KALEX LLC.

Superior Efficiency
Reduced Costs
Viable Alternative Energy

Kalex
Kalina Cycle Power Systems For Ocean Thermal Energy Conversion Applications

Introduction:

Ocean Thermal Energy Conversion is a zero-emissions, fully renewable source of power that is well suited for power generation for coastal power consumers who are near ocean water that has an adequate difference between its surface temperature and the temperature of deep water. In places where the prerequisites for it exist, OTEC has the potential to be a highly viable and profitable means of power generation.

OTEC operates by utilizing the temperature difference between warm surface water and cold deep ocean water.

Because the warm surface water exists in equilibrium with the ambient, the real source of energy potential (exergy) is represented by the cold water. However, because the warmer surface water is far easier to obtain than the colder deep water, the supply of cold water is the limiting factor in OTEC applications.

It is therefore desirable to utilize the given flow of cold water to the greatest possible extent. In other words, it is desirable for an OTEC power system to heat the cold water flow to the highest temperature possible. Correspondingly, it is desirable to cool the warm water to the lowest temperature possible. In this way, the maximum use is made of the energy potential available between the cold and warm water.

This maximum use of the energy potential of the cold and warm water defines the degree of utilization of an OTEC system's energy source. The higher this degree of utilization, the lower the final temperature of the warm water and the higher the final temperature of the cold water. Therefore, the higher the degree of utilization, the lower the mean temperature of the warm water, and the higher the mean temperature of the cold water.

Therefore, the higher the degree of utilization, the lower the thermal efficiency potential of the power system, as defined by the Second Law of Thermodynamics.

It is possible to attain a high thermal efficiency in such a system, by using only the higher temperature portion of the heat in the warm water and the lower temperature portion of the cold water. However, though the thermal efficiency of such an approach would be higher, the actual power output per unit of cold water, which is the limiting factor of an OTEC application, would be substantially inferior.

Thus, in designing a power system for an OTEC application, there must be a balance between the system's thermal efficiency and the degree of utilization, to deliver a maximum power output per unit of cold water flow.

Kalex Systems for OTEC Applications:

Kalex LLC has developed a series of power systems designed to utilize very low temperature heat sources, designated as SLT (System, Low Temperature,) systems.

Kalex's SLT systems utilize a multi-component working fluid. The composition of this working fluid is varied throughout the system, allowing optimum working fluid characteristics at each point in the power cycle in a way that cannot be matched with a single component, or non-variable composition working fluid. The preferred working fluid for Kalex SLT systems is a water-ammonia mixture; this gives superior thermodynamic qualities, and also allows the use of standard steam turbines.

As with all Kalex systems, the SLT systems are designed to use only proven "off-the-shelf" components that are widely available in the power industry. Moreover, all components in a Kalex system operate within their designed parameters. By avoiding the use of experimental or specialized high cost components, Kalex systems can attain their high performance at low cost, while maximizing reliability and minimizing technological risk.

For OTEC applications, Kalex has designed a system designated SLT-4c.

SLT-4c is described in detail in appendix A.
A flow diagram of SLT-4c is given in figure 1 of appendix A.

System SLT-4c is comprised of two subsystems; one subsystem delivers relatively high pressure, high temperature working fluid to the turbine; the other subsystem provides thermal compression, reducing the pressure at which the condensation of the expanded vapor (exiting the turbine) occurs.

Both of these subsystems has its own separate condenser, through which the flow of cold water passes consecutively. This allows for an increase of the utilization of the cold water flow and also allows for the precise control of the degree of such utilization.

Comparative Performance:

The actual performance of any OTEC system is highly dependant on the available temperatures of cold an warm water, and on the limited volume of cold water that can be delivered to the system. Delivery of water to the system constitutes a fixed cost; once the pipes and pumps needed are installed and paid for, the water they obtain is cost free. However the cost of the equipment needed to obtain the water for an OTEC system is very significant. Of these costs, the cost of delivering cold water is by far the highest cost for the entire system.

For a given cold water flow, Kalex SLT-4c will tend to deliver between 180% to 200% the output of a Rankine Cycle system with the same cold water flow, (depending on the difference in temperature between the warm and cold water; the lower the difference in temperatures, the less overall power a system will deliver, but the greater the margin of superiority of a Kalex SLT-4c system over a Rankine Cycle system.)

It should be noted that the volumes of warm and cold water required for a substantial power output from an OTEC system are very large; on the order of many millions of pounds of water per hour and in some cases, over a hundred million pounds per hour. Therefore, a secondary, but still substantial cost is the cost of the heat exchanger apparatus needed to utilities the very large flows of warm and cold water.

Because of these factors, a useful measure of the efficacy of an OTEC power system is the cost per delivered kilowatt. These costs are highly dependant on the conditions of a given OTEC installation. However, in general, Kalex's SLT-4c system will tend to give a cost per delivered kilowatt that is between 60% and 90% lower than the cost of a comparable Rankine Cycle system, with the same available flow of cold water, (which, as noted above, is the primary limiting factor of an OTEC system.) (The lower the temperature difference between the available warm and cold water, the higher the overall cost per installed kilowatt, but at the same time, the greater the relative savings in costs between a Kalex SLT-4c system and a Rankine Cycle system.)

As can be seen above, SLT-4c substantially outperforms the Rankine cycle, both in terms of total power output and in terms of cost per delivered kilowatt. SLT-4c does usually require a larger flow of warm water, but in OTEC applications, it is cold water flow that is the limiting factor.

Kalex OTEC Brochure
Appendix A:
SLT-4c

System SLT-4c uses a mixture of at least two components with different normal boiling temperatures. (In the preferred embodiment of the system, water-ammonia is used.) Working fluid streams with a high concentration of the low-boiling component are referred to as "rich," and working fluid streams with a lower concentration of the low-boiling component are referred to as "lean."

SLT-4c operates as follows:

Warm water from the surface of the ocean, with parameters as at point 40, is pumped by a pump, P4, to an elevated pressure, obtaining parameters as at point 41, and then passes through a heat exchanger, HE3, which serves as a boiler for the power system's working fluid.

After passing thought HE3, stream 40 is cooled, transferring its heat potential to the working fluid (stream 3-8) and obtains parameters as at point 42.

Stream 42 is now divided into two substreams, having parameters as at points 43 and 45. Stream 43 now passes through a heat exchanger, HE2, where it is further cooled, (providing heat for the preheating of the working fluid, process 2-3, see below,) and obtains parameters as at point 44.

Meanwhile, stream 45 passes through a heat exchanger, HE4, where it is cooled, (providing heat for the vaporization of the auxiliary stream of working fluid, process 6-5-7, see below,) and obtains parameters as at point 46.

Thereafter, streams 46 and 44 are combined, forming a stream of water with parameters as at point 47, which then discharged from the system.

Meanwhile, fully condensed working fluid, (a rich solution,) with parameters as at point 1, corresponding to a state of saturated or slightly subcooled liquid, enters into a feed pump, P1, where its pressure is increased to a required level, and obtains parameters as at point 2, corresponding to a state of subcooled liquid.

Thereafter, stream 2 passes through HE2 (preheater,) where it is heated in counterflow with a stream of warm water, 43-44 (see above,) obtaining parameters as at point 3, corresponding to a state of saturated or slightly subcooled liquid.

Thereafter stream 3 enters into the boiler, HE3, where is further heated in counterflow by a stream of warm water 41-42 (see above,) is vaporized, and obtains parameters as at point 8, corresponding to a state of vapor-liquid mixture.

Stream 8 is now sent into a gravity separator, S1, where it is separated into a stream of saturated vapor with parameters as at point 16 and a stream of saturated liquid with parameters as at point 11.

Stream 16 is now sent through an admission valve, TV2, where its pressure is slightly reduced, obtaining parameters as at point 17. Stream 17 is then sent into the turbine, T1, where it is expanded, producing power, and obtains parameters as at point 18, corresponding to a state of wet vapor. The pressure at point 18 is substantially lower than the pressure at point 1 (see above.)

Stream 18 is now combined with a stream of lean liquid, having parameters as at point 21, forming a stream of vapor-liquid mixture with parameters as at point 22. Stream 22 is referred to as an intermediate solution, and is substantially leaner than the base working solution, as at point 1. This allows stream 22 to be condensed at substantially lower pressure than the pressure at point 1 (see above.)

Stream 22 is then sent into a low-pressure condenser, HE6, where it is fully condensed by a stream of cool water, 51-52, (see below,) and obtains parameters as at point 23, corresponding to a state of saturated liquid. The concentration of low-boiling component, and correspondingly pressure of condensation, at point 23 is substantially lower than at point 1. As a result, the rate of expansion in T1 is increased, with a corresponding increase in power output.

Stream 23 is now sent into a circulating pump, P2, where its pressure is increased to an intermediate level (slightly higher than the pressure at point 1,) obtaining parameters as at point 9, corresponding to a state of subcooled liquid.

Stream 9 is sent into a recuperative preheater, HE5, where it is heated in counterflow with a stream of lean working solution (24-10, see below,) and obtains parameters as at point 6, corresponding to a state of saturated or subcooled liquid.

Stream 6 is now sent into HE4 where it is heated in counterflow by a stream of warm water (45-46, see above,) is partially vaporized, and obtains parameters as at point 7, corresponding to a state of vapor-liquid mixture.

Meanwhile, stream 11 is divided into two substreams, having parameters as at points 12 and 13. Stream 12 contains the majority of the flow of stream 11.

Stream 12 then passes through a throttle valve, TV1, where it is throttled reducing its pressure to the pressure at point 15, and obtaining parameters as at point 25.

Meanwhile, stream 7 enters into a gravity separator, S2, where it is separated into a stream of very rich saturated vapor with parameters as at point 15 and a stream of lean saturated liquid with parameters as at point 20.

Now, stream 25 is mixed with a stream 15, (exiting from S2,) forming a stream of rich working solutions with parameter as at point 26.

Because stream 25 is richer than the intermediate solution (as at point 23) the formation of stream 26 requires a lesser quantity of rich vapor (with parameters as at point 15.) This allows the use of a leaner composition in stream 23. This, in turn lowers the pressure at point 23 and giving a corresponding reduction in pressure at point 18. This reduction in pressure at point 18 increases the expansion ratio, and the output, of the turbine.

Meanwhile, stream 13 (consisting of the remaining portion of stream 11 that was not sent into stream 12) is throttled in a throttle valve, TV4, where its pressure is reduced, and obtains parameters as at point 14.

Stream 14 is then mixed with stream 20 (the liquid from S2, see above,) forming stream 24. Stream 24 is now sent into HE5 where it is cooled, providing heat for process 9-6 (see above,) and obtains parameters as at point 10.

Stream 10 is then sent through a throttle valve, TV3, where its pressure is reduced to a pressure equal to the pressure at point 18, obtaining parameters as at point 21. Stream 21 is then combined with stream 18, forming a stream of intermediate solution with parameters as at point 22 (see above.)

Meanwhile, stream 15 is combined with a stream of intermediate solution with parameters as at point 25 (see above,) forming a stream of base working solution with parameters as at point 26, corresponding to a state of vapor-liquid mixture.

Stream 26 is then sent into a condenser, HE1, where it is cooled in counterflow by a stream of cool water, 52-53, (see below,) is fully condensed, and obtains parameters as at point 1, (see above.)

The cycle is closed.

Cool water, delivered from deep under the surface, having initial parameters as at point 50, is pumped to a required pressure by a water pump, P3, and obtains parameters as at point 51.

Stream 51 is then sent into HE6, where it cools process 22-23 (see above,) obtaining parameters as at point 52.

Thereafter stream 52 passes through HE1, providing cooling for process 26-1 (see above,) and obtains parameters as at point 53. Stream 53 is then discharged from the system.

As follows from this description, the cool water used as coolant in the condensers is used in the condensers HE6 and HE1 consecutively. This allows a drastic reduction in the required flow rate of the cooling water per unit of power produced.
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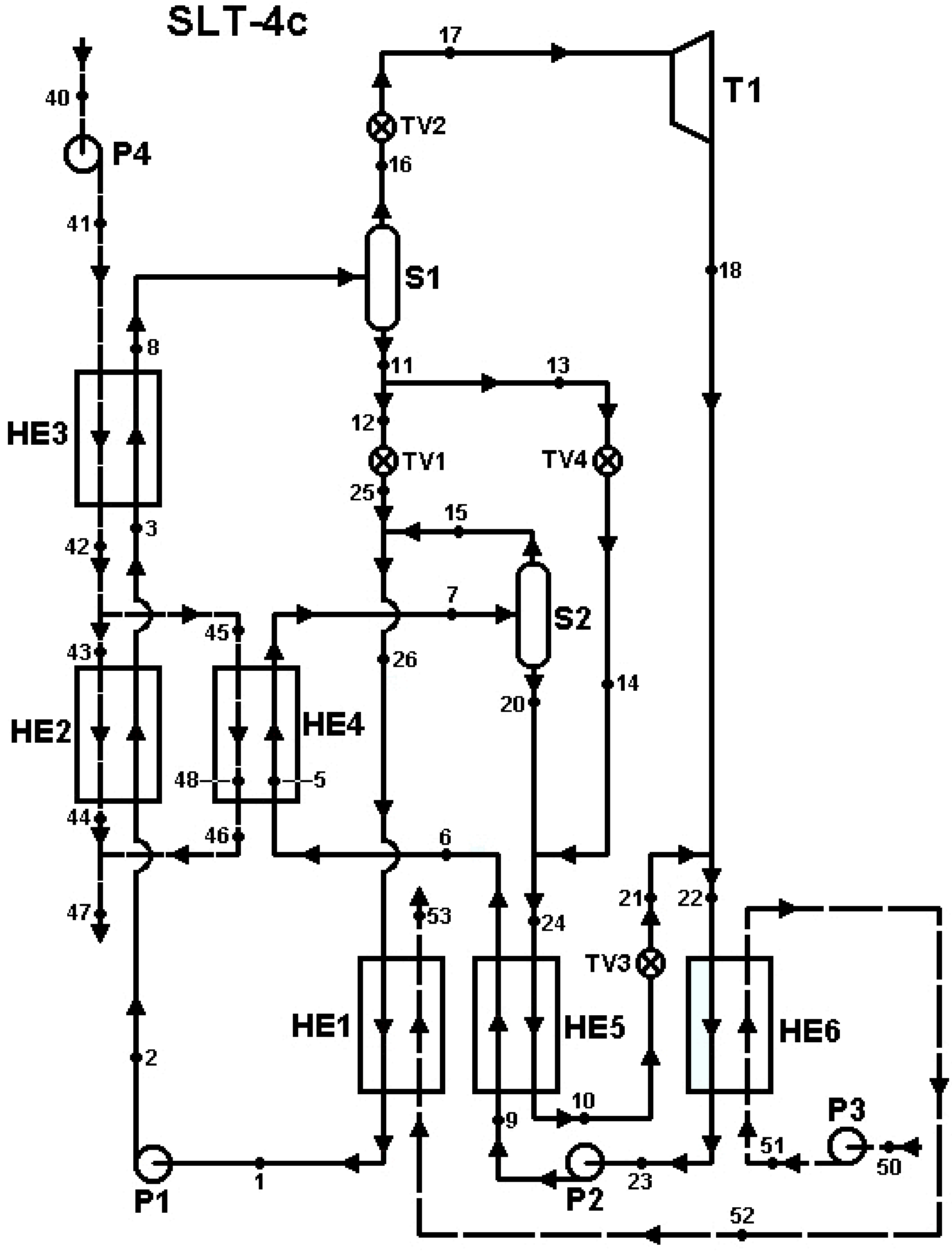
Figure 1:


SLT-4c
40
P4
41
17
T1
TV2
16
S1
18
8
11
13
HE3
12
TV1
TV4
25
15
3
42
7
S2
45
43
26
14
20
HE2
HE4
48
5
44
46
6
47
21
22
53
24
TV3
HE1
HE5
HE6
10
9
P3
2
51
50
P1
1
P2
23
52