

# TURBINES: The Most Likely Benefactor of BZT Fluids

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This paper describes several practical power system thermodynamic cycles and shows how the common Rankine cycle is the only one that can make use of the BZT (Bethe-Zel'dovich-Thompson) behavior of high molecular weight fluids. The typical application of the Rankine cycle uses a turbine as the device that extracts power from the working fluid. The goal is for the fluid passing through the blade row to have the BZT behavior to gain the benefit of the abnormal supersonic effects.

By studying the parameters that impact the selection of the cycle conditions it is possible to understand the importance of the properties of the working fluid. In particular, the thermodynamic properties of the fluid must be such that the selected cycle will demonstrate good performance with the chosen fluid.

With the cycle and the fluid selected, the impact of the BZT behavior of the fluid can be determined. The goal is to have the turbine operate through the region where the BZT behavior is most pronounced. The selection of the turbine type, either impulse or reaction, will have a significant impact on the operating region of the turbine.

The final result of considering these various selection criteria is that establishing a set of conditions where the turbine will operate in the desired region is rather difficult. To do so requires the availability of a BZT behavior fluid that has the proper thermodynamic properties for the given conditions.

## Introduction

The modern world's economy is driven by the abundance of available power and, most specifically, electrical power. This electrical power is generally made available through the burning of fossil fuels and the conversion of the heat to mechanical and then electrical power. The efficiency of the conversion process is important in several regards but most importantly in the economics and in the ecology of the process. A more efficient process produces more electricity for the same amount of fossil fuel used making the electricity less costly and producing fewer pollutants. Therefore, the question is, how can the BZT behavior of some heavy fluids be used to improve the performance of power cycles?

## Power Cycles

The principals established by Sadi Carnot in 1824 govern the conversion of heat to work. Specifically, Carnot showed that the conversion efficiency is a function of the maximum temperature and minimum temperature of the system. Further, the conversion efficiency is limited by the 'Carnot efficiency', which, in equation form is:

$$\text{Efficiency} = (\text{max temp} - \text{min temp}) / \text{max temperature}$$

where the temperatures are based on an absolute temperature scale.

For any practical power system this efficiency represents the ultimate goal as the Carnot cycle upon which this efficiency is derived uses ideal (i.e. perfect) components. In the real world there will be losses and inefficiencies in each component making the real cycle efficiency less than the Carnot.

The two practical power cycles used today are the Brayton and the Rankine. The Brayton cycle is used in the gas turbine engine (jet aircraft and gas turbine power systems) and employs a gaseous working fluid through out the cycle. It operates far out in the superheat region (thermodynamically) and therefore is not a candidate for the use of a BZT fluid. Furthermore, the Brayton cycle is usually used as an open cycle device, taking in air (at the

compressor inlet) and discharging the exhaust gases (after the turbine exit).

On the other hand, the Rankine cycle makes use of the phase change of the working fluid and typically operates closed cycle. This cycle uses a condenser to convert the working fluid to a liquid. This high-density fluid is pressurized using a pump (as opposed to using a compressor for the low-density fluid in the Brayton cycle) before it enters the heat exchangers that will convert it back to a vapor. The Rankine cycle is shown in Figure 1, a typical temperature – entropy chart showing the vapor dome and the cycle. The turbine inlet is usually near the saturated vapor condition making it a likely benefactor of BZT fluid behavior. However, it will be necessary to investigate this further to ascertain how this benefit may take place and how much benefit could be expected.

The familiar steam power plant uses the Rankine cycle. Steam is selected for the working fluid as it is readily available, inexpensive, and has excellent thermal stability at the high operating temperature of the system. Organic working fluids would be the fluid of choice for power systems making use of waste heat or other, lower temperature heat sources. Therefore, a cycle using a BZT fluid would most likely use waste heat as the source. Thermal stability of the fluid would also dictate a heat source with a temperature lower than a normal flame temperature.

### **Power Cycle Selection Criteria**

As stated earlier, the efficiency of the cycle will be largely dependent on the maximum and minimum temperatures of the system. The maximum temperature is generally the temperature of the heat source. If the heat source is fossil fuel, it is desirable to burn it at as high a temperature as possible – considering NO<sub>x</sub> generation, metallurgical considerations, etc in order to achieve as high a conversion efficiency as possible. However, if the heat source is waste heat from another process or some other source then the temperature will generally be dictated by the source. The minimum temperature of the system is generally the ambient, i.e. the surrounding air, a lake, river, etc.

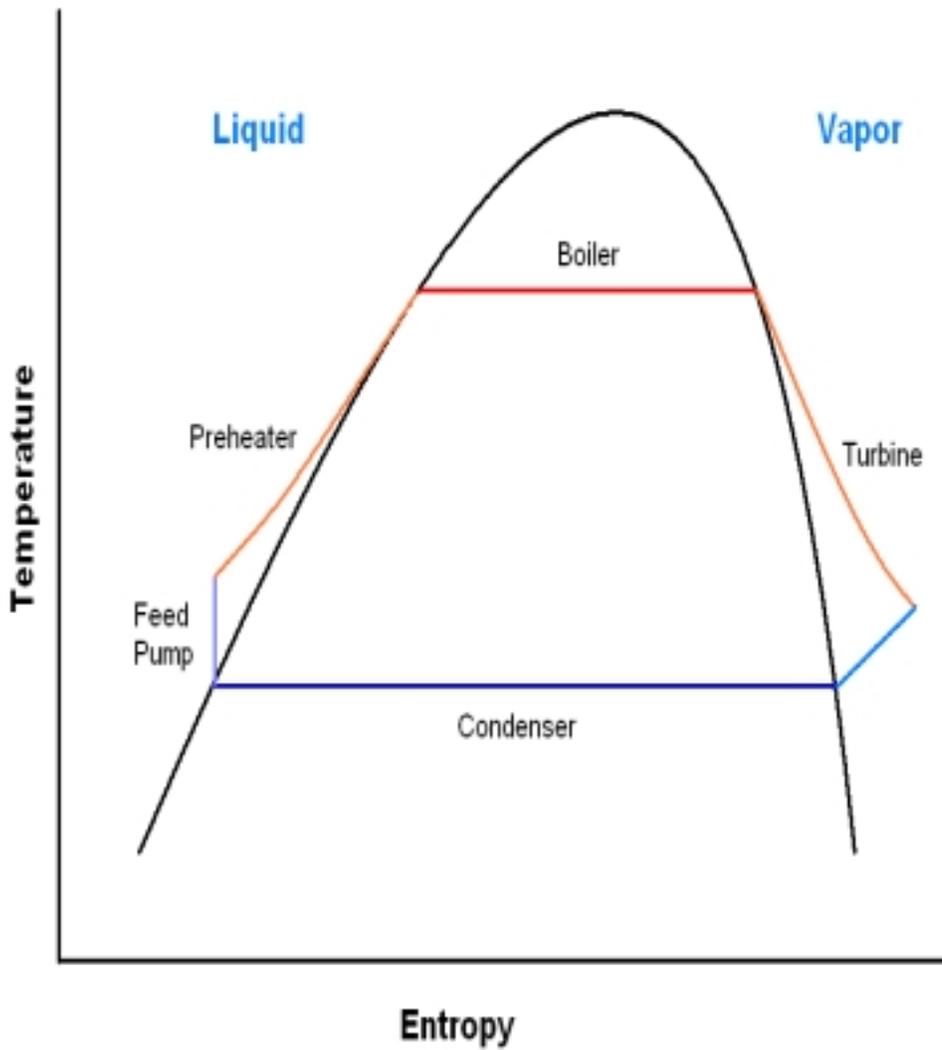


Figure 1  
Rankine Cycle  
On  
Temperature-Entropy Chart

The engineer designing the power system will endeavor to make use of the maximum and minimum available temperatures. The temperature difference between the source (or sink) temperatures and the actual working fluid temperatures is a loss attributable to the heat exchangers. This loss will be part of the reason the actual cycle efficiency will be less than Carnot. Using larger (and more costly) heat exchangers can reduce the temperature loss in the heat exchangers. The final choice of heat exchanger size will be made based on economics.

Given the source and sink temperatures and the heat exchanger selection, the working fluid conditions at the turbine inlet and exhaust will be known. Now it is possible to further explore the use of a BZT fluid in the process.

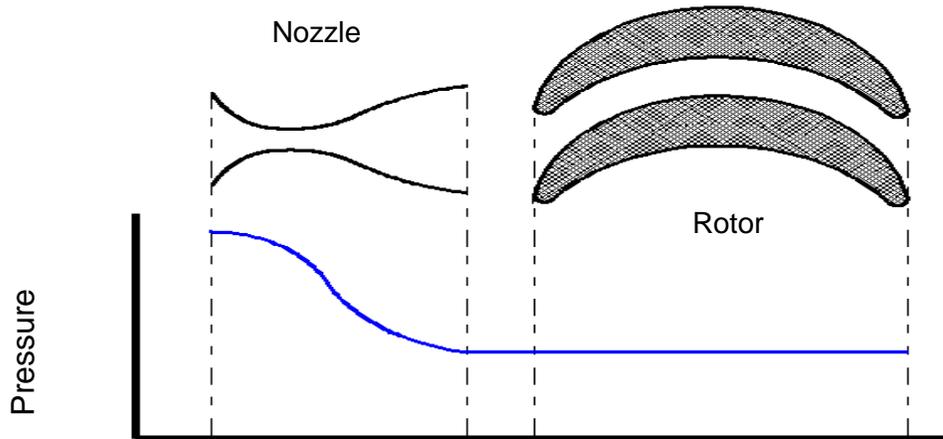
### **Turbine Anatomy**

A typical turbine, as used in modern machines, is composed to two components: the nozzle (stator) and the rotor. From a terminology standpoint, the word turbine can refer to the overall device (and will be used in that manner here) or can refer to the rotor. This distinction will be important to the discussion that follows.

The purpose of the turbine is to convert the energy of the working fluid to mechanical energy that will, in turn, be converted to electrical energy in a generator. The energy of the working fluid is in the form of pressure (enthalpy). This pressure energy will be converted to velocity (kinetic energy) and then to mechanical energy by momentum exchange in the rotor.

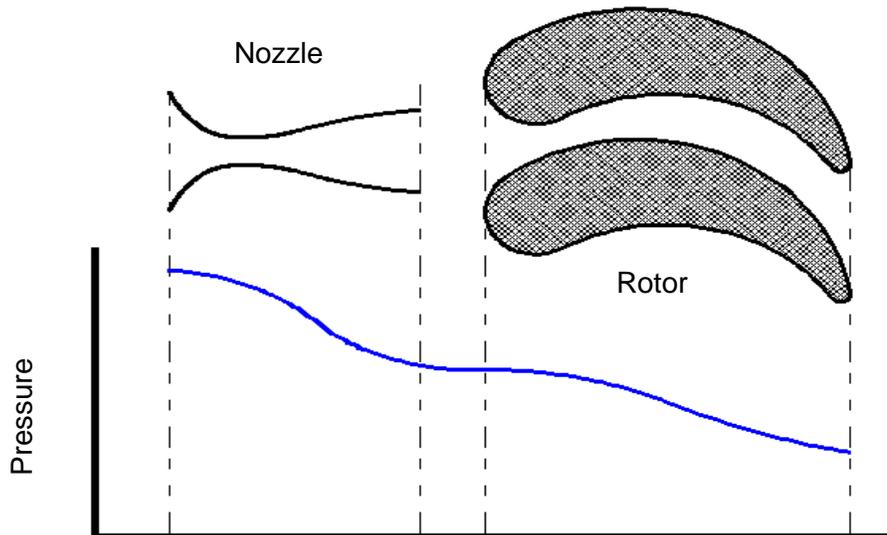
There are two major classes of turbines – impulse and reaction. This refers to where the pressure drop is taken, i.e., where the conversion from pressure to velocity takes place. In the impulse turbine the entire pressure drop is in the nozzle with only momentum exchange taking place in the rotor (Figure 2). In the reaction turbine, some percent of the pressure drop occurs in the nozzle and the rest of the pressure drop takes place through the rotor (Figure 3). With a reaction turbine the maximum pressure drop in the rotor does not usually exceed more than 50 percent of the total.

**Figure 2 – Impulse Turbine**



Pressure variation through nozzle and rotor

**Figure 3 – Reaction Turbine**



Pressure variation through nozzle and rotor

## Making Use of the BZT Behavior

The expansion of a BZT fluid through a turbine could potentially make the power extraction process more efficient. Typical turbine efficiency is around 80 percent. If this could be improved by the use of a BZT fluid, the added power produced goes directly to the net output of the system, improving the economics and reducing the pollution generated.

The nozzle expansion, with today's analytical techniques, is essentially shock free and has very little loss. Therefore, the use of a BZT behavior fluid in the nozzle would have little, if any benefit. On the other hand, the loss in the rotor is not insignificant.. A BZT fluid could make the supersonic flow through the turbine rotor more efficient by reducing the shock losses. Therefore, the goal is to have the flow through the turbine rotor (and not the nozzle) take place in the BZT regime.

The BZT behavior of high molecular weight (dense gas) fluids is exhibited in a region near the critical conditions and adjacent to the vapor saturation line (Figure 4). This region is relatively small but is in the general proximity of the turbine expansion of a Rankine cycle. However, establishing the proper selection criteria such that the turbine rotor does truly operate in that region is rather elusive.

Dr. Brady Brown (Krispin Technologies Inc), Dr. Brian Argrow (University of Colorado – Boulder), and Barber-Nichols personnel recently studied several fluids and endeavored to find a match for some selected conditions but were not successful. The difficulty is that the nozzle expansion carries the fluid through the BZT region and then the flow through the rotor is in normally behaving conditions. Our selection criteria included practical considerations such as availability, cost, and thermal stability. The critical point must also lie within the range of the maximum temperature contemplated for the system. These are often conflicting requirements and greatly decreases the number of candidate fluids.

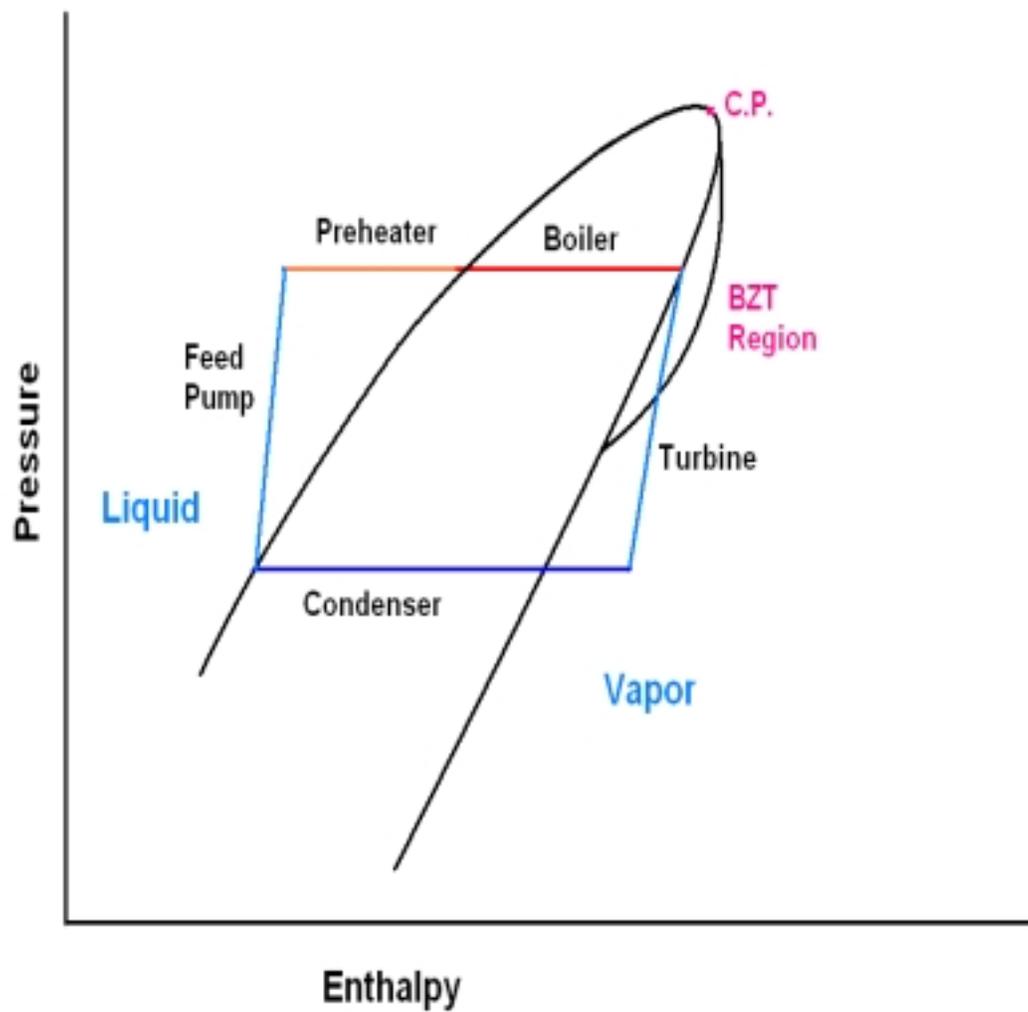


Figure 4

BZT Fluid with Rankine cycle

## **Where to go from here**

The obvious goal is to have a fluid with a very large region of BZT behavior along with the other necessary and desirable attributes as outlined above. The proper combination of a practical cycle and the required fluid properties may very well exist but will require extensive searching. It may also be possible to utilize a specialized turbine design that would more readily make use of the BZT behavior. One possible novel approach would use guide vanes (rather than nozzles) to create pre-swirl for the rotor in order to have the energy drop through the rotor and not in a nozzle.

Given that such a combination can be found the plan of action is well defined. The cycle analysis and turbine design would define the operating conditions for the turbine rotor. Through CFD analysis the blade shape could be optimized for the BZT behavior. The hardware would be constructed and tested to validate the CFD model. Through analytical techniques the performance of this dense gas system could be compared to a conventional system.

## **The Potential Benefit**

If the use of a BZT fluid in a Rankine cycle power system could be made to work and the system does prove to be more efficient, the potential benefit could be tremendous. The most likely heat source to make use of this technology is waste heat. Currently, there is a tremendous amount of waste heat going into the atmosphere because it is uneconomical to make use of it. This represents very large amounts of fossil fuel that could be conserved if this waste heat could be converted to electricity. The benefit to mankind is obvious.