A Combined Spiral Tube Steam Generator – Primary Pb Pump Unit Study
for a DEMO LFR

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Abstract – An effort has been initiated in Argonne National Laboratory to develop a preconceptual reactor design for a demo Lead-cooled Fast Reactor. This design incorporates most of the key features, such as, spiral tube steam generator, compact core arrangement, of the European Lead-cooled System (ELSY). The main focus of this work is to systematically study the steam generator, as addressed in a steam generator pump parameter study and a spiral coil tube heat exchanger parameter study. A mathematical model is developed to solve the heat transfer and energy balance equations for the spiral coil tubes in a steam generator, which is then numerically solved. In addition, a study on key parameters, such as, steam generator size, tube length, maximum allowed lead velocity, etc., is also summarized.

I. INTRODUCTION

An effort has been initiated in Argonne National Laboratory to develop a preconceptual reactor design for a demo Lead-cooled Fast Reactor, which incorporates most of the key features of the European Lead-cooled System (ELSY). A combined spiral tube steam generator - primary Pb pump unit used in this demo LFR is a major feature of the ELSY concept, which enables the primary Pb coolant volume to be reduced and reactor vessel exposed to cool Pb only during normal operation conditions. The main purpose of the presented work is to systematically study this combined unit for the demo LFR, including a brief pump study and a detailed model to solve the heat transfer problems for the spiral coil tubes in the steam generator.

II. PUMP STUDY

As shown in Fig. 1, the combined steam generator and primary pump arrangement indicates the choice of an axial flow pump, by which the hot lead flow is driven vertically. At the current preconceptual level of design, the primary pump dimensions and design operating conditions are chosen based on use of a $N_s-D_s$ diagram on which general pump performance information is correlated for different general pump types (e.g., axial versus radial) and operating regime. In an $N_s-D_s$ diagram, the efficiency of a pump and pump/flow type are plotted against specific speed ($N_s$) and specific diameter ($D_s$). The dimensional variables, specific speed and specific diameter are functions of rotor diameter, volume flow rate, adiabatic head, and rotating speed. These two dimensional variables are defined as below,

\[ N_s = \frac{\sqrt[4/3]{V}}{H^{1/4}} \]  
\[ D_s = \frac{DH^{1/4}}{\sqrt{V}} \]
For the demo fast reactor design, the inlet lead volume flow rate can be calculated from lead thermal properties and the single steam generator thermal duty, which in turn is calculated from the reactor thermal power and number of steam generators. The lead volume flow rate for each steam generator can be approximately calculated as,

$$V'_i = \frac{P}{N_{SG} \rho PV}$$

The adiabatic head, $H_{ad}$, is assumed to be equal to the primary loop flow pressure drop. Another two dependent parameters, rotor diameter, $D$, and rotating speed, $N$, can be properly chosen to meet the axial pump type with high pump efficiency. The product of these two parameters, namely twice the maximum rotor blade tip velocity, has to be limited to a certain value due to the lead corrosion to steel structural material at high temperature and high speed. Normally, the maximum allowable lead velocity for steel structures in a lead-cooled fast reactor is of the order of 1 m/s. This value shall be used as a limiting value in the present investigation. However, the maximum allowable lead velocity in a pump may be higher by using advanced material for the rotor. A possible material is Ti$_3$SiC$_2$ (three-one-two). Show in Fig. 2, by plotting the possible Ns-Ds pairs onto the Barber and Nichols Ns-Ds diagram, a rotor diameter of 0.8 m and maximum blade tip velocity of 5–15 m/s, which corresponds rotating speed of 120–360RPM, are selected for current preconceptual design.

III. STEAM GENERATOR STUDY

III.A. Model Description

A steam generator is modeled as layers of identical horizontal spiral tubes bounded by the steam generator inner shell and outer shell, shown in Fig. 3. Both inner and outer shells are perforated cylindrical plates. A hot lead pool with higher surface level forms within the inner shell driven by the pump, shown in Fig. 1. The hot lead flows outward horizontally through the spaces between adjacent tube levels. Several approximations are made to simplify the model. The vertical inlet and outlet tubes, which connect the spiral tubes to feed water and steam collector, are ignored in current model. The lead flow through the gaps between tubes is assumed to be evenly distributed axially and therefore calculation is necessary only for a single tube. The heat transfer from lead to water is then modeled in terms of continuous control volumes, where the heat transfer rate, lead pressure drop, and water pressure drop are calculated. A schematic drawing of a control volume is shown in Fig. 4.

In a control volume, the heat transferred from lead to water can be calculated as,

$$\frac{dQ}{dt} = H_{lead} (T_{lead,in} - T_{water,in})$$

where, the effective heat transfer coefficient, $H$, is given by,

$$\frac{1}{H} = \frac{1}{h_{lead}} + \frac{d}{2k_{lead} \ln \left( \frac{d}{d_t} \right) } + \frac{1}{h_{water}} + \frac{1}{h_{outer}} + \frac{1}{h_{inner}}$$

A convection heat transfer coefficient correlation for liquid metal through tube bundles is suggested to calculate the lead convection heat transfer coefficient to tube outer surface, $h_{lead}$.
uniformly distributed, the tube bundle height with four steam generators is exactly half that with two steam generators. As expected, a taller steam generator has a small diameter because the required single tube length is reduced as the number of tubes increases. However, as the number of tubes increases, the diameter does not decrease significantly. At the maximum allowable lead velocity fixed at 1 m/s, the required tube bundle height is larger than that for a 30 mm pitch because a larger pitch is required for a maximum lead velocity of 1 m/s.

Fig. 6 shows the single tube length results, where the single tube length is plotted against the steam generator height. The single tube length has a similar trend as the steam generator diameter versus steam generator height. A taller steam generator with more tubes requires a smaller single tube. The water pressure loss is approximately a linear function of the single tube length, and therefore a similar trend is observed from the calculation, shown in Fig. 7. The principal quantity of interest is the total tube length of all of the spiral tubes in the all steam generators, which is directly related to the steam generator weight and cost. One approach to optimizing the steam generator dimensions is to choose those dimensions that minimize the total steam generator tube length. The total tube length versus the tube bundle height is shown in Fig. 8. For a demo with two 200 MWt heat duty steam generators, the optimal bundle is 4 m in height and 1.75 m in outer diameter, with a Pb velocity limitation of 1 m/s.

The maximum allowable lead velocity, 1 m/s, 2 m/s and 3 m/s are studied, and the results are shown in Fig. 9–12. In general, a higher allowable lead velocity allows a smaller gap between tube layers with same number of tubes per steam generator, and therefore, a smaller height. However, the height does not change dramatically, since the gap between tube layers is only a small portion of the total steam generator height, Fig. 9. A higher lead velocity also gives a better lead convection heat transfer coefficient, which in turn reduces the tube length of an individual tube required, which results in a correspondingly smaller water pressure loss, Fig. 10 and 11. However, similarly, the tube length does not change significantly at different lead velocities, which is because the heat transfer resistance from lead to the tube outer surface is a smaller part of the total heat resistance, which is a sum of lead to tube convection, tube conduction, crud layer, and water side heat transfer resistances. The results show that about a 10% difference in total tube length is calculated between the 1 m/s and 3 m/s lead velocity cases, Fig. 12.

Both SS316 and T91 are potential materials for fabrication of steam generator tubes for the demo fast reactor design. T91 has a higher stress value and therefore a smaller tube thickness is required. In addition, T91 has a higher thermal conductivity, which enhances energy transfer from hot lead to water. The required tube thickness
is calculated from ASME code for tubes thickness (ASME B31.3-2008). By combining the ASME requirement and potential Pb corrosion, ~40µm used in current study, for tubes with 25.4mm outer diameter, the estimated tube thicknesses are 2.05mm and 1.70mm for SS316 and T91, respectively. Fig. 13~16 shows the comparison of these two materials. A better performance, namely, smaller tube bundles size and more than 10 % smaller single/total tube length, is calculated for a steam generator incorporating T91 tubes.

The feasibility of the steam generator tube bundle arrangement has also been studied by constructing a three-dimensional computer aide design (CAD) model of a steam generator bundle having 84 tubes. At the spiral outer diameter, all of the vertical tubes can be situated in a single row but two rows of vertical tubes are needed at the spiral inner diameter. The vertical tubes are observed not to significantly occlude the Pb radial flow paths at the bundle inner and outer diameters.

IV. CONCLUSIONS

This work mainly describes a spiral tube steam generator – primary Pb pump modular unit, which can be potentially used in the demo fast reactor, to eliminate hot lead washing over the reactor vessel inner surface during normal operation, maintaining natural circulation flow through the core in the event of loss of the main Pb pumps, and minimizing the Pb inventory required thereby minimizing the reactor size and mass. Both the pump and tube parameters were investigated for the purpose of optimizing the preconceptual design of the steam generator-pump module. Only the pump rotor diameter and rotating speed are considered, and further details have to be considered in future design. Type 316 stainless steel and T91 ferritic steel are considered as potential steam generator tubes material at this moment. Parameters studies, including number of steam generators, tube number per steam generator, pitch length, and maximum allowable lead velocity, are presented. Higher lead velocity and using T91 as tube material also require smaller total tube length.
Fig. 8. Total Steam Generator Tube Length for All Tubes in the Bundle versus Tube Bundle Height for Cases of Maximum Pb Velocity of 1 m/s and Maximum Tube Axial Pitch of 30 mm.

Fig. 9. Effect of Maximum Allowable Pb Velocity Upon Tube Bundle Diameter versus Tube Bundle Height.

Fig. 10. Effect of Maximum Allowable Pb Velocity Upon Length of a Single Steam Generator Tube in the Tube Bundle Diameter versus Tube Bundle Height.

Fig. 11. Effect of Maximum Allowable Pb Velocity Upon Water-Side Pressure Drop versus Tube Bundle Height.

Fig. 12. Effect of Maximum Allowable Pb Velocity Upon Total Steam Generator Tube Length for All Tubes in the Bundle versus Tube Bundle Height.

Fig. 13. Effect of Tube Material Upon Tube Bundle Diameter versus Tube Bundle Height.
Fig. 14. Effect of Tube Material upon Length of a Single Steam Generator Tube in the Tube Bundle Diameter versus Tube Bundle Height.

Fig. 15. Effect of Tube Material Upon Water-Side Pressure Drop versus Tube Bundle Height.

Fig. 16. Effect of Tube Material Upon Total Steam Generator Tube Length for All Tubes in the Bundle versus Tube Bundle Height.

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NOMENCLATURE

\( A \) \quad \text{Area}
\( C_p \) \quad \text{Specific heat capacity}
\( d \) \quad \text{Tube diameter}
\( D \) \quad \text{Rotor diameter}
\( D_h \) \quad \text{Hydraulic diameter}
\( dQ/dt \) \quad \text{Heat flux}
\( D_s \) \quad \text{Specific diameter}
\( f \) \quad \text{Friction factor}
\( G \) \quad \text{Mass flux}
\( h_e \) \quad \text{Heat transfer coefficient}
\( H_{ad} \) \quad \text{Pump adiabatic head}
\( h_{lv} \) \quad \text{Latent heat}
\( k \) \quad \text{Thermal conductivity}
\( N_s \) \quad \text{Specific speed}
\( N_{SG} \) \quad \text{Number of steam generators}
\( Nu \) \quad \text{Nusselt number}
\( P \) \quad \text{Reactor power}
\( P \) \quad \text{Pressure}
\( Pr \) \quad \text{Prandtl number}
\( Re \) \quad \text{Reynolds number}
\( T \) \quad \text{Temperature}
\( V_i \) \quad \text{Pump inlet volume flow rate}
\( x \) \quad \text{Mass vapor quality}
\( X_{\Pi} \) \quad \text{Martinelli parameter}
\( Y_w \) \quad \text{Parameter used in equation (11)}
\( Z \) \quad \text{Parameter used in equation (12)}

Greek Symbols

\( \alpha_d \) \quad \text{Void fraction}
\( \mu \) \quad \text{Viscosity}
\( \rho \) \quad \text{Density}
\( \sigma \) \quad \text{Surface tension}

Subscript

\( FC \) \quad \text{Forced convection}
\( i \) \quad \text{i.d., inlet}
\( l \) \quad \text{Liquid}
\( NB \) \quad \text{Nucleate boiling}
\( o \) \quad \text{o.d., outlet}
\( Pb \) \quad \text{Lead}
\( sat \) \quad \text{Saturation}
\( TP \) \quad \text{Two phase}
\( v \) \quad \text{Vapor}
\( w \) \quad \text{Water}

REFERENCES


