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Molten Salt as Heat Transfer Fluid in Concentrating Solar Plants

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Abstract— Our research focuses on molten salts and their potential as a heat transfer fluid. Molten salts have been used in high temperature applications such as coal gasification medium, waste oxidation at high temperatures, thermal energy storage medium, and heat transfer fluid (HTF) in Concentrating Solar Power (CSP) systems. They are particularly useful as a heat transfer fluid in a CSP due to their main characteristics such as low vapor pressure, wide operating range, low viscosity, and high volumetric heat capacity. Molten salts are compared to conventionally used HTFs, as well as other low temperature fluids such as water and experimental fluids such as liquid metals and their eutectic mixtures. The molten salts chosen for this report are primarily binary, ternary, or quaternary mixtures containing alkali and alkaline earth metal nitrates such as sodium, potassium, lithium, caesium, calcium nitrate, and sodium nitrite. The thermophysical properties of the salts were compared. These are melting point, density, viscosity, heat capacity, and thermal conductivity. The effect of using molten salts as a heat transfer fluid on plant performance and economics has also been discussed. The fluids under consideration have great potential for current and future applications in renewable energy storage and transformation processes.

Keywords— Concentrating Solar power, Heat transfer fluid, molten salts, Thermophysical properties, viscosity, density, composition, solar, etc..

I. INTRODUCTION

The heat from solar irradiance is transferred to a heat transfer fluid in solar concentrator plants. Transferring heat to a fluid with higher thermal conductivity and heat storage capacity than water is a more popular method. More heat can be transferred to the working fluid as a result of this. For this purpose, heat transfer fluids such as heat transfer oils are used. Therminol VP-1 and Dowtherm Heat Transfer Fluid are two examples (HTF). These oils have excellent heat transfer properties and a relatively broad operating temperature range of 12 to 350 degrees Celsius. However, once the oils have passed their operating temperature range, they rapidly degrade, putting a limit on the maximum temperature of the Rankine steam cycle and forcing it to operate at a lower efficiency. By replacing these oils with salt, it may be possible to raise the solar field output temperature to 450-500 °C, increasing the power block steam turbine's Rankine cycle efficiency to the 40% range. This compares to current plant designs, which have a solar field outlet temperature and cycle efficiency of 393 °C and 37.6%, respectively. Furthermore, due to the low maximum temperature, the concentrator concentration ratio must be adjusted in order to keep the fluid's operating temperature below its maximum. Other heat transfer fluids, such as molten salts (alkali nitrates and alkali halides) and liquid metal alloys such as NaK and Pb-Bi eutectics, are being considered as viable alternatives to overcome these deficiencies. Molten salts, specifically fluoride salts, have been widely used as heat transfer in nuclear power plants for decades prior to their use in CSP [1,36]. Simultaneously, molten salts are used in the chemical industry for processes such as coal gasification, dehydration, and salt baths for molten salt oxidation. Only in the last four decades, as concerns about conventional energy resources and environmental protection have grown, have molten salts been used as heat transfer fluids in CSP to improve their effectiveness.

The inexpensive cost, high heat storage capacity, low viscosity, and greater maximum working temperature of molten salts have led to a general consensus that they are a better option to their organic equivalents. According to reports, inorganic salt mixes like Hitec can withstand temperatures of up to 550 °C for brief periods of time and have a maximum temperature of roughly 450 °C. In comparison to their organic equivalents, their high heat storage capacity indicates that more heat may be transferred to the working fluid with a given amount of heat transfer fluid, and their low viscosity implies that improved heat transfer properties and low pumping power can be achieved.

Eutectic mixes are used to lower the melting point of salts. A combination is said to be eutectic if its melting point is lowest, even lower than the sum of its separate parts, at a particular composition level. Sun salt®, which contains 60 weight percent $NaNO_3$ and 40 weight percent KNO_3, is an example of such a mixture. It is thermally stable in the liquid phase up to 600 °C and melts at 223 °C.

II. LITERATURE REVIEW

1) Heat transfer fluids for concentrating solar power systems – A review by K. Vignarooban

In this paper working on the main problems with molten salts, which was studied in this essay, is how very corrosive they are to metal alloys. Several new molten salts are being proposed, as noted in the present study, however there is no information on their corrosive characteristics in the literature. Before using molten salts as the HTF in CSPs on a commercial scale, the corrosion difficulties must be fully handled.

2) Recent Developments in Heat Transfer Fluids Used for Solar Thermal Energy Applications by Umish Srivastva

In this paper An ideal heat transfer fluid is one that operates as a Thermally Stable, Easily Pumpable, Negligible Vapour Pressure, Fully Compatible, Non-Corrosive, Single Phase Liquid at all operating temperatures having so many of these characteristics. These characteristics are available state-of-the-art technologies in heat transfer fluids for concentrated solar power (CSP) plants, which is the solar energy technology of immense importance and need in today's world for generating reliable and dispatchable renewable energy.

3) A Review of Solar Collectors and Thermal Energy Storage in Solar Thermal Applications by Tian Y.

This paper has reviewed the two primary subsystems, thermal energy storage subsystems and solar collectors, that make up the state-of-the-art in solar thermal applications. Both non-concentrating and concentrating types of solar collectors have been discussed. PVT solar collectors display the best overall performance among non-concentrating collectors. The optical optimisation, decrease of heat loss, improvement of heat recovery, and various sun-tracking techniques of sun-tracking concentrated solar collectors have also been studied. Heliostat field collectors, parabolic dish collectors, and parabolic trough collectors are three distinct categories of concentrated solar collectors that have been described and contrasted.

4) Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field by D. Kearney and B. Kelly

In this paper observed the potential for performance and financial benefits brought on by the implementation of a salt HTF in the solar field and storage system. If the HTF is VP 1, the less expensive Solar Salt is utilised for storage, whereas the salt HTF uses calcium nitrate salt for both the HTF and storage.

5) Molten Salts as Heat Transfer Fluids for Solar Thermal Power Plants by Krysten Minnici

In this report the NaCl and KCl were examined for density and heat capacity in the solar power plant simulation to determine their suitability as heat transfer fluids. NaCl and KCl were unable to match the first fluid Powell and Edgar utilised. NaCl and KCl, both of which are in crystal form at 600 K, the temperature used for the power plant simulation, were a major cause of mistake. To better understand their relationship and produce more power, random values of heat capacity and density were examined.

6) Molten salts as engineering fluids – A review Part I. Molten alkali nitrates by V.M.B. Nunes a,b,

The paper conclude that, precise data as well as the identification of new mixes with improved attributes in order to apply molten salts in upcoming technologies like MSO and CSP. It is reasonable to assume that these engineering fluids' properties will not yet be fully utilised. The characteristics and uses of molten fluorides, carbonates, and their corresponding combinations will likewise be the subject of a similar analysis, as we anticipate.

7) Effect of composition on the density of multicomponent molten nitrate salts by Bradshaw, R.W.

In this paper, the density of multi-component molten nitrate salts was measured in an experiment to ascertain the impacts of the constituents, which included varying ratios of nitrates of potassium, sodium, lithium, and calcium. Measurements of the density of multicomponent mixtures were compared to data published in the literature for the individual constituent salts or straightforward combinations, like the binary Sun Salt mixture of NaNO3 and KNO3. The findings show that, in contrast to potassium or sodium nitrate, calcium nitrate enhances density while lithium nitrate decreases density, in line with findings for binary mixes.

IV. CONCENTRATING SOLAR POWER SYSTEMS

Mirrors are used in concentrated solar power (CSP) technologies to reflect and concentrate sunlight into a single point, where it is gathered and transformed into heat. Electricity can then be generated using this thermal energy. The solar receiver with receiver first converts solar radiation to heat, and the heat engine with carnot then transforms that heat into work. The following formula can be used to get the overall conversion efficiency: $\eta_o = \eta_r \times \eta_c$

$$\eta_r = \frac{Q_{ab} \times Q_{lost}}{Q_{Solar}}$$

$$\eta_c = 1 - \frac{T_0}{T}$$

Where,

η_r, η_c and η_o are the receiver, Carnot and overall efficiencies of the system

Q_{ab} is the heat absorbed by the receiver

Q_{lost} is the heat lost by the receiver

Q_{solar} is the total heat absorbed

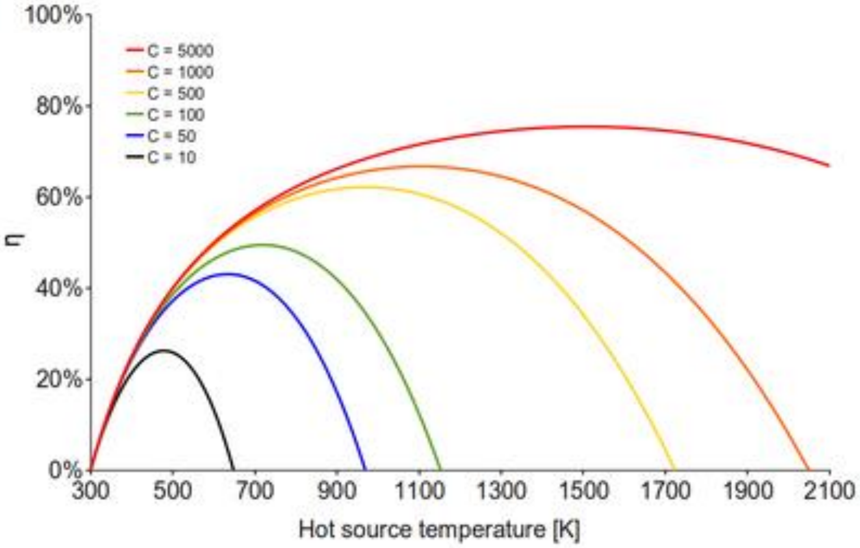

Figure 1 Overall efficiency vs Temperature of the receiver in a CSP

Figure 1 depicts the overall efficiency change as receiver temperature increases. The efficiency of the receiver does not rise with temperature, despite the fact that the efficiency of the heat engine (Carnot efficiency) grows. Instead, when temperature increases, the quantity of energy that the receiver cannot absorb (Qlost) increases by the fourth power, lowering its efficiency. The receiver sets a maximum temperature that can be reached. Utility-scale projects often use concentrating solar power systems. In CSP plants, a receiver that receives sunlight and heats a high-temperature fluid to drive a turbine or an engine that drives a generator is heated by the sunlight focused by mirrors. Electrical energy is the end result.

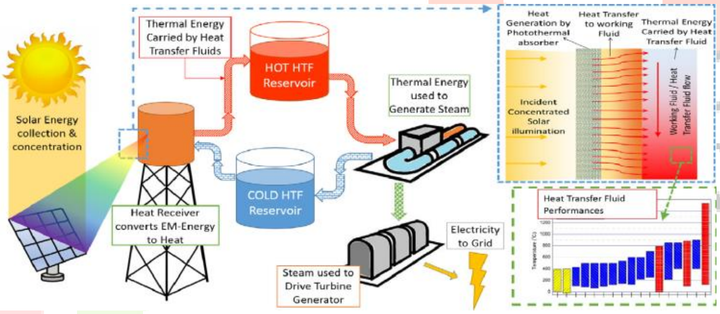

Figure 2 Working of a Concentrating solar power plant with molten salt as heat transfer fluid and heat storage fluid

The parabolic trough and the linear Fresnel are two examples of concentrators for linear systems. The receiver consists of a tube bundle linear Fresnel reflector and an evacuated tube in a parabolic trough. Low average concentration ratios, between 30 and 100, are a distinctive feature of linear concentrators. Point focusing concentrators are capable of achieving high concentration ratios, ranging from 300 to 1500 and beyond. Systems that use point focusing direct all of the sun's beams at the parabola's centre. There are many different technological receiver possibilities for both systems.

Heat transfer fluid (HTF) becomes heated by absorbing heat from the receiver. The HTF is then transferred to a hot HTF reservoir, which stores the fluid in an insulated tank, after which it is utilised to heat a secondary thermal energy storage medium and generate steam to power the turbine. For the purpose of producing steam, the fluid is subsequently pushed to the heat exchanger. The HTF is subsequently moved to the cold HTF reservoir, which serves as a low-temperature storage for the HTF. The fluid temperature is consistently kept well above the freezing point thanks to the cool HTF reservoir. Due to their ability to be employed for passive heating at night, these storage units significantly cut down on the start-up periods and energy usage of electrical heating systems.

V. CLASSIFICATION OF HEAT TRANSFER FLUID

One of the most crucial elements for the overall effectiveness and performance of CSP systems is HTF. As a CSP plant needs a lot of HTF to run, it's important to keep HTF's price as low as possible while still getting the most out of it. Hot HTF can be kept in an insulated tank for use in power generation during times of low solar insolation and during non-peak hours in addition to being transferred from the receiver to steam generator. Low viscosity, high thermal conductivity, high heat capacity for energy storage, low cost, low vapour pressure (1 atm) at high temperature, low corrosion with metal alloys used to confine the HTF, low melting point, high boiling point, and thermal stability are all desired properties of an HTF.

Based on their working temperature range, the HTFs are roughly divided into six primary groups: (1) air and other gases, (2) water/steam, (3) thermal oils, (4) organics, (5) molten salts, and (6) liquid metals.

VI. SALT USED IN RESEARCH

Molten salts are regarded as the best materials to employ in solar power plants due to their outstanding thermal stability at high temperatures, low vapour pressure, low viscosity, high thermal conductivities, non-flammability, and non-toxicity. Nitrates, chlorides, fluorides, and carbonates are some of the currently molten salts. Because they can store a lot of heat, fluorides are typically employed in nuclear reactors. Because of their inexpensive cost and high fusion heat, chlorides are appealing. However, due to their high levels of corrosion, neither fluorides nor chlorides have a wide range of applications in CSP. For high temperature latent heat storage, carbonated beverages are utilised. Nitrates and nitrites are suitable for heat transfer and thermal storage applications in solar thermal power plants due to their low chemical reactivity, low corrosiveness, thermal stability in the upper temperature range required by steam Rankine cycles, very low vapour pressures, availability, and affordability. Because of this, unless otherwise stated, all salt mixes indicated in this study have nitrates/nitrites anion.

1) Binary Salts
2) Ternary Salts
3) Quaternary Salts
4) Quinary Salts:

VII. THERMOPHYSICAL PROPERTIES OF MOLTEN METAL

Melting point:-

The melting point of a eutectic mixture is the lowest of any comparable mixture made up of the identical components. In ternary salt mixes, eutectic behaviour can be considerably more extreme and is frequently observed. More complicated salt mixes, such as quaternary or higher order mixtures, exhibit eutectic behaviour and more severe melting point lowering.

Viscosity:-

The viscosity of the Hitec® is just 1.3 cP at 400 °C, that of the solar salt and the ternary salt containing calcium and lithium nitrate is 1.5 cP. Depending on the composition, the $Ca(NO3)2$ mixtures exhibit viscosity values that range from 4 to 8 cP at 440 °C. The ternary eutectic K-Li-Ca nitrate, Hitec, Hitec XL, and these mixes all have low enough viscosities to allow for efficient heat transfer and decreased flow resistance.

Density:-

In addition to being a component of several dimensionless groups used in heat transfer and fluid flow calculations, such as the Prandtl number and Reynolds number, density is required for system sizing estimates. The volume change brought on by solidification can be calculated using the molten salt density at the liquidus temperature. Lithium nitrate had the impact of making combinations with $KNO3$ less dense, whereas calcium nitrate was shown to have the opposite effect, making mixtures more dense. Similar densities exist for molten salts at temperatures of 400–500 °C (1.7–1.9 g/cm3).

Specific heat and Volumetric Heat capacity:-

The temperature dependence of the specific heat of molten salts, which is in the order of T5, is rather difficult to understand and ranges from 1.3 to 2.6 kJ/kg-K. The THERMINOL® 66, on the other hand, exhibits a significantly greater value (2.5 kJ/kg-K).

A higher volumetric heat storage capacity would be implied by a higher density and specific heat of the heat transfer fluid. The specific heat capacity and density of the salt mixture will both increase when calcium and/or magnesium nitrate are added to solar salt.

Thermal conductivity:-

The thermal conductivity of a liquid is the amount of heat per degree rise in temperature that can be carried in that liquid when mass transport is not present. With the exception of a specific composition described by Y.Y. Chen [16], whose thermal conductivity is 3.25 W/m-K, the documented thermal conductivity of salts ranges from 0.1-0.65 W/m-K. If the published results are accurate, it follows that altering the component composition could modify the salt mixes' thermal conductivity.

VIII. IMPACT OF SALT HTF ON ECONOMICS

It is essential to assess the proposed salt HTF concept's economics and contrast it with other HTFs. To accurately assess the economic effectiveness of the HTF systems, the evaluation would be based on their Levelized Cost of Electricity (LCOE). The LCOE accounts for both performance and cost. The only way to choose the optimal idea design is to evaluate the costs and performances of various strategies.

The Levelized Cost of Electricity (LCOE) of VP-1 and molten salt were compared in a study by NREL. The highest LCOE for VP-1-using power facilities without thermal storage was $140/MWh. A two-tank molten salt storage system can be integrated with a cutting-edge SEGS to lower the LCOE by 6%, and a thermocline storage system can reduce it even more. The LCOE would be further reduced by 9% by swapping the HTF for the calcium nitrate salt. The improvement would be 13% at operating temperatures as high as 500°C.

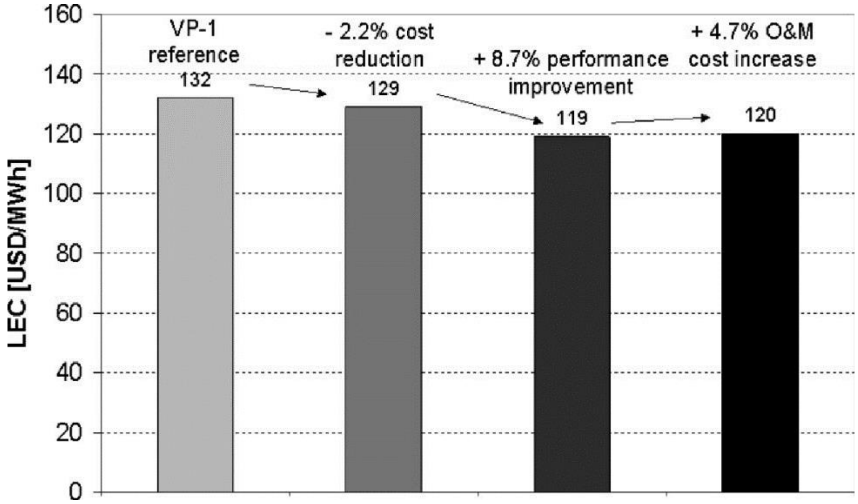

Fig.3 Individual effect on LCOE of Synthetic oil and molten salt as HTF, D. Kearney et.al, 'Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field', J. Solar Energy Engineering, May 2003, Volume 125, Issue 2

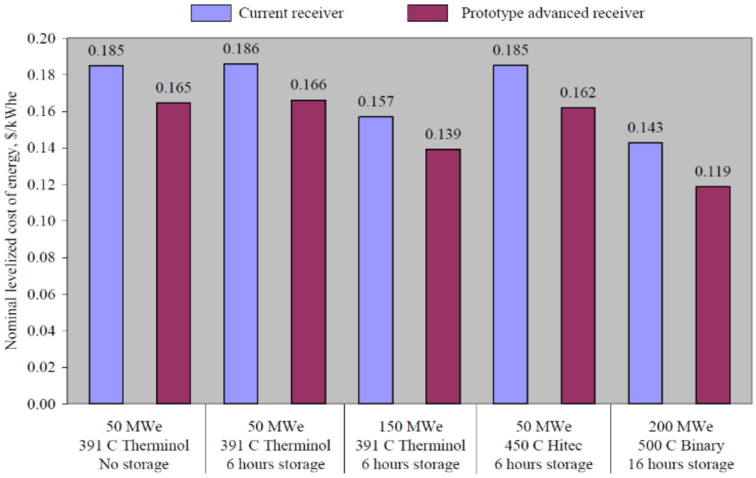

Figure 6 Project economics, Bruce Kelly, Henry Price, Doug Brosseau and David Kearney, 'Adopting Nitrate/Nitrite Salt Mixtures as The Heat Transport Fluid in Parabolic Trough Power Plants', 2007 ASME Energy Sustainability Conference (ES2007), June 2007, ES2007-36172

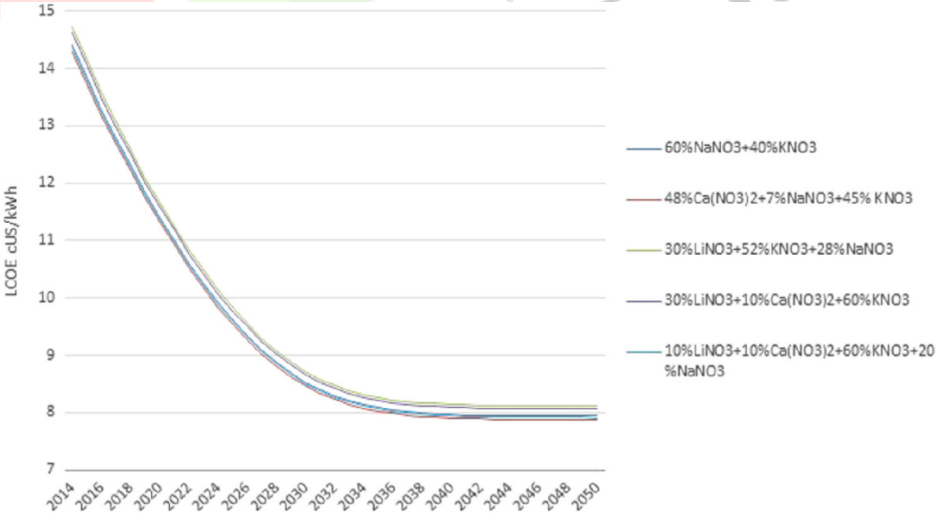

Figure 7 Projection of LCOE for the years 2014 through 2050, Víctor Andrés Patiño Mantilla et. al, 'Technical-Economic Analysis of CSP Technology with Parabolic Trough Solar Collector Using Different Fluids Work and Thermal Storage System for The Brazilian Conditions', Conference proceedings of 16th Brazilian Congress of Thermal Sciences and Engineering, November 2016.

Table 4 Different HTFs and their impact on plant performance and LCOE, Víctor Andrés Patiño Mantilla et.al, 'Technical-Economic Analysis of CSP Technology with Parabolic Trough Solar Collector Using Different Fluids Work and Thermal Storage System for The Brazilian Conditions', Conference proceedings of 16th Brazilian Congress of Thermal Sciences and Engineering, November 2016.

HTF	Solar Salt	Hitec XL	Hitec	Therminol VP-1
Annual Energy (kWh)	153,840.61	162,575.15	158,833.46	143,122.75
Gross-to-net conversion (%)	65.2	69.5	89.2	79.3
Capacity factor (%)	39	41.2	40.3	37.1
Annual Water Usage (m^3)	59.352	59	54.15	56.425
LCOE (₵/kWh)	25.25	24.05	24.55	26.42

IX. CONCLUSION

The distinct class of fluids known as molten salts offers a number of benefits over other traditional HTFs. For CSP applications, molten alkali nitrates form the basis for many of the salt mixes that have been created or suggested. Due to their decreased freezing point, reduced viscosity, high volumetric heat capacity, environmental compatibility, high working temperature, and high decomposition temperature, these mixes produce good HTFs. Molten salts can be employed as a thermal energy storage medium, which is a significant additional benefit.

The ternary mixture of sodium, potassium, and calcium nitrates is the best formulation of salt mixture for use as HTF, and the quaternary "Sandia Mix" of sodium, potassium, calcium, and lithium nitrate also shows promising results, but mixtures containing lithium nitrate tend to be more expensive than the others. The ternary mixture of sodium, potassium, and lithium nitrate is an excellent option, although it costs more than the "Sandia Mix" since it contains more lithium nitrate.

The best HTFs currently available are molten salts. The fact that Sun Salt is being used as an HTF or thermal energy storage medium, despite its obvious drawbacks such a high melting point and a narrow operating range, only serves to support the previous assertion. As we've already seen, adding a third component to a binary salt mixture like Solar Salt will improve the salt's thermophysical characteristics, such as lowering its melting point, lowering its viscosity, increasing its density and specific heat capacity, and/or enhancing the salt's thermal stability at higher temperatures.

In some circumstances, a ternary salt's qualities can be further enhanced by the addition of a fourth component, albeit at this point, economic considerations enter the picture. Due to this, we have created a new salt blend that contains sodium nitrate, potassium nitrate, and potassium nitrite. By adding a third alkali nitrate or nitrite to the already existing Solar salt composition, this salt mixture shows promise as a ternary mixture. Using this special composition, it is anticipated that the melting point will drop below 220 °C and the maximum operating temperature would rise, extending the operating temperature range. The mixture will be prepared, and after that, its thermophysical characteristics, such as viscosity, density, and specific heat capacity, as well as tests to gauge mass loss that occurs in the mixture at high temperatures, will be measured. A successful completion of this study would suggest a potential replacement for the currently used molten salt HTF, such as Solar salt® and Hitec, and would allow for the evaluation of its long-term performance for use in concentrating solar power plants.

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