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Efficient Conversion of Low Temperature Heat into Work

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Abstract— Historically industries have shown an aversion towards extracting work from low temperature heat sources mainly because the Carnot efficiency with these sources comes out to be lower and on top of it, if one employs the traditional Rankine cycle with these low temperature heat sources the cycle efficiency, in most cases, boils down to a single digit value. But in the recent past many ingenious augmentations have been proposed in our approach of heat extraction which has provided us with a substantial scope of improvement in the cycle efficiency. The aim of this paper is to discuss some of these process side breakthroughs in the field of extracting work from low temperature heat sources. More specifically the paper will be focusing on Kalina cycle and Organic Rankine cycle which are the two most promising and commercially developed options available among all low temperature heat extraction cycles.

Key words: Recuperator, mass fraction, waste heat

I. INTRODUCTION

Renewable energy sources, such as solar thermal and geothermal, and vast amounts of low temperature industrial waste heat are potentially promising energy sources which may prove to be instrumental in reducing carbon footprint significantly.

At present one can think of two application areas for this low temperature heat- Either to covert this low quality heat into work or to use this heat as process heat in industry.

Now, conversion of this low temperature heat into work can be achieved in two ways, viz. by using thermodynamic cycles or by direct conversion into electrical energy. The conversion of low temperature heat into work, if achieved through a conventional steam based Rankine cycle, proves to be highly inefficient due to high exergy losses in steam based cycle & also due to the fact that temperature of heat source is very low, which further lowers the cycle efficiency.

Therefore, to harness the true potential of these moderate and low temperature heat sources, it is essential to develop alternative thermodynamic cycles which are more efficient, only then low grade heat can be put to use economically. Organic Rankine cycle, Kalina cycle, Goswami cycle, and trilateral flash cycle are some of the promising developments in the field of conversion of low-grade heat into electricity. This paper will briefly review these alternative thermodynamic cycles.

II. OVERVIEW OF ALTERNATIVE CYCLES

A. Kalina Cycle

Kalina cycle uses a working fluid comprised of at least two different components, typically water and ammonia. The ratio between those components varies in different parts of the system to decrease thermodynamic irreversibility and therefore increase the overall thermodynamic efficiency.

B. Goswami cycle

This cycle is a combination of Rankine power cycle and an absorption cooling cycle. Its advantages include the production of power and cooling in the same cycle, the design flexibility to produce any combination of power and refrigeration and the efficient conversion of moderate temperature heat sources. The binary mixture used in the cycle consists of water and ammonia.

C. Trilateral Flash Cycle

The Trilateral Flash Cycle (TFC) is a thermodynamic power cycle whose expansion starts from the saturated liquid rather than a vapor phase. By avoiding the boiling part, the heat transfer from a heat source to a liquid working fluid is achieved with almost perfect temperature matching. Irreversibilities are thereby minimized.

D. Organic Rankine cycle (ORC)

Among all these thermodynamic cycles for low-grade heat-to-power conversion, organic Rankine cycle is so far the most commercially developed one. Both large scales and small scales power plants and units are in operation.

The organic Rankine cycle applies the principle of the steam Rankine cycle, but uses organic working fluids with low boiling points, instead of steam, to recover heat from a lower temperature heat source.

There are three types of Organic Rankine cycles depending upon where the four states of cycle occur-

1) Subcritical ORC
2) Transcritical ORC
3) Supercritical ORC

III. KALINA CYCLE

- It is the difference in thermo-physical properties of pure substances like water and those of a mixture, like ammonia & water, which marks the basic difference between Rankine cycle & Kalina cycle.
- The ammonia & water mixture used in this cycle behaves like a new fluid altogether, with its own properties.
- Two of the properties of this mixture which are in contrast to those of pure substances, are-
- First, in contrast to a pure substance, the ammonia & water mixture boils & condenses at varying temperature. Thus the process of phase change is not an isothermal process for this mixture.
- Second, in contrast to a pure substance whose thermo-physical properties are fixed, the properties of this mixture can be easily altered by changing the mass fraction of ammonia.

This property of non-isothermal boiling helps the working fluid of the Kalina cycle to closely match the temperature profiles of a practical heat source which permits the working fluid to extract more heat from the heat source. More importantly, if there are variations in the temperature of heat source or heat sink then the working fluid can be made to match these new profiles, by simply changing the ammonia concentration. This introduces a new degree of freedom in power generation.

However, since ammonia is more volatile than water, so at turbine exhaust one gets a higher pressure and temperature in Kalina cycle. Since this heat is available in the form of sensible heat so heat exchanger, known as a recuperator, can be placed in the turbine exhaust to absorb this sensible heat; this is in direct contrast to Rankine cycle where a large amount of latent heat is present in the turbine exhaust which can't be recovered and simply has to be wasted.

Fig. 1 shows a basic design of Kalina Cycle, which uses a recuperator to extract sensible heat from turbine exhaust.

Another novel design is shown in Fig. 2 which reduces the pressure and temperature at turbine exhaust by employing different concentrations of ammonia in different parts of the cycle.

In fact Kalina cycle can be described as a family of cycles, which are tailored for the temperature profiles of heat sources and heat sinks. This reduces thermodynamic irreversibilities and improves cycle efficiency. For example, in the waste heat environment, it has been observed that Kalina cycle can lead to improvement in cycle efficiency of 20 to 40%.

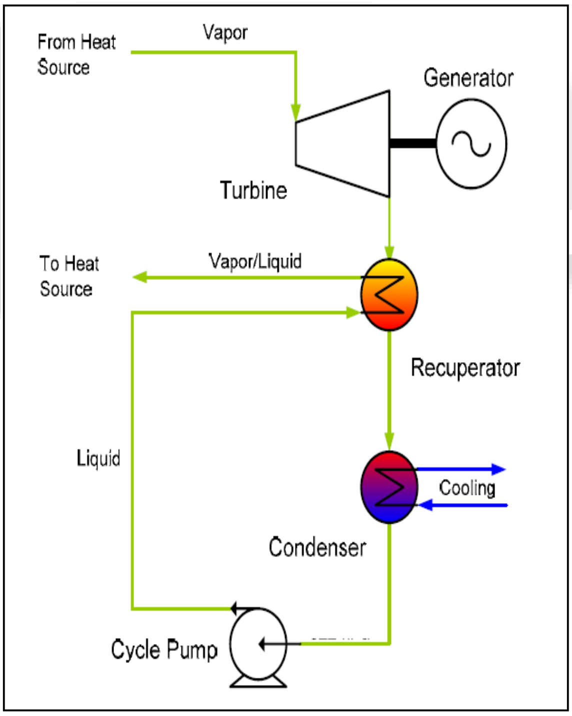

Fig. 1: Kalina cycle schematic- Recuperation- condensation

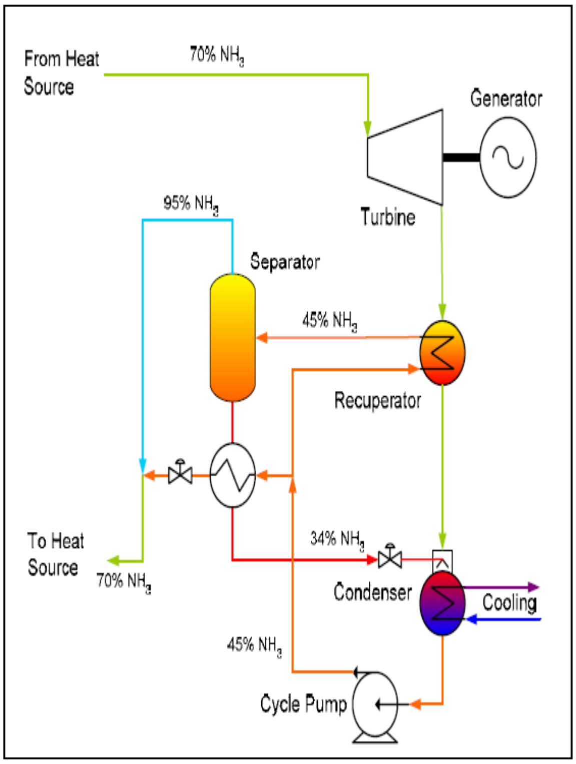

Fig. 2: Kalina cycle schematic- Absorption- condensation [4]

IV. ORGANIC RANKINE CYCLE (ORC)

Organic Rankine cycle can extract energy efficiently and generate power from low temperature heat sources than the conventional steam based Rankine cycle.

The working principle and the main components employed in the ORC are same as those are in Rankine cycle. But the fundamental difference arises due to the choice of working fluid and the peculiar thermo-physical properties of that working fluid.

The organic working fluids have many different characteristics than water.

Firstly, the slope of the saturated vapour line of a working fluid in a T-s diagram can be positive (e.g. isopentane), negative (e.g. R22) or vertical (e.g. R11), and the fluids are accordingly called wet, dry or isentropic, respectively. Wet fluids, like water, usually need to be superheated. This is mainly done to ensure a good vapour quality at the turbine exhaust, to prevent any damage to the turbine last stages. On the other hand many organic fluids, which may be dry or isentropic don't need superheating, because such fluids leaves the turbine either in saturated state or in superheated state, thus no attention is required to be paid to the vapour quality at the turbine exhaust. In fact it has been demonstrated that thermal efficiency with dry and isentropic fluids decreases by increasing the degree of superheat. Although for wet organic fluids the thermal efficiency improves with increase in degree of superheat, just as in case of water.

Fig. 3 below shows the ORC with a dry fluid. Notice that after expansion in turbine from 1 to 2 the fluid actually gets superheated.

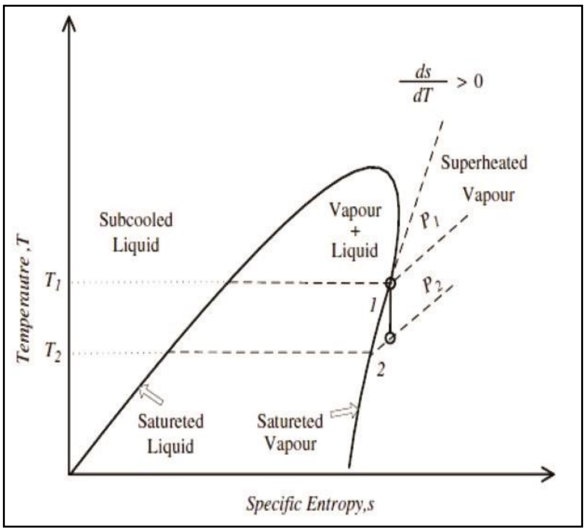

Fig. 3: ORC with a dry fluid [1]

Secondly, the entropy change for water in the phase change process is quite large in comparison to any other organic fluid. Fig. 4 shows comparison between T-s diagram of water and some organic fluids.

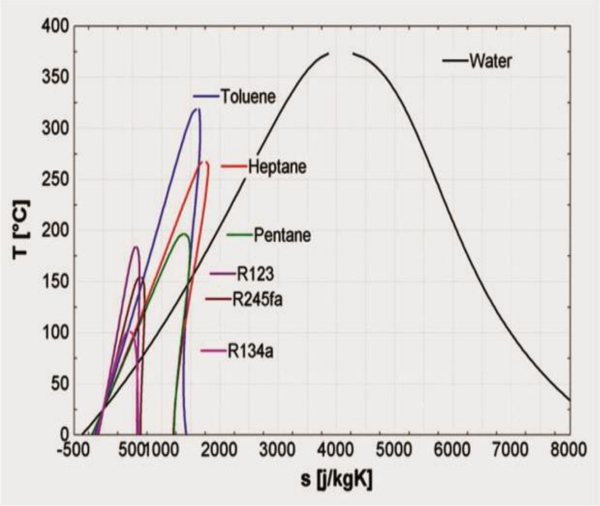

Fig. 4: T-s diagram for water and various organic fluids [5]

It is clear from the figure that water absorbs much more energy during the boiling process than any other organic fluid. This amounts to a lower mass flow rate of water in the evaporator than any other organic fluid. This actually proves to be a disadvantage with organic fluids, because it leads to more pump power and higher cross-section of the piping.

Having said that, for low temperature operation, the advantages with ORC are quite significant; some of which are-

1) High thermodynamic cycle efficiency
2) Absence of moisture in final stages of turbine
3) Size of the evaporator is less
4) Turbine for ORCs only have a single-stage or twin stage expander expander
5) Condenser pressure is usually above atmospheric

V. KALINA CYCLE V/S ORC

Bombarda et al. [6] presented a thermodynamic comparison between the Kalina cycle and an ORC for diesel engines. They concluded that although the obtained electrical power outputs are nearly equal, the KC requires a much higher turbine inlet pressure to attain the same, thereby making it unjustified for such use. Campos Rodríguez et al. [7] presented an exergetic and economic comparison between a Kalina cycle and an ORC for a low temperature geothermal power plant. They found that the KC produces 18 % more power than the ORC with 37 % less mass flow rate. For the case of geothermal power plant Daniël Walraven et al. [8] showed that transcritical and multi-pressure subcritical ORC's are in most cases the best performing cycles and can achieve exergetic plant efficiencies of more than 50%. And perform better than Kalina cycle for low minimum brine outlet temperatures. Like that there are many studies which have studied the two cycles for specific input conditions and results prove to be highly sensitive to minute variations in input conditions.

VI. CONCLUSION

Use of alternative thermodynamic cycles is a very promising option for the conversion of low quality heat into work, in an efficient and economically viable manner. Out of these, Kalina cycle and ORC have gained enormous acceptance, because both of these cycles are just an improvement in Rankine cycle and so don't require design and development of a new component altogether. Now, which cycle to choose from, depends upon the specifics of the operating environment. For example, Kalina cycle performs better than an ORC in a varying heat input conditions because of its additional degree of freedom in terms of choosing the concentration of ammonia in the working fluid. On the other hand for some other scenarios like in geothermal power plant ORC's are in most cases the best performing cycles for low minimum brine outlet temperatures. Moving a step further some industries have started implementing organic mixture based Kalina cycles in order to harness maximum from given condition.

Having said that, there are certain concerns associated with these alternative cycles as well such as safety hazards of working with organic fluids. Also cycle efficiencies need further optimizations before these cycles can claim commercially viability.

So it may take a while before these alternative cycles get a widespread commercial acceptance and implementation.

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