The Impact of Separation Distance between Reactor and Process on the Choice of Secondary Heat Transport Coolant for High Temperature Process Heat Applications

Corresponding author – Fax: +27 18 297 0318
Email: bdt@mtechindustrial.com

J. van Ravenswaay, M-Tech Industrial (Pty) Ltd, 5 Luke Street, Potchefstroom, South Africa.


ABSTRACT

Due to the capability of reaching reactor temperatures in excess of 900°C, the Pebble Bed Modular Reactor is well suited for providing high temperature heat to a number of process heat applications. These processes include both current commercialized industries such as steam methane reforming, but also future possibilities such as thermo-chemical water-splitting for producing hydrogen. Regardless of which high temperature process is coupled to the reactor, the successful coupling of the reactor to the process is dependent on the capability of transporting the heat to the process, economically, safely, reliably and within regulatory and licensing requirements. Key components in the secondary heat transport system (SHTS) include the intermediate heat-exchanger (IHX), long distance ducting, blower/pump, valves, other secondary pipeline components and the process coupling heat-exchanger (PCHX).

Integral to the design of all these components is the choice of secondary heat transport fluid. Thus far, three categories of fluids have been considered for application in the SHTS of a high temperature process heat application, being Helium, liquid salts and liquid metals. The choice of coolant is not only influenced by the fluid physical properties, but also various other aspects such as the melting and boiling temperatures, transient events such as start-up and loss of secondary coolant, material compatibility and research and development requirements etc. First of all, this paper introduces the reader to the different categories of liquid salts and liquid metals. The best candidate within each of these categories of fluids has been selected based on economics, maturity of development, as well as melting and boiling temperatures. A thermo hydraulic comparison between these two fluids and Helium is performed based on pipeline performance at various separation distances, heat transfer performance within the IHX and PCHX, as well as some other operational issues.

INTRODUCTION

The PBMR Process Heat Plant (PHP) project aims at ultimately using the Pebble Bed Modular Reactor (PBMR), under development in South Africa, to provide clean and cost-effective heat to industry processes. This opportunity exists due to the high core exit temperatures realized through the Pebble Bed technology, as well as the inherent safety of the reactor and the modular size, making it feasible to co-locate the reactor with the process plant. Whereas the reactor and its supporting systems are in a mature phase of design and development, the concept of the reactor as a generic heat source and, consequently, the coupling between the reactor and the process, are still in the early developmental stages.

A major technical challenge facing the design of a PHP coupled to any process is the economic, safe and reliable transport of high temperature heat from the primary circuit to the process. A subdivision of this requirement is the choice of secondary heat transport coolant. In this paper, the reader is introduced to the most promising classes of fluids for performing this functionality, as determined through a literature review.

Following the discussion of the different categories of fluids, the author reports on the analysis methodology and subsequently also on the results of a study which was aimed at comparing the steady-state thermodynamic performance of the different classes of fluids at a fixed separation distance between the primary circuit and the process. Whereas the comparison of thermodynamic performance of the fluids is mainly concerned with the pipelines between IHX and PCHX, a subsequent section looks at the relative performance of the fluids within a heat-exchanger.

Besides all the thermodynamic aspects, there are some very important additional factors on the choice of coolant such as operational issues, safety concerns, material...
compatibility and maturity of development of the fluid. These aspects are covered after the heat transfer discussion. The final section of this work compares the thermodynamic performance of the fluids as function of separation distance. As will be shown, the separation distance plays an important role in deciding on the coolant of preference.

**ABBREVIATIONS AND ACRONYMS**

PCHX Process coupling heat-exchanger  
PHP Process heat plant  
IHX Intermediate heat-exchanger  
SHTS Secondary heat transport system  
ORNL Oak Ridge National Laboratory  
LS Liquid salt  
LM Liquid metal

**NOMENCLATURE**

**English Variables**

- \( A \): Area  
- \( c_p \): Specific heat capacity  
- \( C_{\text{capital}} \): Capital cost  
- \( C_{\text{operational}} \): Operational cost  
- \( C_{\text{total}} \): Total cost  
- \( D_h \): Hydraulic diameter  
- \( E_{\text{losses}} \): Total energy losses  
- \( E_{\text{opt}} \): Optimization function  
- \( E_{\text{pump}} \): Pumping power requirement  
- \( k \): Thermal conductivity  
- \( L \): Pipe length  
- \( m \): Mass flow rate  
- \( Nu \): Nusselt number  
- \( Pr \): Prandtl number  
- \( P \): Power  
- \( PR \): Pressure Ratio  
- \( \dot{Q} \): Heat transfer rate/Volumetric flow rate  
- \( R \): Gas constant  
- \( Ra \): Raleigh number  
- \( Re \): Reynolds number  
- \( T \): Temperature  
- \( U \): Overall heat transfer coefficient  
- \( V \): Fluid Velocity

**Greek Variables**

- \( \Delta T_{\text{lm}} \): Logarithmic mean temperature difference  
- \( \Delta p \): Pressure difference  
- \( \varepsilon \): Surface emmisivity  
- \( \gamma \): Gas ratio of specific heats  
- \( \lambda \): Convection heat transfer coefficient  
- \( \rho \): Density  
- \( \mu \): Viscosity  
- \( \sigma \): Stefan Boltzman constant

**Subscripts**

- \( o \): Outer wall of pipe  
- \( w \): Wall of pipe  
- \( a \): Ambient  
- \( LS \): Liquid salt  
- \( LM \): Liquid metal  
- \( He \): Helium  
- \( rad \): Radiation

**CATEGORIES OF FLUIDS**

The three categories of fluids considered mostly in literature for application as SHTS fluid, are gases, liquid salts and liquid metals. The gas category includes fluids such as Helium, Carbon Dioxide, Nitrogen and Air. Perret [1] compared gases based on their thermophysical properties as well as required relative pumping power with equal heat-exchange surfaces. The best candidate gas was found to be Helium. Helium is also widely accepted as the best reactor coolant candidate, due to its superior thermophysical properties and its chemical inertness. The development of reactor systems with Helium as coolant created significant experience with using the gas in thermal-fluid applications.

When considering both liquid salts and liquid metals, a limiting factor is the fluid melting and/or boiling temperature. A too high melting temperature prohibits the fluid from being used at low return temperatures, while a too low boiling temperature renders some fluids inadequate on account of the required process temperatures.

Liquid salt work done in the past was mainly concerned with using the fluid as primary reactor coolant. Programmes such as the Aircraft Reactor Experiment, the Molten Salt Reactor Experiment and the Advanced High Temperature Reactor concept are good examples. With respect to liquid salt, the main focus is the primary reactor loop, which means that the liquid salt must be compatible with the nuclear processes in the core. This limits the choices of salts that can be used. A recent assessment of candidate liquid salt primary coolants is provided in [2].

For non-nuclear environments, such as the SHTS, there is more flexibility in the selection of salts. For such applications, cost is the most important distinguishing attribute amongst salts that are otherwise compatible with operating requirements (e.g., melting point). On this basis, beryllium salts are not likely to be found attractive, despite the low melting points of some mixtures since they are very expensive. There is also a significant toxicity issue with beryllium salts. Beryllium salts tend to have high viscosity, which increases as the relative fraction of beryllium increases. However, this is a significant factor only at levels which nuclear designers like to consider. The 57-43 Na:Be mole ratio for NaF-BeF\(_2\) (melting point = 350°C) has quite reasonable properties. Overall, a NaF-BeF\(_2\) or LiF-NaF-BeF\(_2\) would be very suitable for heat transfer, but not economic or practical.

Chloride salts are potentially inexpensive and have low melting points. The LiCl-KCl eutectic, which would be the leading candidate among chlorine-based salt mixtures, melts
at about 350°C. There is not the same type of extensive database on corrosion of high-temperature alloys in loops for chlorides as there is for fluorides. However, the thermodynamic properties of chloride salts in contact with metallic alloys are not as favorable as fluoride salts.

For SHTS applications where the melting point is not constraining, Flinak (LiF-NaF-KF, melting point = 454°C) is a well characterized, inexpensive mixture with excellent heat transport properties.

For purposes of further comparison in this study, the properties of Flinak will be used as representative of the liquid salt category, as shown below in Table 1 [2]:

Table 1: Properties of LiF-NaF-KF (Flinak) at 700 °C

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point [°C]</td>
<td>454</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>2020</td>
</tr>
<tr>
<td>Specific heat capacity [kJ/kg/K]</td>
<td>1.886</td>
</tr>
<tr>
<td>Viscosity [Ns/m²]</td>
<td>0.0029</td>
</tr>
<tr>
<td>Thermal conductivity [W/m/K]</td>
<td>0.92</td>
</tr>
</tbody>
</table>

There is limited data available in open literature regarding the use of liquid metals as heat transfer fluid. A serious concern regarding the lead-based metals is corrosion issues when used with metallic boundaries at such elevated temperatures.

Some common liquid metals with their respective melting and boiling temperatures are presented in Table 2:

Table 2: Melting and boiling temperatures of some selected liquid metals

<table>
<thead>
<tr>
<th>Liquid metal</th>
<th>Melting Point [°C]</th>
<th>Boiling Point [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bismuth</td>
<td>271</td>
<td>1450</td>
</tr>
<tr>
<td>Lead</td>
<td>327.5</td>
<td>1620</td>
</tr>
<tr>
<td>Lead-Bismuth (44.5%-55.5%)</td>
<td>123.5</td>
<td>1670</td>
</tr>
<tr>
<td>Sodium</td>
<td>97.5</td>
<td>880</td>
</tr>
<tr>
<td>Potassium</td>
<td>62.3</td>
<td>760</td>
</tr>
<tr>
<td>Lithium</td>
<td>186</td>
<td>1336</td>
</tr>
</tbody>
</table>

Bismuth will be chosen as representative of the liquid metals category because it is very similar in characteristics to both lead and the lead-bismuth alloys. Additionally, at the time of this study, it had the most reliable and comprehensive properties table. Sodium and Potassium are incapable of reaching the required upper temperatures. The properties of Bismuth at 760 °C are presented in Table 3 [3]:

Table 3: Properties of Bismuth at 760 °C

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>9467</td>
</tr>
<tr>
<td>Specific heat capacity [kJ/kg/K]</td>
<td>0.1645</td>
</tr>
<tr>
<td>Viscosity [Ns/m²]</td>
<td>0.00079</td>
</tr>
<tr>
<td>Thermal conductivity [W/m/K]</td>
<td>15.6</td>
</tr>
</tbody>
</table>

COMPARISON OF PIPELINE PERFORMANCE AT SEPARATION DISTANCE OF 100 METRES

The thermodynamically ideal heat transfer medium would be one with the following features:

- High heat transfer coefficients leading to smaller heat exchangers.
- High density and high specific heat to lower the pumping power requirement, which is directly influenced by the mass flow rate and to decrease the size of the piping.
- Lower operating pressures in order to reduce pipe wall thicknesses.

In order to compare the categories of fluids with regards to steady-state thermodynamic performance, a representative process application was chosen. In this section only the process feed pipeline and the process return pipeline will be considered. The base case assumes that the process is separated by a distance of 100 [m] from the primary circuit. A schematic illustration of the configuration of the SHTS for this particular application is presented in Figure 1:

Figure 1: A schematic illustration of the components in the SHTS.

The boundary conditions applicable to the SHTS are determined from the requirements of the process as well as the primary circuit design. These are given in Table 4:

Table 4: SHTS boundary conditions

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHTS feed pipe inlet temperature [°C]</td>
<td>900</td>
</tr>
<tr>
<td>SHTS return pipe inlet temperature [°C]</td>
<td>577</td>
</tr>
<tr>
<td>IHX Heat duty [MWth]</td>
<td>287</td>
</tr>
<tr>
<td>PCHX percentage pressure drop [%]</td>
<td>3.3</td>
</tr>
<tr>
<td>Pipeline distance [m]</td>
<td>100</td>
</tr>
</tbody>
</table>

The design of the pipeline presents a challenge due to both material limitations and economics. The elevated pressures and temperatures are beyond the creep limit of ordinary metallics, necessitating the use of advanced, expensive materials. One solution that would ease the demand on the pressure boundary material is the use of internal insulation systems. By using internal pipeline insulation, the temperature of the pressure boundary is decreased, allowing for higher permissible wall stresses. Unfortunately, the required insulation thickness to achieve a specified pressure boundary temperature increases as the heat sink at the outer surface of the pipeline decreases. Higher heat losses in turn are detrimental to process efficiency and economics.

Internal insulation systems can only be used in conjunction with gases as the working fluid, which is a big advantage when using Helium as SHTS fluid. In this study the Helium
pipeline design is based on internal insulation, whereas the liquid salt and liquid metal categories use external insulation. In the case of Helium, the pressure in the SHTS loop was fixed at 9 [MPa] at the exit of the IHX. In the case of the liquid fluids, i.e. Flinak and Bismuth, there is more freedom of choice with regards to the design pressure. It was, however, decided to also fix the pressure at the exit of the IHX at 9 [MPa] for these fluids, since it is expected that the IHX will need to be pressure balanced to a fair degree in order to reduce the stresses in this component. Note that the high pressure will only affect the heat losses to some extent, but not the pumping power requirement.

A model was created to calculate pipe wall thickness, pressure loss, heat loss, temperature drop and average fluid velocity as function of the allowable pipe wall stresses, pipe boundary inputs, pipe diameter and distance between IHX and PCHX. The model included for convection heat transfer at the inside and outside surface of the pipe, conduction through the pipe wall and insulation as well as radiation from the outer surface of the pipe.

The pipe roughness, total secondary loss factor and the surface emmisivity of the outer wall of the pipe were all fixed and kept similar between the models representing the different fluids. Furthermore also take note that, in the absence of adequate costing formulas, the insulation thicknesses were not optimized for in this work. A constant insulation thickness for all cases was therefore used.

The convection at the inner pipe wall was modeled using the well-known Dittus-Boelter correlation [3]:

$$ Nu = 0.023Re^{0.8}Pr^{0.3} $$

(1)

Free convection occurring at the outside of the pipes is modeled with the following correlation from Churchill and Chu [4]:

$$ Nu = \left[0.6 + \frac{0.387Ra^{1/6}}{1 + 0.559/Pr^{9/16}}\right]^{2} $$

(2)

Radiation heat-exchange with the atmosphere was found to contribute substantially to the overall heat losses. The radiation heat-exchange is accounted for by Eq. (3) [3]:

$$ Q_{rad} = \varepsilon \sigma \left(\pi D_{o} L\right) \left(T_{w}^{4} - T_{a}^{4}\right) $$

(3)

The first step in the analysis was to determine the optimum process feed pipeline diameter as well as process return pipeline diameter for each of the three fluids. Ideally, the optimum pipe diameter for each application should be determined by minimizing costing formulas of the form:

$$ C_{total} = C_{Capital} + C_{Operational} $$

(4)

The capital cost would be dependent on the quality and quantity of piping and insulation material as well as additional major costs such as the heat tracers and central storage and draining system in the case of the liquid salts. In the case of Helium, the cost of the inventory system should be considered. The operational costs are evaluated in terms of pumping requirement and heat loss, maintenance costs etc.

At this point in time, the capital cost function is unknown. It was therefore decided to optimize pipe diameters on pumping requirement and heat loss. The weight of the pumping requirement to that of heat loss was set at 2:1 in the optimization function. Using a constant pumping efficiency of 70 percent, the optimum diameter could be calculated, as shown below in Eq (5):

$$ E_{opt} = E_{losses} + 2 \left(\frac{E_{pump}}{0.7}\right) $$

(5)

Using the correlations shown above for the heat transfer rates combined with the supplied input data and boundary conditions, an optimization routine was performed on the model to determine optimum diameters according to Eq. (5).

For Helium, a graphical representation of the resulting optimization function as function of pipe inner diameter is shown in Figure 2:

![Figure 2: Optimization function for Helium at a distance of 100 [m] as function of diameter](image)

In the case of LS, the resulting optimization function is as shown in Figure 3:

![Figure 3: Optimization function for LS at a distance of 100 [m] as function of diameter](image)

In the case of LM, the resulting optimization function is as shown in Figure 4:
As is evident from the figures shown, Helium is mainly controlled by the pumping requirement term in Eq. (5) up to large values for heat losses, i.e., large pipe diameters. In contrast, the liquids category requires much less energy to circulate over the separation distance. In effect, the heat losses to the surroundings is then able to impact the optimum energy function significantly at much lower values for heat loss.

The optimal pipeline diameter ratio at 100 [m] separation distance is displayed in Table 5 (Helium is used as reference):

<table>
<thead>
<tr>
<th>Process Line</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium process feed line</td>
<td>1.00</td>
</tr>
<tr>
<td>Helium process return line</td>
<td>1.00</td>
</tr>
<tr>
<td>LS process feed line</td>
<td>0.20</td>
</tr>
<tr>
<td>LS process return line</td>
<td>0.20</td>
</tr>
<tr>
<td>LM process feed line</td>
<td>0.40</td>
</tr>
<tr>
<td>LM process return line</td>
<td>0.41</td>
</tr>
</tbody>
</table>

A comparison of the thermodynamic performance between the three categories of fluids can be done by back substituting the diameters in Table 5 into the relevant models, and then calculating the applicable performance parameters. Table 6 compares the three classes of fluids with respect to pumping power requirement, heat losses to surroundings as well as required pipe wall thickness. Again, results are displayed in terms of ratios with Helium used as reference.
The hydraulic diameter of a compact type heat-exchanger are very small. Liquid salt and liquid metal type compact heat-exchangers have only recently received some attention. Although one might be able to decrease the hydraulic diameter of the flow channels on the liquid salt/metal side (and therefore enhance the convection coefficient), a major concern with using this type of heat-exchangers in combination with these fluids is plugging of the flow channels. It is therefore assumed that the hydraulic diameters of the flow channels of the three classes of fluids are similar. Comparing the thermal conductivities of the various fluids then follows that the ratio of convection heat transfer coefficients within laminar flow are as follows (Table 7):

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>Pumping Power</th>
<th>Heat loss</th>
<th>Wall thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium feed line</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>LS feed line</td>
<td>0.17</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>LM feed line</td>
<td>0.37</td>
<td>0.41</td>
<td>0.40</td>
</tr>
<tr>
<td>Helium return line</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>LS return line</td>
<td>0.25</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>LM return line</td>
<td>0.42</td>
<td>0.45</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 7 illustrates that liquid salts offer superior characteristics in terms of pumping power, heat losses as well as pipe wall thickness. The liquid metals category in turn fares better than Helium. Note that the heat losses for Helium are higher than those for the liquids on account of the larger pipe diameter leading to an increase in heat-exchange surface. The larger diameter is a direct consequence of the large pumping requirement per heat transferred at a fixed temperature differential. Additionally, the large diameter pipes resulting for Helium leads to a large pipe wall thickness requirement, since the stress in the pipe wall is directly proportional to the diameter of the pipe.

### COMPARISON OF HEAT TRANSFER PERFORMANCE IN HEAT-EXCHANGERS

Besides the pipeline performance of the three fluids, their relative heat transfer capability plays an essential role in establishing the most promising fluid in a purely thermodynamic sense. The heat transfer rate in a heat-exchanger is represented by:

\[ Q = UA \Delta T_{\text{m}} \]  \hspace{1cm} (8)

It then follows that an increase in the overall heat transfer coefficient results in lower values for \( \Delta T_{\text{m}} \) for the heat-exchangers. This creates both a cost saving (the reduction in area resulting in reduced costs for the heat-exchanger), as well as a benefit for the process since it may be possible to increase the delivery temperature to the process.

The fluid impacts on the overall heat transfer coefficient of a heat-exchanger through the fluid convection coefficient, \( \lambda \). Under usual circumstances, it is desirable to obtain turbulent flow within a heat-exchanger in order to obtain better heat transfer and as a result reduce the size of the heat-exchanger. However, with fluids such as Helium, pumping requirement becomes an important trade-off. Additionally, since a compact type heat-exchanger seems to be a necessity in reducing costs of the PHP, the hydraulic diameters of the heat-exchanger can potentially be very small. Because of the latter two observations it was thought appropriate to compare the heat transfer capabilities of the fluids in both laminar as well as turbulent flow.

It is shown in Annex B that, when laminar flow is prevailing within a flow channel, the convection coefficient is directly proportional to the property \( \frac{k}{D_h} \). The hydraulic diameters of a compact type heat-exchanger are very small. Liquid salt and liquid metal type compact heat-exchangers have only recently received some attention. Although one might be able to decrease the hydraulic diameter of the flow channels on the liquid salt/metal side (and therefore enhance the convection coefficient), a major concern with using this type of heat-exchangers in combination with these fluids is plugging of the flow channels. It is therefore assumed that the hydraulic diameters of the flow channels of the three classes of fluids are similar. Comparing the thermal conductivities of the various fluids then follows that the ratio of convection heat transfer coefficients within laminar flow are as follows (Table 7):

Table 7: Ratio of expected convection coefficient for laminar flow within heat-exchangers

<table>
<thead>
<tr>
<th></th>
<th>( \frac{A_{\text{LS}}}{A_{\text{He}}} ) [-]</th>
<th>( \frac{A_{\text{LM}}}{A_{\text{He}}} ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS feed line</td>
<td>2.6</td>
<td>44.6</td>
</tr>
</tbody>
</table>

Annex B also illustrates that the convection coefficient in turbulent flow in pipes is directly proportional to the term \( \left( \frac{\rho^{0.8}k^{0.6}c_p^{0.4}}{\mu^{0.8}D_h^{0.4}} \right) \left( \lambda_{\text{LS}}^{0.3} \right) \). Following the same reasoning as was done for the laminar case, assume that the hydraulic diameter of the flow channels is similar for the three classes of fluids. Next, if it is assumed that the velocity ratio between the helium and the liquid salt and liquid metal are equal to those determined in the previous section, one is able to compare the convection heat transfer coefficient between the fluids in the event of turbulent flow (refer to Table 8).

Table 8: Ratio of expected convection coefficient for turbulent flow within heat-exchangers

<table>
<thead>
<tr>
<th></th>
<th>( \frac{A_{\text{LS}}}{A_{\text{He}}} ) [-]</th>
<th>( \frac{A_{\text{LM}}}{A_{\text{He}}} ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS feed line</td>
<td>6.2</td>
<td>46.5</td>
</tr>
</tbody>
</table>

Studies have been performed on heat transfer coefficients for an IHX of Helium to liquid salt and Helium to Helium, and it was found that the heat transfer coefficients for the liquid salts would be an order of magnitude higher than that for Helium [5]. Other sources found that they are of the same order of magnitude. Nonetheless, taking the previous results into consideration, it would be reasonable to expect liquid metal and liquid salt heat-exchangers to have better overall heat transfer coefficients than Helium.

### OTHER ASPECTS TO CONSIDER

Besides the thermophysical aspects, there are other very important influential factors to be considered. These are:

- Operational aspects
Operational considerations refer to transient events such as start-up, shut-down or accident events such as loss of circulator power and SHTS leak. Because liquid salts have a relatively high melting point, the salts would require a pre-heater in the event of a start-up from atmospheric temperature to increase the temperature of the salt and melt it before circulation can start [6]. This pre-heating would require the design and installation of a centralized handling and storage unit in order to facilitate the melting and introduction of the salt to the loop. A loss of circulator power would cause the liquid salt to eventually freeze. Since it would be very difficult or even impossible to heat the liquid salt within the piping and heat-exchangers after freezing, one would require auxiliary pumping power. Both the drainage facility as well as the auxiliary pumping capacity comes with the penalty of additional capital cost.

When using Helium as SHTS fluid, the major concern is the capital cost of the inventory storage required for Helium. Because the density of Helium change with pressure and temperature which, in turn, change during transient events such as start-up and operation at part load, a careful consideration is necessary to ascertain that enough Helium is present to achieve the required duty.

A very important aspect between using Helium and liquid salt as SHTS fluid is the compatibility of the fluids with the materials of the heat-exchangers, piping, containers etc. In general, due to the high operating temperatures of the SHTS, material creep rate would be a challenge, regardless of the fluid chosen.

In addition to the strength characteristics at high temperature, the chemical stability of the fluid with the component materials should be evaluated, such as corrosion properties of the materials used with the two coolants. Numerous studies in literature suggest that, when the fluorine potential of liquid salts is controlled to be low, their corrosion rates are low when used in combination with carbon or nickel based alloys for the SHTS components. Chromium was found to have a high potential to corrode, implying that the chromium content of the alloys should be kept as low as possible. However, corrosion experiments at ORNL [5] indicated that there exists a potential to even use high chromium alloys such as Hastelloy-N with the salts provided that a reducing environment is maintained. The compatibility of high pressure Helium with materials is not a concern in terms of chemical stability, since clean Helium does not corrode.

Both high pressure Helium and liquid salts provide stored energy sources that have the potential to be released rapidly, in which case flammable or toxic chemicals could be spilled from the process plant, mechanical damage generated or even radioactive exposure when there is enough energy released to damage the primary reactor circuit.

In the case of Helium, the stored energy is a result of the huge amounts of Helium used to transport the heat energy. In the case of liquid salts, the stored energy is a result of the high heat capacity of the salt added by the high operating temperature. These two combinations give rise to the possibility of a steam explosion if the salt contacts a volatile liquid such as water.

In terms of research and development requirements, Helium has a great advantage over the liquid salts and liquid metals groups, especially when considering near term commercializing of a PHP plant. Issues such as compatibility with boundary material, sealing of components within liquid salt and liquid metal systems, valves, plugging of the heat-exchangers and many more are just some of the areas in need of serious research and development work.

**INFLUENCE OF SEPARATION DISTANCE**

Whereas the liquid salt and liquid metals categories offer the potential to greatly improve the efficiency and reduce the cost of the SHTS of a PHP, there is still some major additional developmental work required. One might expect that the separation distance between primary circuit and process plant greatly affects the choice of secondary coolant. If a PHP can be built which is safe and licensable at relative short separation distances, a near term solution would be Helium as SHTS coolant. On the other hand, if large separation distances are a prerequisite for a particular application, there might be merit for developing liquid salts to overcome costing and efficiency problems associated with Helium.

In this section of the study the effect of separation distance on pumping requirement and heat losses for the three categories of fluids are compared. Comparisons are done at distances of 30 [m], again at 100 [m] and then also at a distance of 500 [m].

Following the same routine as was done previously, the optimum process feed pipeline and process return pipeline diameters were determined at each distance. The same input and boundary conditions still apply. Back substitution of the latter results into the respective models then gave the performance for the three fluids at the three distances. In Figure 7 the pumping power requirement as function of separation distance can be seen:

![Figure 7: Pumping power requirement as function of separation distance for Helium, LS and LM.](image)

Figure 8 presents the heat losses as function of separation distance for Helium, LS and LM.
Figure 8: Heat losses as function of separation distance for Helium, LS and LM.

From the resulting graphs presented it is evident that both the pumping requirement as well as the heat losses varies in a linear fashion with increase in separation distance. The ratio of the gradients of these functions is presented in Table 9. Helium is used as reference.

Table 9: The ratio in gradient of pumping power increase and heat losses increase with distance for Helium, LS and LM

<table>
<thead>
<tr>
<th></th>
<th>Pumping Power</th>
<th>Heat Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Liquid salt</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td>Liquid metal</td>
<td>0.46</td>
<td>0.45</td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSION

The thermodynamic steady-state performance of Helium, a typical liquid salt and a typical liquid metal was compared in this study. It was found that the liquid salt category has far better heat transport characteristics than Helium, and is also superior to the liquid metal considered. The major contributing factor leading to the relatively poorer performance of Helium (in most of the aspects addressed) is its low density.

Important aspects which do not favor liquid salts are its high melting point and associated operational implications, as well as research and development requirements. For liquid metals, corrosion/materials compatibility is an additional concern. It is therefore expected that the separation distance and time frame for commercialization will play an essential role in the choice of coolant. Subsequently, the pumping requirement and heat loss as function of separation distance were compared for the three classes of fluids. It was found that Helium pumping requirement and heat loss increased much more rapidly than those of liquid salts and liquid metals.

Considering the issues associated with corrosion of components in contact with liquid metals combined with the results of the thermo hydraulic analysis performed in this study, liquid salts is preferred over the liquid metals category. Although liquid metals provide the potential to greatly improve on system efficiency and also reduce cost, the developmental requirements in terms of salt properties, compatibility with materials and operational concerns render them feasible only as a long term solution. When considering near term application, Helium with piping systems of internal insulation remains the preferred choice.

ACKNOWLEDGMENTS

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REFERENCES


ANNEX A

PUMPING REQUIREMENT FOR HELIUM

For gases, the pumping requirement is represented by

\[
\dot{P} = \dot{m} c_r T_i \left[ \frac{\gamma + 1}{\gamma} \frac{PR^{\frac{\gamma - 1}{\gamma}} - 1}{\gamma} \right]
\]

(9)

where \( PR \) represents the pressure ratio over the blower. Rewriting the previous equation in terms of the pressure differential \( \Delta p \) over the blower leads to:

\[
\dot{P} = \dot{m} c_r T_i \left[ 1 + \frac{\Delta p}{p_i} \right]^{\frac{\gamma - 1}{\gamma}} - 1
\]

(10)

Using the product \( \rho_i Q_i \) to replace the mass flow rate:

\[
\dot{P} = \rho_i Q_i c_r T_i \left[ 1 + \frac{\Delta p}{p_i} \right]^{\frac{\gamma - 1}{\gamma}} - 1
\]

(11)

Eq. (11) can be manipulated using the ideal gas law as follows:

\[
\dot{P} = \left( \frac{c_r}{R} \right) Q_i p_i \left[ 1 + \frac{\Delta p}{p_i} \right]^{\frac{\gamma - 1}{\gamma}} - 1
\]

(12)

The first term within the brackets can be expanded using the binomial theorem as follows:

\[
\dot{P} = \left( \frac{c_r}{R} \right) Q_i p_i \left[ 1 + \frac{\gamma - 1}{\gamma} \frac{\Delta p}{p_i} \right]^{\frac{\gamma - 1}{\gamma}} + \left( \frac{\gamma - 1}{\gamma} \frac{\Delta p}{p_i} \right)^2 \left( \frac{\Delta p}{p_i} \right)^{\frac{\gamma - 1}{\gamma}} + ... - 1
\]

(13)

Assuming \( \left( \frac{\Delta p}{p_i} \right) \) to be small, the second order terms in the previous can be neglected. Then, the pumping requirement becomes

\[
\dot{P} = \left( \frac{c_r}{R} \right) Q_i \frac{\gamma - 1}{\gamma} \dot{Q}_i \Delta p
\]

(14)

which can be further simplified from the definition of the gas properties to give:

\[
\dot{P} = \dot{Q}_i \Delta p
\]

(15)
ANNEX B

FLUID PROPERTY IMPACT ON CONVECTION COEFFICIENT

The convection heat transfer coefficient is defined as:

$$\dot{\lambda} = \frac{Nu \ k}{D_h} \tag{16}$$

In laminar flow, the Nusselt number is a constant, where the value of the constant is dependent on the shape of the cross-sectional area and whether the heat transfer is occurring at constant wall heat flux or at constant surface temperature, but independent of fluid properties. The only fluid property affecting the convection coefficient is therefore the conduction heat transfer coefficient $k$. From this it is clear that the convection heat transfer coefficient would then vary linearly with the conduction heat transfer coefficient for similar sized flow channels (i.e. similar $D_h$) within the heat-exchanger.

Assuming that the heat transfer within the channels of the heat-exchanger can be described by an equation similar to the Dittus-Boelter equation for turbulent flow in pipes, the Nusselt number can be calculated from

$$Nu = CRe^{0.8} Pr^{0.4} \tag{17}$$

where $C$ is a constant.

Substitution of (17) into (16) then leads to:

$$\dot{\lambda} = C \left( \frac{\rho \ k \ \varepsilon \ C_p}{\mu \ V \ D_h} \right)^{0.4} \tag{18}$$