COUPLING SUPERCRITICAL AND SUPERHEATED DIRECT STEAM GENERATION WITH THERMAL ENERGY STORAGE

Joe Coventry[1] and John Pye[2]

[1] PhD, Wizard Power, 11 McKay Gdns, Turner ACT 2612, Australia, +612 6162 3456, joe.coventry@wizardpower.com.au

[2] PhD, Australian National University, +612 6125 8778, john.pye@anu.edu.au

Abstract

Two new concepts have been identified for direct steam generating solar fields that charge a two-tank molten salt storage system. The use of both supercritical and superheated subcritical steam is proposed, and discussed in practical terms and with regards to thermodynamic issues of heat transfer to the salt. Both concepts are found to allow significantly higher hot-tank temperatures than solar systems restricted by temperature limitations in thermal oil, with achievable temperatures comparable to solar tower systems that directly heat salt. This a distinct advantage for minimising the amount of salt required for a given amount of energy storage. Analysis of steam cycle efficiency using these results as a basis once again compared the supercritical and subcritical cases. For the power cycle, it was shown that there are advantages in using a supercritical power block when discharging from molten salt storage, because of the improved matching of the salt and steam cooling curves. Two examples were developed, and an increase in thermal conversion efficiency from 42.4% to 43.8% was found comparing the subcritical to the supercritical steam cases, were a suitable turbine available. Overall, energy transport and storage concepts are presented that maximise the advantages of high temperature that are achievable from high-concentration solar collectors such as solar dishes, in particular, minimisation of molten salt quantities in storage, and maximisation of thermal cycle efficiencies.

Keywords: supercritical, superheated, direct steam generation, molten salt.

1. Introduction

Direct steam generation (DSG) in solar trough plants has been demonstrated through the DISS project [1], driven by the goal of higher temperature steam generation than possible with current-technology heat transfer oils, hence higher efficiencies in the power block. In addition, DSG eliminates the exergetic losses associated with oil-to-steam heat exchangers and avoids the cost of the oil itself. DSG in single-pass boilers in solar dish concentrators has been demonstrated over a long period at the Australian National University (ANU) [2], affording higher temperatures than for troughs, and fewer complications associated with two-phase flow.

In recent years, there has been renewed interest in energy storage systems coupled to solar plants. The two-tank molten-salt thermal storage system is the most advanced energy storage system, having been demonstrated on both troughs (SEGS I) and towers (Solar Two) [3], and presently being deployed at the Andasol-1 plant in Spain. However, the integration of molten salt storage with a DSG system is challenging, due to the 'pinch point' problem, as described by Steinmann et al [4]. The pinch point is the result of a mismatch in heat transfer properties between the storage medium, with purely sensible heat exchange, and the steam, which undergoes latent heat transfer in both charging and discharging phases. A temperature-enthalpy diagram shows the heat exchange between the two fluids. The x-axis shows net heat transfer in the form of total enthalpy change along the heat exchanger (the product of mass flow and specific enthalpy for the fluid). For heat to be transferred, the steam must be at a higher temperature than the storage medium at all points along the heat exchanger. The pinch point problem is demonstrated using this format in Figure 1, which shows upper salt temperature limited to 378°C despite the availability of 600°C steam.

Attempts to resolve the pinch point problem have included use of phase-change-material storage in series with sensible heat storage [4], where oils, phase-changing salts and then liquid salts, in three separate stages, were proposed to obtain a heating and cooling curve more closely matching that of subcritical steam.

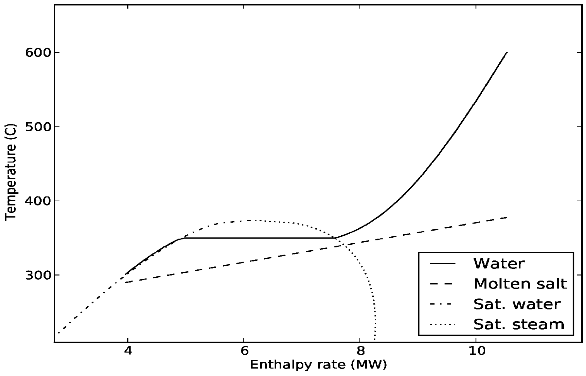


Figure 1. Temperature-enthalpy diagram showing how the 'pinch point' limits the upper temperature of the energy storage medium. Shown is the cooling curve of 165 bar steam.

This paper proposes two different concepts for charging molten salt storage systems with a DSG solar system. Firstly, supercritical steam is proposed as a working fluid that can be used for heat transfer to the thermal storage, thereby reducing the pinch point problem. Secondly, a subcritical steam system is proposed using only superheated vapour for heat exchange to the storage system. Both concepts allow a simpler single-fluid storage system.

2. Solar thermal storage for dispatchable power generation

The energy storage concepts discussed in this paper rely on the ability of the solar field to generate high temperatures (in excess of 500°C). Two-axis tracking solar collectors with higher concentration ratios are more suited to this type of application, due to their significantly higher thermal efficiency at such elevated temperatures. Solar tower plants have the capability of generating suitable high temperature steam; however, for storage applications, direct heating of molten salt in power towers [5] is likely to be preferred. Solar dish technologies are ideally suited to the concepts discussed in this paper, with steam providing the energy transport in the dish field, and the temperatures required can be achieved with relatively low thermal loss.

A simple configuration relevant for both dish and trough collectors concepts is shown in Figure 2. Energy is transported via the steam network to a exchanger. A two-tank molten salt system has a 'hot tank' and a 'cold tank', each maintained at a constant defined temperature. Salt is pumped from the cold tank to the hot tank through the heat exchanger, with the flow rate controlled such that the outlet salt temperature matches the hot tank set-point. To transfer energy from the molten salt storage system to the thermal power block, salt from the hot tank is pumped to the cold tank via one or more heat exchangers to generate steam.

Typically a salt mixture of 60 % sodium nitrate and 40 % potassium nitrate (by mass) has been used for molten salt storage systems, as it offers a favourable combination of density, specific heat, chemical reactivity, vapour pressure and cost [6]. In addition, the practical upper and lower temperature limits of this salt mixture are well matched to thermal steam cycles. The nitrate salt can be used over a range of approximately 260°C to 621°C [7], although a more conservative cold tank temperature of around 290°C is typically adopted. Hot tank temperatures are typically around 390°C for trough applications, and 565°C for tower applications. For the purposes of this paper, a lower salt tank temperature of 290°C is adopted to conform with past industry experience.

Typically conventional coal-fired supercritical steam power plants operate at around 300 bar and 600°C, and suitable steel alloys have been developed for use in these plants [8]. For the purposes of this paper, the upper limits on steam conditions from the solar field are set at 300 bar and 600°C, with the assumption that metallurgical constraints will be similar to existing supercritical steam power plants. This also indirectly imposes an upper limit on the hot salt tank temperature. Solar dish collectors are able to generate temperatures of 600°C with modest thermal losses (around 10-15 %). The Big Dish technology [9], originally developed at the Australian National University, and now being commercialised by Wizard Power,

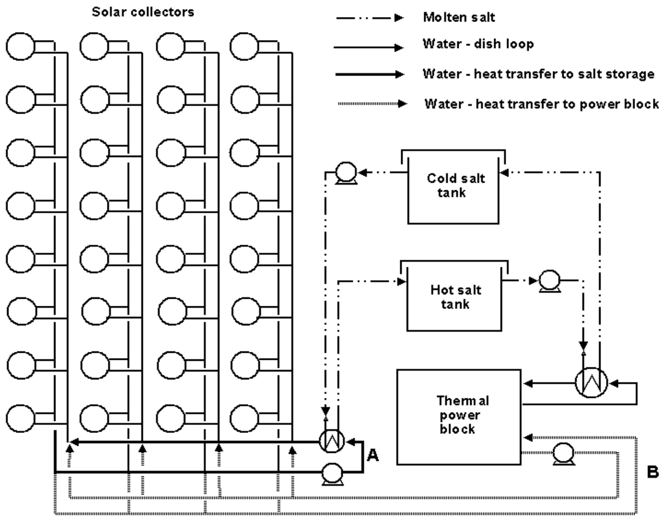


Figure 2. Basic process flow sheet showing interconnectivity of a solar field, molten salt storage system and thermal power block.

is a suitable technology for supercritical steam generation, as are central receiver systems such PS-10, PS-20 and those under development at CSIRO, Australia.

Previous concepts using DSG in combination with molten salt storage have discussed modes of operation of the solar field that allow a combination of both steam generated from the salt storage and steam generated directly by the solar field in the thermal power block [10]. The motivation for such concepts is to avoid exergetic losses in heat transfer into and out of the salt storage, although some exergetic losses are unavoidable due to mixing of steam of different temperatures. Figure 2 suggests an alternative concept where header pipes are duplicated in the solar field, allowing individual rows of collectors to be switched to either the salt storage loop (labelled 'A') or routed directly to the thermal power block (labelled 'B'). This would allow either the thermal power block to operate at a higher temperature corresponding to the maximum outlet temperature from the solar field, or for the dish field to operate at a lower temperature, maintaining the power block steam conditions. Either way, there are efficiency gains in the overall solar-to-electricity cycle due to improved power cycle efficiency or reduced thermal losses from the collectors, respectively.

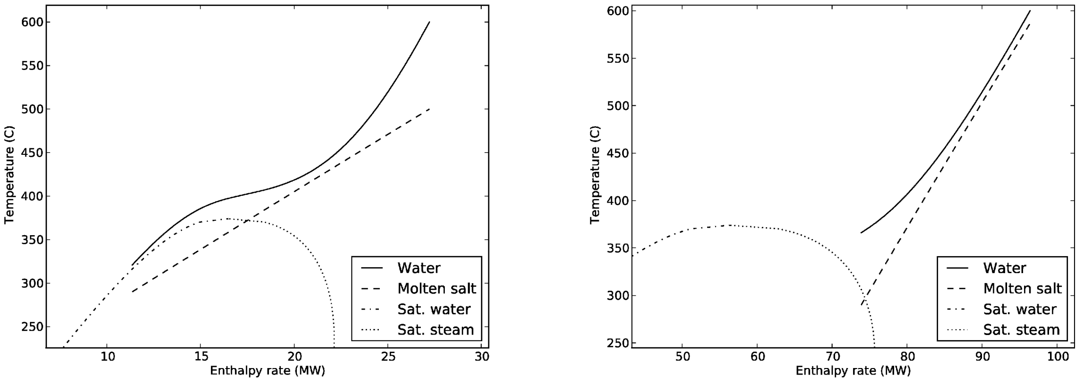
3. Charging of storage

To avoid exergetic losses, an efficient thermal storage system requires that heat transfer occur across the smallest possible temperature difference, both when charging with heat from the solar field, and when discharging heat to the power block. However as discussed, any system that couples latent and sensible heat transfer will result in large temperature differences. By comparison, both concepts discussed below reduce the temperature difference across the heat exchanger, hence reduce exergy destruction, and allow the hot salt storage temperature to reach a value closer to that of the maximum steam temperature from the solar field. The latter point reduces the amount of salt required in storage due to the higher temperature difference between hot and cold tanks, and allows for higher power cycle efficiencies.

3.1. Charging of storage with supercritical steam

It is proposed that DSG can be used with supercritical steam in order to avoid latent heat transfer. The temperature-enthalpy relationship of supercritical steam is a smooth curve that gradually approaches a straight line as pressure increases. The pinch point due to the sharp 'knee' of the subcritical cooling curve is mitigated by a supercritical solar collector loop, although a gentler pinch remains, as is shown in Figure 3(a).

For Figure 3(a), it is assumed that the heat exchanger inlet conditions are 600°C and 300 bar for steam, 290°C for salt, with a minimum heat exchanger 'pinch point' temperature difference of 12°C. Under these conditions, the salt outlet temperature is around 500°C. The plot shows the degree of 'waviness' in the properties of water at 300 bar still limit the salt outlet temperature to well below the practical upper limit for



(a) (b)

Figure 3. Temperature-enthalpy diagrams showing heat transfer to molten salt from (a) supercritical steam at 300 bar, and (b) superheated subcritical steam at 165 bar.

nitrate salts; nonetheless, the temperature range between hot and cold salt tanks is doubled when compared to systems that use synthetic oil as the heat transport medium.

3.2. Charging of storage with subcritical superheated steam

It is proposed that subcritical steam can be used to charge an energy storage system with a single sensible-heat-storage medium, by restricting the steam conditions to the superheat region. The temperature-enthalpy relationship for superheated steam is reasonably matched to that of nitrate salt at a range of pressures. Figure 3(b) shows an example of this relationship for steam at 165 bar.

In Figure 3(b) it is assumed that the heat exchanger inlet conditions are 600°C and 165 bar for steam, 290°C for salt, with a minimum 'pinch point' temperature difference of 12°C. In this case, the salt outlet temperature is significantly higher at 587°C, hence the temperature difference between the hot and cold salt tank is 297°C. This is approximately a factor of three times better than systems limited in temperature by the use of synthetic oil as the heat transport medium, and 50% better than the supercritical steam scheme previously discussed.

While the superheated subcritical scheme has a significant advantage over the supercritical scheme in terms of the attainable hot tank storage temperature and the possibility of using lower-pressure piping, a disadvantage is that the mass flow of water in the pipe network must be significantly higher. This is due to the smaller enthalpy range between water inlet and outlet conditions for the subcritical scheme compared to the supercritical scheme (or, indeed, compared to conventional DSG without storage). Using the two examples presented in the previous sections, the mass flow for the subcritical scheme is higher by a factor of 2.4, and hence the cross-sectional area of the pipes in the solar field will be higher by the same amount if the same flow velocity is assumed.

Reducing the average temperature difference across the heat exchanger further is possible if the steam pressure is lower, but the trade-off is a further reduction in enthalpy difference in the steam between the desired temperature limits. Higher pressures may offer an advantage in this regard, but the trade-off is likely to be an economic one, as more expensive alloys are required in the pipe network. There may be advantage in matching the piping design pressure to the maximum steam turbine pressure to allow maximum benefit when reticulating steam directly to the turbine; for this example, the pressure chosen matches the subcritical Rankine cycle pressure in the example later in this paper.

4. Practical aspects of water reticulation and control philosophy

Figure 4 suggests possible water reticulation details for both steam charging concepts. Under steady state (or gradually changing) solar conditions, mass flow in the solar field can be controlled to achieve the design

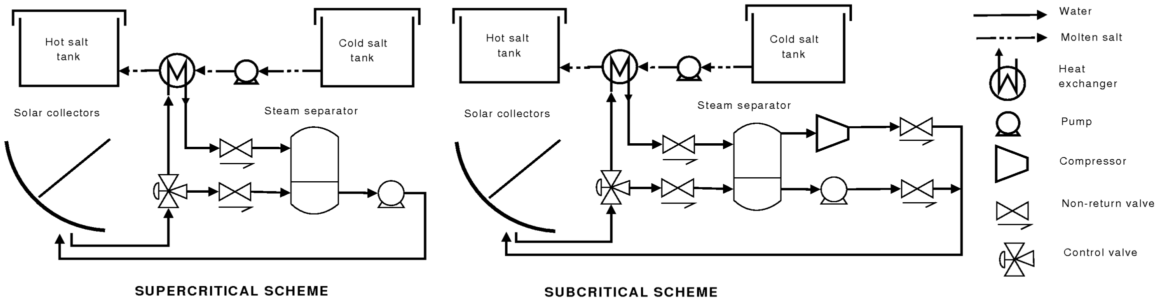


Figure 4. Details of process flow for steam charging of molten salt storage

outlet steam temperatures given in Figures 3(a) and 3(b). Under these conditions, the steam is reticulated to the heat exchanger at the salt storage tanks, and the mass flow of salt is controlled to achieve the hot tank temperature. Liquid water is circulated by a pump for the supercritical scheme, and water vapour circulated by a compressor for the superheated subcritical steam scheme. The rapidly changing nature of the solar resource means that there will be times when the outlet temperature of steam will drop below the target temperature (and will be lower than the temperature of the hot-salt tank). In this case, the salt storage is bypassed, and the fluid is circulated through a separator in bypass mode. If the sun returns, the steam temperature will rise until the desired conditions are regained, and the bypass mode is switched off. Two-phase outlet conditions from the solar collectors are possible in the subcritical steam scheme when in bypass mode. Under these conditions, vapour will continue to be circulated (at reduced mass flow as water is condensed in the separator) until the system pressure drops below some design point. The pump is used only at start up, with fluid circulated to a small portion of the solar field until suitable pressure is achieved to switch reticulation of fluid from the pump to the compressor.

5. Thermal power cycles with molten salt thermal storage

For charging the molten salt storage, there are exergetic advantages in minimising the temperature difference between the salt and steam in heat transfer. Supercritical steam has the same advantage in a power cycle that it has in charging steam: a gently curved temperature-enthalpy relationship that more closely matches the sensible heat characteristics of the molten salt than steam that undergoes phase change. However, heat transfer to subcritical steam is also feasible, as has been demonstrated on projects such as Solar Two [5].

In this section, thermal-to-mechanical efficiencies for both subcritical and supercritical Rankine power cycles are examined, using, as a basis, the higher of the two molten salt hot tank temperatures (587°C) from the schemes discussed above. A Rankine cycle is modelled that includes a reheat stage, and both open and

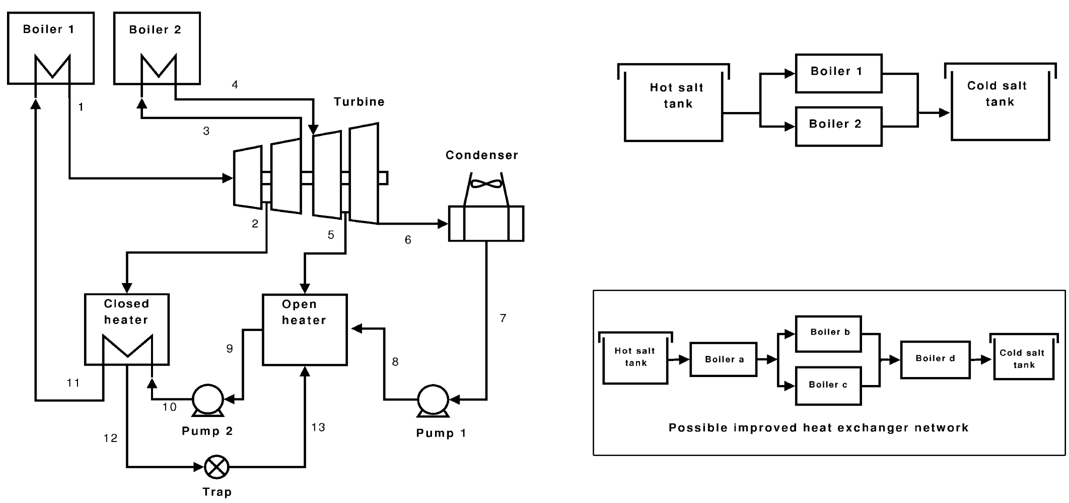


Figure 5. Schematic diagram of thermal power cycle (left), a simple heat exchanger network (top right). Bottom right shows a generic heat exchanger network for improved heat transfer.

closed feed water heaters (Figure 5). For simplicity, it is assumed that the steam generation and reheat are carried out in two parallel heat exchangers (Boilers 1 and 2). Simulations have been carried out using the ASCEND modelling environment [11].

It is noted that in practice Boiler 1 may consist of multiple heat exchangers to match steam conditions, for example, a liquid preheat stage, a steam drum and vapour superheat stage. Boiler 2 is also running as a vapour superheater. More efficient heat exchanger networks that minimise exergetic loss are possible, by matching heat exchangers to more limited temperature ranges. For example, a possible series-parallel network is shown in Figure 5, where the parallel heat exchangers could correspond to only the portions of the steam generation and reheat curves with overlapping temperature ranges.

5.1. Thermal storage discharging to a subcritical steam turbine

A reheat-regenerative Rankine cycle was designed to utilise the two-tank molten-salt thermal supply (Figure 6). Temperature-enthalpy curves in Figure 7 show the heat transfer in each boiler stage for the same power cycle. The abscissae are total enthalpy rates for each fluid, with flow rates adjusted for a net cycle mechanical power output of 50 MW. Maximum cycle pressure is 165 bar, to match specifications of the Siemens SST-700 [12] generator unit in common use in current solar thermal trough projects [10]. The maximum steam temperature also respects the upper limit for this turbine (585°C). Other assumptions include a condensing temperature of 55°C (to allow the use of an air-cooled condenser), isentropic turbine efficiencies 87%, pump efficiencies 80%, and intermediate pressures 20 bar (bleed), 18.67 bar (reheat), 4.9 bar (bleed) and 0.1576 bar (condenser). Minimum heat exchanger temperature difference is 12 °C.

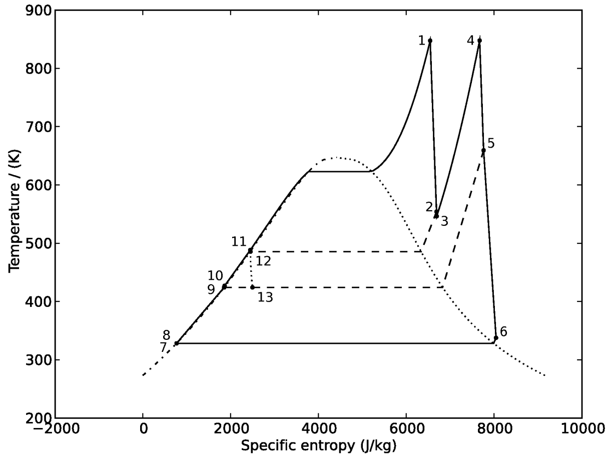
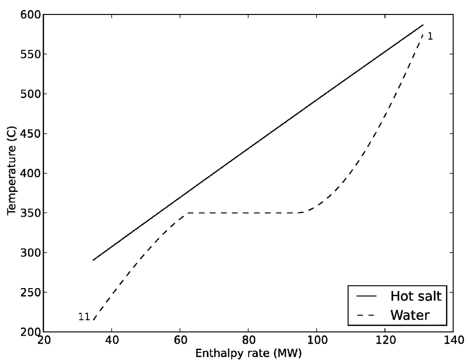
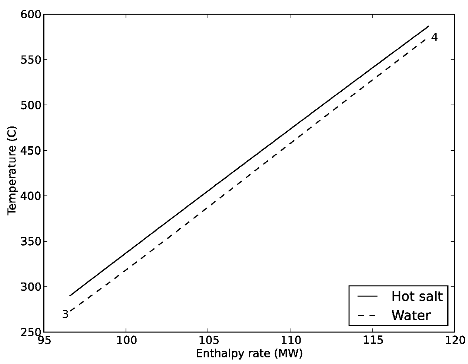


Figure 6. Temperature-entropy diagram for a reheat-regenerative subcritical Rankine cycle



(a)



(b)

Figure 7. Heat transfer temperature-enthalpy curves for the two boiler stages in the subcritical cycle: (a) main boiler and (b) reheater.

Some partial optimisation of the cycle was undertaken, but further improvements will be possible. Attention here was focussed on minimising exergetic losses in the two boilers, using feedwater heating to gain a boiler inlet temperature approaching the cold salt tank temperature. Thermal-to-mechanical efficiency for this example is 42.4 %.

5.2. Thermal storage discharging to a supercritical steam turbine

The temperature-entropy diagram in Figure 8 shows an example of a supercritical power cycle, and, as above, the temperature-enthalpy curves in Figure 9 show the heat transfer in each boiler. An upper steam pressure of 300 bar, is chosen to match current state-of-the-art supercritical power plants [8]. Assumed, as before, are condensing temperature 55°C, isentropic turbine efficiencies 87%, pump efficiencies 80%. In this case, intermediate pressures are 48 bar (bleed), 39 bar (reheat), 4.5 bar (bleed) and 0.1576 bar (condenser). Minimum heat exchanger temperature difference is again 12 °C.

The shape of the supercritical steam T-H curve in Figure 9 matches the molten salt T-H curve somewhat better than in the example of Figure 7, meaning lower exergetic losses, and a higher average temperature in the boilers, contributing to an improved conversion efficiency of 43.8 %. As for the subcritical example, more cycle optimisation will be possible. At present, the availability of supercritical turbines is limited to sizes larger than can be used in any current commercial solar plant. However, the scale of plants is growing, and supercritical cycles may soon be feasible.

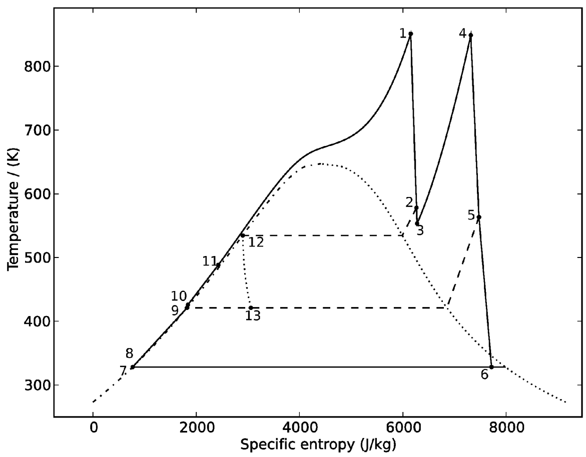
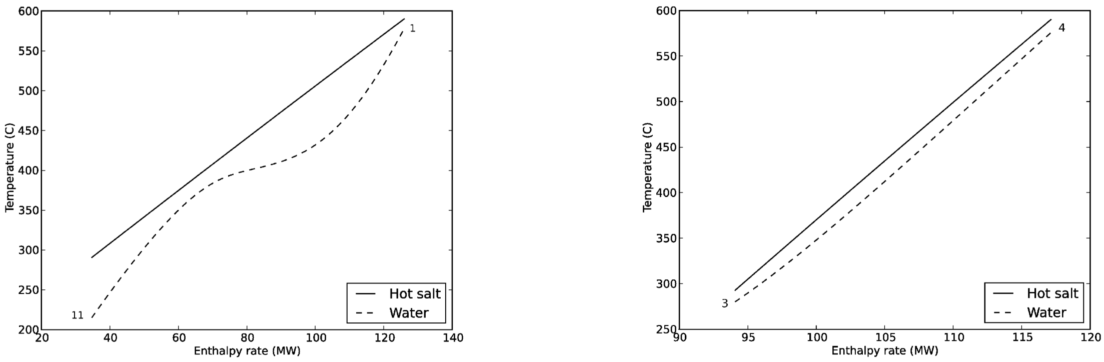


Figure 8. Temperature-entropy diagram for a reheat-regenerative supercritical Rankine cycle.



(a) **(b)**

Figure 9. Heat transfer temperature-enthalpy curves for the two boiler stages in the supercritical cycle, (a) main boiler, and (b) reheater.

6. Conclusion

Two new concepts have been identified for direct steam generating solar fields that charge a two-tank molten salt storage system. The use of both supercritical and superheated subcritical steam is proposed, and discussed in practical terms and with regards to thermodynamic issues of heat transfer to the salt. The severe 'pinch point' problem, previously identified for DSG solar fields charging molten salt storage, is largely avoided in both concepts. In the case of the supercritical steam concept, some mismatch remains between the cooling curves of the steam and the molten salt, resulting in a reduced hot-tank temperature compared to the available steam temperature. However, the superheated subcritical steam concept capitalises on the availability of high temperature steam; for example, assuming 600°C steam generation, hot-tank temperatures as high as 587°C are possible. This gives a large temperature difference between the tanks of around 300°C, three times higher than solar systems restricted by temperature limitations of thermal oil, and comparable to solar tower systems that directly heat salt. This a distinct advantage for minimising the amount of salt required for a given amount of energy storage. Analysis of steam cycle efficiency using these results as a basis once again compared the supercritical and subcritical cases. For the power cycle, it was shown that there are advantages in using a supercritical power block when discharging from molten salt storage, because of the improved matching of the salt and steam cooling curves. Two examples were developed, and an increase in thermal conversion efficiency from 42.4% to 43.8% was found comparing the subcritical to the supercritical steam cases, were a suitable turbine available. Overall, energy transport and storage concepts are presented that maximise the advantages of high temperature that are achievable from high-concentration solar collectors such as solar dishes, in particular, minimisation of molten salt quantities in storage, and maximisation of thermal cycle efficiencies.

The ANU Solar Thermal Group has a continuing interest in energy storage technologies for dish concentrators. Wizard Power is currently commercialising the Big Dish technology with the goal of delivering solar energy, on demand, at large scale.

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