Sonic Enhanced Ash Agglomeration and Sulfur Capture

**Quarterly Report
October - December 1994**

January 1995

Work Performed Under Contract No.: DE-AC21-89MC26288

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Manufacturing and Technology Conversion International, Inc.
Columbia, Maryland

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PREFACE

This 22nd Quarterly Technical Progress Report presents the results of work accomplished during the period September 26, 1994 through January 1, 1995 under Contract No. DE-AC21-88MC26288 entitled "Sonic Enhanced Ash Agglomeration and Sulfur Capture."

There were no activities or fundamental studies conducted by West Virginia University and Penn State University during this period due to delays in issuing subcontract modifications.

In view of the potentially large repowering market in the U.S., several possible configurations were formulated in concert with DOE/METC and evaluated for application to the repowering market. The technical and market issues associated with each of these configurations were identified and summarized. MTCI performed combustor island and/or first-order cycle analysis calculations for the configurations.

An initial system simulation test for the system operating at inlet air temperatures of 700 - 800°F as for a gas turbine application was conducted. The results indicated that acoustic performance can be improved by modifying gas injectors.

Development of the advanced vortex aerovalve continued.

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SECTION 1.0

INTRODUCTION

1.1 PROJECT DESCRIPTION AND WORK STATUS

A major concern with the utilization of coal in directly fired gas turbines is the control of particulate emissions and reduction of sulfur dioxide, and alkali vapor from combustion of coal, upstream of the gas turbine. Much research and development has been sponsored on methods for particulate emissions control and the direct injection of calcium-based sorbents to reduce SO₂ emission levels. The results of this research and development indicate that both acoustic agglomeration of particulates and direct injection of sorbents have the potential to become a significant emissions control strategy.

The Sonic Enhanced Ash Agglomeration and Sulfur Capture program focuses upon the application of an MTCI proprietary invention (Patent No. 5,197,399) for simultaneously enhancing sulfur capture and particulate agglomeration of the combustor effluent. This application can be adapted as either a "hot flue gas cleanup" subsystem for the current concepts for combustor islands or as an alternative primary pulse combustor island in which slagging, sulfur capture, particulate agglomeration and control, and alkali gettering as well as NO_x control processes become an integral part of the pulse combustion process.

The goal of the program is to support the DOE mission in developing coal-fired combustion gas turbines. In particular, the MTCI proprietary process for bimodal ash agglomeration and simultaneous sulfur capture will be evaluated and developed. The technology embodiment of the invention provides for the use of standard grind, moderately beneficiated coal and WEM for firing the gas turbine with efficient sulfur capture and particulate emission control upstream of the turbine. The process also accommodates injection of alkali gettering material if necessary. This is aimed at utilization of relatively inexpensive coal fuels, thus realizing the primary benefit being sought by direct firing of coal in such gas turbine systems. The proposed technology provides for practical, reliable,

and capital (and O&M) cost-effective means of protection for the gas turbine from impurities in the coal combustor effluent.

1.2 PROGRAM OBJECTIVES

The major objective of the Phase I test program is to confirm the feasibility of the MTCI bimodal particle size approach to enhance particulate control by acoustic ash agglomeration. An ancillary objective of the Phase I effort is to demonstrate and confirm the feasibility of an acoustic field to enhance sulfur capture by increasing sorbent reactivity. Phase I tests are designed to cover the frequency range between 50 and 1400 Hz, establish monomodal baseline performance as a benchmark from which to measure the degree of enhancement expected from the bimodal approach, and, finally, to confirm the effectiveness of low-frequency fields over high-frequency fields for realistic particulate streams.

The program will demonstrate the effectiveness of a unique approach which uses a bimodal distribution composed of large sorbent particles and fine fly ash particles to enhance ash agglomeration and sulfur capture at conditions found in direct coal-fired turbines. Under the impact of high-intensity sound waves, sorbent reactivity and utilization, it is theorized, will increase while agglomerates of fly ash and sorbents are formed which are readily collected in commercial cyclones. The work will extend the concept from the demonstration of feasibility (Phase I), through proof-of-concept (Phase II) to the construction (Phase III) of a coal-fired pulsed combustor with in-furnace sorbent injection. For Phase I, Pennsylvania State University will conduct studies for enhanced sulfur capture in The Combustion Laboratory and agglomeration tests in the High Intensity Acoustic Laboratory.

1.3 SUMMARY STATUS FOR THE PERIOD

In view of the potentially large repowering market in the U.S., several possible configurations were formulated and evaluated for application to the repowering market. Based on discussions between the DOE/METC team members and MTCI staff, seven different configurations were proposed for further evaluation. These were:

- 1) Sonic Agglomeration Combustor - Natural gas-fired 1½ generation PFBC.
- 2) Sonic Agglomeration Combustor - Coal-fired 1½ generation PFBC.
- 3) Sonic Agglomeration Combustor - Second-generation PFBC.
- 4) Sonic Agglomeration Carbonizer - Second-generation PFBC (same as pulse coal combustor/PFBC island).
- 5) Sonic Agglomeration Carbonizer - AFBC with topping cycle.
- 6) Sonic Agglomeration Carbonizer - AFBC with modified topping cycle.
- 7) Sonic Agglomeration Carbonizer - Modified second-generation PFBC.

The technical and market issues associated with each of these configurations were identified and summarized. MTCI performed combustor island and/or first-order cycle analysis calculations for configurations 1, 2, 4, 5 and 6. METC is conducting ASPEN simulations to facilitate more detailed thermodynamic comparison of these configurations.

An initial system simulation test for the system operating at inlet air temperatures of 700 - 800°F as for a gas turbine application was conducted, indicating that acoustic performance can be further improved by modifying gas injectors.

Development of the advanced vortex aerovalve continued.

SECTION 2.0

TECHNICAL DISCUSSION OF THE WORK ACCOMPLISHED DURING THE REPORTING PERIOD

2.1 TASK 2, SUBTASK 2.8: SHAKEDOWN

For gas turbine application, the bimodal combustion system has to operate at air inlet temperatures in the 700 - 800°F range. To simulate this condition, a combination of a vortex gas burner and a vitiated air pulse combustor was tested. In this combination, vitiated air from the exit of the vortex combustor is supplied to the air plenum of the pulse combustor. A test with gas fed only to the vortex burner was conducted to check the performance of the burner. The test showed no problem in starting and operating the burner. While the vortex burner was running, the pulse combustor was started. Firing rate of the vortex burner was sustained at 0.32 MMBtu/hr. Firing rate of the pulse combustor ranged from 0.19 MMBtu/hr to 0.83 MMBtu/hr to find the best performance of the pulse combustor. The acoustic performance was less than desired sound pressure level (SPL) was 171 dB at a frequency of 84 Hz. Temperature in the combustion chamber was 2100°F. To improve acoustic performance of the pulse combustor it was decided to change size and number of holes of the four gas injectors to increase gas velocity for better air and gas mixing. This modification is in progress.

2.2 TASK 4: ENGINEERING EVALUATION

PULSE COMBUSTOR ISLAND CONFIGURATION

In the previous Quarterly Technical Progress Report, a combined pulse coal combustor/PFBC island configuration was proposed for the second-generation advanced concept combined-cycle plant. This configuration targeted 1/10th NSPS and was primarily amenable to greenfield applications. This concept was presented in a meeting at DOE/METC. In view of the potentially large repowering market in the U.S., other possible configurations were asked to be formulated and evaluated for application to the repowering market. Based on discussions between

the DOE/METC team members and MTCI staff, seven different configurations were proposed for further evaluation. These were:

- 1) Sonic Agglomeration Combustor - Natural gas-fired $1\frac{1}{2}$ generation PFBC.
- 2) Sonic Agglomeration Combustor - Coal-fired $1\frac{1}{2}$ generation PFBC.
- 3) Sonic Agglomeration Combustor - Second-generation PFBC.
- 4) Sonic Agglomeration Carbonizer - Second-generation PFBC (same as pulse coal combustor/PFBC island).
- 5) Sonic Agglomeration Carbonizer - AFBC with topping cycle.
- 6) Sonic Agglomeration Carbonizer - AFBC with modified topping cycle.
- 7) Sonic Agglomeration Carbonizer - Modified second-generation PFBC.

The technical and market issues associated with each of these configurations were identified and summarized. MTCI performed combustor island and/or first-order cycle analysis calculations for configurations 1, 2, 4, 5 and 6. METC is conducting ASPEN simulations to facilitate more detailed thermodynamic comparison of these configurations.

Based on a review of available information, MTCI favors configuration 5. This system is flexible enough to be configured for both repowering and green-field applications. A schematic of the proposed system is shown in Figure 1. The combustor island comprises a pulse coal combustor, hot gas cleanup (HGCU) section, two-stage hot cyclone, topping pulse combustor, and an atmospheric fluidized bed sulfater. To facilitate applicability to different end-use markets (greenfield or repowering), a coal classifier has been included. The crushed coal is classified to yield coarse coal and coal fines. The coarse coal is fed to the atmospheric fluidized bed while the coal fines are pulverized and injected into the pulse coal combustor and HGCU section. For greenfield application, all the coal will be pulverized and injected into the pulse coal combustor (PCC) and HGCU. For repowering application, 50 to 90 percent of the coal could be directed to the fluidized bed and the remainder to the PCC/HGCU. Optionally, waste material could be substituted partially or fully for coarse coal.

FIGURE 1: SCHEMATIC OF COMBINED PULSE COAL COMBUSTOR HOT GAS CLEANUP ISLAND

To ensure combustion stability and achieve high sound pressure level in the non-slugging mode, the pulse coal combustor is operated near-stoichiometrically rather than in the substoichiometric regime. Coal reburning in the HGCU is employed to reduce/control NO_x emissions. This is effected by injecting pulverized coal fines into the HGCU. The HGCU is operated in the 2100 to 2300°F range and fuel-rich mode to permit the use of calcium-based sorbents for sulfur capture. Under reducing conditions, the thermodynamic equilibrium temperature limit for sulfur capture with calcium-based sorbents is about 2400°F (see Figure 2 in the previous Quarterly Report). Pulverized alkali-gettering material such as emathlite or hectorite or kaolinite is injected into the HGCU to aid alkali vapor capture. Solids collected at the bottom of the HGCU and in the primary and secondary cyclone catch are routed to a fluidized bed sulfater to oxidize the CaS to CaSO_4 and burnout any remaining carbon. A U-tube arrangement is employed for the HGCU to minimize heat loss, solids deposition and acoustic losses.

An additional amount of sorbent is fed to the sulfater to achieve high levels (99%) of sulfur capture. Fluidizing air to the sulfater is provided by a forced draft (FD) fan. The flue gases from the sulfater enter a cyclone for dropout of solids. The flue gases pass through a heat recovery steam generator (HRSG) on the way to a baghouse. Compressed air is preheated in the air jacket of the sulfater and is injected over the tailpipes of the topping pulse combustor. Solids from the sulfater and the cyclone are delivered to an ash-cooling system prior to disposal. Flue gases from the topping pulse combustor are used to drive a gas turbine.

The pulse coal combustor and HGCU, in effect, operate in combustion staging mode with integrated hot gas cleanup. The pulse combustion of coal also provides the acoustics for ash agglomeration, sulfur capture and alkali vapor capture. Steam is used to fluidize the agglomerates at the bottom of the HGCU. These agglomerates are drained and fed into the sulfater for sulfation of the spent sorbent (CaS) and burnout of the carbon remaining, if any. The HGCU operates in the staging and reburn mode with steam addition to reduce/control NO_x emissions. Staged air addition in a topping pulse combustor downstream of the secondary cyclone completes burnout and raises the temperature for inlet to the gas turbine.

The pulse combustor operates in the non-slagging or dry ash rejection mode. The pulse combustion chamber temperature is to be regulated in the 2300 - 2500°F range depending on the ash fusion characteristics. The HGCU is to be designed to operate in the temperature range of between about 2100°F and 2300°F.

The pulse combustor is generally operated substoichiometrically (~ 0.6) to reduce NO_x formation whereas superstoichiometric operation will generate high acoustic output for agglomeration effectiveness. Since very efficient agglomeration is required to minimize particulate carryover into the turbine, the pulse combustor will be operated near stoichiometrically and coal reburn will be incorporated to minimize NO_x emissions.

The HGCU in effect acts as a dynamic filter wherein fly ash from the coal fines agglomerate with the larger sorbent particles due to collisions between the fine particles and the sorbent agglomeration foci. Acoustic agglomeration is a pretreatment process that increases the average size of entrained particles, making it possible to obtain high collection efficiency using hot cyclones. The primary cyclone is a low velocity cyclone to capture agglomerates with minimal breakup and the secondary cyclone is a high velocity, high efficiency cyclone to capture the fines.

A preliminary process design summary is shown in Table 1.

Additionally, at METC's direction, a combustor island configuration was proposed and evaluated for Warren Station repowering. This combustor island is intended for integration with the proposed externally fired combined-cycle (EFCC). A schematic of the MTCI combustor island for this application is shown in Figure 2. A preliminary plan view is shown in Figure 3. Combustor island design calculations were performed. Table 2 provides the run summary. The nominal power output is 65 MW_e. A preliminary cost estimate placed the cost of the combustor island to be between 35 and 40 million dollars.

TABLE 1:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR A NOMINAL 450 MW POWER PLANT**

NOTE: Two (PC+HGPU+HC) Feed two TPC and one sulfater;
a total of four (PC+HGPU+HC+TPC) & two sulfaters.

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
TOTAL FIRING RATE, MMBtu/hr	3,542	
FUEL	Pitts. No. 8	
NO. OF PULSE COMB/HOT GAS CLEANUP SEC.	4	
PC FIRING RATE, MMBtu/hr	487.0	*4
REBURN FIRING RATE, MMBtu/hr	398.4	*4
TOPPING PULSE COMB. FIRING RATE, MMBtu/hr	258.9	*4
TOTAL COAL FEED RATE, lb/hr	274,200	
TOTAL SORBENT FEED RATE, lb/hr	39,215	
REBURN SORBENT FEED RATE, lb/hr	7,500	*4
SULFATER SORBENT FEED RATE, lb/hr	4,608	*2
TRANSPORT AIR MASS RATIO	1	
TRANSPORT AIR TEMPERATURE, °F	200	
COMPRESSED AIR FLOW RATE, lb/hr	4,846,227	Total
- Pulse Coal Combustor	278,852	*4
- Hot Gas Cleanup Section	0	*4
- Coal Feed System	130,245	*4
- Sorbent Feed System	7,500	*4
- Sulfater	0	*2
- Sulfater HX Section	624,482	*2
- Topping Pulse Combustor	482,669	*4
- Instrumentation	200	
AMBIENT AIR, lb/hr		
- Coal Transport	0	*4
- Sorbent Transport	4,608	*2
AMBIENT AIR PRESSURE, psia	14.70	
AMBIENT AIR TEMPERATURE, °F	59	
RELATIVE HUMIDITY	60%	
INSTRUMENTATION AIR, lb/hr	50	*4
INSTRUMENTATION AIR PRESSURE, psia	270	
INSTRUMENTATION AIR TEMPERATURE, °F	59	
FORCED DRAFT FAN FOR SULFATER		
- Air Flow Rate, lb/hr	274,200	*2
- Exit Air Pressure, psia	16.73	

TABLE 1:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR A NOMINAL 450 MW_e POWER PLANT**

(Continued)

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
STOICHIOMETRY		
- Pulse Coal Combustor	85.0%	
- Hot Gas Cleanup Section	61.5%	
- Topping Pulse Combustor		
- Sulfater		
MEAN TEMPERATURE, °F		
- Pulse Coal Combustor	2,362	
- Hot Gas Cleanup Section	2,239	
- Topping Pulse Combustor	2,250	
- Sulfater	1,550	
MEAN PRESSURE, psia		
- Pulse Coal Combustor	200.20	
- Hot Gas Cleanup Section	199.70	
- Topping Pulse Combustor	198.70	
- Sulfater	15.60	
SORBENT Ca/S MOLAR FEED RATIO		
- Hot Gas Cleanup Section	1.50	
- Sulfater	1.50	
FLUE GAS MASS FLOW RATE, lb/hr		
- Hot Gas Cleanup Section Exit	499,502	*4
- Hot Cyclone Exit	478,430	*4
- Topping Pulse Combustor Exit	1,273,339	*4
- Sulfater Exit	290,765	*2
SOLIDS MASS FLOW RATE, lb/hr		
- Slag	0	*4
- Hot Cyclone	21,072	*4
- Sulfater Bed Drain	8,705	*2
- Sulfater Cyclone Catch	26,090	*2
FLUE GAS PRESSURE, psia		
- Hot Gas Cleanup Section Exit	199.20	
- Hot Cyclone Exit	198.50	
- Topping Pulse Combustor Exit	198.20	
- Sulfater Exit	14.60	

TABLE 1:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR A NOMINAL 450 MW_e POWER PLANT**

(Continued)

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
FLUE GAS TEMPERATURE, °F		
- Hot Gas Cleanup Section Exit	2,150	
- Hot Cyclone Exit	2,130	
- Topping Pulse Combustor Exit	2,100	
- Sulfater Exit	1,550	
FLUE GAS COMPOSITION		
- Hot Cyclone Exit		PPMV
- Oxygen, Vol.%	0.00	
- Carbon Dioxide, Vol.%	10.90	
- Nitrogen, Vol.%	66.53	
- Carbon Monoxide, Vol.%	10.08	
- Hydrogen, Vol.%	2.24	
- Hydrogen Sulfide, Vol.% (PPMV)	0.03	320
- Water Vapor, Vol.%	10.20	
- Hydrogen Chloride, Vol.% (PPM)	0.00	0
- Ammonia, Vol.% (PPMV)	0.09	925
- Particulates, PPMW	21	
- HHV, Btu/lb	541	39
- Topping Pulse Combustor Exit		Btu/scf
- Oxygen, Vol.%	10.53	
- Carbon Dioxide, Vol.%	8.15	
- Nitrogen, Vol.%	75.09	
- Carbon Monoxide, Vol.%	0.00	20
- Sulfur Dioxide, Vol.%	0.01	124
- Water Vapor, Vol.%	6.21	
- Hydrogen Chloride, Vol.% (PPM)	0.00	0
- Nitrogen Oxide - NO, Vol.% (PP)	0.01	90
- Particulates, PPMW	8	
- Sulfater Exit		
- Oxygen, Vol.%	3.69	
- Carbon Dioxide, Vol.%	12.68	
- Nitrogen, Vol.%	76.72	
- Carbon Monoxide, Vol.%	0.03	306
- Sulfur Dioxide, Vol.%	0.02	191
- Water Vapor, Vol.%	6.84	
- Hydrogen Chloride, Vol.% (PPM)	0.00	0
- Nitrogen Oxide - NO, Vol.% (PP)	0.02	184
- Particulates, PPMW	90	

TABLE 1:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR A NOMINAL 450 MW_e POWER PLANT**

(Continued)

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
SOLIDS COMPOSITION		
- Slag		
- Carbon, Wt.%	0.00	
- Ash, Wt.%	0.00	
- Hot Cyclone		
- Oxygen, Wt.%	3.09	
- Carbon, Wt.%	34.43	
- Nitrogen, Wt.%	0.61	
- Hydrogen, Wt.%	2.29	
- Sulfur, Wt.%	8.90	
- Ash, Wt.%	50.68	
- Sulfater		
- Oxygen, Wt.%	0.07	
- Carbon, Wt.%	0.85	
- Nitrogen, Wt.%	0.01	
- Hydrogen, Wt.%	0.06	
- Sulfur, Wt.%	10.60	
- Ash, Wt.%	88.41	
PULSE COMBUSTION ISLAND:		
Combustion Efficiency, %	99.74	
Sulfur Capture Efficiency, %	90.03	
NO _x Emissions, lb/MMBtu	0.16	
SO ₂ Emissions, lb/MMBtu	0.46	
Particulates Emissions, lb/MMBtu		
- Total	0.027	
- Topping Combustor Exit	0.012	
- Sulfater Exit	0.015	
CO Emissions, lb/MMBtu	0.07	
HCL Emissions, lb/MMBtu	0.00

FIGURE 2: SCHEMATIC OF THE MTCI PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND FOR WARREN STATION

PCC: PULSE COAL COMBUSTOR
 TPC: TOPPING PULSE COMBUSTOR
 HC: HOT CYCLONE
 SC: SULFATER CYCLONE

FIGURE 3: PRELIMINARY PLAN VIEW

TABLE 2:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR WARREN STATION**

NOTE: Two (PC+HGCU+HC+TPC) Feed one CER and sulfater;
a total of two (PC+HGCU+HC+TPC), one CER HX, one sulfater.

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
TOTAL FIRING RATE, MMBtu/hr	616	
FUEL	Pitts. No. 8	
NO. OF PULSE COMB/HOT GAS CLEANUP SEC.	2	
PC FIRING RATE, MMBtu/hr	166.2	*2
REBURN FIRING RATE, MMBtu/hr	141.6	*2
TOPPING PULSE COMB. FIRING RATE, MMBtu/hr	196.0	*4
TOTAL COAL FEED RATE, lb/hr	48,097	
TOTAL SORBENT FEED RATE, lb/hr	6,902	
REBURN SORBENT FEED RATE, lb/hr	2,718	*2
SULFATER SORBENT FEED RATE, lb/hr	1,467	*1
TRANSPORT AIR MASS RATIO	2	
TRANSPORT AIR TEMPERATURE, °F	500	
TURBINE EXHAUST AIR FLOW RATE, lb/hr	811,602	Total
- Pulse Coal Combustor	86,047	*2
- Hot Gas Cleanup Section	0	*2
- Coal Feed System	23,917	*2
- Sorbent Feed System	3,432	*2
- Sulfater	100,364	*1
- PC Air Preheat Section	30,339	*2
- Topping Pulse Combustor	211,884	*2
- HRSG	-0	
TURBINE EXHAUST AIR PRESSURE, psia	14.50	
TURBINE EXHAUST AIR TEMPERATURE, °F	901	
AMBIENT AIR, lb/hr		
- Coal Transport	24,180	*2
- Sorbent Transport	3,470	*2
AMBIENT AIR PRESSURE, psia	14.70	
AMBIENT AIR TEMPERATURE, °F	59	
RELATIVE HUMIDITY	60%	
INSTRUMENTATION AIR, lb/hr	113	*2
INSTRUMENTATION AIR PRESSURE, psia	100	
INSTRUMENTATION AIR TEMPERATURE, °F	59	

TABLE 2:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR WARREN STATION**

(Continued)

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
STOICHIOMETRY		
- Pulse Coal Combustor	86.0%	
- Hot Gas Cleanup Section	57.9%	
- Topping Pulse Combustor		
- Sulfater		
MEAN TEMPERATURE, °F		
- Pulse Coal Combustor	2,411	
- Hot Gas Cleanup Section	2,127	
- Topping Pulse Combustor	2,350	
- Sulfater	1,600	
MEAN PRESSURE, psia		
- Pulse Coal Combustor	14.40	
- Hot Gas Cleanup Section	14.30	
- Topping Pulse Combustor	13.70	
- Sulfater	14.10	
SORBENT Ca/S MOLAR FEED RATIO		
- Hot Gas Cleanup Section	1.50	
- Sulfater	1.50	
FLUE GAS MASS FLOW RATE, lb/hr		
- Hot Gas Cleanup Section Exit	166,345	*2
- Hot Cyclone Exit	159,565	*2
- Topping Pulse Combustor Exit	401,778	*2
- Sulfater Exit	114,972	*1
SOLIDS MASS FLOW RATE, lb/hr		
- Slag	0	
- Hot Cyclone	6,780	*2
- Sulfater Bed Drain	3,019	*1
- Sulfater Cyclone Catch	8,695	*1
FLUE GAS PRESSURE, psia		
- Hot Gas Cleanup Section Exit	14.20	
- Hot Cyclone Exit	13.70	
- Topping Pulse Combustor Exit	13.60	
- Sulfater Exit	13.50	

TABLE 2:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR WARREN STATION**

(Continued)

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
FLUE GAS TEMPERATURE, °F		
- Hot Gas Cleanup Section Exit	1,900	
- Hot Cyclone Exit	1,880	
- Topping Pulse Combustor Exit	2,250	
- Sulfater Exit	1,600	
STEAM, MMBtu/hr	56.59	*1
FLUE GAS COMPOSITION		
- Hot Cyclone Exit		PPMV
- Oxygen, Vol. %	0.00	
- Carbon Dioxide, Vol. %	8.79	
- Nitrogen, Vol. %	63.31	
- Carbon Monoxide, Vol. %	16.46	
- Hydrogen, Vol. %	10.19	
- Hydrogen Sulfide, Vol. % (PPMV)	0.03	329
- Water Vapor, Vol. %	1.19	
- Hydrogen Chloride, Vol. % (PPM)	0.02	168
- Ammonia, Vol. % (PPMV)	0.11	1,129
- Particulates, PPMW	61	
- HHV, Btu/lb and Btu/scf	1,228.62	68.28
- TOPPING PULSE COMBUSTOR EXIT		
- Oxygen, Vol. %	6.76	
- Carbon Dioxide, Vol. %	11.06	
- Nitrogen, Vol. %	75.79	
- Carbon Monoxide, Vol. %	0.00	36
- Sulfur Dioxide, Vol. %	0.01	144
- Water Vapor, Vol. %	6.35	
- Hydrogen Chloride, Vol. % (PPM)	0.01	74
- Nitrogen Oxide - NO, Vol. % (PP)	0.01	124
- Particulates, PPMW	25	
- SULFATER EXIT		
- Oxygen, Vol. %	6.49	
- Carbon Dioxide, Vol. %	10.10	
- Nitrogen, Vol. %	77.12	
- Carbon Monoxide, Vol. %	0.02	243
- Sulfur Dioxide, Vol. %	0.02	157
- Water Vapor, Vol. %	6.22	
- Hydrogen Chloride, Vol. % (PPM)	0.01	80
- Nitrogen Oxide - NO, Vol. % (PP)	0.01	147
- Particulates, PPMW	3,151	

TABLE 2:

**RUN SUMMARY - PULSE COMBUSTION AND HOT GAS CLEANUP ISLAND
FOR WARREN STATION**

(Continued)

	<u>100% LOAD</u>	<u>NUMBER OF MODULES</u>
SOLIDS COMPOSITION		
- Slag		
- Carbon, Wt.%	0.00	
- Ash, Wt.%	0.00	
- Hot Cyclone		
- Oxygen, Wt.%	1.74	
- Carbon, Wt.%	30.93	
- Nitrogen, Wt.%	0.66	
- Hydrogen, Wt.%	2.21	
- Sulfur, Wt.%	9.70	
- Ash, Wt.%	54.76	
- Sulfater		
- Oxygen, Wt.%	0.04	
- Carbon, Wt.%	0.71	
- Nitrogen, Wt.%	0.01	
- Hydrogen, Wt.%	0.05	
- Sulfur, Wt.%	10.76	
- Ash, Wt.%	88.43	
PULSE COMBUSTION ISLAND:		
Combustion Efficiency, %	99.78	
Sulfur Capture Efficiency, %	90.03	
NO _x Emissions, lb/MMBtu	0.19	
SO ₂ Emissions, lb/MMBtu	0.47	
Particulates Emissions, lb/MMBtu		
- Total	0.563	
- Topping Combustor Exit	0.033	
- Sulfater Exit	0.530	
CO Emissions, lb/MMBtu	0.08	
HCL Emissions, lb/MMBtu	0.14	

2.3 ADVANCED VORTEX AEROVALVE DEVELOPMENT (MTCI)

The aerovalves currently used on pulse combustors at MTCI are of the converging-diverging (venturi) type. These aerovalves are easily constructed and non-fouling but are limited to a low diodicity¹, theoretically equal to the exit-to-throat area ratio, as shown by results from research at West Virginia University. The aerovalve produces a backflow pressure loss by causing the flow to separate at a sharp edge throat. This allows no dynamic pressure recovery and provides the high impedance necessary for combustion compression. The actual diodicity is less than the theoretical diodicity due to frictional losses in the diffuser and by flow separation. Both the sharp-edged throat and a high exit-to-throat area ratio induce flow separation in the diffuser. These losses can be diminished by using a long, small divergence angle diffuser and designing for low area ratios. The ratio of the combustion chamber temperature to aerovalve inlet temperature (T_r) also affects the diodicity. Because of the lower density and mass flow rate of the high-temperature backflow, the diodicity is increased. By operating at ambient inlet temperature (high temperature ratios), a significant increase in diodicity can be achieved. But for high inlet operating temperature conditions, such as exist in the bimodal configuration, the diodicity will still be low.

The vortex aerovalve attempts to augment the diodicity of the venturi aerovalve by increasing the reverse flow (backflow) pressure loss, while maintaining the same inflow characteristics. This is achieved by adding a reverse flow *double cone vortex chamber*. This addition is necessary to improve the performance of the combustor (sound pressure level, chamber temperature). The vortex aerovalve directs the separated reverse flow from multiple venturi passages into the vortex chamber. As the flow enters the vortex, its velocity increases due to conservation of angular momentum. The resulting high flow velocity (high dynamic pressure) and high backflow impedance is responsible for the increase in diodicity. The forward flow pressure characteristics are maintained by avoiding large flow cross-sectional area changes both upstream and downstream of the throat, and by avoiding large axial flow turning angles. Based on earlier

¹Ratio of the forward (inflow) to reverse (backflow) mass flow rates at a given pressure drop.

experiments at West Virginia University, the total throat area of the flow passages was increased by 15 percent over that of the venturi aerovalve. This increase was implemented to correct for boundary layer growth in small areas (the passage throats).

To compare the performance of the vortex aerovalve with that of the venturi aerovalve, a vortex aerovalve was designed and constructed at MTCI. The design was based on the original idea of a reverse flow vortex developed through a joint effort between MTCI and West Virginia University. The aerovalve was tested on a small MTCI pulse combustor, of which the performance was already well known. Note here that the combustor used for the tests can operate without any excitation air when the venturi aerovalve is used. This is because the pressure in the combustion chamber is (during recharge) lower than the pressure at the inlet to the aerovalve, thus fresh recharge air is drawn in and additional excitation air is not necessary. The goal is to achieve the same function with the vortex aerovalve, but with an increase in chamber temperature and peak pressure pulse. An analysis of the vortex aerovalve performance is detailed in *Appendix A*.

Aerovalve Construction

The design parameters obtained from the computer design program are shown in Table 3. A drawing of this configuration is shown in Figure 4. The aerovalve was fabricated from stainless steel in four sections as shown in Figures 5 to 8. Construction in this manner allowed access to each individual part; each one easily removable for cleaning and inspection. Note the similarity between the conical sections on each end of the aerovalve in Figure 5. The forward flow direction is from left to right, and in order to bring the flow from the outer radius back to the centerline an almost exact duplicate of the reverse flow cone was added. This of course produced another pressure loss, but the loss was minimized by designing the double cone forward flow exit chamber to have a small flow cross-sectional area change between the passage exits and the exit of Section 3 (Figure 7).

TABLE 3:
ADVANCED VORTEX AEROVALVE DESIGN PARAMETERS

Parameter	Value	Parameter	Value
N	3	s_{ex}	0.602"
A_{th}	0.5843 in ²	R_{lvx}	1.608"
s_{th}	0.466"	R_{2vx}	1.524"
r_a	0.466"	R_{lix}	0.718"
r_l	0.776"	R_{2ix}	0.502"
r_{in}	0.587"	ϕ_{lx}	41°
r_v	1.566"	ϕ_{2x}	49°
B_v	0.34"	r_{ix}	0.61"
r_p	1.383"	A_{ex}	1.17 in ²
r_s	1.631"		
β	39.52°		
L/D_{act}	2.864"		
r_{lv}	1.634"		
r_{2v}	1.498"		
r_{li}	0.913"		
r_{2i}	0.639"		
ϕ_1	40°		
ϕ_2	50°		
s_c	0.827"

FIGURE 4: ADVANCED VORTEX AEROVALVE FOR PULSE COMBUSTOR

FIGURE 5: VORTEX AEROVALVE FABRICATION - SECTION 1

FIGURE 6: VORTEX AEROVALVE FABRICATION - SECTION 2

FIGURE 7: VORTEX AEROVALVE FABRICATION - SECTION 3

FIGURE 8: VORTEX AEROVALVE FABRICATION - SECTION 4

The construction process itself was complicated by the geometry of the inner plug, particularly the passages themselves. The simplest method was to construct the center section with the cones first. The pattern of the passages was marked on a pipe section with inner and outer radii equal to r_p and r_o , respectively. The passage sections were then machined out and the remaining sections welded to the cone section. Filing and polishing removed the roughness from the machining. After construction of the two end pieces the aerovalve was assembled in Section 4.

Experimental Apparatus and Procedure

The vortex aerovalve was initially tested on November 17, 1994 at the MTCI-Baltimore laboratory. The aerovalve was mounted to the existing combustor, as also shown in Figure 4. To monitor the combustor SPL (sound pressure level) a Dytran water-cooled piezoelectric pressure transducer was connected to the combustion chamber via a Hewlett Packard FFT Signal Analyzer. This allowed monitoring of the combustor decibel level and pulse frequency. A thermocouple was used to monitor the chamber temperature, and existing pressure gauges and flow meters were used to monitor the gas and air pressures and flow rates.

At the beginning of the test the ambient air pressure and temperature were recorded. The signal analyzer was calibrated to minimize noise and the transducer mounted to the combustion chamber. The gas, air and cooling water supply lines were then turned on. The combustor was then ignited by first enabling the spark plug, increasing the air flow rate to about 2 SCFM, and increasing the gas flow rate to about 1 SCFM. The combustor was then allowed to operate at this condition for approximately two minutes as a warm-up. The gas and air flow rates were then adjusted such that the combustor was operating smoothly. At a constant excitation air flow rate and pressure, the test procedure was as follows:

- Step 1 - Record the time, gas pressure/flow rate, air pressure/flow rate, combustion chamber temperature, and SPL of the combustor.
- Step 2 - Decrease the gas flow rate by 0.1 SCFM, allow the combustor to settle at the new condition, and record the data again as in Step 1.
- Step 3 - Repeat Step 2 until the combustor stops operating due to lack of gas.
- Step 4 - Record the ambient conditions at the end of the test.

Results and Discussion

The data obtained from the vortex aerovalve test is shown in Table 4. The combustion chamber temperature ranged from 2127°F at a gas flow rate of 1.5 SCFM to 1775°F at 1.1 SCFM. The decibel level ranged from 173.8 dB to 171 dB for the same gas flow rate range and the pulse frequency from 146 Hz to 162 Hz, also for the same gas flow rate range. Excitation air required to maintain combustor operation was 8.5 SCFM throughout the test.

Figure 9 is a plot of the combustion chamber temperature versus the gas flow rate for the vortex aerovalve. The plots show the increase in chamber temperature with increasing gas flow rate. Figure 10 shows the SPL characteristics of the vortex aerovalve. The peak operating conditions of the pulse combustor with a venturi aerovalve at the inlet are a chamber temperature of 2050°F and an SPL of 180 dB at 160 Hz (with no excitation air). From Figures 9 and 10, which both show the peak performance with the vortex aerovalve in place, a lower chamber temperature, decibel level and frequency resulted.

The above results indicate that the vortex aerovalve is not functioning as predicted. Reasons for this may be one or more of the following:

- The forward flow pressure loss due to friction may not be adequately compensated for by the increase in throat area;
- The passage inlets, even though they have been rounded slightly, may be causing early flow separation through the throat and poor diffuser performance. Rough surfaces may also be causing separation;
- The forward flow exits of the passages are subject to an abrupt expansion, even though the flow cross-sectional area has been designed to be equal to that of the existing aerovalve holder inlet;
- Due to the nature of the geometry of the passages, a vortex motion may be imparted to the forward flow, thus creating an undesirable pressure loss;
- The inlet area of the passages does not encompass the full annular area at the exit of the vortex chamber in forward flow, thus small flat sections exist perpendicular to the flow causing small pressure losses as the flow is turned toward the inlets.

TABLE 4:
RESULTS FROM ADVANCED VORTEX AEROVALVE TEST ON MTCI PULSE COMBUSTOR

Vortex Aerovalve Test						
Date: 11-17-94						
Ambient Conditions						
Start:	$P_{amb} = 1021 \text{ mbar}$		End :		$P_{amb} = 1021 \text{ mbar}$	
	$T_{amb} = 54 \text{ }^{\circ}\text{F}$				$T_{amb} = 54 \text{ }^{\circ}\text{F}$	
Time	Hour	15:50	15:55	16:00	16:05	16:10
Gas	SCFM	1.5	1.4	1.3	1.2	1.1
	psig	0	0	0	0	0
Excit. Air	SCFM	8.5	8.5	8.5	8.5	8.5
	psig	90	90	90	90	90
C.C.	$^{\circ}\text{F}$	2127	2100	2071	1951	1775
SPL	dB	173.8	173.57	173.1	172.5	171
	Hz	146	154	156	160	162

FIGURE 9: PLOT OF COMBUSTION CHAMBER TEMPERATURE vs. GAS FLOW RATE FOR VORTEX AEROVALVE TEST

FIGURE 10: PLOT OF SPL CHARACTERISTICS vs. GAS FLOW RATE FOR VORTEX AEROVALVE TEST

Of the possible problems listed above, the forward flow pressure loss due to friction and flow separation is the most important. The pressure difference in forward flow must be as close to that of the venturi as possible for performance comparison. Because of the increase in excitation air, an undesirable decrease in chamber temperature and decibel level resulted. Although the vortex aerovalve design tries to minimize the forward flow pressure loss and flow resistance, it was obvious that these losses were present. To discover the characteristics of the forward flow as it passes through the conical chambers and the venturi passages, it was proposed that a steady flow test facility be constructed. Pressure taps along the venturi passages and on the surface of the conical chambers would reveal the pressure distribution through the aerovalve and would indicate areas where the geometry should be improved.

Due to the periodic nature of the flow in the pulse combustor, the reverse flow vortex may not be established because of the short duration of the backflow. this design-related issue will be explored further once the initial pressure losses have been minimized.

Steady Cold Flow Test Facility

A steady air flow facility was constructed at the MTCI-Baltimore laboratory. The facility, shown in Figure 11, mainly consists of a 6.5 ft length of 1.5" Sch. 40 pipe, a 1.5" to 3/4" bell reducer, and a reducing tee section. Pressurized air was connected to the facility through the bell reducer. To measure the inlet total and static pressure, a Pitot-static probe was placed in a tee section as shown. The probe was connected to a differential manometer. A straight pipe section was placed downstream of the tee section and the aerovalve connected as shown.

Instrumentation of the Advanced Aerovalve

For the forward flow pressure test, a 1.5" coupling was welded to the inlet section of the aerovalve as shown in Figure 12. Static pressure tap holes of 1/16" diameter were drilled perpendicular to the cone surfaces on the inlet and

FIGURE 11: STEADY AIR FLOW FACILITY

FIGURE 12: MODIFICATION OF INLET SECTION OF VORTEX AEROVALVE FOR STEADY FLOW TEST

exit sections, as shown in Figure 13 for the exit section. Connecting holes running parallel to the centerline were drilled, and small stainless steel tubes were glued in place with epoxy resin. The outer pipe section containing the three individual sections was replaced by a clear acrylic tube, 6.5" length x 3.5" ID x 4" OD. The valve was assembled in the acrylic section, the locations for the pressure taps along the venturi passages clearly marked (inlet, throat and exit of each passage), and the valve disassembled. This method allowed the 1/16" diameter tap holes to easily be drilled before the arovalve was sealed in the tube. Next, stainless steel tubes were glued into each tap hole. Figure 14 shows the pressure taps along one of the three venturi passages. When all glue was fully dry, the arovalve was again assembled in the acrylic tube and silicone rubber was used to seal the inlet and exit sections to the acrylic tube (Figure 15). When the seal was fully cured it also acted as a retainer on both ends of the tube, preventing the inner sections from sliding out.

Test Setup

Once the arovalve was connected to the test facility, a short length of clear vinyl tube 1/16" ID was attached to each pressure tap tube. The stainless steel tubes each had an OD of 0.065", allowing a sufficient seal. Each tube was numbered to prevent confusion of reading location, with four taps on the front and rear conical surfaces and three along each passage. With 17 pressures taps (excluding the Pitot-static tube) and limited manometer facilities, every tube not in use was closed off and the pressures were read one at a time for each flow rate. The Pitot-static probe was used to measure the total and static conditions of the inlet flow. The test was conducted as follows:

- Step 1 - Date, time, and ambient pressure and temperature were recorded.
- Step 2 - A starting flow rate of 10 SCFM was established and recorded.
- Step 3 - The values of the total and static inlet pressures were recorded from the manometers.
- Step 4 - Each tap on the arovalve was connected to a Magnehelic pressure gauge reading from 0 to 4 inches of water. The pressure on each tap was recorded.

FIGURE 13: STATIC PRESSURE TAPS ON EXIT SECTION

FIGURE 14: STATIC PRESSURE TAP CONFIGURATION ALONG VENTURI PASSAGE

**FIGURE 15: FULLY ASSEMBLED VORTEX AEROVALVE
USED IN STEADY COLD FLOW AIR TEST**

Step 5 - The pressure at the exit plane was read using a small Pitot probe and recorded.

Step 6 - The flow rate was increased and Steps 3, 4 and 5 repeated.

Step 7 - Step 5 was repeated up to a flow rate of 17 SCFM.

Step 8 - The time and ambient pressure/temperature at the end of the test were recorded.

Steady Flow Test Results and Discussion

Figure 16 is a plot of pressure in inches of water versus the tap location along the centerline for five different mass flow rates. Table 5 contains the data for Figure 16. The plot shows the variation of pressure over the cone surfaces and also along each of the venturi passages. The first four data points at each flow rate show the uniform pressure increase as the flow slows down over the inlet cone. This indicates a small area change between the aerovalve inlet and the venturi passage inlets. A pressure loss occurs between the inlet cone taps and taps 5, 8 and 11, caused by flow separation at the inlet of the passages. Also, tap 4 is located at a point where the flow is turned towards the passage inlets. The higher pressure here is the result of the flow impacting the wall and stagnating. The three columns of points in the center of the plot show the performance of the venturi passage sections. In each case, the recovered static pressure at the diffuser exit is seen to be only about 50 percent of the passage inlet pressure. Another pressure loss occurs between the passage exits (taps 7, 10, and 13) and tap 14. The pressure then rises slightly at tap 15, indicating the abrupt separation at the passage exits. The roughly uniform decrease in pressure towards the exit indicates the effect of a slight area change between the passage exits and the exit plane. The pressure at the center of the exit plane (not shown on the plot for clarity) is negative. This indicates a swirling of the flow in the rear cone section. Inspection of oil streaks on the cone section also confirms this. All phenomena observed here are fairly constant for the flow rates tested.

From this simple inspection analysis of the pressure distribution, recommendations for improvement were made. By minimizing the area of the flat sections which the flow sees before it enters the passages, the stagnation of the

FIGURE 16: PLOT OF PRESSURE IN THE VORTEX AEROVALVE vs. TAP LOCATION FOR VARIOUS FLOW RATES

TABLE 5:
STEADY COLD FLOW TEST RESULTS

Advanced Vortex Aerovalve Steady Flow Air Test

Date : 1-12-95																			
Time : Start - 8:30 AM End - 9:40 AM																			
Test Starting Conditions : $P_{amb} = 1020$ mbars $T_{amb} = 42.7$ °F																			
Test Ending Conditions : $P_{amb} = 1022$ mbars $T_{amb} = 42.8$ °F																			
$\dot{m}$	P_T	P_S	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}
10	1	0.9	0.8	0.7	0.7	0.8	0.8	0.5	0.5	0.6	0.3	0.5	0.7	0.3	0.5	0.4	0.4	0.4	0.3
12	1.5	1.4	1.3	1.3	1.3	1.5	1.3	0.8	0.9	1.3	0.7	0.9	1.3	0.6	0.8	0.7	0.7	0.6	0.5
14	2.3	2.1	1.9	1.8	1.8	1.9	2.0	1.3	1.4	1.9	1.0	1.3	1.8	1.0	1.4	1.0	1.1	0.95	0.8
16	3.5	3.3	3.1	3.1	3.1	3.3	2.8	1.8	2.0	2.9	1.5	2.0	2.9	1.4	2.0	1.6	1.6	1.45	1.1
17	4.5	4.2	3.9	3.9	3.9	4.2	3.6	2.3	2.6	3.6	1.8	2.5	3.4	1.6	2.9	2.4	2.5	2.1	1.7
P_c																			
-25			Units: Pressure - "H ₂ O, Flow Rate - SCFM																
-35																			
-55																			
-95																			
-13																			

flow and turning losses would be reduced. This can be achieved by increasing the number of throats to take up the extra area. The pressure losses at the inlet and exit of the passage sections can be improved by further rounding the sharp edges, especially the edge where the nose radius r_n is perpendicular to the flow. Diffuser pressure recovery can be improved by further polishing of the walls of the passage. The abrupt expansion of the flow from the exit of the passages can be eliminated only by complicating the design to include the extension of the passage exits through the exit chamber. The extensions would end at the exit of Section 3, eliminating the abrupt expansions. An improvement to the current passage design, one in which the flow is directed to exit axially, may also help. This modification would also help to reduce the forward flow swirl problem as the flow would be directed to the exit.

The test results presented indicate that some modifications are necessary to the vortex aerovalve in order to improve the current performance, and also to determine whether or not the vortex effect is present in reverse flow and if forward flow pressure loss can be minimized. It is recommended that correction of the above problems be the priority before any further testing resumes.

SECTION 3.0

PLANS FOR NEXT PERIOD

- Complete the vortex aerovalve characterization.
- Evaluate aerovalve performance at higher (700-800°F) air inlet temperatures.
- Examine acoustic profile in a U-tube agglomeration chamber simulator.
- Quantify and generate the design modifications necessary to reconfigure the PDU.
- Generate a Test Plan.

APPENDIX A

VORTEX AEROVALVE DIODICITY

To minimize the forward flow diffuser losses, the venturi type aerovalve is limited in area ratio ($A_R = A_e/A_{th}$) to about 1.6. In forward flow the pressure drop is controlled by the exit dynamic pressure and the friction factor (f_F) or

$$\Delta p_F = \frac{1}{2} \rho V_{e_F}^2 (1 + f_F) = \frac{\frac{1}{2} \dot{m}_F^2 (1 + f_F)}{\rho A_e^2}$$

Reverse flow separates at the throat which becomes then the exit area (A_{th}) and the exit dynamic pressure is then

$$\Delta p_R = \frac{1}{2} \rho V_{th_R}^2 (1 + f_R) = \frac{\frac{1}{2} \dot{m}_R^2 (1 + f_R)}{\rho A_{th}^2}$$

The cold flow diodicity ($D_{vent} = \dot{m}_F/\dot{m}_R$) at same $\Delta p_F = \Delta p_R$ is then

$$D_{vent} = A_R \sqrt{\frac{1 + f_R}{1 + f_F}} \quad \text{scalesym250} \sim A_R$$

with $f_R \sim 0.7$ and $f_F \sim 0.5$. When the temperature difference between the inlet and the combustion chamber is taken into account, the theoretical diodicity becomes

$$D_{vent} = A_R \sqrt{\left(\frac{1 + f_R}{1 + f_F}\right) T_R} \quad \text{scalsym250} \sim A_R \sqrt{T_R}$$

Vortex Aerovalve Geometry

The geometry of the advanced vortex aerovalve is shown in Figure A-1. To calculate the vortex chamber radius r_v , assume that half the axial flow area A_{ax} is located beyond r_v or $\frac{1}{2}A_{ax} = \pi(r_o^2 - r_v^2)$. Replace A_{ax} with the expression above to give:

$$r_v = \sqrt{r_o^2 + \frac{1}{4}s_{th}^2 - \frac{1}{2}s_{th}} \quad (1)$$

The axial streamline vane passage length equals the radius of the convex vane r_s . The throat streamline makes an angle $\beta (= \sin^{-1}[r_s/(r_s + r_n + s_{th})])$ with the axial direction. The larger β , the more angular momentum is generated. The maximum value of $B_v = s_{th}/[\sqrt{\{r_s^2 + (r_s + s_{th} + r_n)^2\}} - r_n]$, with $r_s = Cs_{th}$ where C is some constant. For example for $r_v/r_i = 3$, $A_R = 1.6$ and $N = 4$ find $r_s/s_{th} = 5.77$ and $\beta = \sin^{-1}(5.77/7.77) = 48^\circ$. Note that the re-curved vane does not exit exactly parallel to the axis. This requires calculation of an effective area ratio based on the exit flow angle.

As an example assume: $A_{th} = 500$, $A_R = 1.5$ and $N = 4, 6$, or 8 , $\Phi_v = 45^\circ$, $f_F = 1.28$ find: $s_{th} = \sqrt{A_{th}/N}$, $r_n = s_{th}$, $B_v = 1/[2(r_v/r_i)\sqrt{(\pi/A_R N)}]$, $r_v = \sqrt{[r_o^2 - \frac{1}{2}A_{th}/(B_v\pi)]}$, $r_p = r_o - s_{th}$, $r_i = \sqrt{(4A_i/\pi)}$, $r_s = Cs_{th}$ and $r_v = r_i(r_v/r_i)$. The angle Φ_v is chosen as 45° to reduce the abrupt flow turning angles and the associated pressure losses. The two wall cone angles ϕ_1 and ϕ_2 are calculated such that $A = A_i$ at both $r = r_v$ and $r = r_i$, and from this the cone tip spacing s_c is found.

Parameter Equations

The flow cross-sectional area A is the lateral surface of the frustrum of a circular cone of height H and radii R_1 and R_2 , or $A = \pi(R_1 + R_2)/\cos(\phi_v)$ set $A = A_i$ and then at radius $r = r_v$, set $R_1 = R_{1v}$ and $R_2 = R_{2v}$ and $\frac{1}{2}(R_{1v} + R_{2v}) = r_v$ or $R_{2v} = 2r_v - R_{1v}$, from these two equations solve for R_{1v}

$$R_{1v} = \frac{A_i \cos(\Phi_v)}{4\pi r_v} + r_v \quad (2)$$

Next set $A = A_i$ at $R_1 = r_i$.

$$R_{1i} = \frac{A_i \cos(\Phi_v)}{4\pi r_i} + r_i \quad (3)$$

and $R_{2i} = 2r_i - R_{1i}$. The cone angle ϕ_1 is then

$$\Phi_1 = \tan^{-1} \left(\frac{R_{1v} - R_{1i}}{\frac{r_v - r_i}{\tan(\Phi_v)} + \frac{\tan(\Phi_v)}{2} ((R_{1i} - R_{2i}) - (R_{1v} - R_{2v}))} \right) \quad (4)$$

and the angle ϕ_2 is

$$\Phi_2 = \tan^{-1} \left(\frac{R_{1v} - R_{1i}}{\frac{r_v - r_i}{\tan(\Phi_v)} - \frac{\tan(\Phi_v)}{2} ((R_{1i} - R_{2i}) - (R_{1v} - R_{2v}))} \right) \quad (5)$$

The distance between the tips of the two cones (s_c) is

$$s_c = (R_{1v} - R_{2v}) \tan \Phi_v + \frac{R_{1v}}{\tan \Phi_1} - \frac{R_{2v}}{\tan \Phi_2} \quad (6)$$

The angle β is found as

$$\beta = \sin^{-1} \left(\frac{r_s}{(r_s + s_{th} + r_n)} \right) \quad (7)$$

The divergence radius r_d of the diffuser is found as follows from triangle 1-2-3 in Figure A-2.

The distance c (side 1-2 = a , side 2-3 = c , side 3-1 = b) is found from the cosine rule as

$$c = \sqrt{a^2 + b^2 - 2ab\cos(\beta)}$$

with

$$a = r_s + s_{th}$$

$$b = r_s + A_R s_{th}$$

(8)

The angle α is found from

$$\cos(\alpha) = - \left(\frac{b^2 - a^2 - c^2}{2ac} \right)$$

(9)

The diffuser radius r_d is

$$r_d = \frac{c}{2\cos(\alpha)}$$

(10)

From Figure A-2 the flow enters the combustion chamber at a slight angle to the axial direction, and the effective area ratio $A_{R,eff}$ is found using the sine rule as

$$\frac{A_{R_{eff}}}{A_R} = \frac{\sin(\delta)}{\sin(\pi - \gamma - \delta)}$$

(11)

with

$$\delta = \pi - \alpha - \beta$$

$$\gamma = \alpha - \delta$$

The curvature of the inlet radius R_{in} was found by fitting an arc between the radii r_i and R_{1i} as such

$$R_{in} = \frac{(R_{1i} - r_i)}{1 - \cos(\Phi_1)}$$

(12)

The calculation for the vortex chamber cone angles was repeated for the cone at the exit of the forward flow, the only difference being the inlet and outlet areas.

A computer program written to solve these equations for a specific design configuration was used to determine a vortex aerovalve configuration for the small demonstration pulse combustor at the MTCI Baltimore laboratory. This was completed by measuring the throat area and exit-to-throat area ratio of the existing venturi aerovalve, modifying the throat area as described earlier, and choosing the number of vortex aerovalve passage throats to be used on the new aerovalve.

FIGURE A-1: ADVANCED CONCEPT VORTEX AEROVALVE

FIGURE A-2: ADVANCED VORTEX AEROVALVE PASSAGE SECTION GEOMETRY