WAVE ROTOR

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ABSTRACT

The Wave Rotor technology and its most known applications is innovative concept. The Wave Rotors also known as Pressure Wave Machines or Pressure exchangers are unsteady-flow devices that can transfer energy directly between two fluids, by means of pressure waves (shock waves). In a wave rotor, two fluids with different pressures are brought into direct contact. Then pressure exchange occurs faster than mixing. The wave rotor can have a higher isentropic efficiency than steady-flow devices, like compressors or diffusers, but may be more challenging to control. In the past, because of the unsteady nature of the flow inside the wave rotor, process simulation was very inaccurate, time consuming and labor intensive. Recently, because of the increase in calculation power of the computers and more accurate commercially available software packages, significant progress was made in understanding the complex wave phenomena.

Keyword: *Wave Rotor, Dynamic Pressure Exchanger, Energy Exchanger, Gas Turbine, Shock Wave, Expansion Wave, Unsteady Flow*

I INTRODUCTION

There is a continual demand to increase the performance of thermodynamic cycles beyond the limits of conventional turbo machinery. Traditionally, these cycles often function based on steady-flow processes with relatively well understood fluid mechanics and predictable performance. Utilizing unsteady-flow machines has been considered as a possible solution for increasing significantly the efficiency of simple steady-flow or semi-steady devices. The basic concept underlying these unsteady devices, known as wave machines or wave engines, is employing compression and expansion waves to add or remove energy from a fluid flow. It has been proved that for modest pressure ratios, more efficient compression processes can be achieved using pressure waves rather than blades or pistons. Among several wave machines, pulse detonation engines (PDE) and wave rotors have received significant attention. Wave rotors do not use mechanical components such as pistons or vane impellers to compress the fluid. Instead, the pressure rise is obtained by generating compression waves in appropriate geometries. It has been proven that for the same inlet and outlet Mach numbers the pressure gain in time-dependent flow devices can be much greater than in steady flow devices. The essential feature of wave rotors is an array of channels arranged around the axis of a cylindrical drum. [6]

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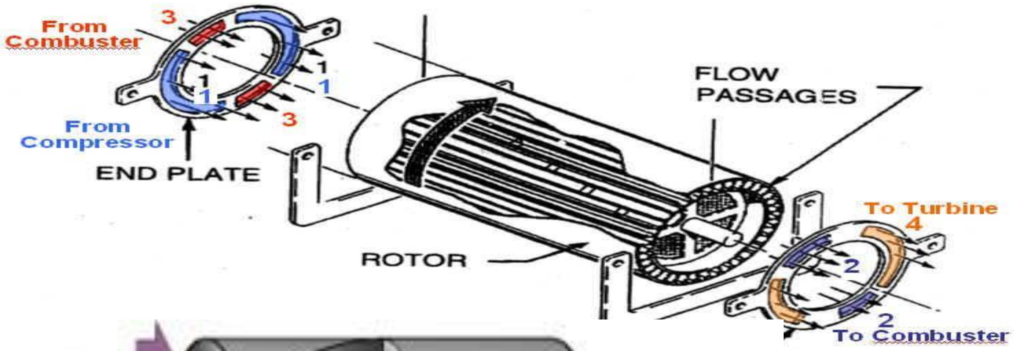
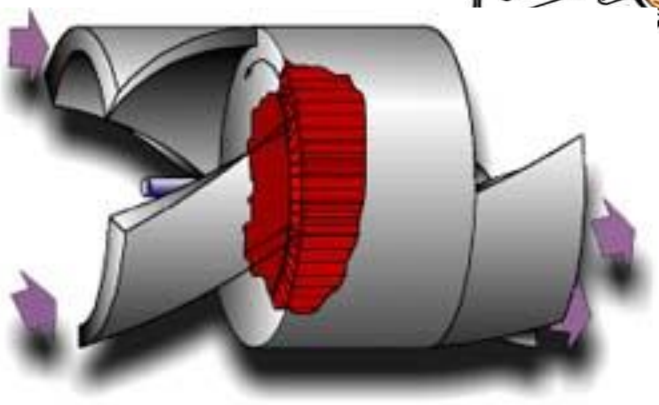
II THE WAVE ROTOR

Wave Rotor is a device of full potential to improve the gas turbine performance drastically, when synthesized as a topping cycle. The intention of its use for aero-engines is not new, but it has been known as a dynamic pressure wave exchanger with various ways of application like diesel superchargers, wave engines, pressure-gain combustors, air-cycle refrigeration, etc. Although the wave rotor research efforts tend towards machines of larger power size, it should be nowadays noticed that distributed or mobile micro innovative power or energy system is getting popular and of increasing demand, whilst the performance of gas turbines are very much deteriorated if conventional design methodology for large turbo-machines is straightly adopted for miniaturization, so that the mechanical blade work might be efficiently replaced by wave dynamic power conversion devises. The direction of research for Micro Wave Rotors is therefore needed to be further explored.





When the wave rotor rotates it opens up different ports to specific flow passages at different points in the cycle. The exact timing of the opening and closing of these flow passage is very important. The process occurring in each of the flow passages, it is arbitrarily chosen that the first step of the process is the inlet of air from the compressor, as it is then easier to understand. [6]

2.1. WAVE ROTOR ENHANCED-CYCLES

Two basic wave rotor cycles termed as four-port through-flow (TF) and four-port reverse-flow (RF) cycles can be considered. They may provide identical topping and overall performance enhancement, but they differ substantially in their internal process. [1]

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a.) Through flow:-

In the TF configuration, for both gas and air, the inlet ports are located on one side of the rotor as shown in the Fig.2.2 While the outlet ports are located on the other side of the rotor. Thus, the hot gas and in particular the relatively cold air route through the full length of the rotor leading to the self-cooling feature, which is essential for very high gas temperatures in gas turbine applications.

b.) Reverse flow;-

In the RF configuration, the fresh air enters and exits at the same end of the rotor (air casing), as shown in the Fig.2.3, while the burned gas enters and exits the rotor at the other end (gas casing). Hence, the RF cycle does not inherently result in such a well self-cooled rotor. The cold air never reaches the other side of the rotor, which is also true for the hot gas. Thus, the air side of the rotor is relatively cool, while the gas side of the rotor is relatively hot. To achieve a better self-cooled RF design, a two cycle per revolution design of the RF configuration can be constructed, which orients the cycle alternately right and left on the rotor.

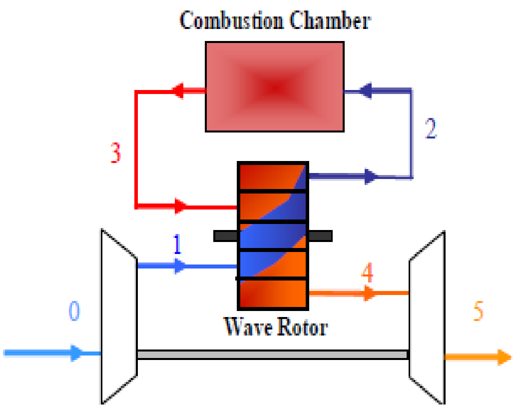

Fig.2.2 Through flow wave rotor

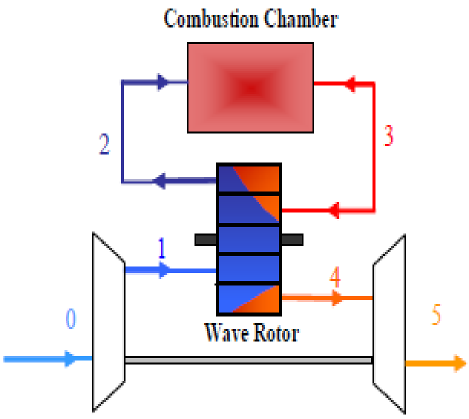

Fig.2.3 Reverse flow Wave rotor

2.2. WAVE ROTOR DESCRIPTION

The wave rotor is a tubular entity, like a drum, and when in use it rotates axially. On the circumference of the drum are tubular chambers, called flow passages. In each of these flow passages the same process occurs. This process that occurs in these chambers is cyclic and is the heart of the wave rotor concept. The fact that it's cyclic means that the once the process in a flow passage completes it starts over again. The rotation then is important to support the cyclic concept, and not to create angular momentum.

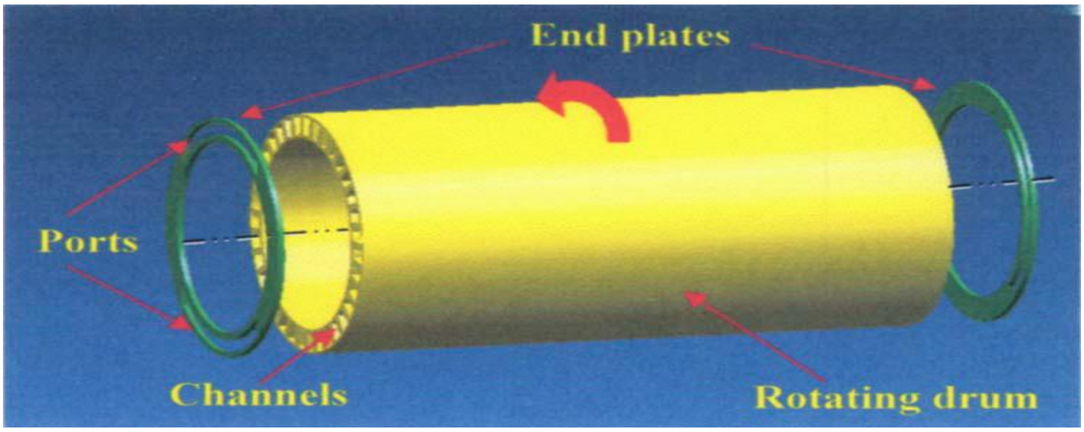

Fig. 2.4 Schematic configuration of a typical wave rotor

As schematically shown in Fig. 2.4, the drum rotates between two end plates each of which has a few ports or manifolds, controlling the fluid flow through the channels. The number of ports and their positions vary for different applications. By carefully selecting their locations and widths to generate and utilize wave processes, a significant and efficient transfer of energy can be obtained between flows in the connected ducts. Through rotation, the channel ends are periodically exposed to the ports located on the stationary end plates initiating compression and expansion waves within the wave rotor channels. Thus, pressure is exchanged dynamically between fluids by utilizing unsteady pressure waves. Unlike a steady-flow turbo machine that either compresses or expands the fluid, the wave rotor accomplishes both compression and expansion within a single component. Even though the wave rotor is internally unsteady, the flows in the ports are almost steady, aside from the fluctuations due to the opening and closing of the channels as they enter and exit port regions. Therefore, the wave rotor outflow shows very low pulsating behavior.

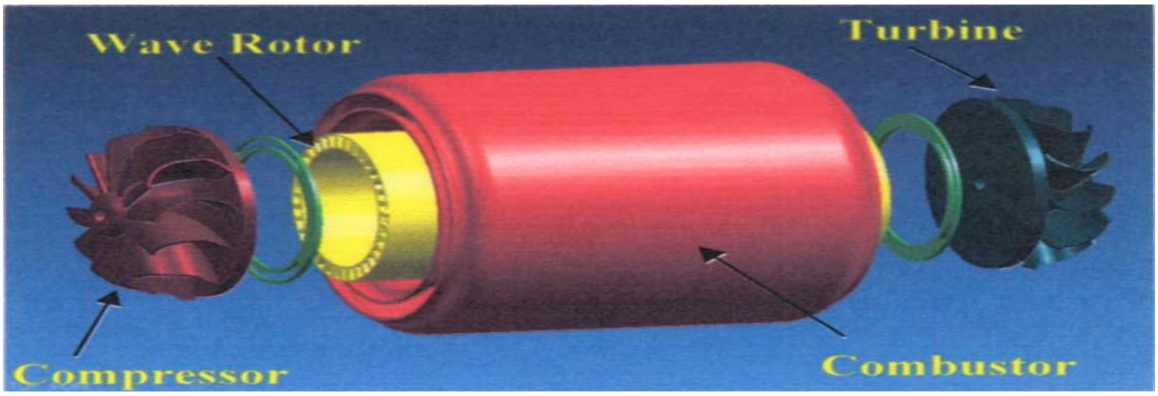

Fig. 2.5 Schematic example of the physical implementation of a wave rotor in a gas turbine exploded view, piping not shown…

To minimize leakage, the gap between the end plates and the rotor has to be very small, but without contact under all operating and thermal expansion conditions. With axial channels and matched port flow alignment, the power required to keep the rotor at a correctly designed speed is negligible. It only needs to overcome rotor wind-age and friction. In such a configuration, the rotor may be gear or belt driven or preferably direct driven by an electrical motor not shown. Alternatively, a self-driving configuration, known as the "free-running rotor," can drive itself by using port flow incidence on channel walls to turn the rotor. In a conventional arrangement, the wave rotor is embedded between the compressor and turbine "parallel" to the combustion chamber Figure 2.5 schematically shows how the wave rotor could be embedded physically into an un-recuperated baseline engine that uses single-stage radial compressor and turbine. [4]

III WORKING OF THE WAVE ROTOR:

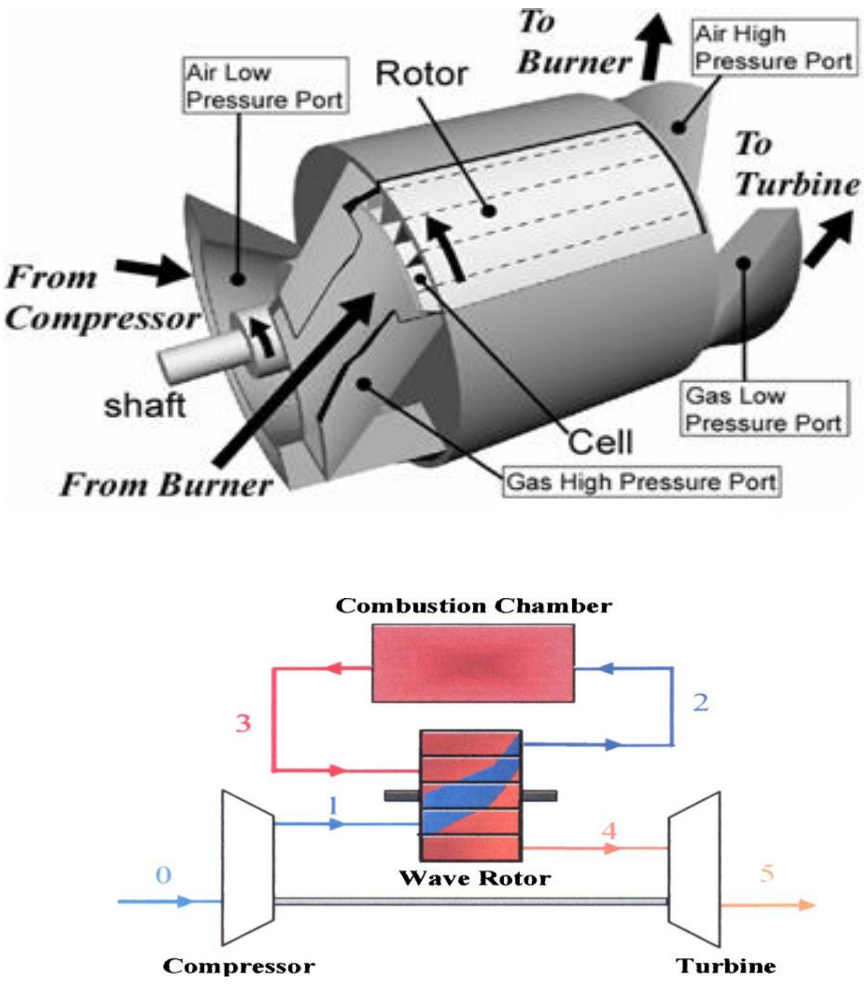

Fig. 3.2 Gas turbine topped by a four-port wave rotor

Following the flow path shown in Fig. 3.2, air from the compressor enters the wave rotor (state 1) and is further compressed inside the wave rotor channels. After the additional compression of the air in the wave rotor, it discharges into the combustion chamber (state 2). The hot gas leaving the combustion chamber (state 3) enters the wave rotor and compresses the air received from the compressor (state 1). To provide the energy transfer to

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compress the air, the burned gas partially expands in the wave rotor en route to the turbine (state 4). Due to the pre-expansion in the wave rotor, the burned gas enters the turbine with a lower temperature than that of the combustor exit. However, the turbine inlet total pressure is typically 15%–20% higher than the air pressure delivered by the compressor. This pressure gain is in contrast to the un-topped engine, where the turbine inlet pressure is always lower than the compressor discharge pressure, due to the pressure loss across the combustion chamber. As a result of the wave rotor pressure gain, more work can be extracted from the turbine increasing engine thermal efficiency and specific work. Finally, the channels are re-connected to the compressor outlet, allowing fresh pre-compressed air to flow into the wave rotor channels and the cycle repeats. [2]

3.1 PERFORMANCE OF WAVE ROTOR AS COMPARED TO BASED LINED ENGINE:

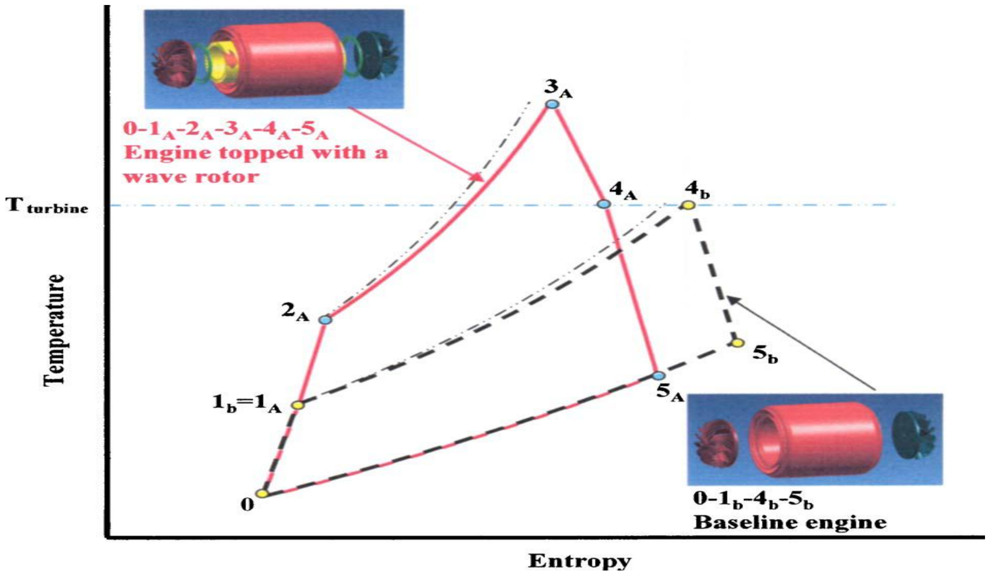

Fig. 3.3 Schematic T-s diagrams for a gas turbine baseline engine and the most common implementation case of a topping wave rotor

The general advantage of using a wave rotor becomes apparent when comparing the thermodynamic cycles of baseline and wave rotor- enhanced engines. Figure 3.3 shows schematic T-s diagrams of the baseline engine and the corresponding wave-rotor-topped engine. The shown wave rotor implementation is the one most commonly discussed in references, referred to as Case A in this study. It is evident that both gas turbines are operating with the same turbine inlet temperature and compressor pressure ratio. Each wave rotor investigated in this work has zero shaft work. Therefore, the wave rotor compression work is equal to the wave rotor expansion work. Thus, the energy increase from state “1b” to “4b” in the baseline engine and from state “1A” to “4A” in the wave rotor- topped engine is the same. This results in the same heat addition for both cycles. However, the output work of the topped engine is higher than that of the baseline engine due to the pressure gain across the wave rotor (pt4A> pt4b, where subscript “t” indicates total values). Therefore, the thermal efficiency for the topped engine is higher than that of the baseline engine. The inherent gas dynamic design of the wave rotor compensates for the combustor pressure loss from state “2A” to “3A,” meaning that the compressed air leaving the wave rotor is at higher pressure than the hot gas entering the wave rotor. There are several other important advantages of wave rotor machines. Their rotational speed is low compared with turbo machines, which results in low material stresses. They can respond on the time scale of pressure waves with no rotor inertial lag. From a mechanical point of view, their geometries can be simpler than those of turbo machines. Therefore, they can be manufactured relatively inexpensively. Also, the rotor channels are less prone to erosion damage than the blades of turbo machines. This is mainly due to the lower velocity of the working fluid in the channels, which is about one-third of what is typical within turbo machines. Another important advantage of wave rotors is their self cooling capabilities. In heat engine applications, the rotor channels pass both air (being compressed) and hot gas (being expanded) in the cycle at least once per rotor revolution, alternating faster than thermal diffusion rates. The rotor temperature equilibrates between the temperature of the cooler air and the hotter gas, allowing peak cycle temperature above materials limits. [2]

IV. FEATURES

Self-cooling. The rotor surfaces are alternatively washed by the relatively low temperature compressor discharge and high temperature burner discharge at frequencies much higher than the material thermal response-time. The rotor remains substantially (e.g., 25 to 30%) cooler than the burner discharge; therefore, the burner discharge temperature of the topped engine is significantly higher than that of the baseline engine while the rotating component temperatures are comparable.

Low corrected flow. The component is aerodynamically compatible with the low corrected specific flow rates supplied by the core compressors of modern aero propulsion engines. The discharge from the full annulus of the compressor diffuser is ducted at nearly constant radius to the partial-annular port of the wave rotor. This flow concentration accommodates aerodynamically efficient rotor passage geometries. Furthermore, the rotor is shrouded so that tip leakage losses are eliminated.

Low Rotative Speed. Typical wave rotor corrected tip-speeds are a factor of five or six lower than those of modem turbo machines. The simple rotor geometry, the operating temperature, and the need to maintain acceptable hoop stress levels suggest that ceramic rotors may be an attractive design choice.

Rapid Transient Response and Stability. The wave rotor responds (gas dynamically) to transients in adjacent components within a couple of rotor revolutions (e.g., ten milliseconds). The fast response is quite independent of its instantaneous rotative speed, in contrast to turbo machinery components that must spool up or down.

V APPLICATIONS

5.1. Gas turbine topping:

The general advantage of using a wave rotor becomes obvious when comparing the thermodynamic cycles of baseline and wave-rotor-enhanced gas turbine engines. This is demonstrated in a schematic temperature-entropy diagram for a gas turbine baseline engine (dashed line) and the corresponding wave-rotor-topped engine (solid line) in Figure. While many other advantageous implementation cases of the wave rotor into a given baseline engine are possible.[3]

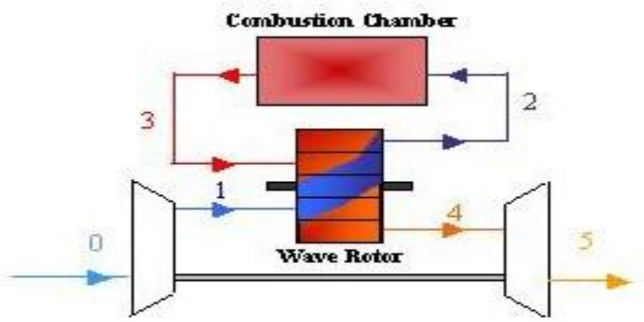

FIG.5.1 Gas turbine topping

5.2. ICE Superchargers

Compared to the turbocharger, the wave rotor has the advantage of a better response time to engine acceleration, (no turbo-lag), and its efficiency does not decrease with the size reduction of the device. These characteristics make the wave rotor more suitable for small displacement engines than the TC, as it can be seen in Fig.6.2. The wave rotor has also self-cooling capability, due to the continuous circulation of the air through the rotor. Figure displays the main components of the ICE wave rotor system. The channels are placed axially at the periphery of a cylindrical rotor. In the Comprex case, it is a RF wave rotor, which determines the rotor to have a "hot" side and a "cold" one. The hot side contains the engine exhaust gases ports, while on the cold side the air port are placed, as well as the rotor bearings. The engine crankshaft drives the rotor via a belt drive [5]. The wave rotor does not use mechanical work from the engine to compress the air like a mechanical supercharger. Instead, the rotor is driven in order to match the wave phenomena with the load and speed requirements of the engine. The wave rotor is more suitable for a steady-state function, but the ICE works on a wide range of speeds and loads, so there are mismatched working conditions between the two systems.[3]

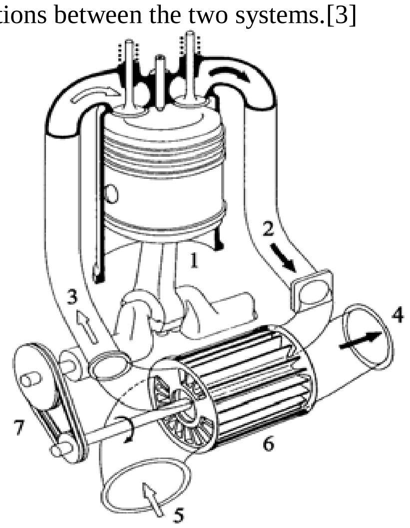

Fig.5.2 Internal combustion engine supercharger

5.3. Refrigeration Applications

Wave rotors also have been used for air-cycle refrigeration systems. Power Jets Ltd in the U.K. utilized wave rotor technology in the design and development of two prototype air-cycle refrigerators used for environmental cooling purposes. Recently, a unique and cutting-edge application of wave rotors in refrigeration cycles using water (R718) as a refrigerant has been studied. In fact, the wave rotor implementation can increase efficiency and reduce the size and cost of R718 units. A three-port wave rotor has been introduced as a condensing wave rotor that employs pressurized water to pressurize, desuperheat, and condense the refrigerant vapor –all in one dynamic process. Besides, giving the possibility of an additional rise of the vapor pressure, the condensing wave rotor eliminates the need of a bulky condenser because full condensation occurs inside the rotor channels.[5]

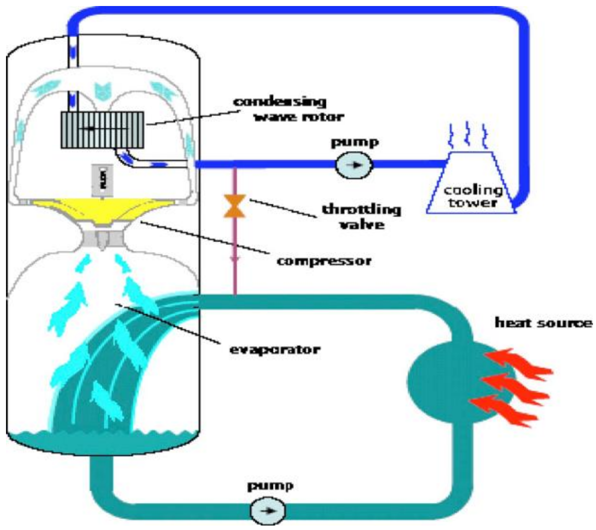

Fig.5.3 Novel compact R718 water chiller with integration of a Condensing wave rotor

VI ADVANTAGES & DISADVANTAGES:

ADVANTAGES

1. Reduce the specific fuel consumption.
2. It works low pressure differences, reducing safety precautions.
3. It has no global warming potential.
4. Easy to handle.
5. Increases efficiency of the device.

DISADVANTAGES

1. Complex in design.
2. Process simulation was very inaccurate.
3. Time consuming.

4. Labor intensive.

VII CONCLUSION

The wave rotor is the new emerging technology which can over take the mechanical blades and piston in generation of the power. This technology increases the performance of the thermodynamic cycle and due to this directly the efficiency of the devices working under thermodynamics cycles increases. Recent progress in knowledge and technology has provided the opportunity to consider wave rotor concept as innovative technology.

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