3.2.1.4.1
Trapped Vortex Combustion

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3.2.1.4.1-1 Trapped Vortex Combustion

Benefits to IGCC Gas Turbines of Trapped Vortex Combustion

The Trapped Vortex Combustion (TVC) technology has the potential to:

- Burn a wide variety of medium and low-BTU gases including hydrogen-rich gasified coal, biomass products, and landfill gas;
- Operate in a low NO_x, lean premixed mode combustor environment on hydrogen-rich syngas to accommodate the high flame speed that is a characteristic of these fuels;
- Achieve extremely low NO_x emissions without the added expense of exhaust gas after-treatment;
- Eliminate the costly requirement for high pressure diluent gas (nitrogen, steam or carbon dioxide) for NO_x emissions control;
- Accommodate more types of gas turbines for IGCC applications by decreasing the mass flow through the turbine section;
- Improve the overall cycle efficiency of the gas turbine by decreasing the pressure drop through the combustor; and
- Extend the lean blowout limit offering greater turndown, (load following), with improved combustion and process stability.

3.2.1.4.1-2 The Challenges of IGCC Gas Turbine Combustion

The Integrated Gasification Combined Cycle (IGCC) is emerging as a best available technology to utilize low quality energy resources, such as coal or oil, and meet emission limits not achievable by other conventional or advanced competing technologies. However, the success of the IGCC in the energy sector requires continuous enhancement in performance and reduction in capital costs. New, more efficient, gasification technologies are in demonstration; hot gas cleanup is improving; and gas turbines for IGCC applications are advancing in efficiency, capability and reliability.

Commercially available gas turbines have been developed for the use of natural gas, (i.e. a methane-rich fuel with high calorific values of 800 to 1200 BTU/scf). The gas turbines for these IGCC power plants have been adapted to burn syngas, a hydrogen-rich fuel[1] with low calorific values of 100-300 BTU/scf, but their design features are not generally optimized for these fuel applications.

The gas turbine encounters two major changes when transitioning from natural gas to syngas:

- For the same fuel heat input, the fuel mass flow is four to five times greater than for natural gas, due to the lower heating value.
- Premixed natural gas and air combustion systems have become common place for controlling NO_x emissions. These systems are not used with syngas due to the high content of hydrogen and the potential for flashback of the flame into the fuel injection system. Diffusion flame or "non-premixed" combustors are used with syngas to control the NO_x emissions by diluting the syngas with nitrogen, steam or carbon dioxide. The diluent reduces the flame temperature and consequently the formation of NO_x.

These two factors, greater fuel flow and the addition of diluent for NO_x emissions control, substantially increase the overall mass flow through the turbine. This increase in flow creates backpressure to the compressor and can bring the engine close to surge conditions. Some gas turbines such as the GE 9001 EC are able to accommodate the increase in mass flow through the turbine expander. Unfortunately, the majority of gas turbines are not able to accept the overcapacity to the turbine expander.

3.2.1.4.1-3 Combustion of Syngas

NO_x emissions from coal based IGCC plants are as low or lower than those from the best conventional coal fired power plants. Nevertheless, NO_x emissions from syngas gas fired turbines are inevitably compared to those of natural gas fired gas turbines without a good understanding of the differences in composition of the two fuels[2].

Dry (i.e. no addition of steam or water) Low NO_x (DLN) combustors can achieve less than 10 ppmvd (parts per million by volume, dry, at 15% Oxygen) NO_x emissions with natural gas fuel. DLN combustors rely on the premix principle that reduces the flame temperature, and subsequently the NO_x emissions. DLN combustors are able to achieve much lower NO_x emissions than diluted non-premixed combustors because of an increase in premixing time prior to entering the combustion region.

The high hydrogen content (up to 60% by volume) in syngas results in a flame speed that is up to six times faster than typical natural gas. The high flame speed of syngas makes the use of a DLN combustion system impossible because the flame will draw back into the premix zone and destroy the fuel injection hardware.

The diluted non-premixed combustors have a chemical kinetic limit when too much diluent is added for further reduction of NO_x emissions. The increase in diluent will cause flame instabilities in the combustion zone and eventual engine flame-out. The best case, practical NO_x reduction limit for syngas combustors is between 10 and 20 ppmvd NO_x.

In order to further reduce NO_x emissions in an IGCC power plant, the popular selective catalytic reduction (SCR) post-combustion control method will be required. Unfortunately, the SCR method which is very effective for sulfur-free natural gas, will not work if the sulfur cannot be removed from the syngas. Unlike natural gas, syngas does contain some sulfur which can be converted in the SCR to sulfur compounds and subsequently be deposited on the tube surfaces of the heat recovery steam generator.

As an example, the Polk IGCC power plant located in Florida, owned by Tampa Electric Company, has experienced some sulfur deposits on the tube surfaces. The DOE reported that any additional deposits that would be generated by the addition of a SCR system would make the Polk plant inoperable on syngas in its current configuration.

3.2.1.4.1-4 DOE NETL IGCC Turbine Program

In response to the challenges of burning syngas in IGCC gas turbines, the DOE has initiated a new multiyear program (Enabling Turbine Technologies for High-Hydrogen Fuels: DE-PS26-05NT42380) that will fund the development of technologies and products to serve the central station power generation market.

The program will address key technologies needed to enable the development of advanced gas turbines and gas turbine-based systems that will operate cleanly and efficiently when fueled with coal-derived syngas. This is an investment in securing future U.S. electric power production through the use of the Nation's largest fossil fuel energy resource.

In order to address these technical challenges the participants in the program will pursue new combustor design approaches that include hydrogen premixing, catalytic combustion, and novel concepts such as TVC.

3.2.1.4.1-5 Trapped Vortex Combustion – Breakthrough Technology

Trapped Vortex Combustion technology holds tremendous promise for IGCC gas turbine applications with improved efficiency, lower emissions, greater flame stability, added fuel flexibility, increased durability, and reduced capital costs.

The TVC concept was originally conceived in the early 1990s for aero-propulsion applications with high through-put velocity requirements. It was not until the early 2000s that research and development organizations initiated the first design concepts for industrial applications.

The TVC technology has the potential for product insertion into a wide variety of industrial applications including gas turbine power generation, manufacturing processing, chemical process heating, steam boiler systems, and incineration.

The requirements of low fuel consumption and low pollutant emissions are paramount for all types of combustors, with the combustor primary zone airflow pattern of prime importance to flame stability, combustion efficiency, and low emissions. Many different types of airflow patterns are employed by non-TVC concepts, but one common feature to all is the creation of a toroidal flow reversal that recirculates (figure 1) and entrains a portion of the hot combustion products to mix with the incoming air and fuel to stabilize the flame. Although these designs have long been used in many practical combustion devices, there are limitations, especially for lean premixed applications.

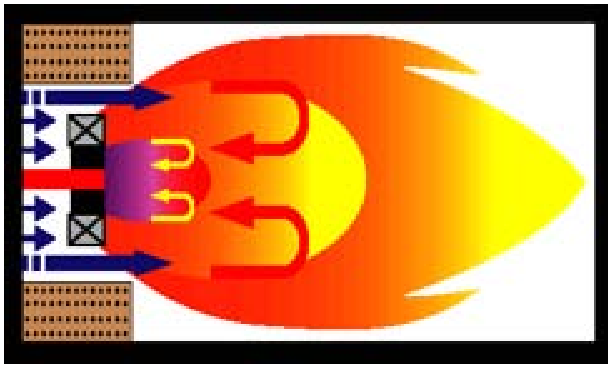

Fig. 1. Non -TVC Swirl Stabilized Combustion
(Courtesy of National Combustion Equipment, Inc.)

Flame stability is achieved though the use of recirculation zones to provide a continuous ignition source which facilitates the mixing of hot combustion products with the incoming fuel and air mixture. Swirl vanes are commonly employed (figure 2) to establish the recirculation zones. This method creates a low velocity zone of sufficient residence time and turbulence levels such that the combustion process becomes self-sustaining. The challenge, however, is selection of a flame stabilizer which ensures that both performance (emissions, combustor acoustic and pattern factor) and cost goals are met.

In contrast to conventional combustion systems which rely on swirl stabilization, the TVC employs cavities (figure 3) to stabilize the flame and grows from the wealth of literature on cavity flows. Much of the historical effort examines the flow field dynamics established by the cavities, as demonstrated in aircraft wheel wells, bomb bay doors and other external cavity structures. Cavities have also been studied as a means of cooling and reducing drag on projectiles and for scramjets and waste incineration.

Fig. 2. Industrial Fuel/Air Swirler
(Courtesy of National Combustion Equipment, Inc.)

The actual stabilization mechanism facilitated by the TVC is relatively simple. A conventional bluff or fore body is located upstream of a smaller bluff body - commonly referred to as an aft body. The flow issuing from around the first bluff body separates as normal, but instead of developing shear layer instabilities which in most circumstances is the prime mechanism for initiating blowout, the alternating array of vortices are conveniently trapped or locked between the two bodies.

In a TVC concept, the re-circulation of hot products into the main fuel-air mixture is accomplished by incorporating two critical features. First, a stable recirculation zone must be generated adjacent to the main fuel-air flow. If the vortex region, or cavity region, is designed properly, the vortex will be stable and no vortex shedding will occur. This stable vortex is generally used as a source of heat, or hot products of combustion.

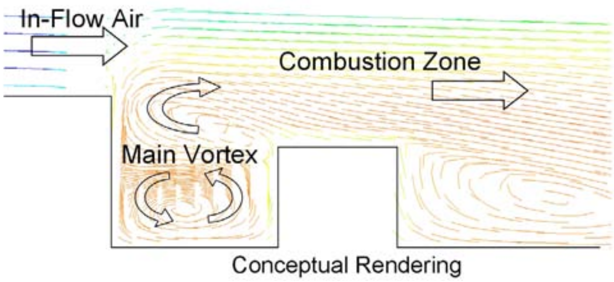

Fig. 3. Trapped Vortex Combustion

The second critical design feature involves transporting and mixing the heat from the vortex, or cavity, region into the main flow. This is accomplished by using wake regions generated by bodies, or struts, immersed in the main flow. This approach ignites the incoming fuel-air mixture by lateral mixing, instead of a back-mixing process. By using geometric features to ignite the incoming fuel-air mixture, instead of pure aerodynamic features, the TVC concept has the potential to be less sensitive to instabilities and process upsets. This is particularly important near the lean flame extinction limit, where small perturbations in the flow can lead to flame extinction.

The very stable yet more energetic primary/core flame zone is now very resistant to external flow field perturbations, yielding extended lean and rich blowout limits relative to its simple bluff body counterpart. Early research has demonstrated that the TVC configuration can withstand through-put velocities near Mach 1. This unique characteristic of the TVC technology provides a fluid dynamic mechanism that can overcome the high flame speed of hydrogen-rich syngas and potentially allow IGCC gas turbines to operate the combustor in premixed mode.

This system configuration also has greater flame holding surface area and hence will facilitate the more compact primary/core flame zone essential to promoting high combustion efficiency and reduced CO emissions.

3.2.1.4.1-6 TVC Development

Several TVC approaches from government research organizations and private companies are reviewed. Each design shares in the common fundamental features of the TVC technology but also exhibit the unique features that set them apart from each other.

1. Air Force Research Laboratory

The Air Force program started in the early 1990s at the Air Force Research Laboratory (AFRL) in Dayton, Ohio.

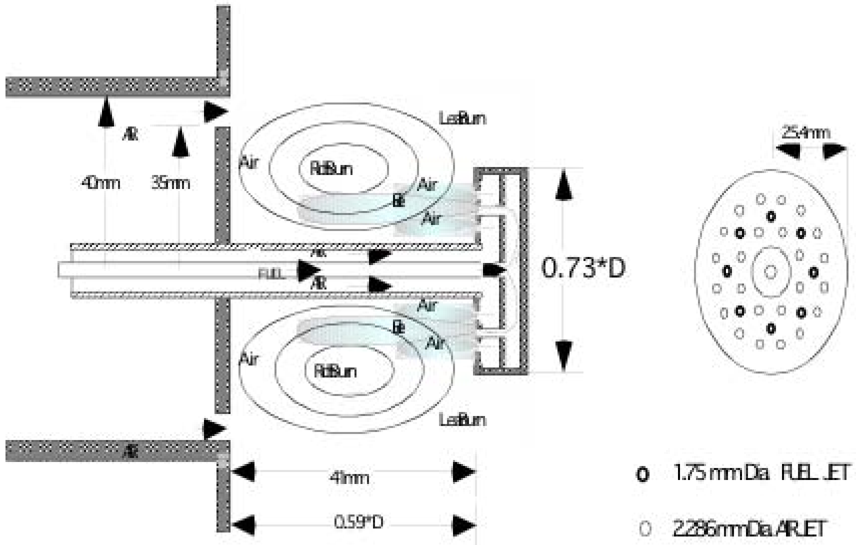

Fig. 4. AFRL First Generation TVC
Source: See note 5 (Ren, Egolfopoulos, and Tsotsis 2002).

The phenomena of locked or trapped vortices has been known to reduce aerodynamic drag for years[3], and the geometric features required to produce a locked or trapped vortex are the same features used to minimize drag. Hsu et al. in 1995 was first to report using this feature to stabilize reactions in gas turbine combustors for aero-propulsion applications[4]. Since then, several papers and patents have described the results from using this TVC concept to achieve stable and low combustor emissions[5]. The AFRL continues to investigate potential TVC applications for advanced military gas turbine engines[6]. The AFRL TVC development efforts have focused primarily on liquid fuel burning aero-propulsion applications and not on industrial natural gas or syngas burning applications.

The developmental evolution of the TVC concept at the AFRL is extremely well summarized by Roquemore et al.[7]. The first generation TVC is shown in figure 4. The cavity is formed between the two disks in tandem. Katta and Roquemore used a time-dependent, axisymmetric model to predict the results of reducing the drag of bluff-bodies in non-reacting flow and the experimental results of the first generation TVC[8].

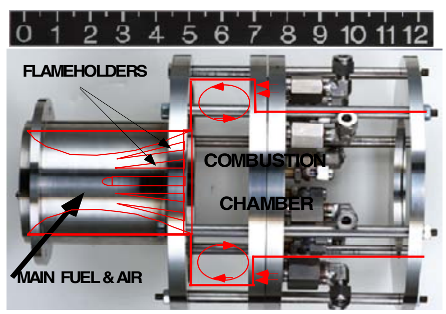

Fig. 5. AFRL Second Generation TVC
Source: Same source as for fig. 4.

The second generation TVC design, shown in figure 5, was an axisymmetric can-type configuration with the cavity on the outside of the main burner. The depth of the cavity was approximately the same as that for the optimum first generation TVC.

The third generation TVC shown in figures 6 and 7 was a two-dimensional sector designed for easy replacement and optical viewing of the cavities. The objective of the design effort was to develop a liquid fuel burning TVC concept for gas turbine engine applications.

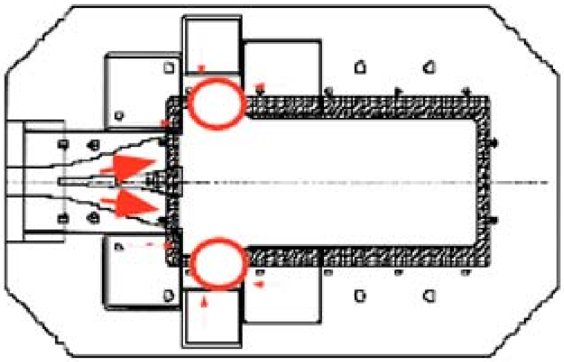

Fig. 6. AFRL Third Generation TVC
Source: Same source as fig. 4.

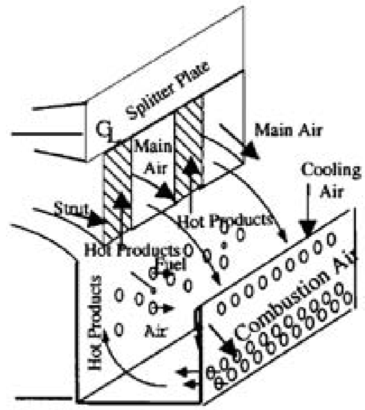

Fig. 7. AFRL Third Generation TVC Cavity
Source: Same source as fig. 4.

The development program at AFRL concluded that the TVC offers significant improvements to aircraft gas turbine engines in lean blow out (LBO) and altitude relight when compared to conventional swirl stabilized combustors. Also, a wider operating range and the potential to achieve lower NO_x emissions were demonstrated. The TVC concept can operate in a staged, main-pilot mode as well as in a rich burn–quick quench–lean burn (RQL) mode. Even though encouraging rig results have been obtained to date, no full engine test as been completed with an integrated TVC concept.

2. General Electric Company

The General Electric (GE) Company has been developing TVC concepts for gas turbine engines since the mid 1990's. At least ten GE TVC patents have been either filed and/or cleared since 1995. The majority of the patent work has been in the area of military gas turbine engines. More recently, GE has filed two TVC patents for low NO_x emissions industrial gas turbine engine applications. The invention was made with support from the U.S. DOE.

Aircraft Application

GE Aircraft Engines and the AFRL have been jointly developing a novel TVC concept for military gas turbine engines since 1996[9]. This effort represents an extension of earlier AFRL research with the third generation TVC concept. The work led to the fabrication of a rectangular sector test rig shown in figure 8 with a pressure capability of up 20.5 atmospheres and temperatures as high as 900 K. The performance evaluation covered all aspects of a gas turbine engine. The operating conditions with JP-8 fuel provided simulations of current commercial and military aircraft gas turbine engine cycles as well as some advanced cycles. Data was also obtained at selected conditions for the LM2500 marine Navy duty cycle using #1 Diesel.

The TVC test rig demonstrated that ignition, blow out, and altitude re-light were up to 50% improved over current swirl stabilized combustors. The NO_x emissions were in the range from 40% to 60% of the U.N. International Civil Aviation Organization (ICAO) standard. The combustion efficiency was maintained at or above 99% over a 40% wider operating range than a conventional aircraft gas turbine engine combustor.

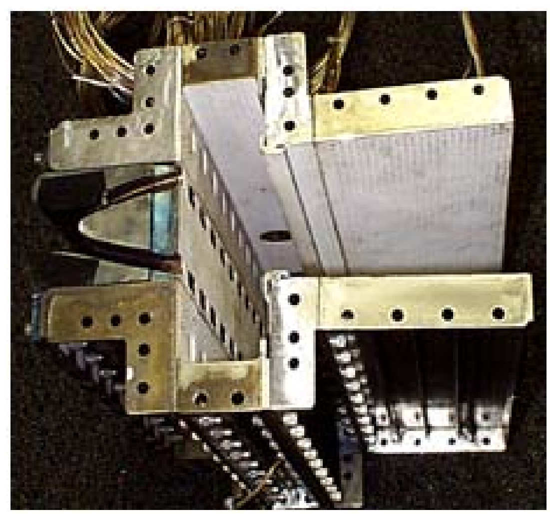

Fig. 8. GE TVC Sector Rig
Source: See note 9 (Phillips).

Industrial Application

GE Research is pursuing the application of TVC concepts to industrial gas turbine engines that can meet sub-9 ppmv NO_x emissions. The objective of DOE Contract No. DE-FC26-01NT41020 is to explore advanced combustor concepts that show promise to meet future emissions requirements. The results of this DOE program are not published at this time. Any further information from GE regarding their low emissions TVC development effort was unavailable.

3. DOE National Energy Technology Laboratory

The U.S. DOE is developing technologies for ultra-clean energy plants with efficiency and emission goals that are well beyond the capability of current gas turbine power plants. The DOE reports that ninety-percent of new power plants currently under construction will be fueled by a natural gas-based fuel. A key feature of these future power plants will be fuel diversity and flexibility. The gas turbine combustor designs will require the capability to operate on a wide range of fuels including hydrogen-rich synfuels. The DOE has also selected the TVC concept as a promising technology for future gas turbine combustor designs.

A collaborative effort began in 1999 between the AFRL and the NETL to evaluate the TVC concept for stationary power applications. The project was co-sponsored by the DOE Advanced Turbine Systems (ATS) program and the DOD Strategic Environmental Research and Development Program (SERDP).

The primary intent was to assess the low-emissions capabilities of a novel RQL staged combustor shown in figure 9[10]. The goal was to achieve NOx and CO emissions that are comparable to other commercial natural gas burning DLN systems. High BTU-fuels and fuels containing significant amounts of fuel-bound nitrogen were evaluated.

NETL has continued to pursue the development of TVC concepts and combustor configurations with their own internal research program and through separate collaborative projects with GE and Ramgen Power Systems (RPS). The recently released multi-year turbine development program (DE-PS26-05NT42380) is evidence that the DOE is committed to the advancement of novel combustor designs such as the TVC concept.

Fig. 9. NETL RQL TVC
Source: See note 10.

NETL and RPS with support from the California Energy Commission (CEC Contract # 500-02-025) completed in early 2005 a series of rig tests that demonstrated less than 3 ppmv NOx at industrial gas turbine operating conditions without the need for a stabilizing catalyst or exhaust after-treatment.

The potential use of the RPS Advanced Vortex Combustion (AVC) technology with industrial gas turbines can best be described in the spring 2005 edition of the DOE *Clean Coal Today*:

> *Researchers at NETL's high pressure test combustion facility, in collaboration with Ramgen Power Systems, have completed testing of a fuel-flexible Advanced Vortex Combustion (AVC) concept that can achieve NOx emissions of less than 3 ppmv, and combustion efficiencies of over 99 percent. The Advanced Vortex Combustor is dynamically stable over a wide range of operating conditions, which makes this approach significantly more attractive than other lean premixed combustion approaches. In addition, the pressure drop associated with this combustion approach is significantly lower than a conventional gas turbine combustor, which translates into an improvement in the overall cycle efficiency. The relatively high velocities and low pressure drops achievable with this technology make the AVC approach an attractive alternative for hydrogen fuel applications.*

4. Ramgen Power Systems

RPS is pursuing the development of its unique AVC technology that has tremendous promise for improved efficiency, lower emissions, greater flame stability, fuel flexibility, increased durability, and reduced manufacturing costs. RPS is evaluating the potential for product insertion into a wide variety of industrial applications including gas turbine power generation and mechanical drive, manufacturing processing, chemical process heating, steam boiler systems, and incineration. The immediate AVC application is for low emissions stationary gas turbine engines.

In 2002, RPS tested the first AVC concept (figure 10) with support from the DOE NETL (Contract No. DE-FC26-00NT40915) and achieved 9 ppmv NO_X emissions on natural gas in lean premixed mode[11]. The testing was conducted at the GASL facility in New York. The development of AVC concepts for gas turbine applications has continued since the test program at GASL. RPS and NETL with support from the CEC have recently completed a joint project that has shown tremendous promise for the AVC technology for extremely low emissions and acoustically stable combustion.

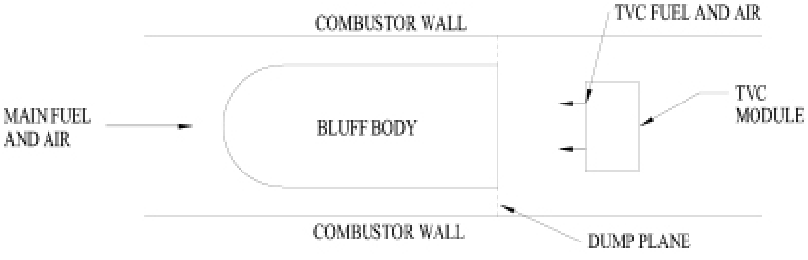

Fig. 10. RPS AVC Configuration
Source: See note 11 (Little, Jr.).

These test results indicate the potential to achieve unprecedented emissions levels of 1 ppmv NO_x and 9 ppmv CO at industrial gas turbine operating conditions. At these levels, the AVC technology offers the potential to meet the stringent emission requirements in such regions as California and New York without further exhaust after-treatment.

The tests were conducted in the NETL Low Emissions Combustion Test and Research (LECTR) facility at 10 atmospheres with combustor inlet temperature of 625°F. The combustor is air-cooled to closely simulate actual gas turbine conditions. The series of parametric tests allowed for variation in inlet pressure, fuel flow, air flow loading, lean blowout and pressure dynamics. A 4inch-by-4inch quartz window allowed for flame visualization up to 5 atmospheres.

The test results can be summarized as follows:

- Data taken at 10 atmospheres and 625°F
- Air-cooled combustor functioned as designed and without incident
- Combustor ignited at ambient conditions
- System was stable throughout start-up and shut-down
- Flame structure was observed and recorded by video through the quartz window
- Overall combustor pressure drop was less than 2.6%
- NOx emissions are not pressure dependent under ultra-lean conditions
- Lowest measured NOx with acceptable CO emissions: 3 ppmv NOx and 20 ppmv CO
- Combustion efficiencies greater than 99.9%
- Recorded combustion pressure oscillations with high frequency probe were insignificant

RPS will continue to advance the development of its AVC technology and identify product insertion opportunities in industrial applications including gas turbine power generation and mechanical drive applications. The AVC technology is scalable to various sizes and heat load capabilities.

5. ALM Turbines

Many turbine and combustor experts, including those at ALM, are increasingly optimistic about the promise of TVC[12]. It is ALM's position that the TVC concept has many real potential advantages over both diffusion flame and DLN combustors, including lower emissions, multi-fuel capability, better flame stability, uniformity of flame, better dynamics, greater lean blowout limit offering greater turndown, higher efficiency due to lower combustor pressure drop losses, compactness, and lower manufacturing costs. Over the last few years, ALM has designed, manufactured and tested a number of proprietary prototype TVCs that have demonstrated many of the above mentioned advantages.

ALM has been developing and testing its own proprietary version of TVC for both microturbines and large MW scale industrial turbines. In 2003, ALM and Alturdyne successfully designed, manufactured, and incorporated a TVC combustor into a Sunstrand T-62 APU. ALM has also designed, manufactured and rig tested two MW scale prototypes at ambient conditions that meet GE 7E 85MW operating conditions.

The ALM TVC consists of two autonomous sections – a thermal nozzle and vortex (figure 11). The time of complete fuel burning, at the primary combustion temperature, is less than 2 milliseconds. ALM has achieved combustion at very low temperatures without use of any catalysts. The ALM design is notably different from all other TVC concepts. The concept utilizes its vortex and manages the recirculation flows in a different manner. The combustion mainly takes place in the thermal nozzle and not in the vortex.

ALM uses a laminar boundary layer between the recirculation vortex flow and the fuel air mixture flow, to create certain desirable chemical reactions, and in turn a thermal nozzle effect which significantly improves the combustion process over other combustor designs. This laminar boundary layer, along with ALM's unique use of the vortex distinguishes the ALM TVC from other TVC designs.

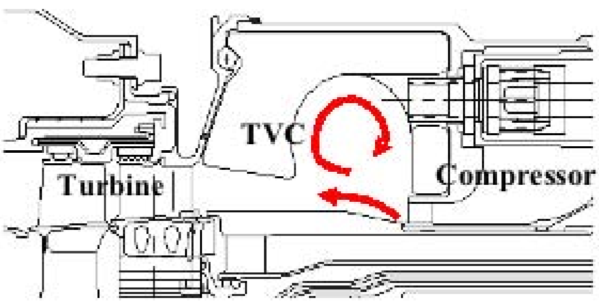

Fig. 11. ALM TVC Concept
Source: See note 12 (Mair).

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Dr. Steele has almost 20 years experience in gas turbine combustion fundamentals and applications. He was the Combustion team leader for the Mars SoLoNOx engine at Solar Turbines. He joined Ramgen in 2000 and has been involved in the development of lean premixed "trapped" or "advanced" vortex combustion designs for gas turbine applications. He holds a M.S. in Aeronautics and Astronautics and a Ph.D. in Mechanical Engineering from the University of Washington. Having authored 30 technical publications, Dr. Steele is a prior member of the Combustion Institute, a member of the Combustion and Fuels committee of the ASME, and an Affiliate Adjunct Professor at the University of Washington.