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STEAM GENERATOR COMPONENT MODEL IN A COMBINED CYCLE OF POWER CONVERSION UNIT FOR VERY HIGH TEMPERATURE GAS-COOLED REACTOR

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Abstract - The U.S. Department of Energy and Idaho National Laboratory (INL) are developing a Next Generation Nuclear Plant (NGNP), Very High Temperature Gas-Cooled Reactor (VHTR) to serve as a demonstration of state-of-the-art nuclear technology. The purpose of the demonstration is two fold (1) efficient low cost energy generation and (2) hydrogen production. While hydrogen production and advanced energy cycles are still in its early stages of development, research toward coupling VHTR, electrical generation and hydrogen production is under way

The focus of this study was the verification of a steam generator model used in a combined Rankine bottom cycle and Brayton upper cycle as part of power conversion cycle studies we conducted at INL. Using two different computer codes, we compared heat transfer coefficients and the overall results of heat transfer were in good agreement.

I. INTRODUCTION

The NGNP reference concepts are helium-cooled, graphite-moderated, thermal neutron spectrum reactors with an outlet temperature initially set up to 1000^0C. The high temperature will allow the reactor to be used for a large number of process heat applications, including hydrogen production.

The NGNP reactor core could be either a prismatic graphite block type core or a pebble bed core. Use of various working coolants is also being evaluated.[1] The process heat for hydrogen production will be transferred to the hydrogen plant through an intermediate heat exchanger (IHX). The reactor thermal power and core configuration will be designed to assure passive decay heat removal without fuel damage during hypothetical accidents. The fuel cycle will be a once-through very high burnup low-enriched uranium fuel cycle.

The basic technology for the NGNP[2] has been established in the former high-temperature gas-cooled reactor test and demonstration plants (DRAGON, Peach Bottom, AVR, Fort St. Vrain, and THTR). In addition, the technologies for the NGNP are being advanced in the Gas Turbine-Modular Helium Reactor (GT-MHR) Project[3], and the South African state utility ESKOM sponsored project to develop the Pebble Bed Modular Reactor (PBMR).[4] Furthermore, the Japanese HTTR and Chinese HTR-10 test reactors are demonstrating the feasibility of some of the planned NGNP components and materials. (The HTTR achieved a maximum coolant outlet temperature of 950^0C in 2004.) Therefore, the NGNP project is focused on building a demonstration reactor, rather than simply confirming the basic feasibility of the concept.

One or more technologies will use heat from the high-temperature helium coolant to produce hydrogen. The first technology of interest is the thermochemical splitting of water into hydrogen and oxygen. There are a large number of thermochemical processes that can produce hydrogen from water, the most promising of which are sulfur-based and include the sulfur-iodine, hybrid sulfur-electrolysis, and sulfur-bromine processes (which operate in the 750 to 1000 C range). The second technology of interest is thermally assisted electrolysis of water. The high-efficiency Brayton cycle enabled by the NGNP may be used to generate the hydrogen from water by electrolysis. The efficiency of this process can be substantially improved by heating the water to high-temperature steam before applying electrolysis.

II. MODELING OF STEAM GENERATOR

A steam generator component model [5] was developed for the HYSYS [6] process code. The following describes the development and verification of the HYSYS steam generator component model.

A combined cycle could be envisioned for the power conversion unit to be coupled to the very high-temperature gas-cooled reactor (VHTR). In Figure 1 the combined cycle configuration consists of a Brayton top cycle coupled to a Rankine bottoming cycle by means of a steam generator. A detailed two phase heat transfer scheme, temperature and pressure drop, and sizing model of a steam generator is not readily available in the HYSYS processes code. Therefore a four region boiling model was developed for implementation into HYSYS.

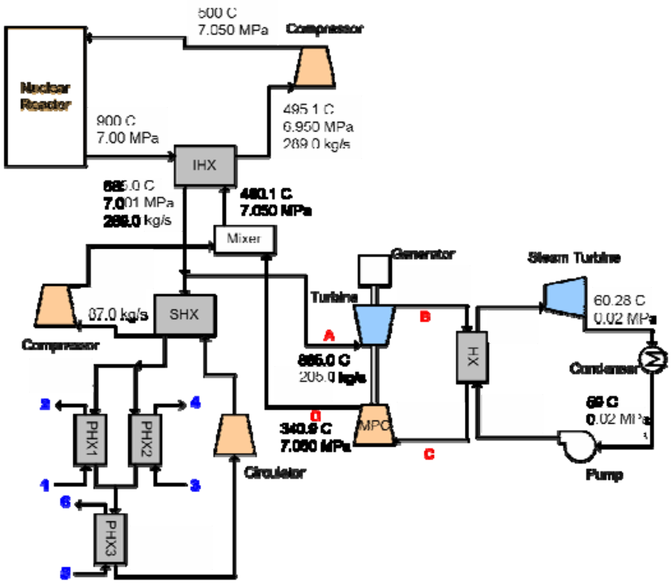

Figure 1. Simplified schematic of the combined cycle configuration.

The steam generator was assumed to be a counter flow shell and tube heat exchanger with the Brayton cycle working fluid (helium) on the shell side and the Rankine cycle working fluid (water) on the tube side. Since the Brayton cycle working pressure, approximately 7 MPa, is lower than that for the Rankine cycle, 15 MPa, the pressure boundary requirements on the shell will be reduced. Because the diameter of the tubes is small, normal tube thicknesses can endure the high pressure. A shell diameter of 4.5 m, an inner and outer diameter of 6 mm and 7.3 mm for the tubes, a pitch to outer diameter ratio of 1.3 and a triangular array were assumed for the steam generator. These values are typical of existing steam generator designs. Alloy 617 was used for the construction material of the steam generator. This material was chosen based on the stress analysis given in Davis et al..[7]

To account for the phase change in the cold side, the steam generator was divided into four heat transfer regions: subcooled, nucleate boiling, post critical heat flux and superheated. The subcooled region begins at the inlet to the steam generator and ends when the water reaches saturation conditions. Here we have neglected subcooled boiling. Since this region is single phase flow, the heat transfer coefficients were calculated using the Dittus-Boelter correlation with a leading coefficient of 0.023 for turbulent flow,[8]

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{1}$$

where

$$Nu = h\frac{D_{hy}}{k}. \tag{2}$$

For laminar flow, the heat transfer coefficients were calculated from the exact solution for fully developed flow with constant heat rate,[9]

$$Nu = 4.364. \tag{3}$$

The pressure drop in the subcooled region was assumed to come from friction losses and was calculated using the following equation:

$$\Delta p = f\frac{L}{D_{hy}}\frac{G^2}{2\rho}, \tag{4}$$

where f is the friction factor, L is the length, D_{hy} is the hydraulic diameter of the channels, ρ is the density, and v is the velocity. The friction factor was determined using a correlation for turbulent and laminar flow. For turbulent flow f was calculated using

$$f = \frac{0.3164}{\mathrm{Re}^{.25}}, \tag{5}$$

and for laminar flow

$$f = \frac{64}{\mathrm{Re}}. \tag{6}$$

The nucleate boiling region begins at the saturation point and ends when the fluid reaches critical quality. The Chen correlation was used in this region to determine the convection heat transfer coefficient. Chen assumes that the total convection coefficient in this region can be thought of as the superposition of the convection and nucleate boiling heat transfer coefficient [10],

$$h_{2\phi} = h_c + h_{NB}. \tag{7}$$

Chen assumed that the convective component, h_c, could be represented by a Dittus-Bolter type equation.

$$h_c = .023\left(\frac{G(1-x)D_{hy}}{\mu_f}\right)^{0.8}\left(\frac{\mu c_p}{k}\right)_f^{0.4}\left(\frac{k_f}{D_{hy}}\right)F, \tag{8}$$

where F is an additional correction factor defined as,

$$F = \left(\frac{\mathrm{Re}_{2\phi}}{\mathrm{Re}_f} \right)^{0.8}. \tag{9}$$

Chen originally determined F empirically; however he later derived F using a Reynolds analogy as follows,

$$F = \left(\phi_f^2 \right)^{0.444}. \tag{10}$$

where ϕ_f^2 is the two phase friction multiplier based on the pressure gradient from fluid alone. Using the Martinelli parameter ϕ_f^2 is defined as,

$$\phi_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2}, \tag{11}$$

where C = 20 for turbulent-turbulent flow. The Martinelli parameter is based on the fluid properties at the saturation point and is defined as,

$$X = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_g}{\rho_f} \right)^{0.5} \left(\frac{\mu_f}{\mu_g} \right)^{0.1}. \tag{12}$$

The nucleate boiling component of the Chen correlation also uses fluid properties at the saturation point and is defined as,

$$h_{NB} = 0.00122 \left[\frac{\left(k^{0.79} c_p^{0.45} \rho^{0.49} \right)_f}{\sigma^{0.5} \mu_f^{0.29} h_{fg}^{0.24} \rho_g^{0.24}} \right] \Delta T_{sat}^{0.24} \Delta p_{sat}^{0.75} S, \tag{13}$$

where S is the suppression factor that takes into account the difference between the wall superheat and the mean superheat in the boundary layer. S can be calculated using Reference 11.

$$S = \frac{1}{1 + 2.53 \times 10^{-6} \left(\mathrm{Re}_f F^{1.25} \right)^{1.17}}. \tag{14}$$

The Chen correlation determines the heat transfer coefficient at a point where the local quality is *x*. In this analysis a value of half the critical quality was chosen to give an average heat transfer coefficient over the entire region.

To determine the length and volume of the nucleate boiling region of the heat exchanger, the critical quality must be known. In order to determine the critical quality an iterative process must be implemented. First an initial guess of the critical quality must be made; in this case 0.75 was used. Using this initial guess the tube side heat transfer coefficient is determined along with the universal heat transfer coefficient. Using the ε-NTU method, the heat transfer area is determined. The effectiveness, ε, of the heat exchanger in this region was calculated using

$$\varepsilon = \frac{q}{q_{\max}} \tag{15}$$

where

$$q_{\max} = C_{\min} (T_{h,i} - T_{c,i}) \tag{16}$$

and C_{min} refers to the smaller of C_{hot} or C_{cold}, where

$$C_{hot} = c_{p,hot} \dot{m}_{hot} \tag{17}$$

$$C_{cold} = c_{p,cold} \dot{m}_{cold} \tag{18}$$

The NTU value was calculated using,

$$NTU = \frac{1}{C_r - 1} \ln \left(\frac{\varepsilon - 1}{\varepsilon C_r - 1} \right) \qquad C_r < 1 \tag{19}$$

$$NTU = \frac{\varepsilon}{1 - \varepsilon} \qquad C_r = 1 \tag{20}$$

where $C_r = C_{min/} C_{max}$.

Next the heat transfer area (A13) and the length were calculated,

$$A = \frac{NTU}{U} C_{\min} \tag{21}$$

$$l = \frac{A}{\pi d_{in} N_t} \tag{22}$$

where d_{in} is the inside diameter of the tubes and N_t is the number of tubes in the heat exchanger. The number of tubes is given by the following formula,

$$N_t = \frac{d_{in,shell}^2 \pi}{4 p^2 \sin\left(\pi/3 \right)}. \tag{23}$$

where $d_{in,shell}$ is the inner diameter of the shell and p is the pitch. The length is then inserted into the CISE-4 correlation and a new critical quality is calculated and reiterated until it converges. The CISE-4 correlation[12] is given as,

$$x_{crit} = \frac{a_{CISE4} l_{crit}}{l_{crit} + b_{CISE4}} \quad (24)$$

$$a_{CISE4} = \frac{1}{1 + 1.481\times10^{-4}\left(1 - \frac{p}{p_c}\right)^{-3} G} \qquad G < G^* \quad (25)$$

$$a_{CISE4} = \frac{1 - \frac{p}{p_c}}{\left(\frac{G}{1000}\right)^{1/3}} \qquad G < G^* \quad (26)$$

$$b_{CISE4} = 0.199\left(\frac{p_c}{p} - 1\right)^{0.4} G * d_{in,tube}^{0.4} \quad (27)$$

$$G^* = 3375\left(1 - \frac{p_c}{p}\right)^3 \quad (28)$$

where p_c is the critical pressure of water.

The pressure drop calculation was obtained by multiplying the pressure drop calculated assuming the total fluid was liquid, Δp_{fo} by a two phase friction multiplier, ϕ_{fo}^2.

$$\Delta p = \Delta p_{fo} \phi_{fo}^2 \quad (29)$$

$$\Delta p = f_{fo} \frac{L}{D_{hy}} \frac{G^2}{2\rho_f} \quad (30)$$

Collier and Thome[10] recommend the Friedel correlation for the two phase friction multiplier for flows where

$$\mu_f / \mu_g < 1000 \cdot$$

The Friedel correlation[10] is given as,

$$\phi_{fo}^2 = A_1 + \frac{3.24 A_2 A_3}{Fr^{0.045} We^{0.035}} \quad (31)$$

where

$$A_1 = (1-x)^2 + x^2\left(\frac{\rho_f f_{go}}{\rho_g f_{fo}}\right) \quad (32)$$

$$A_2 = x^{0.78}(1-x)^{0.224} \quad (33)$$

$$A_3 = \left(\frac{\rho_f}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_f}\right)^{0.19}\left(1 - \frac{\mu_g}{\mu_f}\right)^{.7} \quad (34)$$

$$Fr = \frac{G^2}{gD\bar{\rho}^2} \quad (35)$$

$$We = \frac{G^2 D}{\bar{\rho}\sigma} \quad (36)$$

In the post critical heat flux region, which ranges from dry-out to saturation, the Groeneveld correlation was used. This is a common method used in calculating the heat transfer in the region [11] and is given by the following equation,

(A28)

$$Nu = 0.00109\left\{\mathrm{Re}_g\left[x + \frac{\rho_g}{\rho_f}(1-x)\right]\right\}^{0.989} \mathrm{Pr}_g^{1.41} Y \quad (37)$$

$$Y = \left[1 - 0.1\left(\frac{\rho_f - \rho_g}{\rho_g}\right)^{0.4}(1-x)^{0.4}\right]^{-1.15}. \quad (38)$$

Again an average quality is used to give an average heat transfer coefficient over the region.

The pressure drop calculation in the post critical heat flux region was obtained using the same Friedel correlation that was used in the nucleate boiling region.

For the superheat region the heat transfer becomes single phase and methodology from the single phase region was used to calculate the heat transfer coefficient and the pressure drop. Average properties were used to calculate the heat transfer coefficient and the pressure drop.

On the hot side there is no phase change and Equations 1-3 were used to calculate the heat transfer coefficient and Equations 4-6 were used for the pressure drop.

The overall heat transfer coefficient [13] in each region was calculated as

$$U = \left(1/h_{cold} + d_{out}/2k_{metal} \ln\left(d_{out}/d_{in}\right) + d_{out}/d_{in}h_{hot}\right)^{-1},$$

where h_{hot} is the heat transfer coefficient for the hot channels, h_{cold} is the heat transfer coefficient for the cold channels, k_{metal} is the thermal conductivity of the metal and d_{in} and d_{out} are the inner and outer diameters of the tubes.

III. VERIFICATION

A baseline combined cycle using helium as the Brayton cycle working fluid was modeled in HYSYS. The four regions of the steam generator are modeled as four heat exchangers in HYSYS as seen in Figure 2. The HYSYS model predicted a steam generator volume of 133.9 m^3, length of 11.6 m and an overall heat transfer of 457.3 MW.

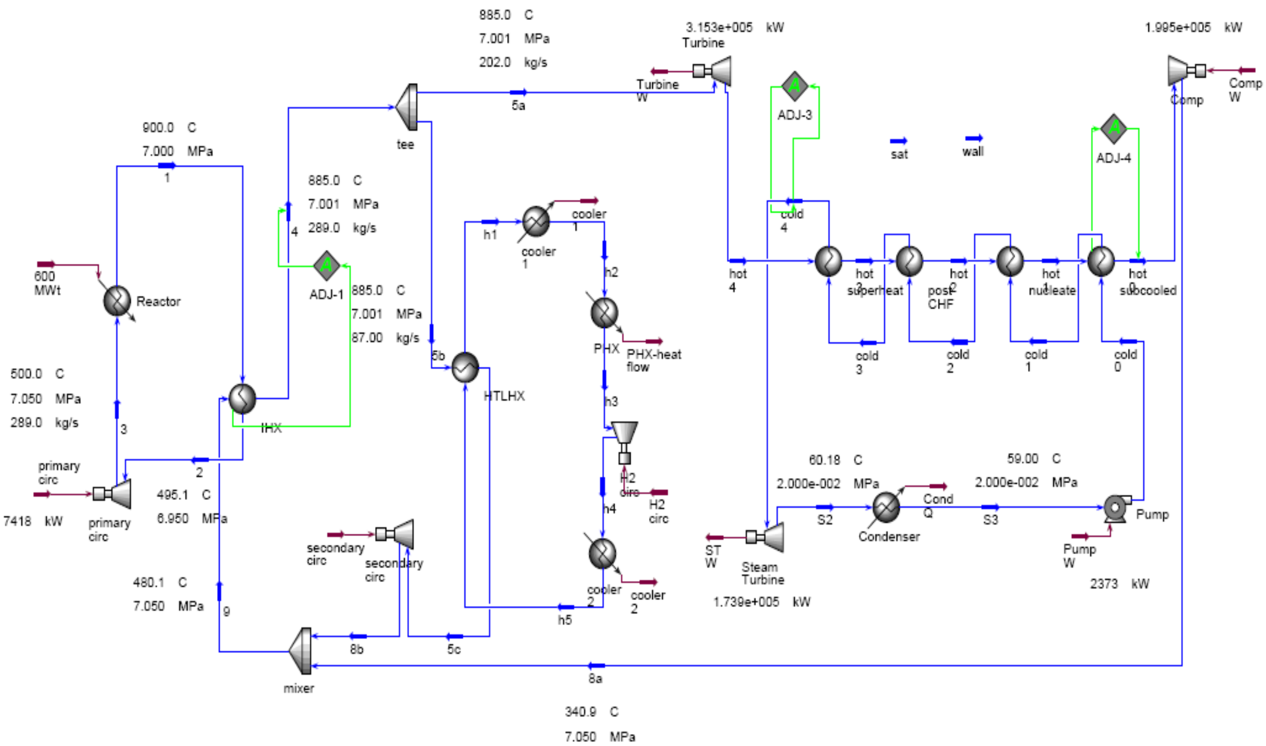

Figure 2. HYSYS model of the combined cycle with a four-region steam generator model.

To verify the HYSYS model, a RELAP5 (INEEL 2005) model of the steam generator was created and is depicted in Figure 3. The steam generator was modeled as a once through shell-in-tube vertical heat exchanger. The water served as the cold-side coolant in the tubes and the helium served as the hot-side fluid in the shell.

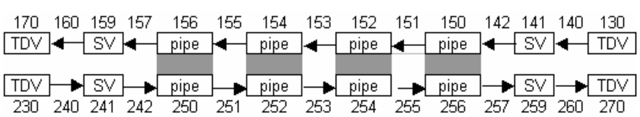

Figure 3. RELAP5 model of the steam generator.

The input parameters of the RELAP5 model were closely matched to that of the HYSYS model and are shown in Table 1. Unfortunately, a small discrepancy between these inputs occurred. The discrepant values are marked by an asterisk. The error was due to a pressure change that occurred as the flow moved from the time-dependent volume (TDV) 230 to the single volume (SV) 241. The input conditions were originally set for 860.65 K and 3.12 MPa, but were altered by RELAP5 because of physical reasons to 862.46 K and 3.1395 MPa. For our purposes and also because of the small magnitude of this discrepancy in temperature and pressure, this error was ignored.

Table 1. Input parameters for the RELAP5 steam generator model.

Input Parameter	**Tubes**	**Shell**
	Cold-side – H20	Hot-side - He
RELAP Volume Number Range	130-170	230-270
Inlet Temperature (K)	332.94	**862.46***
Inlet Pressure (Pa)	1.50E+07	**3.1395E+06***
Mass Flow (kg/s)	140.7	202
Rod Pitch to Diameter Ratio	1	1.3
Heated Diameter (m)	6.00E-03	6.735E-03
Hydraulic Diameter (m)	6.00E-03	6.711E-03
RELAP Geometry Type	101	110
Cross Sectional Area (m^2)	3.697	5.394

The heat exchanger total length was taken from the HYSYS calculation and divided into four pipes as shown in Figure 3 and Table 2. The reason the heat exchanger was divided into four separate pipes was to adjust the pipes for refinement in nodalization of a particular region of flow in the event it would be needed and also to avoid the 99 node limitation per pipe of RELAP5.

Table 2. RELAP5 pipe and node sizes.

PIPE	**No. of Nodes**	**Pipe Length (m)**	**Node Size (m/node)**
150/256	20	3	0.15
152/254	20	3	0.15
154/256	30	3	0.1
146/250	30	2.6021	0.08674

Table 3 summarizes the results of the heat transfer and lengths for the HYSYS and RELAP5 models. The results are graphically summarized in Figures 4 through 6. From Figure 4, it can be seen that the overall heat transfer is in good agreement, with a difference of about 2.1 % between models. The outlet temperatures and temperature drops across the steam generator also show reasonable agreement of less than 5.1% difference as illustrated in Tables 4 and 5.

Table 3. Regime length and heat transfer comparison.

Regions	Length HYSYS (m)	Length RELAP5 (m)	Q HYSYS (MW)	Q RELAP5 (MW)
Single-phase Liquid, Sub Nucleate Boiling	7.955	8.8	210.9	204.84
Saturated Nucleate Boiling	2.505	0.547	117.8	78.38
Post Critical Heat Flux	0.153	1.301	23.2	114.46
Superheated Vapor	0.989	0.954	105.4	50.20
Total	11.602	11.602	457.3	447.87

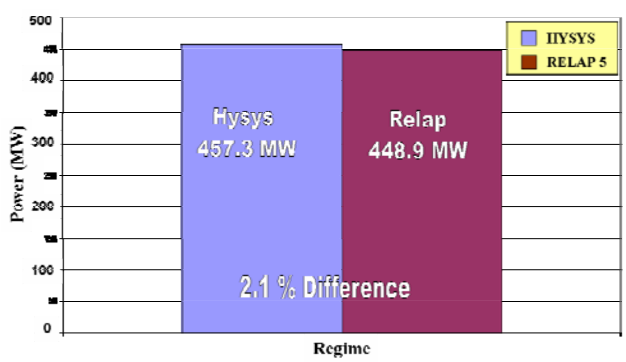

Figure 4. Overall heat transfer comparison.

Table 4. Comparison of outlet temperatures.

	Temperature Outlet of He (K)	Temperature Outlet of H20 (K)
HYSYS	424.65	848.15
RELAP5	441.75	822.87
Difference (°)	17.1	25.28
% Difference	4.0%	3.1%

Table 5. Comparison of temperature drops.

Temperature Drops	Hot-side - He	Cold-side – H20
HYSYS	436	515
RELAP5	420.7	489.92
% Difference	3.6%	5.1%

Larger differences can be seen when examining the individual components of heat transfer and length as shown in Figures 5 and 6. In Figure 5, the heat transfer in the single phase forced convection and sub-cooled nucleate boiling regions show results within fair agreement, less than 3 % difference. The other regions show greater variance. The length comparison in Figure 6 shows a fair agreement in the single-phase forced convection/sub-cooled nucleate boiling and the superheated vapor regions.

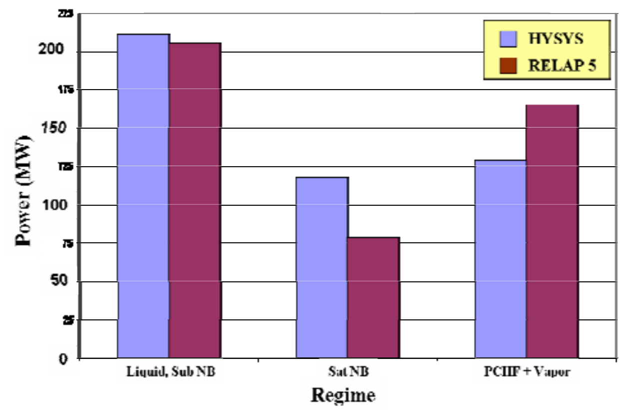

Figure 5. Regime heat transfer comparison.

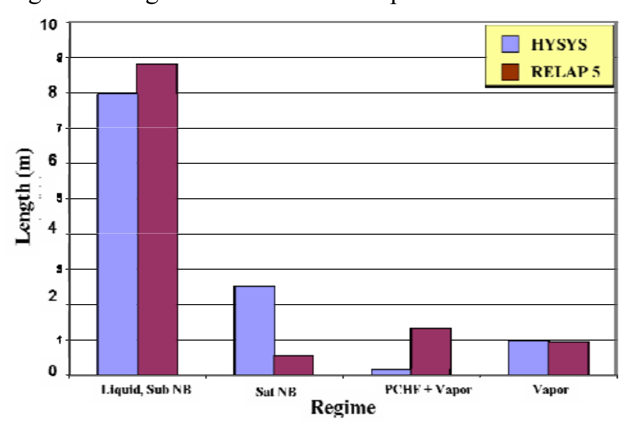

Figure 6. Regime length comparison.

IV. CONCLUSIONS

The verification of the HYSYS model with RELAP5 shows that the HYSYS model produces reasonable results of fluid entry and exit properties and heat exchanger length . Using the length calculated by HYSYS in RELAP5, the heat transfer power difference between the two is about 2.1 %. The outlet temperatures and temperature drops across the steam generator also show reasonable agreement with less than 5.1% difference. The differences seen in the regime lengths is not of a concern for our assessment because the economic analyses utilizes only the total length and surface area of the steam generator geometry.

It is possible that the two models agreed in good fortune at tested conditions with a heat transfer of approximately 450 MW. Therefore, to eliminate this possibility, another case was tested with a total heat transfer of 370 MW. This was performed by increasing the inlet temperature of the cold-side from 60° C to 200°C. The new length calculated by HYSYS was re-inserted into the RELAP5 model and the overall heat transferr comparison differed by less than 2%. These calculations indicate that the four-regime model developed for HYSYS produces reasonable agreement with a much more detailed RELAP5 model and is applicable for our purposes of calculating a total steam generator length and inlet/outlet fluid conditions for cost analyses.

ACKNOWLEDGMENTS

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