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Internal Combustion Wave Rotors for Gas Turbine Engine Enhancement

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ABSTRACT

Recent research in internal combustion wave rotor technology proposed operating cycles with deflagrative and detonative combustion. Earlier research, examining primarily deflagration, sought to improve on pressure exchanger wave rotor cycles topping a conventional gas turbine. Turbulent premixed combustion with reasonable flame speeds is predicted to allow operating frequency comparable to pressure exchanger cycles. Cycles that completely evacuate the wave channel to high- and low-pressure turbines may require faster combustion. More recent research on detonation cycles followed developments in pulse detonation engine technology. While detonative combustion is extremely fast, the wave cycle must isolate peak pressures and velocities from turbomachinery. Ignition presents a degree of uncertainty for all designs, and fuel distribution control is a critical strategy. The relative merits and challenges of various modes of combustion and cycles are discussed for typical applications in propulsion and power generation. Research and development needs, and recommended experimental strategies are described and evaluated.

INTRODUCTION

A wave rotor is a device that utilizes non-steady wave motion to exchange energy by direct work action between fluids, which may be chemically inert or reacting. It consists of a number of channels arranged about an axis. By rotation, the ends of the channels are periodically ported to high- and low-pressure manifolds (ducts), which synchronically generate and utilize waves in the channels. Because the number of channels is large, the flow in the ducts is practically steady, and is directed to other steady flow components. An important feature is that as gases of a wide temperature range flow through the rotor, the mean temperature of the channel wall is lower than the highest gas temperature. Rotational speed is low relative to conventional turbomachines, and the geometry is usually simpler, allowing greater strength and lower cost. For detailed descriptions of wave rotor principles and applications see Welch et al. (1997), Nalim (1994), Shreeve and Mathur (1985).

A wave rotor acting as a pressure exchanger can be used (together with a conventional combustor) as a topping unit to enhance the performance of a gas turbine engine. Fundamental thermodynamics (Nalim, 1998) and detailed simulations (Jones and Welch, 1996) (Wilson and Paxson, 1996) (Welch et al., 1997) indicate a substantial pressure gain possible between the compressor and the turbine (Seippel, 1946) (Shreeve and Mathur, 1985). Multiple wave channels with automatic phasing allow nearly steady inlet and outlet conditions. Wave rotor devices for gas turbine applications have been studied extensively (Welch et al., 1997) (Antonini and Andriani, 2001) to improve engine efficiency, including research test-rigs (Wilson and Fronek, 1993).

Alternatively, this pressure gain could be obtained using an internal-combustion wave rotor (ICWR). In this case, combustion occurs sequentially within the wave channels, each channel being periodically charged and discharged as it rotates past properly-sized and timed inlet and outlet ports. Simplified combustion and wave processes are illustrated in the wave rotor sketch in Fig. 1. By accomplishing combustion in the rotor, the external combustor needed in a pressure-exchanger topping cycle is eliminated, as is the associated ducting. The significant performance advantage is retained, as well as the considerable, but technologically addressable, thermal and sealing challenges. In most designs, premixed air-fuel mixture is selectively introduced into the axially straight rotating chambers through the inlet manifold, but fuel injection from the stator end plate is also possible. A spark igniter or a hot gas injection duct initiates the deflagration or detonation waves. As in other wave rotors without combustion, shock and expansion waves are generated as the channels experience sudden opening and closing at inlet and outlet ends. The process repeats itself each cycle, with high-pressure gas being continuously supplied to the turbine(s). It is possible to have more than one gas dynamic cycle per revolution, which improves mechanical load balancing, but may complicate ducting.

RESEARCH REVIEW

This concept is related to the earliest working gas turbines, which had valved, pulsating combustion chambers (Foa, 1960), and no compressor, relying entirely on the pressure produced by confined combustion to drive the turbine. The notion of a wave rotor with internal combustion first appeared in the 1950's (Goldstein et al., 1958), and interest resumed in the 1990's. Contemporary studies of pulsed detonation engines are of related

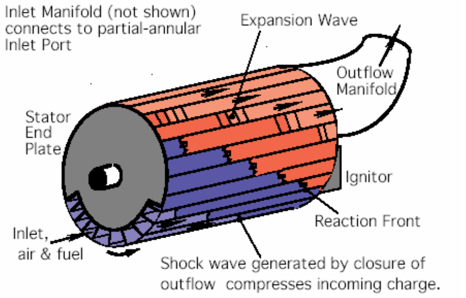

Fig. 1 Sketch of Internal Combustion Wave Rotor

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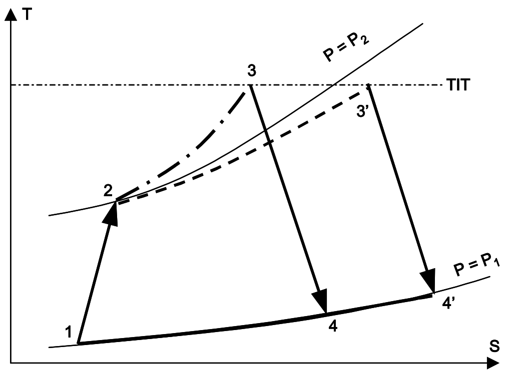

Fig. 2 Pressure-Gain Combustion Engine Cycle

interest (Kentfield and O'Blenes, 1988). Current interest is in enhancing gas turbine engines that are otherwise limited in compressor pressure ratio.

The thermodynamic cycle of a pressure-gain two-port wave rotor (1-2-3-4) is sketched on a T-s diagram in Fig. 2, and contrasted with a conventional gas turbine operating on a Brayton cycle (1-2-3'-4'), with the relative pressure gain of process 2-3 allowing more turbine work output without increasing turbine inlet temperature (TIT). One disadvantage of the two-port combustion wave rotor is that the higher exhaust pressure prevents complete purging of the exhaust gas in a single cycle of operation. For this reason it is preferred in some applications to have an additional exhaust port, allowing a low-pressure second outflow, and thereby complete evacuation of each wave channel in a single cycle. The expansion processes are still described by 3-4 in Fig. 2, but a portion of the expansion of the second stream takes place in the wave rotor, reducing its effective pressure gain.

From the gas turbine systems point of view this configuration is a compact rotary combustor, which may be integrated with turbomachinery as shown in Fig. 3 for each possible type. Flow through the ports is essentially steady unlike all kinds of non-rotary pulsed combustors described by Kentfield (1993), thus maximizing the benefit of constant-volume combustion (Nalim, 1998). Experimentally (Anonymous, 1997) and computationally (Pekkan and Nalim, 2002a), their low NO_x characteristics have been demonstrated. Beneficial off-design performance like an extended stall range (Greendyke et al, 2000) and high part-load efficiency is predicted (Sladky, 1984).

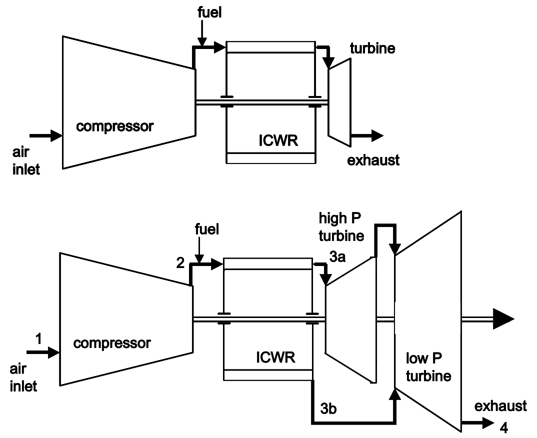

Fig. 3 Two Configurations of Gas Turbine Engines with ICWR.

Recently, there have been significant developments in the development of pulsed detonation engines (PDE) for direct thrust application, and they have also been considered for gas turbine enhancement. More so than other pulsed combustors with a single-chamber, the PDE delivers a highly unsteady flow to the turbine. Although multi-chamber PDE designs have been developed for thrust applications, there remains significant unsteadiness in velocity, pressure and temperature of the outflow that may be unacceptable for utilization in a turbine (Kailasanath, 2000) (Paxson, 2001) (Kentfield, 2001) (Nalim, 2001).

Under all operating conditions of a gas turbine engine the overall fuel-air ratio is usually below the lean flammability limit of typical fuels. This necessitates the use of a richer primary zone for stable combustion in conventional combustors, with additional air being mixed in downstream to bring the overall mixture to turbine-acceptable temperature. In wave rotor combustion, a similar strategy may be necessary. One method consists of separating the inlet air into a number of premixed sectors fueled by separate continuous-flow fuel injectors, enriching sectors that supply the zones where combustion is initiated. This provides a stratified mixture in the wave rotor channels. As load varies, injectors may be modulated to maintain flammable mixture or are turned off.

In the pioneering work by ABB (Anonymous, 1997) that received little outside attention, a 36-cell counter-flow wave rotor was built with 200 mm rotor inner diameter. The rotor is manufactured from a heat resistant Nimonic alloy and estimated operating temperature was around 1100 K. A special electro-mechanical control device was employed to compensate for rotor thermal expansion. Various fuels were tried, and fuel mixture was stratified via four injection nozzles. This 3-port cycle had high-pressure and low-pressure outflows, enabling it to scavenge the exhaust gas in one cycle. The wave diagram for the design is shown in Fig. 4, which indicates that two cycles of operation are completed in a single revolution with inlets and outlets on alternating sides, so that the cycles are mirror images of each other and help maintain a uniform rotor temperature. Both spark plug and self-sustaining hot gas-injection ignition methods were utilized.

The following problem areas were reported: (i) inhomogeneous mixture in the cell, resulting in a slow diffusion flame, (ii) leakage caused misfiring at high chamber pressures and premature ignition, (iii) thermal stresses on the ignition ring, (iv) inadequate cantilever single bearing rotor support, (v) electromechanical device for controlling leakage gap was very complicated and sensitive, (vi) five-stage honeycomb seal produced best results. Major remedies recommended to make the system better include (i) lead away duct for leakage gas removal, (ii) rotor cooling by air (Zauner, 1996), (iii) two-sided rotor support and (iv) mechanical control for thermal expansion (Kantrowitz, 1954).

At NASA Glenn Research Center, Ohio, more recent studies were directed towards aerospace gas turbine systems (Wilson and Paxson, 1996). Experimental studies on four-port wave rotor (Wilson and Fronek, 1993) and wave divider engine (Wilson, 1997) enabled the estimation of loss budgets (Paxson, 1995a) and validation (Paxson and Wilson, 1995) of Paxson's quasi-1-D gas dynamic cycle design code (Paxson 1995b). Combustion prediction capability was added to the wave rotor code by Nalim and Paxson (1997), enabling the exploration of wave cycles involving both detonation and deflagration modes of combustion (Nalim, 1999) (Nalim, 2000). Mixing controlled reaction is combined with a simple eddy diffusivity model, temperature kinetics factors and a total-energy flammability limit (Nalim and Paxson, 1997).

The performance of detonative and deflagrative cycles was studied (Nalim and Paxson, 1997) by combined CFD and system simulation. It was determined that deflagrative combustion with longitudinal fuel stratification could be accomplished in reasonable time for wave rotor size to be competitive with pressure-exchanger designs using a separate combustor (Nalim, 2000). The importance of thermal management of leakage flows and of rotor and end-wall

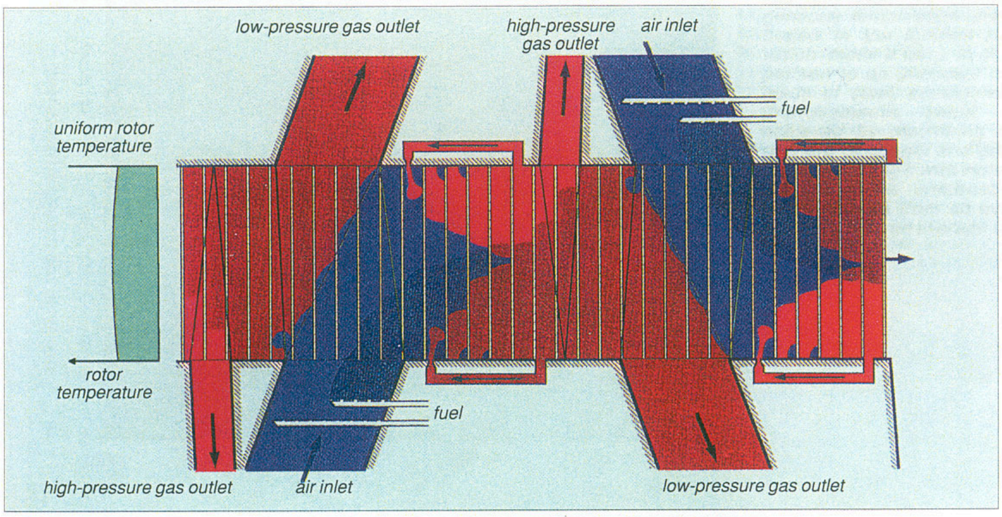

Fig. 4 Wave Diagram for ABB Experimental ICWR (Anonymous, 1997).

temperatures was highlighted, with illustration of the impact of hot ignition gas and cold buffer zones on end walls. This is consistent with the major challenges revealed by the ABB experiment.

Current research at Indiana University Purdue University Indianapolis (IUPUI) by the first author of this paper focuses on deflagrative combustion with radial stratification (Pekkan and Nalim, 2002a) and detonative combustion cycles for propulsion engines (Nalim and Jules, 1998) (Nalim, 2002). Radial stratification using a pre-combustion partition enables the introduction of a relatively cooler buffer zone close to the leakage gaps thus reducing hot gas or fuel leakage to the rotor cavity. Fig. 5 is a contour plot of Mach number from a simulation of deflagrative combustion in a stoichiometric partition region propagating into a leaner mixture in the main chamber. Above and below the partitions, there is no fuel and this gas may leak out without danger of overheating or hot gas leaking in during the filling process. These thermal management approaches are possible by extensive cycle design studies and analysis, and seek to alleviate the challenges recognized by ABB and NASA. This technique also helps burn leaner mixtures, resulting in reduced NO_x emissions, similar to other pilot combustion or lean-burn techniques in conventional engines (Pekkan and Nalim, 2002a). For this approach, radial leakage flows (Pekkan and Nalim, 2002c) and combustion models were studied in detail (Pekkan and Nalim, 2002b). These ideas have not yet been tested experimentally.

Interest in detonative combustion initially focused on pulsed detonation engines (PDE) has evolved to consideration of the wave rotor as an effective implementation of the concept (Nalim, 2002), and a means of overcoming challenges to PDE concepts that involved integration with conventional turbomachinery. In effect the wave rotor provides automatic high-speed valving, nearly steady inflow and outflow, and the use of a steady ignition device for multiple tubes. However, detonative combustion is fundamentally restricted to highly energetic mixtures and sufficiently large passage widths, and generates a strong pressure wave. This results in the outflow being highly non-uniform in pressure, velocity, and possible temperature.

Fig. 5 Mach Number Distribution of Partition Exit Flow.

To better utilize the output of a wave rotor PDE it has been proposed to add an ejector element to the wave rotor (Nalim and Izzy, 2001). The rotary wave ejector admits bypass air after the detonation tubes to transfer energy and momentum. Numerical simulations using a quasi-1-D code, modified to account for radial-type bypass flows, have shown that the specific impulse at static thrust conditions can be doubled, after accounting for flow-turning and shock losses, comparing with an equivalently loss-free PDE cycle. A sample wave diagram and a schematic sketch are given in Fig 6, where the cold ejector gas flow is clearly distinguishable.

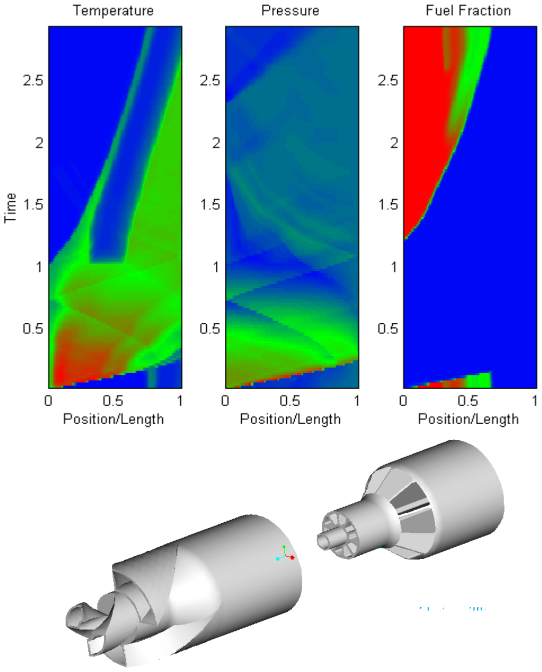

Fig. 6. Wave Ejector Rotary Pulse Detonation Engine (Nalim and Izzy, 2001).

Another approach to utilize detonative wave rotor combustion in conjunction with turbomachinery has been proposed by Allison Advanced Development Co., in collaboration with IUPUI. A novel four-port device was proposed (Snyder et al., 2002) for supersonic turbofan engines (Smith et al., 2002). A recirculation duct allows air that is compressed by the shock of a detonation wave to be reinjected with fuel. Air-buffer regions both between fuel/air-combusted gas interface and at the exit end plate are inherent in the cycle design, allowing self-cooling of the walls. The inflow and outflow of this engine concept is designed to be nearly uniform and acceptable to modern turbines, compared to conventional rotary detonation cycles (Snyder et al., 2002), Fig 7.

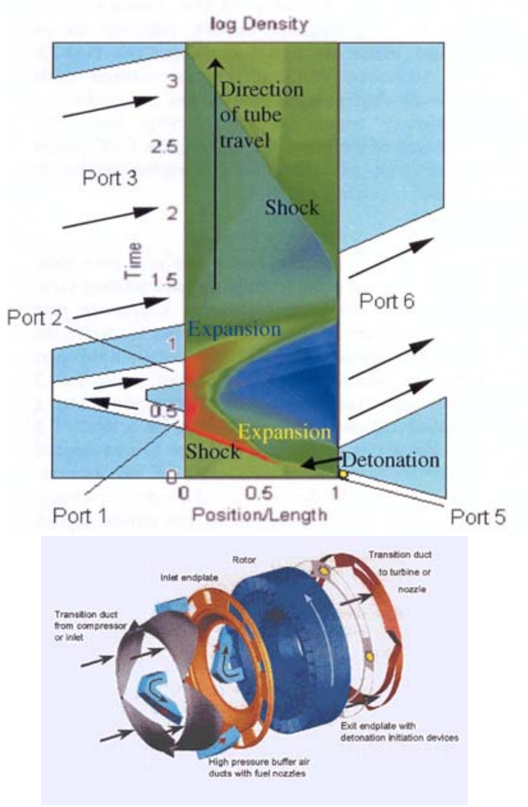

Fig. 7 Wave Rotor Pulse Detonation – the ‘CVC’ Engine. (Snyder et al., 2002)

RESEARCH NEEDS AND PROMISING APPLICATIONS

Computational studies confirm that overall performance measures are consistent with the thermodynamic limits of constant volume processes (Nalim, 1998). However, despite the number of proposed and produced engine types, there are still many unknowns in the dynamic constant-volume combustion process. Combustion in wave rotors, which is intermittent and confined approximately at constant volume, is obviously different from the steady gas turbine combustion process. But it also differs from the familiar internal combustion engines. The relatively long passage and wave rotor inlet design allows for finer stratification than is possible in piston engines, while a high level of turbulence of unknown scales and decay characteristics is expected from the preceding high speed inlet flow and shock compression processes.

Several mechanisms exist for generation of large-scale turbulence. Apart from upstream duct surfaces and bends, an early mechanism for generation of such structures is the opening and closing of channels of finite width in the presence of significant pressure differences between the port and the channel. The partitions intended for stratification may add to stirring at the inlet plane. It can be shown that turbulence on the scale of the channel width will typically not dissipate significantly over the intake period of a wave cycle (Nalim, 1999). As the large structures break down, their energy reaches scales that promote mixing later in the cycle. Pressure waves interacting with flames or other density gradients or discontinuities produce vorticity by baroclinic forces (Richtmyer-Meshkov instability), and this can further create large vortical structures. Large-scale mixing also occurs when hot gas is reinjected at high speed to penetrate the fresh mixture over a distance greater than the channel width. This can be extended by the use of partitions for thermal management and pilot ignition (Pekkan & Nalim, 2002). These phenomena all interact with the combustion process and perhaps present the greatest uncertainty and motivation for research in developing wave rotor combustion.

Propagation of a fully developed detonation does not need turbulence, but turbulence can aid transition from initially deflagrative propagation. Other methods of generating a detonation may involve multiple ignition sites, external pre-detonation, or shaped wave interactions. In any case, detonations are only supported by a narrow range of fuel-air mixtures and they require a minimum tube size. Much of the data on detonations is limited to easily detonable fuels (hydrogen, ethylene), ambient temperature mixtures, and round tubes. Research is needed for other fuels, high inlet temperature conditions typical of gas turbine combustor operation, and rectangular channels.

For preliminary cycle design and loss estimates, one-dimensional gas dynamic analysis is a useful tool. However, cycle time and other design features are sensitive to the complex combustion process. Therefore, multi-dimensional and more accurate simulations are needed in the detailed design phase. Nevertheless, it appears that the simulations presented in the review section are presently adequate to undertake design of some basic experiments. It is necessary that combustion experiments be conducted under conditions very near to a wave rotor, including turbulence generation and wave propagation influences. For this reason the following section describes a proposed combustion experiment intended to precede a combustion wave rotor design.

Currently, there appear to be two new application areas where the potential pay off is commensurate with the high degree of risk perceived in this technology, and where the need to exceed the performance limits of turbomachinery outweighs perceived uncertainties. One area is the improvement of small (‘micro’) turbines for distributed power generation. For small combustors, detonative propagation appears unlikely, and premixed turbulent combustion processes must be demonstrated in basic experiments prior to combustor design. The other area is that of high-speed propulsion of long-range supersonic aircraft using high-efficiency engines to reduce aircraft weight and sonic boom. Combustor channels for such engines may be large enough to support detonative combustion and exploit the high-temperature conditions to minimize cycle time and thus combustor weight.

BASIC WAVE ROTOR COMBUSTION EXPERIMENTS

Some experiments reported previously have focused on single-channel studies. Single-cell experiments with various shutter valves can produce useful information for understanding of actual wave rotor engines (Anonymous, 1997), but may not have the same inlet aerodynamics and turbulence characteristics that influence combustion. As in stationary-channel pulsed engines, shutter valves also introduce a lot of unsteadiness in the upstream compressor/intake flow which can only be overcome by a rotary combustor with high number of blades, i.e. a wave rotor with properly shaped angled inlet ducts. Similarly, the turbulence in the single cell experiments will be affected by the upstream valve operation; it is likely that unpredictable turbulence levels will alter the turbulent combustion rate. This variation is reported both in the computational studies (Pekkan and Nalim, 2002a), and confirmed experimentally (Anonymous, 1997). Fundamental combustion research on stationary tube pulse detonation engine applications is also relevant to wave rotor studies, but an organized experimental effort focusing on ICWR engines is needed.

Experiments that attempted a complete ICWR included all real fluid phenomena such as turbulence and mixing, but have generally not been convincing demonstrations because of the difficulty of instrumenting rotating channels. This suggests an intermediate experiment, namely a stationary-rotor/rotating-valve configuration, which facilitates easy combustion instrumentation access. In Fig 8, a possible “Rotary Valve - Stationary Rotor” engine test-rig is sketched. While this differs mechanically from a wave rotor configuration, it has advantages in terms of experimentation, and possibly, flow and combustion visualization. Stationary rigs employing shutter type valves will not duplicate the real rotary wave rotor combustion process exactly unless a finite length aerodynamically shaped rotary valve is used at inlet, as shown here. For studying combustion, this requirement is not needed for the shape of the downstream rotary valve.

CONCLUSION

The integrated combustion wave rotor is an important development option for gas turbine engines. From the hardware and design point of view this concept has potential high performance gains achievable with the current state of turbine technology, and can be a compact, low-NO_x system. Recent research efforts and successfully operated prototype engines demonstrate its viability.

However, in the area of combustion process control, there are still fundamental unknowns that must be studied. A good experimental plan is needed, including well-instrumented stationary channel combustor rigs, both single-channel and multiple-channel, with carefully constructed inlet aerodynamics and sealing systems. With knowledge gained from such experiments, rotating combustor wave rotors may be designed and tested with particular fuels and operating cycles for intended applications.

Unlike in early wave rotor history when construction of a typical wave diagram took weeks to complete, current computational tools (even with simple combustion models) are quite developed and can be used routinely in design studies to shorten development time. The real remaining challenge is to undertake a sustained and careful experimental effort that leads to a fuller understanding of possible combustion modes and rates for various mixtures, and to solutions for the anticipated mechanical design issues. Much could be gained from the application of modern optical diagnostic techniques.

After fundamental experiments have confirmed the general feasibility of the proposed modes of wave rotor combustion, specific experiments should be planned to develop modes that are appropriate for specific applications. For example, military applications seeking high thrust engines may focus on detonated modes, but disregard pollutant emissions. On the other hand, most commercial and industrial applications would be subject to stringent environmental restrictions that conventional combustion engines were able to accommodate only after decades of painstaking research. It is unlikely that complex emissions, efficiency, and power density trade-offs would become evident in preliminary experiments. Therefore, a patient and realistic approach would focus on achieving stable combustion in an appropriate mode as an initial goal.

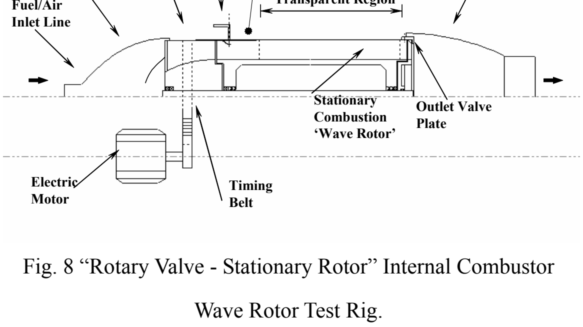

Fig. 8 “Rotary Valve - Stationary Rotor” Internal Combustor Wave Rotor Test Rig.

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