Thermohydraulic Analysis of the Z-Pinch Power Plant Primary Cycle

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Abstract— In this paper, we investigate the thermohydraulic characteristics of the Z-Pinch Power Plant (ZIFE) primary cycle. The generation of electric energy using a power cycle is possible only if a minimum operating temperature is achieved and maintained in the primary cycle. Many energy losses are associated with the operation of the primary cycle. These thermal and pressure losses have a direct impact on the development of the Concentrated Thermal Energy Source (CTES) temperature profile. It also affects the component performance and the net electric energy generation. The effect of some important thermal and pressure losses is evaluated and their impact on the CTES temperature profile is estimated. The energy losses are grouped and presented as a percent of the total energy input. The temperature profile is modeled using two different approaches. The results of these models are used to determine the time needed to reach steady state conditions. The major components of the primary cycle are: the CTES, the main heat exchanger (MHX), and the piping system. Lithium is a required component of the liquid wall for breeding the tritium fuel required to sustain the process. In this study Flibe is selected to serve as the heat transport media. Flibe is a 2:1 mixture of the salts lithium fluoride (LiF) and beryllium fluoride (BeF$_2$). Thermodynamic analyses were performed for each component. The outcome of the two models can be used as two limiting cases to establish the correct time to start the energy generation. These preliminary results serve as the basis for future research toward the development of a general thermohydraulic model of the ZIFE power plant.

I. INTRODUCTION

Projected shortages on the energy generation in the United States, accompanied by high prices of fuels, serve as a great incentive to promote alternate efficient energy generation systems. Many alternatives have been proposed to meet the growing energy demand. Among other factors that play an important role in the selection of the best alternatives for future power generation are: economical competitiveness, safety, waste minimization, nonproliferation, societal impact, and environmental problems related to plant operation and decommissioning. The Z-Pinch power plant (ZIFE) delivers electric energy in the range of commercial nuclear plants but without generating the type and quantities of waste produced by other technologies. The ZIFE concept is a member of the Inertially-confined Fusion Energy (IFE) research programs. IFE concepts use the energy from discrete capsules containing fusion material ignited by lasers or X-rays and contain the energy release within physical walls, either liquid or solid. The ZIFE is the first concept to use the results at Sandia National Laboratories’ Z accelerator in a power plant application. Assuming high yield fusion pulses of 3 – 5 gigajoules per shot at a rate of 0.1 to 0.3 Hz, a unique shock and energy absorbing system is being considered to contain and utilize the released energy. The absorbed fusion energy is then utilized to drive a power cycle to produce electrical energy. The total electrical power output of the ZIFE plant considered is 1 GWe. The high temperatures developed in the primary cycle make it suitable to provide a heat source for high efficiency hydrogen generation plants [1].

II. CONCENTRATED THERMAL ENERGY SOURCE (CTES)

A schematic of the CTES energy balance is shown in Figure 1.

![Figure 1 CTES Energy Balance](image)

Figure 1  CTES Energy Balance

In simplifying the problem, the following assumptions were made: the fluid is perfectly mixed, the energy shot is instantly and uniformly distributed throughout the control volume, flow is one dimensional and uniform, friction effects are negligible, there is no work or heat interaction, the specific heat remains constant, there is quasi-equilibrium in the system, and there are negligible changes in kinetic and potential energy [2].

The application of the energy balance principle to the system shown above leads to equation (1). The integration is carried out from $T(t)$ to $T(t + \delta t)$ for the temperature and from $t$ to $t + \delta t$ for time. The energy release during a detonation is the only source of energy input considered in the analysis. The flow work is assumed to be negligible.

$$mc \frac{dT}{dt} = rQ_s + mcT_i - mcT - U(T - T_m) - Q_L \quad (1)$$

where:

- $T$ is the temperature (K)
- $t$ is the time (s)
\( m \) is the mass in the system (kg)
\( c \) is the specific heat (kJ/kg-K)
\( r \) is the energy input selection factor
\( Q_{\text{i}} \) is the heat input (kJ)
\( m \) is the mass flow rate (kg/s)
\( T_i \) is the initial temperature (K)
\( U \) is the heat transfer factor (kW/s.K)
\( T_\infty \) is the ambient temperature (K)
\( \delta t \) is the time interval between shot
\( LQ \) represents other thermal losses (kW)

\[
\begin{align*}
  r &= \begin{cases} 
    1 & \text{if } t_{ci} = 0 \\ 
    0 & \text{Otherwise} 
  \end{cases} \\
  t_{ci} &= \text{Mod} \left( \frac{t}{\delta t} \right) \\
  \delta t &= 10 \text{ s}
\end{align*}
\]

The solution for Equation 1 is presented in Equation 4, which is referenced as “Model 1” in this paper.

\[
T(t + \delta t) = \frac{b}{a} \left[ \frac{b}{a} - T(t) \right] e^{-\frac{a}{mc} t} 
\]

where:

\[
\begin{align*}
  &a = -\frac{mc + U}{mc} \\
  &b = \frac{1}{mc} \left( -r Q_{\text{i}} + m c T_i + U T_\infty + Q_{\text{i}} \right)
\end{align*}
\]

Equations 4, 5, and 6 describe the temperature profile of the CTES from initial temperature \( T_i \) to operating conditions. The transient and steady state conditions are both included. The transition from transient to steady is achieved when changes are less than 1% in magnitude of consecutive calculations. This steady state temperature is primarily a function of the initial temperature and mass flow rate, which is determined by specifying the temperature drop in the main heat exchanger (HX). This is the heat exchanger that couples the primary and secondary cycles. It is assumed that the fluid circulates through the heat exchanger since the beginning of CTES operation. Some heat flows through the heat exchanger during the transient heat up. This produces a retarding effect to obtain steady state conditions. This energy is considered a part of the thermal loss since no power is generated during this period. Nonetheless, this energy loss can be viewed as the required energy to gradually warm the piping and other components.

This temperature profile can be used as a general or average description of the thermal processes that take place in the CTES. It does not intend to provide details of the numerous (most of them not very well understood) heat interactions that occur before, during, and after a detonation.

The effect of the detonation on the thermodynamic and transport properties of the fluid could lead to change in magnitude of the heat transfer and flow rate estimation. The accurate determination of the temperature distribution in the CTES represents one of the major analytical and experimental challenges for the ZIFE thermal modeling. Many thermal processes take place in the CTES. Some of them are not very well suited for an analytical approach. The temperature distribution will be influenced by other factors such as the energy shot penetration and distribution, profile of the energy absorbed by the fluid curtain, the irreversibilities developed by abrupt heat transfer processes, local temperature gradients, heat losses through the walls, and changes in physical and chemical properties in part of the fluid (such as plasma formation and dissociation). As the time passes, new perspectives on the analysis of the CTES processes are being developed. A more comprehensive understanding of the dynamic behavior of the system could lead to substantial changes on the magnitude and shape of the present temperature estimates.

Figure 2 shows how the CTES operating temperature decreases as the heat loss increases from 0 to 15% of the total energy input. The steady state temperature for a heat loss of 15% is approximately 927 K. A heat loss greater than 15% could compromise the efficient operation of the power cycle. In addition, the maximum temperature drop in the heat exchanger will be reduced, resulting in a need for and increased mass flow rate through the heat exchanger. This will also increase the pressure losses. Heat losses through the CTES wall alone may account for up to 5% of the total energy input if the system is not well insulated. The selection of the CTES size has a direct impact on the time needed to reach operating conditions. When the diameter of the chamber is increased from 6 to 10 meters, the time to reach steady state conditions increases from 500 to 2200 seconds (50 to 220 shots). The time to reach the steady state temperature is a cubic function of the diameter.

Figure 3 shows the CTES temperature distribution as a function of time for different temperature drops in the heat exchanger. It is important to notice that, for a temperature drop of a 100 K, the operating temperature is about 900 K. This is
probably the lowest limit of operation if the operating pressure is maintained at 15 MPa. In this case, higher temperatures are required for a safe and efficient operation of the power cycle. At lower temperatures, the humidity content at the turbine exit is frequently above the design limit. This also makes the part-load operation of the plant impractical.

Another way to model this system is by separating the unsteady state process from the steady state one. In this case, the unsteady state process will describe the heating up of the Flibe from the initial condition (800 K) to the operating condition (950 K). During this process the fluid is circulated through the system to maintain the chamber curtain but no heat is extracted from the system for power generation purposes. The time to reach steady state depends on the amount of thermal energy used to gradually increase the temperature of the pipe and the heat losses to the environment (these are not considered here). This is Model 2, which is represented by Equation 7.

\[ mc \frac{dT}{dt} = r Q_{in} \]  

(7)

Integrating between temperature limits \( T(t) \) and \( T(t + \delta t) \) and time from \( t \) to \( t + \delta t \), the temperature profile is obtained from the following expression.

\[ T(t + \delta t) = T(t) + \frac{r Q_{in} \delta t}{mc} \]  

(8)

Once the system reaches the steady state temperature, the power cycle starts operation. This temperature will remain essentially constant (with minor fluctuations) since the power cycle is designed to use thermal energy at the same rate as the energy is input in the CTES. The minimum time required to start generating energy through the power cycle after the CTES starts operation is between 320 and 1100 seconds (32 and 110 energy shots). This approach seems to be a more accurate representation of reality [3]. A comparison of the temperature profile from Models 1 and 2 is presented in Figure 4.

III. PUMPING POWER

The layout of the pumping system is shown in Figure 5. Two major pumps are needed to circulate the fluid through the system. One is used to feed continuously the curtain reservoir. The second pump circulates part of the fluid through the power cycle. The proposed chamber is spherical with 4 m internal radius. The effective curtain thickness is 0.65 m and should be located at least two meters from the target. The corresponding volumetric flow rate is 3.56 m³/s. The curtain should be in place right before the detonation occurs.

It takes about two seconds for the fluid to travel the curtain length. If the fluid curtain is maintained for a longer period of time for safety reasons, the volumetric flow rate need to be
increased accordingly. The properties used for Flibe are calculated from the Zinkle’s model: density equal 1912 kg/m$^3$ and dynamic viscosity equal 5.31x10$^{-4}$ kg/s-m$^2$ [4]. The pumping power ranges from 0.65 to 0.85 MWe, depending on the height of the feeding reservoir, the type of pipe used, the height of the bottom pool, and the efficiency of the selected pump. To keep a good safety margin, 1 MWe should be reserved for this process. The second pump is used to circulate the fluid though the main heat exchanger. In this case, the required pumping power is principally determined by the pipe friction and the heat exchanger pressure losses.

IV. HEAT EXCHANGER

Due to the large flow rates, a shell and tube heat exchanger was selected for this application. The purpose of this heat exchanger is to transfer thermal energy from Flibe to water. For the present work, it is modeled as a single component. In practice, the heat exchanger consists of many sections ordered in an array with three different functions. In the first section, liquid water is heated to a point close to the saturation temperature for the given pressure. In the second section, the water is converted to vapor. Finally, in the third section, the vapor is superheated up to the turbine operating temperature. The main objective of this design is to evaluate some important parameters of the flow and its interaction with the solid structure. Since this is the only point of contact between the primary and secondary cycle, the performance will have a direct impact on both cycles.

Among the most important design parameters for the heat exchanger are: the inlet and outlet pressure and temperature of both fluid, thermodynamic and transport properties, flow arrangement, heat exchanger material, numbers of passes, number of shells, and surface area needed for the exchange of heat. For this application, each shell contains passes that are multiples of four. The material is stainless steel, baffle pitch is 15, tube pitch is triangular, tube outer diameter is 3”, tube pass per shell equals 10 and the fouling factors are 0.0018 and 0.0005 for the tube and shell side, respectively. The results of the calculations indicate that an area of 810 m$^2$ is needed to transfer an amount of heat of 340 MW, with an effectiveness of 85% [5, 6].

V. MATERIALS

Material availability, compatibility, and cost for nuclear high-temperature applications (over 800°C) seem to be one of the greatest challenges on the development of highly efficient power generation systems with fusion energy. In addition to the evaluation of the material thermo-mechanical properties, special attention needs to be placed on the corrosion and activation problems. New materials are being developed to meet new design requirements for severe operating conditions. Materials such as metals, superalloys, and ceramics comprise the principal focus of research interest due to their stability and performance at high temperature. The selection of materials for developing the CTES and advanced high temperature heat exchangers will depend on the ability of prospective materials to meet design and service requirements, and to be fabricated and assembled according to design and performance specifications. The capability of the selected material to meet these requirements is determined by its mechanical, physical, and corrosion properties as well as its susceptibility to forming, shaping, and bonding by feasible means. The high-temperature ferritic steels (particularly oxide-dispersion ferritic steels) offer good performance under fusion and fission neutron irradiation, to temperatures around 750°C. The value of the selected material depends on its compatibility with molten salts for the fusion application. The advanced carbon and silicon carbide composites have excellent mechanical strength to temperatures exceeding 1000°C. Many options are available that trade fabrication flexibility and cost, neutron irradiation performance, and coolant compatibility. They are potential candidates for application with helium and molten salt coolants [7, 8].

VI. CONCLUSIONS

The outcome of the two models developed for the CTES temperature distribution can be used as two limiting cases to establish the correct time to start the energy generation. A correct selection of the CTES initial temperature and the HX temperature drop are essential to ensure an appropriate operation of the power cycle.

VII. REFERENCES