INCREASED RANKINE STEAM CYCLE EFFICIENCY USING THE RADMAX TWO-PHASE POSITIVE-DISPLACEMENT COMPRESSOR AND EXPANDER

Subject Information Paper

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According to the U.S. Energy Information Administration (EIA), approximately 85% of electricity produced in the U.S. was generated by steam power plants in 2016. EIA 2016 data indicates that for each 1% improvement in cycle efficiency, about 0.6 Quads (0.6 quadrillion BTUs) of fuel can be saved annually, with a corresponding 35 million metric tonnes reduction in CO_2 emissions; or, equivalently, an additional 95 billion kWh of electricity can be generated. Currently, the average efficiency of such plants is approximately 36% *(see figure 1)*; with higher efficiencies requiring significant expenditures in additional equipment, as, for example, in the case of combined Brayton and Rankine cycles.

Steam Plant Overall Efficiency By Fuel Type

Fuel	% of Total Electricity Production Using Steam	Kwh Produced* (trillion)	Ave. Fuel Heat Rate for Steam Generation (BTU/Kwh)	Weighted Average Overall Plant Efficiency
Natural Gas	33.8%	1.38	7,870	43.4%
Coal	30.4%	1.24	10,493	32.5%
Nuclear	19.7%	0.80	10,459	32.6%
Petroleum	0.6%	0.02	10,811	31.6%
Other Gases	0.3%	0.01	10,811	31.6%
Steam Total	**84.8%**	**3.46**	**9,443**	**36.1%**

** 4.08 trillion kWh total 2016 US electricity production* *Source: EIA 2016 Data*

Figure 1: Steam Plant Overall Efficiency

Analyses show that if two-phase expanders and compressors that can operate with wet steam were implemented, efficiencies well above 50% can be reached without additional equipment. Based on an approximate 16% improvement over current average efficiencies *(see figure 1),* the use of two-phase expanders and compressors can reduce the fuel requirement by 10 Quad and annual CO_2 emissions by about 560 million metric tonnes, or increase yearly capacity by an additional 1.5 billion kWh of electricity with no additional fuel consumption.

The Rankine steam cycle has been used for decades as the primary engine for efficient, large-scale steam power plants. Various means have been employed to increase cycle efficiency including such things as heating steam to transcritical temperatures, multi-stage reheat and expansion, and multiple-stage feedwater reheat. Current technology and equipment face operational limits because of the need to operate turbines with dry steam and to operate pumps with liquid water.

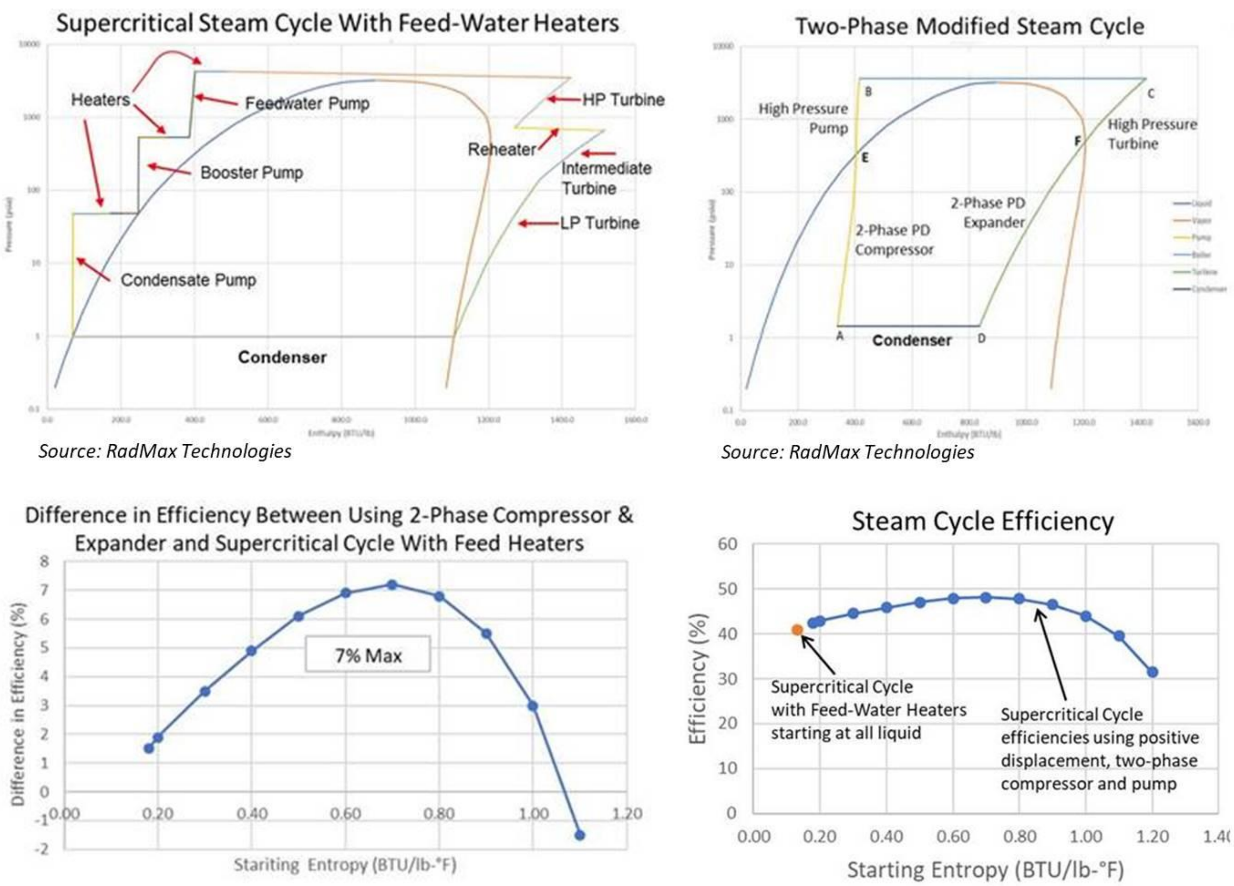
Steam Cycle Efficiency Comparison

Steam Cycle	Simple (kW)	Supercritical w/Heat Recovery (kW)	Modified 2-Phase (kW)
Boiler	1,887,618	1,316,996	1,250,985
Reheater	345,766	307,927	-
Total Heat	**2,233,384**	**1,624,923**	**1,250,985**
HP Turbine	216,591	216,629	815,803
Int Turbine	247,016	214,640	-
LP Turbine	330,813	302,071	-
Total Work	**794,420**	**733,340**	**815,80**
Cycle Efficiency	**34.0%**	**41.0%**	**47.8%**

Calculations based on actual plant data that includes equipment and operational inefficiencies. *Source: RadMax Technologies*

Figure 2: Steam Cycle Efficiency Comparison

No such limits exist when using the proposed RadMax® Two-Phase Compressor (TPC) and the RadMax® Two-Phase Expander (TPX). For example, in the case of the latter, the charge within each TPX chamber undergoes a closed system expansion due to the chamber volume increasing as the cam revolves around the shaft. Since the chambers are stationary, no bulk motion is imparted to the charge. Consequently, the erosion problems that are inherent when turbines operate with wet vapors are here precluded.



Source: RadMax Technologies *Source: RadMax Technologies*

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Figure 3: Steam Cycle Efficiency Comparison

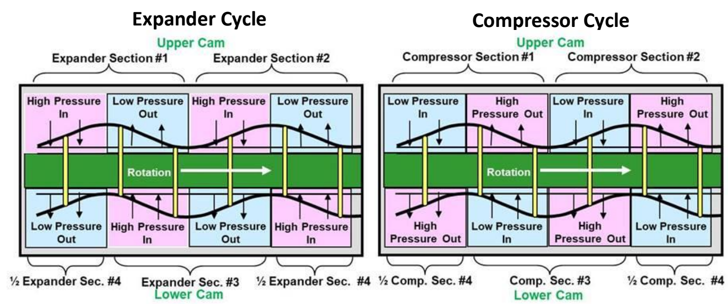
Analyses show that RadMax® technology positive-displacement, axial sliding-vane two-phase compressors and expanders can potentially improve power plant overall steam cycle efficiency by about 7% over the more efficient steam plants, or about 16% over the average plant *(see figure 2)*. This gain in efficiency is primarily accomplished by replacing water pumps and low-pressure turbines with RadMax® TPC and TPX positive-displacement devices that are able to compress and expand wet steam, respectively. Use of these two-phase devices allow the pumping and expansion processes to proceed within the liquid-vapor dome, thus permitting selection of optimum start and end states that maximize the cycle's efficiency *(see figure 3)*. Additionally, this approach is less complicated and requires less equipment investment than other methods currently used to enhance steam cycle efficiency.

Although still early in the development process, initial estimates for replacing the low pressure feedwater pumps and low pressure turbines in existing lower efficiency power plants with RadMax® TPC and TPX devices show a payback period of 2 – 5 years.

More research and economic analysis is needed to determine exactly where the optimum operation point is for different size plants in order for the best technologies to be adapted.

Cycle efficiency improvements provided by the adoption of two-phase compressors and expanders offers the potential for smaller and less expensive, sub-critical plants to be as efficient as the most efficient large plants. This can result in more, smaller efficient plants being built closer to the demand instead of building fewer, more distance plants, consequently reducing the load on the distribution system and creating a more secure and responsive grid.

Piston and screw positive-displacement technologies have limited abilities when handling two-phase fluids and are less efficient in producing rotary power whereas the efficient rotary positive-displacement operation of the RadMax® axial sliding-vane technology is perfectly suited for two-phase compressor and expander steam applications.



RadMax Rotary Cycle: Vanes slide axially through the rotor as they follow machined cams in the ends of the stationary stator housing. Chambers form at both sides of the rotor between the rotor, stator walls and vanes. The chamber volume changes as the vane follows along the cam profile during rotor rotation creating compression or expansion events. Desired device configuration is accomplished through the flexible placement of simple intake and exhaust ports in the cam. (www.radmaxtech.com)

Figure 4: RadMax Rotary Expander and Compressor Cycles

The RadMax® rotary cycle *(see figure 4)* is better suited for steam expansion and compression applications due to the efficient positive-displacement operation, high output-to-size and weight ratio, ease of manufacturing, scalability, and the ability to handle two-phase fluids. RadMax® prototype expanders and compressors have already undergone testing with compressed air *(see figure 5)*.

RadMax Technologies is currently planning the design, building and testing of a 25 - 50 kW proof-of-concept prototype compressor (TPC) and expander (TPX) capable of handling dry and wet steam of any quality.

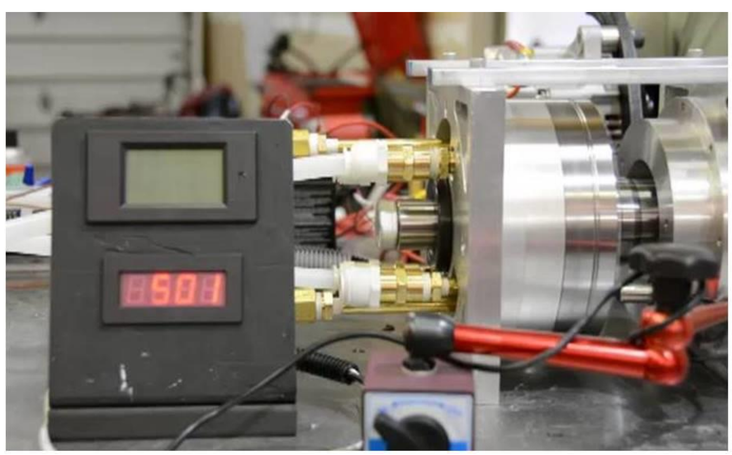


Figure 2: RadMax® TPX Prototype Testing