases its T_{ex} in the reactor core (Fig. 5). In addition, decreasing P_{Rx} decreases both the total flow rate of liquid sodium and its T_{ex}. For a given P_{Rx}, increasing H_{Ch} increases the driving pressure head, ΔP_d, which increases the liquid sodium total flow and decreases its T_{ex}. On the other hand, for a given H_{Ch}, increasing P_{Rx} increases T_{ex}, increasing ΔP_d and hence the liquid sodium mass flow rate. Results show it is possible to operate the SLIMM reactor at 100 MW_{th} with a chimney height as low as 6 m, and still keep $T_{ex} < 820$ K. In addition, decreasing H_{Ch} to 3 m, limits P_{Rx} to 65 MW_{th}. Beyond this power, the height of the in-vessel HEX would exceed that of the riser, or $H_{HEX} > (H_{Ch} - 1.0\ m)$ (Figs. 2 and 5).

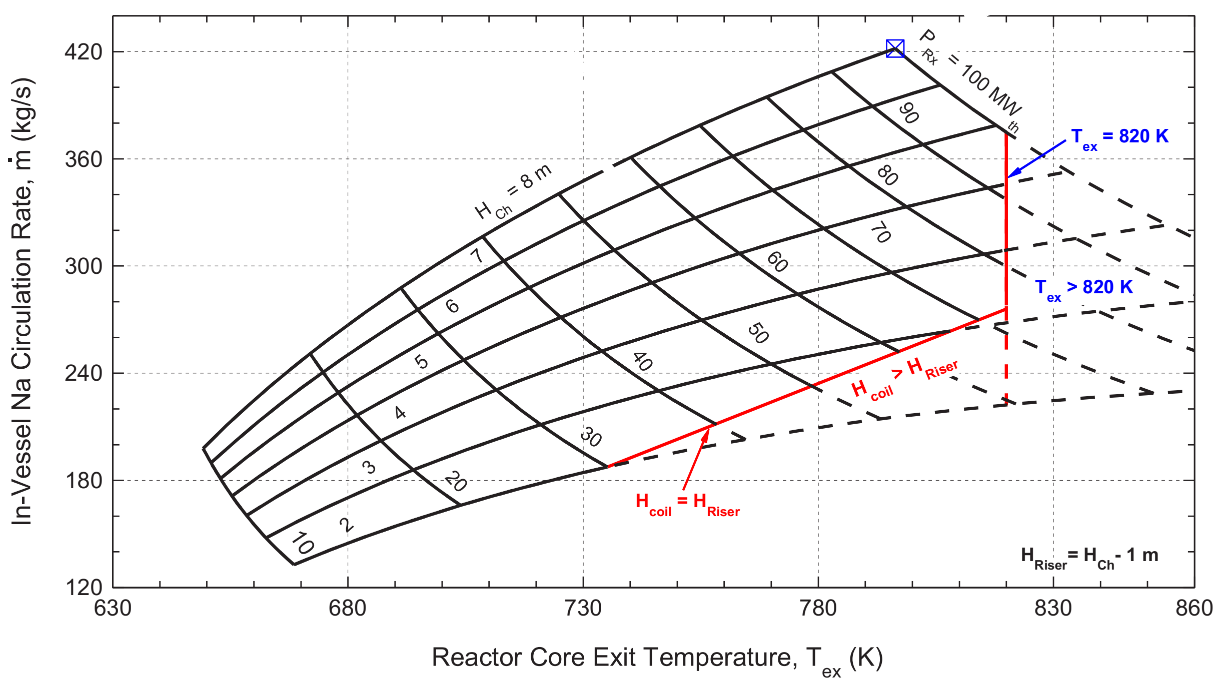

Figure 5. Performance Surface for SLIMM reactor Cooled by Natural Circulation of Sodium.

4.2. Effect of HEX Design on SLIMM Reactor Performance

Changing either the number of the concentric coils in the HEX (6-14) or the coils tube diameter strongly affects the liquid sodium flow rate and T_{ex}. The results in Figs. 6a-6c are for the base case design of the SLIMM reactor (Table 1) with $P_{Rx} = 100\ MW_{th}$ and $H_{Ch} = 8$ m (Table I). For a given n_{co}, increasing d_t increases the flow rate of liquid sodium through the core and decreases its T_{ex}. The decrease in the exit temperature continues up to a minimum value, beyond which a further increase in the tube diameter of the HEX coils decreases the liquid sodium flow rate and increases its T_{ex}. (Fig. 6a)

Increasing the HEX coils tube diameter introduces two effects with opposite impacts on the friction pressure losses in the HEX and hence the liquid sodium flow rate and T_{ex}. First, increasing d_t linearly decreases the H_{HEX} (Fig. 6b), which decreases the friction pressure losses in the HEX, ΔP_{HEX}. Conversely, increasing d_t decreases the coolant flow area through the HEX, rapidly increasing its mass flux and ΔP_{HEX} (Fig. 6c).

However, the net effects on the estimates of ΔP_{HEX}, the liquid sodium flow rate, and T_{ex} depend on n_{co} and d_t. For small d_t, the decrease in the friction pressure losses due to the decrease in the total HEX height outweighs the increase of the pressure losses due to the increase in the liquid sodium mass flux in the HEX. The net effect of decreasing d_t is decreasing ΔP_{HEX} and T_{ex}. Conversely, for a large d_t, since the former effect is smaller than the latter, ΔP_{HEX} increases. For the same P_{Rx} and H_{Ch}, increasing ΔP_{HEX} decreases the liquid sodium total flow rate and increases T_{ex}.

At the minimum sodium exit temperatures, indicated in Figs. 6a-6c by solid triangles, the decrease in ΔP_{HEX} due to the decrease in the total height of the HEX equals the increase caused by the higher mass flux of the liquid sodium between the coils (Fig. 6c). Results in Figures 6a-6c show that increasing n_{co} from 6 to 14 monotonically decreases the minimum temperature of the liquid sodium exiting the reactor core. For example, with n_{co} = 6, the minimum sodium exit temperature is ~ 808 K and decreases to 793 K for the HEX with fourteen helically coiled tubes (n_{co} = 14). For these two HEXs, the coils tube diameter corresponding to the minimum sodium exit temperature is ~ 6.6 cm and ~ 2.15 cm, respectively.

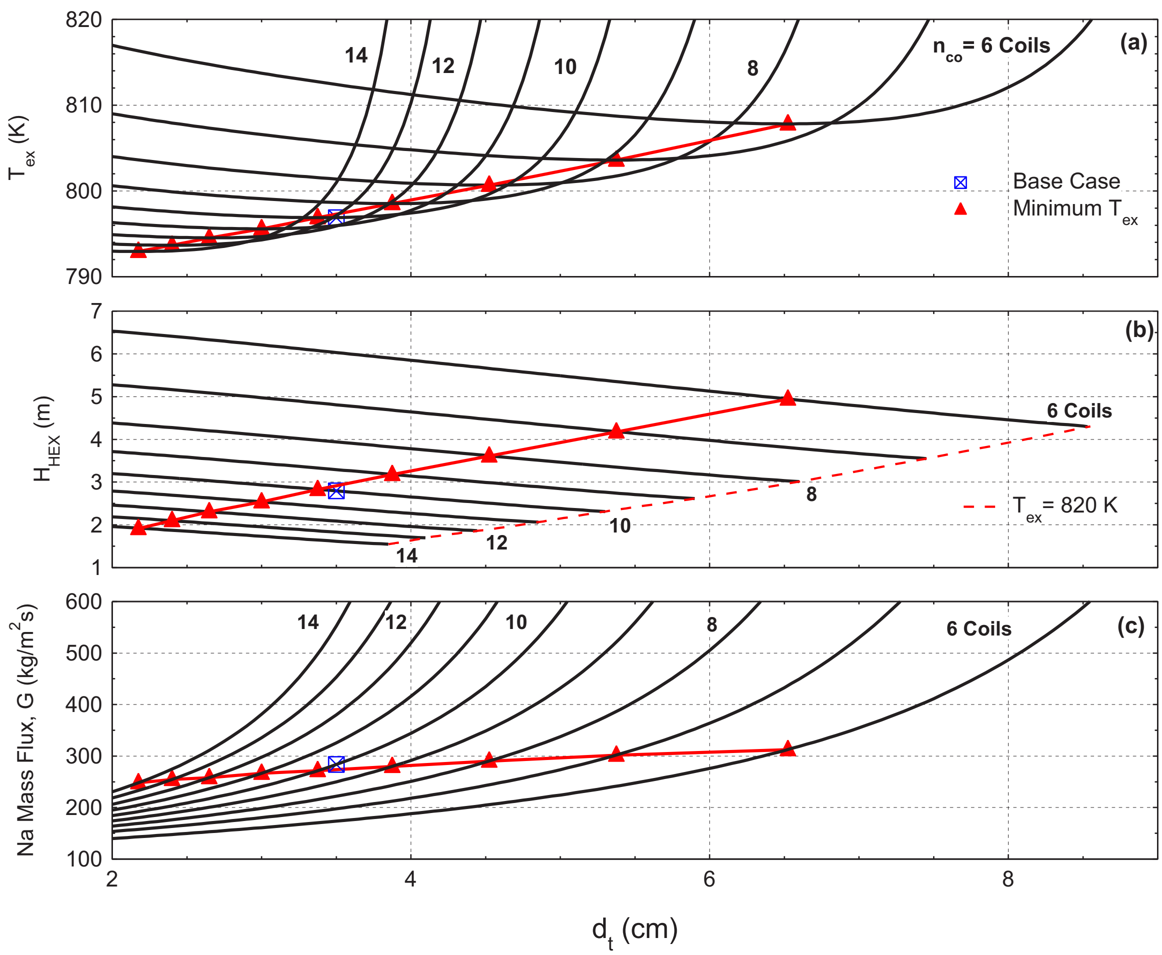

Figure 6. Effect of HEX Design Parameters on the Core Exit Temperatures While Cooled by Natural Circulation of In-Vessel Liquid Sodium.

Results in Figures 7a-7c demonstrate the effect of changing d_t, for the base reactor design parameters (Table I), including n_{co} = 10, P_{Rx} = 100 MW_{th}, and H_{Ch} = 8 m. When T_{ex} = 796.8 K, there is only a single HEX coils tube diameter, d_t, that satisfies the system equations (1) through (9) for cooling the reactor core by natural circulation. In Fig. 7a, $d_t \sim 3.34$ cm is that corresponding to the minimum sodium temperature exiting the reactor core. For a slightly higher exit temperature (T_{ex}=797.2 K), there are two coils tube diameters that satisfy the reactor's overall energy balance (Eq. 1) and momentum balance (Eq. 2) (Fig. 7b). These are d_t = 2.80 cm and 3.86 cm (Fig. 7b). For a T_{ex} that is higher by an additional 0.9 K, the coil tubes diameter that satisfy the system's energy and momentum balance equations are d_t = 2.05 cm and 4.23 cm (Fig. 7c).

For the SLIMM base case design parameters in Table I, Fig. 8 compares the total pressure losses within the reactor vessel as functions of d_t. The pie charts in Figs. 9a-9d illustrate graphically the percentages of the individual contributions to the total pressure losses in the SLIMM reactor. These results are for nominal operation at 10 and 100 MW_{th}, with H_{Ch} = 8 m and d_t of 3.5 and 5.0 cm. Fig. 8 shows that the friction pressure losses in the various regions within of the SLIMM reactor vessel, except the HEX, decrease with increasing d_t. Conversely, the friction pressure losses in the HEX increase with increasing d_t as do the total friction pressure losses for the natural circulation of liquid sodium in the reactor vessel. The friction pressure losses in the heat exchanger, ΔP_{HEX}, increase rapidly with increasing d_t, due to the decrease in the flow area between the HEX coils, which increases the mass flux of liquid sodium in the HEX.

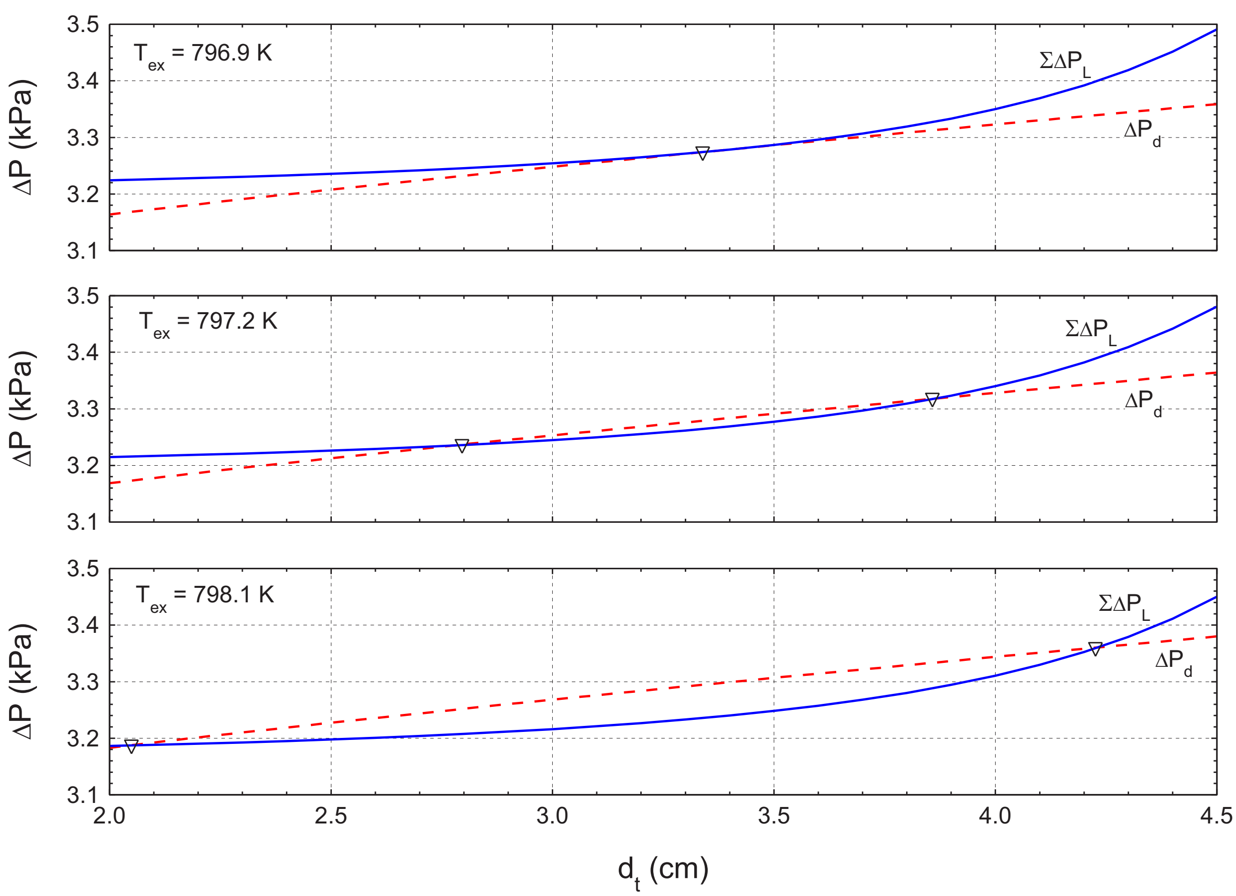

Figure 7. Tube Diameters for HEX Coils for the SLIMM Reactor Base Design Cooled by Natural Circulation of Liquid Sodium.

For turbulent flow of liquid sodium, these friction pressure losses increase with increasing the liquid sodium mass flux to the power 1.8 (equation 7) [13, 14]. Figure 8 shows that for d_t = 3 cm, ΔP_{HEX} ~ 1.2% of the total friction pressure losses in the SLIMM reactor vessel, increasing to as much as 20% when d_t increases to 5 cm. The results in Figs. 8 and 9 show that the friction pressure losses in the reactor core are the largest contributor to the total losses, followed by the those due to various flow contractions and expansions encountered by the circulating liquid sodium in the SLIMM reactor vessel (Fig. 2). The pressure losses in the HEX come third, while those in the chimney and the downcomer are negligibly small. It is worth noting that the current estimate of the friction pressure losses in the HEX is low, owing to simplifying assumption "(b)" indicated earlier. Preliminary CFD results suggest that these losses could as much as an order of magnitude higher. This would increase the total friction pressure losses by < 10%, making the estimate for the HEX the second largest contributor.

Figures 9a and 9b show that, for P_{Rx} = 100 MW_{th}, increasing d_t from 3.5 cm to 5 cm increases the total friction pressure losses from 3.28 kPa to 3.56 kPa. The contribution of the reactor core to the total pressure losses decreases from 65% to 54.75%, while the contribution of the HEX pressure losses increases from 1.7% to as much as 12%. The contribution of the in-vessel flow contractions and expansions to the total friction pressure losses in the reactor vessel is ~32%, regardless of the value of d_t. Figures 9a & 9c and 9b & 9d show that decreasing P_{Rx} by an order of magnitude to 10 MW_{th}, significantly decreases the total friction pressure losses of circulating liquid sodium in the SLIMM reactor vessel to 0.80-0.82 kPa. For d_t = 3.5 cm and 5.0 cm, the contribution of the core friction pressure losses decreases from 69% to 64%, while that due to the contractions and expansions pressure losses increases from ~30% to ~33%, respectively. The HEX pressure losses increase from being negligibly small (Fig. 9c) to ~ 1.9% (Fig. 9d), respectively.

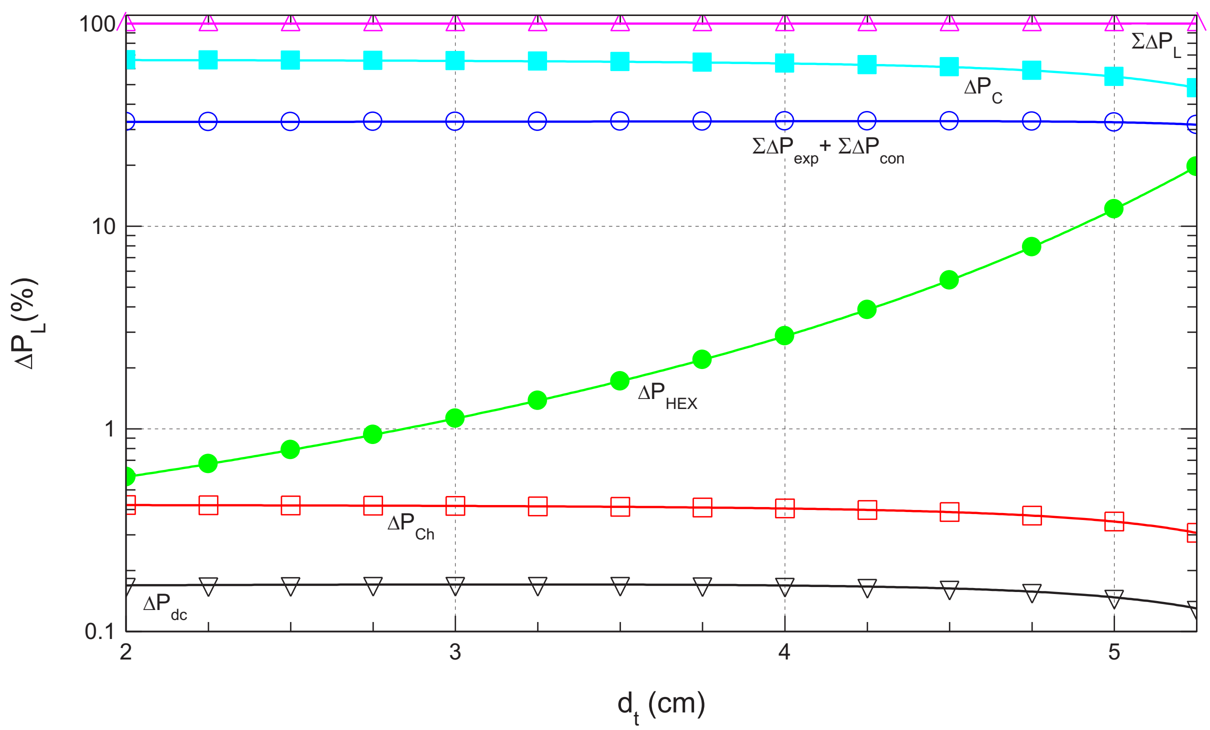

Figure 8. Effects of HEX Coils Tube Diameter on Individual Pressure Losses the Reactor Vessel.

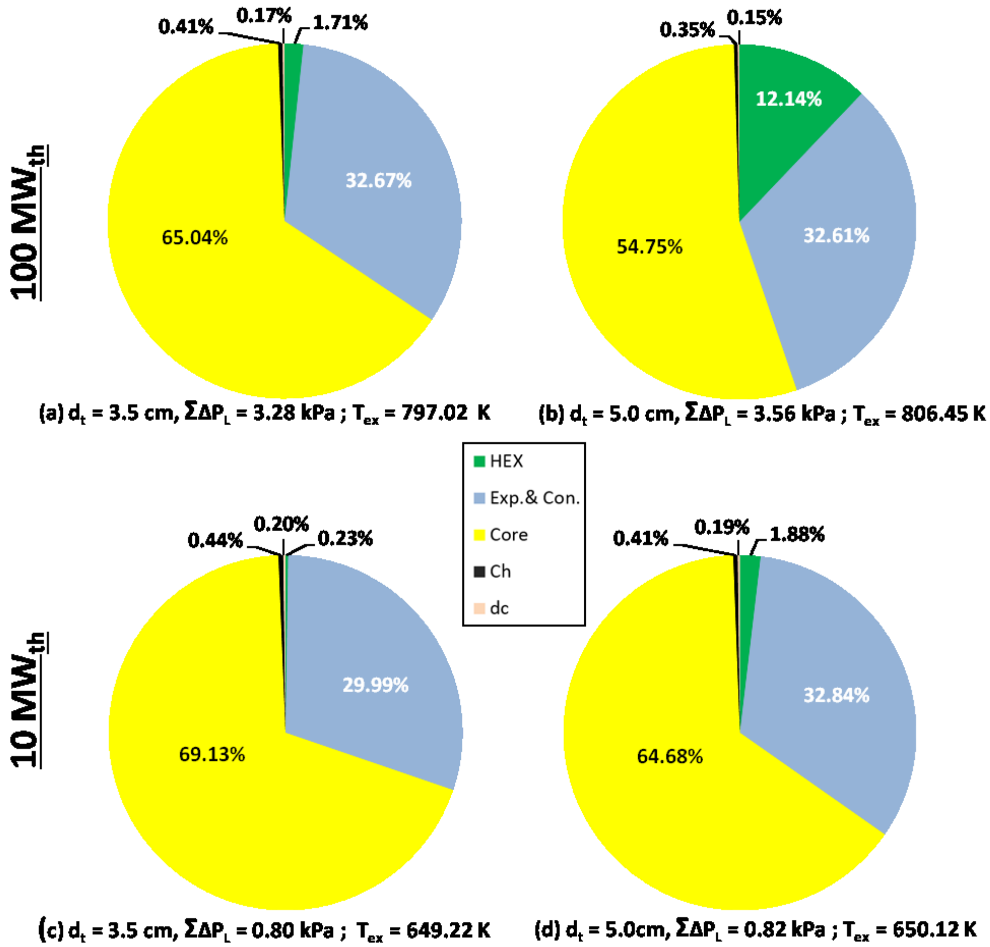

Figure 9. Contributions to Total Friction Pressure Losses of In-vessel Circulating Liquid Na in the SLIMM Reactor Vessel at Different Values of P_{Rx} and d_t.

5. SUMMARY AND CONCLUSIONS

Presented is a natural circulation model for simulating the performance of the SLIMM reactor during steady state nominal operation. In-vessel natural circulation of liquid sodium cools the reactor core, with the aid of an in-vessel tall chimney and a HEX comprised of concentric helical coils. The results presented in this paper are for the SLIMM reactor base design (Table I). The circulation rate of the in-vessel sodium coolant and T_{ex} in the reactor core depend on P_{Rx}, H_{Ch} and the design of the in-vessel Na/Na HEX (Figs. 2 and 4). For P_{Rx} = 100 MW_{th} and H_{Ch} = 6-8 m, it is possible to cool the SLIMM reactor by natural circulation of liquid sodium, without exceeding a core exit temperature of 820 K.

Investigated are the effects of the HEX design parameters (the number of the concentric helical coils, the coils tube diameter, and pitches and HEX height) and the in-vessel chimney height, H_{Ch}, on the SLIMM reactor steady state operation. For given reactor thermal power and a fixed pitch-to-diameter ratio of 1.2 of the innermost coil in the HEX, changing the number of the helical coils and/or the coils tube diameter strongly affect both the liquid sodium flow rate and T_{ex} in the core. The height of the in-vessel helically coiled tubes, Na/Na heat exchanger, H_{HEX}, decreases with increasing the coils tube diameter, d_t, and/or increasing the number of the coils, n_{co}. The exit core temperature, T_{ex}, however, decreases with increasing

n_{co}, and with increasing d_t, to a minimum before increasing with further increasing d_t. The lowest T_{ex} as well as the corresponding d_t increase with decreasing the number of the HEX coils, n_{co}.

Increasing the reactor thermal power increases the circulation rate of the in-vessel liquid sodium and its exit temperature in the core. Increasing the in-vessel chimney also increases the circulation rate of liquid sodium, but decreases the exit temperature in the core. Increasing either the reactor thermal power or the chimney height increases the net driving pressure for natural circulation as well as the total friction pressure losses. The friction pressure losses in the core is the primary component of the total in-vessel friction pressure losses in the SLIMM reactor. The friction pressure losses in the reactor core, the in-vessel chimney, the downcomer and the expansions decrease slowly with increasing the coils tube diameter, d_t, in the HEX. Conversely, the pressure losses in the HEX, although relatively small, increase rapidly with increasing d_t.

Future work will advance the capability of the natural circulation model of the SLIMM reactor to simulate operation transients, including startup and shutdown, and the passive removal of decay heat after reactor shutdown, and to accurately calculate the friction pressure losses in the HEX. The results of ongoing 3-D CFD analyses of the helically coiled tubes HEX in the SLIMM reactor would provide an extensive database for developing an empirical friction pressure losses correlation.

NOMENCLATURE

C_p	Specific heat capacity (J/kg-K)
d	Diameter (m)
D	Coil diameter (m)
D_e	Equivalent hydraulic diameter (m)
g	Gravity acceleration (m/s^2)
G	Mass flux (kg/m^{2}s)
h	Heat transfer coefficient (W/m^2 K)
H	Height (m)
H_{Riser}	$(H_{Ch} + H_C - H_{HEX})$, Fig. 2 (m)
k	Thermal conductivity (W/m K)
$\dot{m}$	Total mass flow rate (kg/s)
Nu	Nusselt Number, hD_e/K
p	HEX coil pitch (m)
P	Thermal power (MW_{th})
Pe	Peclet Number, GD_eC_p/k
T	Temperature (K)

Greek

ΔP	Pressure difference (Pa)
ΔT	Temperature difference (K)
μ	Dynamic viscosity (kg/m-s)
ρ	Density (kg/m^3)

Subscripts

C	Core
Ch	Chimney
co	Coil
con	Contraction
d	Driving head
dc	Downcomer
ex	Core exit
exp	Expansion
HEX	Helically coiled tubes heat exchanger
i	HEX coil number, i
in	Core inlet
L	Losses
$pinch$	Between primary and secondary Na flows
Rx	Reactor
s	Inside HEX coil tubes
t	Tube
th	Thermal
w	Tube wall

Superscripts

$-$	Average

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support for this research by the University of New Mexico's Institute for Space and Nuclear Power Studies (UNM-ISNPS), and a U.S. NRC Graduate Fellowship under

Grant #.NRC-38-09-931 to the University of New Mexico. The authors thank Dr. Timothy Schriener and Mr. Luis Palomino of the UNM-ISNPS for the valuable input and discussion.

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