**PERFORMANCE INCREASE IN REFRIGERATION CYCLE THROUGH EXERGY RECOVERY**

**Subject Information Paper**

RadMax Technologies, Inc.

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According to U.S. Energy Information Administration (EIA) data, space cooling and refrigeration are two of the largest users of electricity in the U.S., accounting for approximately 900 billion kWh in 2016. Evaluation of the vapor compression refrigeration cycle shows that by capturing lost exergy and converting it to electrical power a seasonal coefficient of performance (COP) increase of 3% to 8% is possible, depending on refrigerant type and load factor. Likewise, higher energy $CO_2$ (carbon dioxide) based systems show potential for a 15% - 35% increase in COP. Additionally, ongoing analysis suggests that similar gains are possible by replacing traditional compressors with variable speed, two-phase, positive displacement compressors capable of dynamically optimizing system efficiency to the changing load requirements. Fully implementing two-phase expanders and compressors in existing space cooling and refrigeration systems in the U.S. could save up to 300 billion kWh of electricity annually, and eliminate roughly 200 million metric tonnes of related fossil fuel $CO_2$ emissions.

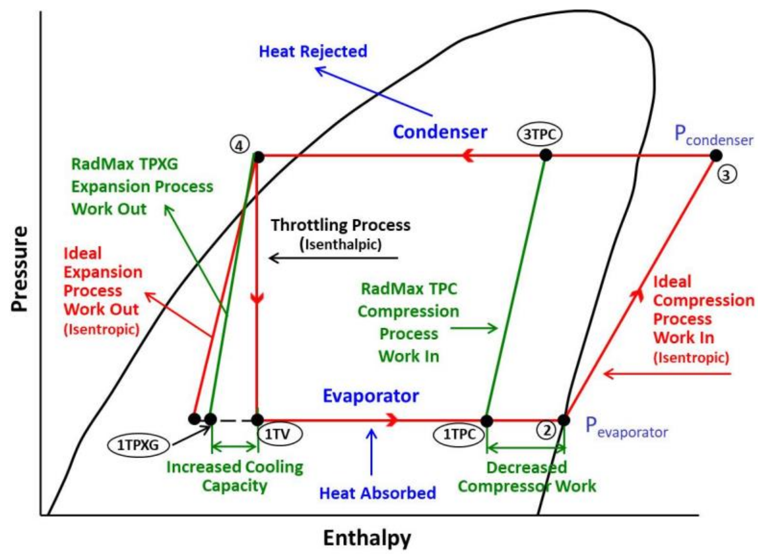



*Figure 1: RadMax® Modified Vapor Compression Cycle*

Modern vapor-compression cooling and refrigeration systems use a compressor to increase the pressure and temperature of the refrigerant. The hot, high-pressure vapor is then converted to liquid in the condenser. Normally, the liquid is then expanded to a lower pressure using expansion (throttling) valves. This expansion process results in a cold, two-phase mixture of vapor and liquid that is used to absorb the heat load in the evaporator. However, throttling processes dissipate exergy. Consequently, the development of positive-displacement rotary devices capable of working with liquid-vapor mixtures can lead to recovery of much of this lost exergy *(see Figure 1)*.

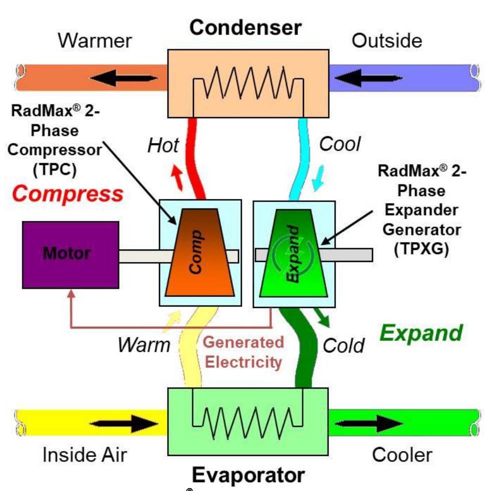



*Figure 2: RadMax® Cycle Piping Diagram*

The RadMax® Two-Phase Expander Generator (TPXG), based on RadMax® axial sliding-vane technology, is a two-phase, positive-displacement rotary expander capable of working within the liquid-vapor dome. In this design, the charge within each TPXG 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 inherent in turbines when operating with wet vapors do not apply. The TPXG converts exergy currently lost in the throttling process into shaft power that is used to generate electrical power integrally within the RadMax® device *(see Figure 2)*. Alternatively, the shaft power created may be used to drive an external generator, a compressor, or other equipment. The positive-displacement nature of the TPXG also enables control of the mass flow rate thereby eliminating the need for additional control devices.

In addition to the throttling expansion valve, limitations in current compressor designs introduce further system inefficiencies because they are restricted to operating with refrigerants that are in the gas phase. Replacing such devices with a RadMax® Two-Phase Compressor (TPC), additional improvements in cycle efficiency are possible by dynamically optimizing the state points of the cycle as a function of changing lift. The unique design of the RadMax® TPXG and TPC allows for the capability of "on-the-fly" variable expansion and expansion ratios.

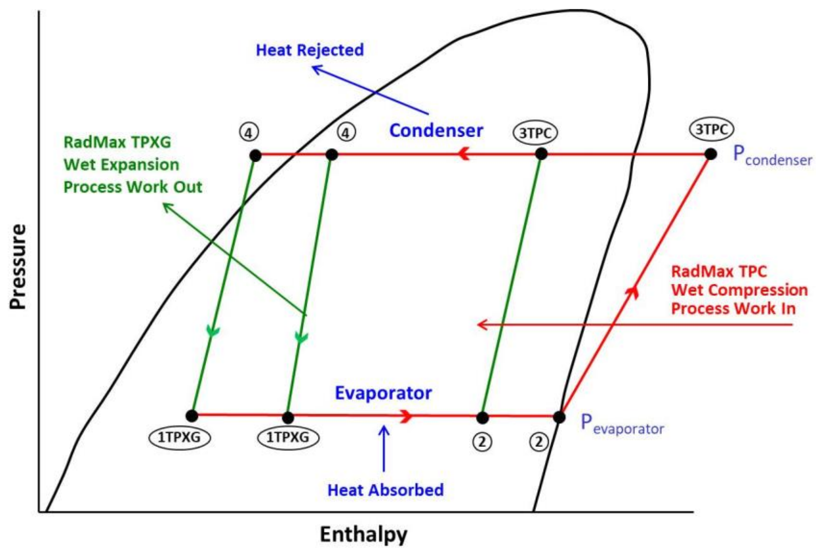



***Figure 3: COP$_R$ Maximization in Partial Load Operation with RadMax TPXG & TPC***

The adoption of two-phase expanders and compressors has the potential to not only reduce the operating costs of space cooling and refrigeration, but to also change the way refrigeration cycles are optimized *(see Figure 3)*. First, throttling valves can be replaced with an expander so that compression exergy can be recovered. Second, mass flow rates can be controlled as a function of required cooling capacity. Third, the ability to compress or expand two-phase fluids allows operation within the liquid-vapor dome, permitting optimization of the cycle without concerns of compressor flooding. Furthermore, the adoption of two-phase expanders and compressors

**Two-Phase System Efficiency Comparison**

| | | System Efficiency (%) | |
|---|---|---|---|
| | **Refrigerant** | **R134a** | **R744 ($CO_2$)** |
| **Turbine/ Expander** | Current Technology | 66.7 | 33.7 |
| | Two-Phase Tech. | 73.3 | 44.5 |
| **Compressor** | Current Technology | 66.7 | 33.7 |
| | Two-Phase Tech. | 74.6* | 47.2* |
| **Total** | Current Technology | 66.7 | 33.7 |
| | Two-Phase Tech. | 81.3 | 60.0 |

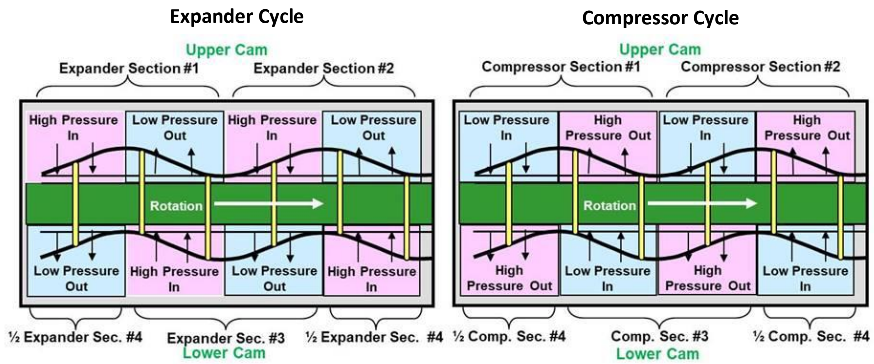
**Estimated efficiency improvement based on alternative two-phase fluid*
*80% efficiencies are assumed for the expander, compressor and electrical generator* Source: RadMax Technologies, Inc.

***Table 1: Two-Phase System Efficiency Comparison***

may also allow for low GWP refrigerants, such as $CO_2$, to become more economically feasible. This could facilitate significant reductions in the use of high GWP refrigerants. *Table 1* summarizes the theoretical improvements in efficiency achievable using two-phase expanders and compressors over current technology for two refrigerants.

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

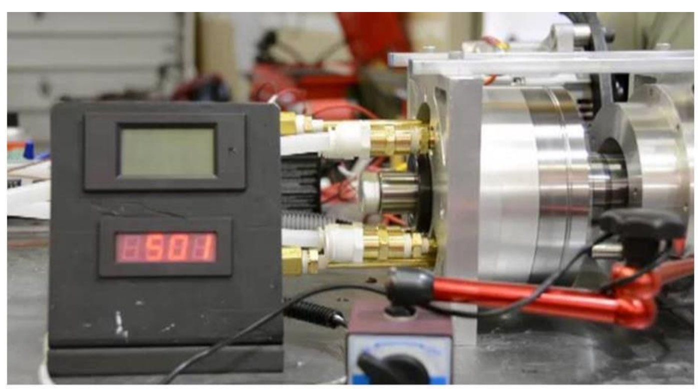
The RadMax® rotary cycle *(see Figure 4)* is better suited for refrigeration expansion and compression applications due to the efficient positive-displacement operation, high output-to-size and weight ratios, ease of manufacturing, scalability, and the ability to handle two-phase fluids. A RadMax® prototype expander *(see Figure 5)* has already undergone testing with compressed air, and a compressor has been tested with refrigerant R134a.




**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***

Although still early in the development process, it is believed that RadMax® compressors and expanders can be manufactured in quantity at competitive prices to currently available alternatives. While RadMax® devices may have more parts than other positive displacement devices that use scroll and screw mechanisms, there a few unique parts, and RadMax® devices can be less expensive to produce than piston devices. RadMax® devices are easily scalable, and price competitive, especially for higher capacity models.




**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 5: RadMax® TPXG Prototype Testing***