NaK as a primary heat transfer fluid in thermal solar power installations

Johannes P. Kotzé[1], Theodor W. von Backström[2] and Paul J. Erens[3]

[1]M.Eng (Mechatronic), Student, Dept. Mechanical and Mechatronic Engineering, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa, Phone: +27 82 493 8687, E-Mail:jpkotze@sun.ac.za

[2]Ph.D, Senior Researcher, Dept. Mechanical and Mechatronic Engineering, Stellenbosch University, Phone: +27 21 808 4267

[3]Ph.D, Mechanical Engineer, Phone: +27 82 556 1112

Abstract

Current developments in concentrating solar power focus on the reduction of levelised electricity cost. This can be done through the increase of thermal efficiency, and the decrease of plant operational cost. Some of the current limits on plant operational parameters are due to the limitations of the primary heat transfer fluids. The limitations of thermal oil, molten salt, direct steam, air and sodium are discussed.Generally the operational temperature range of the heat transfer fluid is the greatest limitation. High melting point heat transfer fluids require trace heating to prevent solidification during plant down time.This adds to the operational cost of the plant. Limitation in maximum operational temperature limits the plant's thermal efficiency. As a solution to these limitations a sodium-potassium alloy called NaK is identified as an alternative heat transfer fluid. In its eutectic form it has a melting point of -12.8°C and a boiling point of 785°C at atmospheric pressure. A hypoeutectic NaK composition (NaK46) still has a melting point below 20°C, but has improved heat transfer properties toeutectic NaK. Molten metals such as NaK also yield robust, efficient and high flux receiver designs. The safe use of NaK in the nuclear industry serves as a proof that it is possible to use NaK in concentrating solar power. Thermal storage in metallic phase change materials is proposed as a suitable thermal storage concept for a NaK system.

Key words: heat transfer, NaK, molten metals, thermal efficiency, trace heating

1. Introduction

In a concentrating solar power (CSP) installation thermal energy must be transported from the receiver by a primary heat transfer fluid (HTF). The properties of the primary HTF impose certain operational limits on the CSP plant andset a number of engineering challenges that are associated with that particular HTF. Two of the most prominent limitations are the maximum operational temperature and the melting point of the HTF. Low maximum operational temperature limits the thermal efficiency of the plant, and a high melting point may cause blockages in field or receiver pipes at night.

The heat transfer properties and safety hazards impact other design related aspects of a CSP plant, but generally these are limited to: receiver design, heat exchanger design, heat transfer flow rates and plant operational strategies. All of these are manageable engineering problems and do not seriously impair the inherent plant efficiency.

Current innovations in CSP are aimed at cost reduction through efficiency improvement, reduction in operational and maintenance costs and plant simplification. Efficiency can be improved by improving the plant overall thermodynamic efficiency and by minimizing parasitic losses. The great advantage of CSP over other renewable energy sources (except hydro), is that energy storage is feasible. The temperature at which storage happens also impacts the thermal efficiency of the CSP plant. The current maximum thermal storage temperature is 567°C in direct salt storage in a central tower receiver [1].

Kotzé, Von Backström & Erens [2]proposed a latent thermal energy storage system that stores thermal energy in the latent heat of fusion of metallic phase change materials (PCMs). The metallic PCM in question is a eutectic aluminium-silicon alloy, AlSi12. It has a melting temperature of 577°C. Since regular HTFs such as oil and salt are not well suited for this temperature range, NaK has been proposed as a primary HTF. NaK has a number of distinct advantages, such as: raising the maximum receiver temperature, increasing the maximum thermal flux of the receiver, lowering the operational pressure of the primary HTF loop and preventing solidification in the receiver pipes.

This concept isespecially well-suited for central receiver systems. NaK has a maximum operational temperature of 785°Cat atmospheric pressure, and it can be raised to over a 1000°C with moderate pressurisation. Thus, NaK can be utilized to increase the plant thermal efficiency. This paper will look at current HTFs and explore the idea of using NaK as a HTF.

2. Comparison of primaryheat transfer fluids

The three primary HTFs commonly used in CSP are:

- Thermal oil
- Molten salt
- Direct steam

These HTFs have limitations that inhibit CSP plant performance. The limitations are discussed below along with other proposed HTFs that may offer superior heat transfer performance. The properties of these heat transfer fluids are listed in Table 1 for comparison, and will serve as a reference though the paper.

	Unit	**Sodium (atm)**	**NaK78 (atm)**	**Potassium**	**Hitec XL**	**Hitec**	**Hitec solar salt**	**Dowtherm A**
Melting point	*°C*	97.82	-12.6	63.2	120	142	240	15
Boiling point or maximum operating temperature	*°C*	881.4	785	756.5	500	538	567 (bp 593)	400
Density	*kg/m^3*	820	749	715	1640	1762	1794	1056
Specific heat capacity	*kJ/kg.K*	1.256	0.937	0.782	1.9	1.56	1.214	2.5
Viscosity	*Pa.s*	0.00015	0.00018	0.00017	0.0063	0.003	0.0022	0.0002
Thermal conductivity	*W/(m.K)*	119.3	26.2	30.7	na.	0.363	0.536	0.093
Prandtl number		0.0016	0.0063	0.0043		12.89	4.98	5.38

Table 1. Properties of heat transfer fluids [3], [7], [9], [10]&[11]

2.1. Thermal oil[1]

Some parabolic trough collector (PTC) type solar plantsuse synthetic oil as a primary heat transfer fluid. There are various brands of synthetic oil heat transfer fluids. Synthetic heat transfer oil such as Dowtherm A is stable at higher temperatures than mineral oil. They start to decompose at 400°C. At the maximum operating temperature the vapour pressure of Dowtherm A is 11 bars, which means that all the pipes, joints and receiver tubes need to be pressurised. Thermal oil is highly flammable, especially at high temperature. It is also hazardous to the environment if it should leak out of the system.

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[1] [9]

2.2. Molten salt[2]

Sensible heat storage in molten nitrate salt is one of the most prominent thermal storage mediums today. The high melting point of eutectic nitrate salts means that trace heating needs to be installed in the field piping to keep the salt from freezing. Trace heating is where the HTF is heated to prevent freezing.For this reason it is preferable to use the salt as a primary HTF in a central receiver system where piping is contained within the tower and the power block.

Different molten salt mixtures are available but they generally have similar heat transfer characteristics. The most prominent high temperature salt is known as solar salt. It is a eutectic mixture of sodium nitrate (60 % by weight) and potassium nitrate (40 % by weight). It has a melting point of 238°C, and an operative temperature range of between 260 and 567°C. It is non-toxic, non-flammable and has a low vapour pressure.

For lower temperature applications ternary eutectic products like Hitec and Hitec XL are used. These salt mixtures have melting points of about 100°C lower than that of solar salt, but their maximum operational temperature is between 500 and 538°C. These salts are more applicable for parabolic trough collector (PTC) applications. Table 1 shows the operative temperatures of some molten salts. Solar salt is better suited for high temperature applications.

There is some incentive to use molten salt as a primary HTF in PTC plants[3]: Parabolic trough plants are the most mature CSP concept; the increased maximum operational temperature (from 400°C to 450-500°C) means higher thermal efficiency.

The use of molten salt as HTF in a PTC system needs innovative designs to prevent the solidification of salt in the receiver tubes. The high melting temperature of molten salt poses a potential reliability issue in CSP installations, but the risk is substantially mitigated in central receiver plants. The power consumption of a trace heating system depends on the specific plant and figures may vary extensively. In a study done on a 55 MW_e PTC system using molten salt as a primary HTF, the night time thermal power loss of the solar field was 10.7 MW_{th}[3].

In central receiver plants with storage it is possible to perform thermal storage and operate at a maximum temperature of 567°C. The risk of frozen salt blockage is still present but because the heat transfer pipes are centralized and substantially shorter, freeze protection is more manageable.

2.3. Direct steam

Direct steam allows higher operational temperatures than possible with either molten salt or thermal oil. Theoretically it is possible to achieve superheated temperatures, but the high operating pressuresare a limiting factor. While it is possible to build a regular steam cycle running at supercritical pressures, it is a technical challenge to create receiver equipment that can handle high pressures.

Currently the maximum operational steam conditions for a PTC are 500°C at 120bar in an experimental setup at the REAL-DISS test facility at the EndesasLitoral power plant in Carboneras (Spain). This technology is still in development but the main challenges are[4]:

- Availability in large numbers of high pressure components such as flexible connector hoses and high pressure receiver tubes.
- Suitable thermal energy storage
- Process management of direct steam generation within a large parallel field.

In central receiver systems the pressure limitations are far less, and process control is much simpler, but thermal storage remains an issue.

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[2] [10] [11]

Another limiting factor is the trade-off between receiver tube performance and maximum operating pressure. Higher pressures means that the receiver tubes need to be made of thicker walled tube. The thicker walls impede the heat transfer performance of the receiver tubes.

2.4. Air or gas

In an attempt to achieve higher thermal efficiencies it has been proposed that compressed air or gas be used in a Brayton cycle. Since both the HTF and the working fluid is a gas, the maximum temperature is no longer limited by the HTF or working fluid. But there are a number of drawbacks:

- The low density of the gas/air requires large heat transfer areas for efficient heat exchange to occur
- Since the gas or air is at high pressure, a closed volumetric receiver is needed. This is a major technical challenge for two reasons; the surface area needed for effective heat exchange is large, and the aperture needs to be covered by a completely transparent lens that can withstand high temperature and pressure [5].
- Thermal storage is difficult and needs a large surface area for heat exchange.

One example of proposed CSP concepts using air as a HTF is the SUNSPOT [6] project.

2.5. Sodium

Sodium is a well-known HTF in fast neutron reactors. It has a melting point of 97.8°C and boiling point of 881.4°C$_{@atm}$. It has a very high thermal conductivity and relatively high heat capacity, making it a good HTF, but it is very reactive with water.In the 50’s the United States of America began the development of liquid metal fast breeder reactors (LMFBR). Sodium was chosen as the coolant because of its good heat transfer and nuclear characteristics. The program outcomes were very stringent and they had to satisfy guidelines and standards that ensured reliable operation of sodium cooled power plants, and the ability for operators to live with sodium on a routine basis. All data, guidelines and experience gained over this program were published in the Sodium-NaK Engineering Handbook by the Liquid Metals Engineering Centre[7].

In the 80’s a consortium funded by the IEA investigated the use of sodium as a coolant in CSP applications. Testing was done at the Plataforma Solar de Almería (PSA) as the IEA-SSPS High Flux Experiment [8]. In August 1985 a sodium fire broke out during a maintenance procedure and caused extensive damage to the sodium system and the PSA. This event emphasised the importance of safe liquid metal design practices.

Sodium solidifies at 97.8°C. In a system where the primary source of thermal energy is intermittent the possibility exists that the sodium could solidify somewhere in the system. This causes a hazard and some measures will have to be taken to unblock the system to prevent a sodium spill. This situation is avoided at all costs in the nuclear industry, and Eutectic NaK alloy is used instead [7].

2.6. NaK

In LMFBRs that need to be operated intermittently, the solidification of sodium causes an inherent reliability issue. Therefore NaK is used in these reactors [7]. Similarly one can argue that the use of sodium in a CSP application causes an inherent risk of blockage since the energy source is intermittent, thus NaK is more suitable for CSP applications.

NaK is a eutectic alloy of sodium and potassium that melts at -12.8°C$_{@\ atm}$ and boils at 785°$_{@\ atm}$. If NaK is used as a primary HTF, a maximum operating temperature of 785°C is possible, and the HTF will remain liquid regardless of operating conditions. NaK has heat transfer properties inferior to than those of sodium (see Table 1), and a relatively low specific heat capacity compared to other HTFs, but it is still considered an excellent heat transfer medium. The NaK eutectic system (shown in Figure 1) also allows for different compositions of sodium and potassium. Eutectic NaK has composition of 77.8% potassium by weight and 22.2 % sodium. It is possible to use NaK46 (46% potassium), which has a melting point of 20°C, and has higher thermal conductivity and greater specific heat capacity than eutectic NaK [7]. The properties of sodium, potassium and NaK are shown in Table1. The properties for NaK (in Table 1) is that of eutectic NaK alloy, even though it is acknowledged that NaK alloy with higher sodium content is more suited for CSP applications.

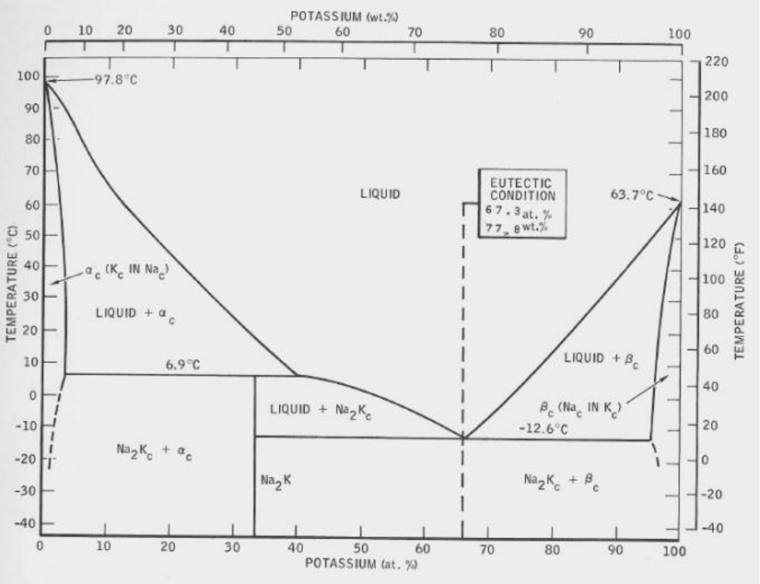

Fig.1. Sodium-Potassium eutectic system [7]

The biggest risk involving NaK and sodium is that it reacts violently with water. This becomes a problem during routine maintenance and when parts need to be replaced. In a system using NaK it is possible to clear the piping using high pressure inert gas when the system has cooled down. This is inherently safer than a situation where there is a risk of pipe blockage during maintenance.

By pressurising eutectic NaK to a pressure of 10bar, the operational temperature of liquid NaK can be increased to over 1100°C [7].

2.7. Conclusion

Considering all the current HTF solutions in CSP, limitations on the maximum operational temperature is the most prominent. Liquid metals pose an elegant but risky solution to the problem, capable of maximum operational temperatures between 785°C (NaK) and 881°C (Sodium) at atmospheric pressure, which can be increased to temperatures exceeding 1100°C with moderate pressurisation. A comparison between the temperature ranges of the HTFs is shown in Figure 2. Note that pressurised NaK46 has an operational temperature range exceeding all of the other heat transfer fluids.

Both NaK and sodium are highly reactive with water, and both pose a serious safety risk. Experience with NaK and sodium as HTFs in LMFBRs yielded an extensive database of regulations, design codes and handling instructions that can be used to create a safe design that use either NaK or sodium as an HTF. Furthermore, NaK's low melting point is more suited for use in CSP than sodium because it does not pose an inherent risk for pipe blockage. Accordingly, it is possible to design a CSP system where personnel can work with the NaK system without danger, and have the advantage of high operating temperatures. The fact that NaK needs no freeze protection means that the entire primary loop can be shut down at night with no risk of damage to the receiver, pumps or heat exchangers. This means that the primary heat transfer system can be designed to be much more robust.

It should also be noted that other NaK compositions can also be used to increase the thermal conductivity, maximum operative temperature and to increase the specific heat capacity. By using a NaK composition of

48% potassium by weight, the NaK alloy still melts at 20°C but the heat transfer properties are improved. This translates to savings in pumping power for the primary cooling loop.

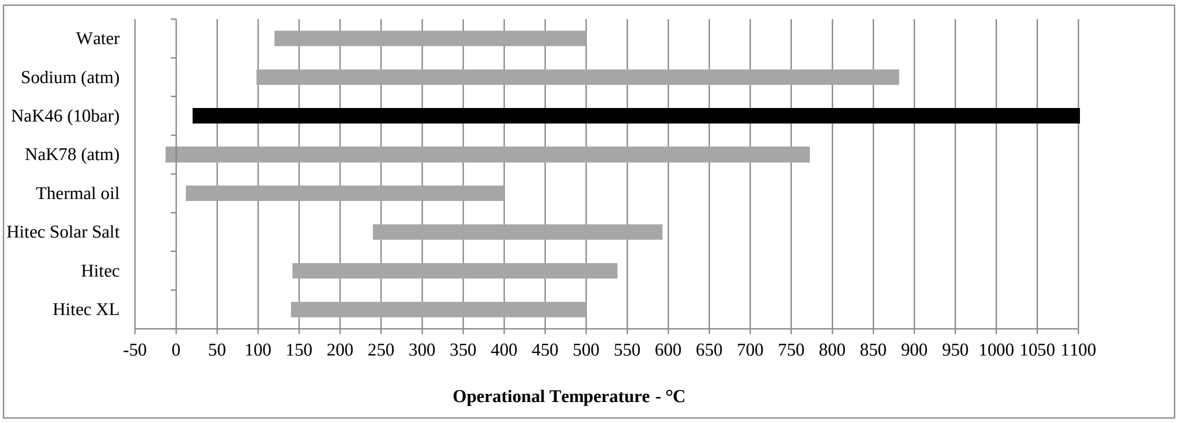

Fig.2.Comparison of HTF operative temperatures

3. Concept possibilities with NaK

The high temperature and high flux capabilities of liquid NaK yields a number of feasible new concepts for CSP, the only limitation being that NaK is reactive with water. For this reason all concepts are essentially limited to central tower applications.

3.1. Molten metal receivers

The heat transfer fluids generally used in central receivers are; water/steam, salt, air/gas or molten metal. The heat transfer characteristics and operational temperature range of these HTFs determine the size and nature of a receiver. One of the primary limitations on the receiver design is the heat flux that can be absorbed through the receiver surface to prevent overheating of the receiver walls. The peak flux for receivers has been measured using various heat transfer fluids, the results are presented in Table 2 below. The data of the table was obtained in a study at the PSA in the 80’s [8]. Each value is measured from a state of the art receiver from that era.

Heat transfer fluid	**Peak flux (MW/m^2)**
Liquid sodium	1.5
Molten nitrate salt	0.8
Steam vapour	0.4
Air	0.22

Table 2. Maximum peak flux possible with various heat transfer fluids [8]

From Table 2 it can be seen that a receiver using sodium will be three times smaller than a receiver using steam and roughly half the size of a molten salt receiver. The high flux minimizes the receiver radiation losses because of the smaller surface aria. Whilst there are no data available for a receiver using NaK, its heat transfer characteristics will be similar to those of liquid sodium, especially NaK46. A Flownex simulation using NaK 78 properties revealed that it will be possible to build a NaK receiver made of Incoloy 800 that can also absorb a thermal flux of $1.5MW/m^2$ (the same as that for sodium). In Figure 3 the surface area of receivers working with different heat transfer fluids are compared. The sodium receiver will be substantially more compact than an air receiver, which is the only other high temperature receiver design in the comparison.

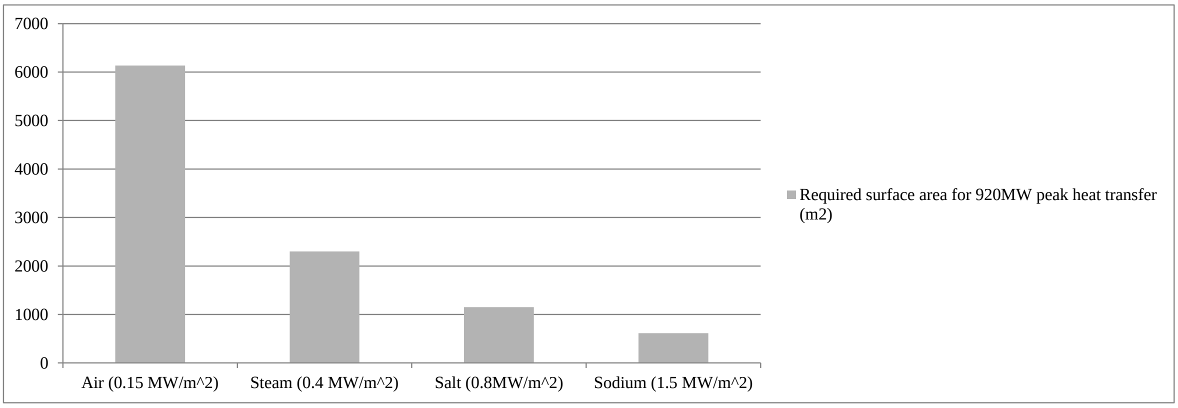

Fig.3. Comparison for surface area for a receiver designed to absorb 920MW of thermal energy [8]

3.2. High temperature storage

Since NaK can operate at temperatures exceeding 1000°C, a storage mechanism is needed that can utilize high thermal efficiency. If the temperature gradient is too large, entropy generation will affect efficiency. Currently the highest possible storage temperature is 567°C in molten salt. Molten salt is a proven technology but again solidification is still a problem.

Kotzé *et al.*[2] proposed a storage system that utilizes the latent heat of fusion in a eutectic aluminium-silicon alloy, AlSi12. The alloy melts at 577°C and storage occurs nearly isothermally. While this concept is still under development, it has some potential advantages including high storage density and the possibility to build a storage system that physically separates the primary coolant from the working fluid. This is made possible through the high thermal conductivity of AlSi12. Figure 4 describes the concept of the storage system. This storage concept can also be adapted for higher temperatures by using other metals.

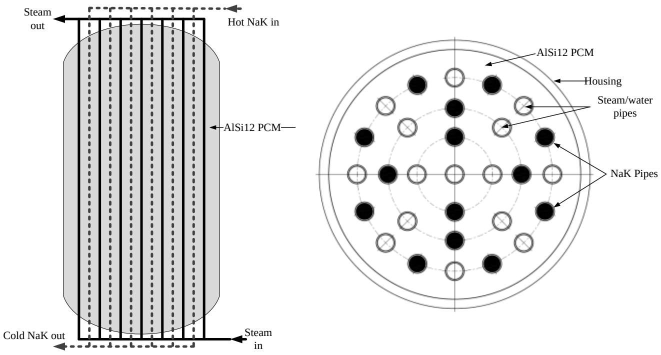

Fig.4. Metallic phase change thermal storage concept

Other phase change materials can also be used in a similar fashion. One prominent example is eutectic Magnesium-silicon alloy (MgSi56 – 56% silicon by mass). It has a melting point of 946°C and a heat of fusion of 757J/g, which is exceptionally high for a metallic phase change material (it must be noted that it has a relatively low density of 790kg/m^3)[2]. This makes metallic PCM storage a prospective storage concept for supercritical CO_2 power cycles.

It is also possible to cascade various PCM's in a latent heat thermal energy storage unit in order to reduce the HTF flow rate and to reduce entropy generation.

3.3. Power cycles

Plant efficiency can be increased by increasing the temperature of the heat source. The heat source is either the storage unit (for plants that have thermal energy storage) or the receiver. Higher temperature thermal energy storage is discussed in section 3.3. High receiver temperatures enable the power plant to operate at higher efficiencies.

The original metallic phase change thermal storage concept was proposed using a superheated steam power cycle. The proposed cycle was specified to deliver 100MWe with 15h of storage. The live steam conditions of the design are 540°C @ 150 bars, and a 540°C @ 30 bars reheat. This is more or less the limits for conventional steam power cycles. The steam generator is divided into three sections, boiler, super-heater and re-heater. The cycle is shown in Figure 5.

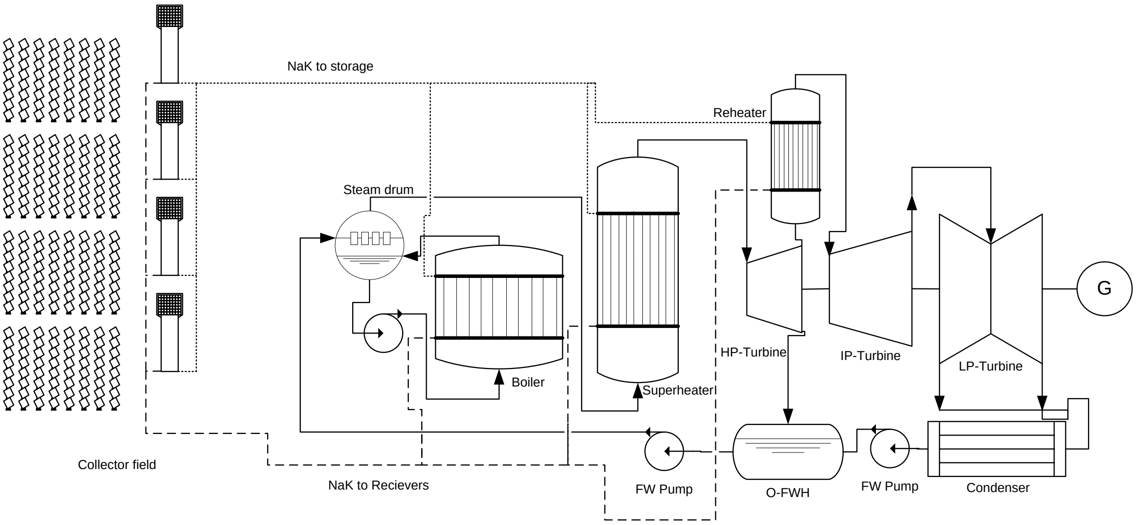

Fig.5. NaK in a steam cycle

Since the temperature of energy storage is limited to 577°C it is not economical to heat NaK up to its maximum temperature. This is due to a trade-off between the cost of achieving such high receiver temperatures, the cost of large heat exchanger surfaces and pumping losses. This means that an optimization is needed between pumping power, heat exchanger design and losses due to entropy generation.

To take full advantage of the high operating temperature of NaK higher storage temperatures are required (section 3.2) and a topping cycle is needed. A low risk solution is the use of a supercritical CO_2 or gas power cycle. A number of super critical power cycles are possible, with or without storage. Generally a super critical CO_2 power cycle will enable the power cycle to operate at a source temperature exceeding 850°C. The reason super critical CO_2 cannot be used directly in the receiver is that high pressures (20MPa) are required, and that high pressure pipes need to be laid all the way up a receiver tower. This has serious cost implications. Furthermore, a 20MPa high temperature receiver will have to be built, which is above the metallurgical limits of any known metal alloy to yield a feasible heat exchanger [12], [13]. NaK will be used as an intermediate heat transfer fluid between the receiver and the super critical CO_2 heat transfer unit, enabling higher receiver temperatures at lower cost.

Using air as a working fluid enables temperatures in the excess of 1000°C. The problem is that air is a very bad heat transfer medium, and that a pressurized volumetric air receiver for a large scale CSP plant is a technical challenge. NaK can be used as an intermediate heat transfer fluid, transferring thermal energy from the compact, more efficient NaK receiver, down to a NaK-Air heat exchanger. Again, a suitable thermal energy storage unit may be added to the cycle.

	Brayton cycle (Air)	**Steam Cycle**	**Super critical CO_2**
Source temperature (°C)	1000	540	850
Sink temperature (°C)	30	30	30
Efficiency (%)	30-42	38.95	48.06

Table 4. Comparison of thermal efficiency of thermal power cycles

Table 4 shows a comparison of the thermal efficiencies attainable by the three discussed power cycles. The efficiencies for Supercritical CO_2 and steam are calculated using the Chambadal-Novikov efficiency correlation. The Chambadal-Novikovcorrelation is not applicable Brayton cycles, but the efficiency of a gas turbine can be taken to be in the range of 30 to 42%. It is clear that there is a significant advantage in using higher temperature heat transfer fluids and appropriate power cycles. Taking all these factors into consideration, NaK-Super critical CO_2 power cycle will probably yield the most feasible high efficiency CSP solution.

4. Conclusion and recommendations

The heat transfer fluid used in the primary loop of a CSP plant has an effect on the receiver performance, the cycle efficiency and plant operation in general. The most prominent limitations are:

- The maximum operational temperature of the heat transfer fluid, which in turn limits the maximum thermal efficiency of the plant.
- The high melting point of conventional HTFs that cause an inherent risk of pipe blockage.

HTF's that were discussed were: Molten salts, high temperature thermal oil, steam, air, sodium and NaK. All of these have advantages and disadvantages, but NaK has the most favourable operational temperature range. Eutectic NaK is liquid at -12.8°C and boils at 785°C, but it has heat transfer characteristics inferior to that of sodium. It is possible to use NaK46, a hypoeutectic NaK composition that is liquid at room temperature, and has heat transfer characteristics closer to that of sodium. The maximum operational temperature of NaK can further be increased with moderate pressurisation.

Liquid metals have been used in LMFBRs since the 1970's, and extensive research programs yielded design codes, property tables and safety regulations. Through years of naval use, it has been demonstrated that a reactor using NaK as a primary HTF, delivering heat to a steam cycle, can be designed and built in a way that it is safe for personnel to interact with it on a daily basis.

The use of NaK in a CSP application yields three challenges:

- How to utilize the high operational temperature of NaK in a way that cost is minimized.
- High temperature thermal storage.
- Safe operation

Work that has been done on sodium receivers shown that receivers that are designed for liquid metals yield robust and compact designs, capable of flux densities up to three times higher than possible with other HTFs. Furthermore it yields by far the most compact, robust and low cost, high efficiency, high temperature receiver designs of any HTF.

An evaluation of power cycles confirmed that a supercritical CO_2 power cycle my yield a significantly more efficient power cycle for high temperature CSP applications. The high pressures associated with supercritical CO_2 requires the use of a primary heat transfer fluid, and NaK is an ideal candidate HTF. Metallic phase change materials may offer high temperature, high density thermal energy storage.

Accordingly, it is recommended that further research is to done on the use of hypoeutectic NaK for CSP applications.

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