REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

0304

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. R
	19-AUG-2002	FINAL (01-APR-2000 TO 30-SEP-2001)

4. TITLE AND SUBTITLE
A 3D-PIV SYSTEM FOR GAS TURBINE APPLICATIONS

5. FUNDING NUMBERS
F49620-00-1-0187

6. AUTHOR(S)
SUMANTA ACHARYA

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
LOUISIANA STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
BATON ROUGE, LA 70803

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
801 N. RANDOLPH STREET
ARLINGTON, VA 22203

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release;
distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Funds were received in April 2001 under the Department of Defense DURIP program for construction of a 48 processor high performance computing cluster. This report details the hardware, which was purchased, and how it has been used to enable and enhance research activities directly supported by, and of interest to, the Air Force Office of Scientific Research and the Department of Defense. The report is divided into two major sections. The first section after the summary describes the computer cluster, its setup, and some cluster hardware, and presents highlights of those efforts since installation of the cluster

20021008 174

14. SUBJECT TERMS	15. NUMBER OF PAGES
	22
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Final Report

DURIP00- A 3D-PIV System for Gas Turbine Applications

Grant No: F49620-00-1-0187

<u>Submitted By</u>

Sumanta Acharya
Mechanical Engineering Department
Louisiana State University
Baton Rouge, LA 70803

<u>Submitted To</u>

AFOSR
Program Manager: Dr. Tom Beuntner
Turbulence and Rotating Flows

Table of Contents

Summary

A stereo Particle Image Velocimetry (PIV) System was acquired under the auspices of the DURIP grant. The PIV system was purchased from TSI inc. In addition, several optical components were purchased to allow PIV measurements in a rotating frame.

The PIV system purchased has been used extensively in measurements of the velocity field in a trapped vortex combustor geometry. These measurements have provided some detailed insights into the flowfield in the combustor. The measurements have also served as a benchmark for model validation studies.

The PIV system is planned for use in a rotating frame to make velocity measurements in a rotating coolant passage. Currently funds are being sought to enable such measurements.

Instrumentation List

A 3-dimensional (3D) particle Image Velocimetry (PIV) system together with additional optical, mechanical and electrical components needed to implement the PIV system on a rotating frame, was purchased. The PIV system was purchased from TSI Inc. while the components for adapting the system on a rotating frame were purchased separately. The contact persons at TSI was Mr. Steve Anderson who can be reached at 1-800-874-2811.

The first table below provides the components for a standard 3D PIV system. The second table provides additional items needed to implement the system on a rotating frame.

Table 1: Components for a 3D PIV System

Item	Model	Qty	Description
1	610015-NW	1	3 pairs of light sheet optics
2	610034	1	Computer Controlled Synchronizer
3	630046	2	PIVCAM 10-30 Cross Correlation Camera, 30 Hz with 60 mm F/2.8 lens, interface cables
4	600067	2	High speed camera interface
5	Insight Stereo	1	Ultra resolution Parallel processing acquisition/ analysis software on Windows NT
6	Y120-15	1	120 mJ/pulse, 15 Hz/laser, dual Yag laser system with mounts accessory kit
7	610052-XX	1	500 MHz, dual Pentium PC with software integration and testing
8	640050	1	Stereo PIV assembly, including Scheimflug mounts, Calibration kit, alignment kit, rotating mounts, base etc

Table 2: Additional Components for PIV Measurements on a Rotating Frame

Item	Description
1	Mirrors, lenses, optical manipulators
2	Traversing mechanisms with stepper motors/controllers
3	Computer for controller
4	Slip rings
5	Bearings, seals
6	Fabrication/machining costs

General Description of the Requested Instrumentation

A 3D PIV system was purchased for characterizing the instantaneous flowfields in turbomachinery flows. Specific applications of interest include coolant flows in the rotating coolant passages of gas turbine blades, secondary flows in turbine blade passages, and gas turbine combustors. These programs are of interest to AFOSR.

A 3D PIV system is a non-intrusive optical diagnostic tool that allows instantaneous mapping of the flowfield as a function of time, and is therefore a unique tool to examine the spatial structures in the flow, and how they develop temporally (limited by the laser pulsing rate). The PIV technique is based simply on measuring the displacement of particles in a region during a fixed interval of time. Two laser pulses, with a time interval Δt apart, are used to record the particle images on a CCD camera (usually with a 1Kx1K pixel resolution). Pulse separations can be as low as a 0.5 μsec permitting measurements of velocities that are several hundereds of m/s. The stored images at each time frame are broken up into interrogation regions, and a cross-correlation is performed between the successive images to deduce the instantaneous velocities. This process is repeated for every pair of stored images, and a time sequence of velocity vectors in a vertical or horizontal plane is obtained.

In a 3D PIV system, to obtain the out-of-plane velocity vectors, two cameras are used to view the illuminated plane at different angles, and the particle images are captured by both these cameras. The two sets of camera images corresponding to the two laser pulses are processed to obtain all three velocity components in the illumination plane. The Scheimpflug offset configuration is most commonly adopted where, the object plane, the image plane, and the plane of the lens all intersect at a common point. This configuration has the advantage that all points in the in the illumination plane are brought into focus in the image plane. A calibration procedure is used to correct the perspective distortion caused by the angular viewing of the illumination plane. The calibration consists of using the two cameras to image a grid of dots, mounted on a traverse, and by repeating this process as the grid is moved normal to the grid plane. This yields a the mapping function to convert the image field information to the flow field information.

The basic components of the PIV system consist of the Laser light source that provide the laser pulses, the CCD camera that allows sequential recording of the images on separate frames, an electronic synchronizer that synchronizes the laser pulse with the camera, and a software that performs the data analysis and processing. For the Laser light source, typically a dual-laser Nd:YAG system is used. The use of two lasers permits precise control of the time interval between laser pulses, and as mentioned above, time intervals as low as 0.5 μsec can be achieved. Thus time intervals between laser pulses can be controlled to permit measurements of flowfields ranging from low to high velocities. For the combustion application of interest to the present study, a Y-120/15 model (supplied by TSI Inc.) is selected, and provides 120mJ/pulse at 532nm with a 15Hz pulse rate. The choice for the higher laser power is dictated by the flame environment. For the camera, a 1Kx1K CCD camera (supplied by Kodak) with a 30Hz operating rate will be used. This framing rate allows continuous capture of the image pairs at a 15Hz rate. Thus the instantaneous vector field information can be obtained only at a 15Hz rate. The camera and the laser pulses must be triggered with the correct sequence and timing, and this is done by an electronic box (called the Synchronizer) which provides the appropriate trigger output to the lasers, so that, the laser pulses are located in the appropriate frames of the recording camera. The software acquires the images, and performs cross-correlations to determine the particle displacement in each region. Knowing the displacement and the time interval, the velocities can be computed. The cross-correlation can be done in sub-regions, and often overlapping regions are used. The 3D instantaneous velocity field can then be used to compute strain rates, mean velocities, and other turbulence statistics of interest.

A listing of the specific PIV components are listed in the earlier section.

Research

I. Flow and Heat Transfer in Rotating Channels

Introduction

Flow and heat transfer in the internal coolant passages of a rotating smooth or ribbed channel is of interest in a variety of applications, most notably, internal cooling of gas turbine blades. A cutaway section of a typical turbine blade is shown in Fig. 1, and illustrates the ribbed serpentine passages. The flow in the serpentine coolant passages of a gas turbine blade are complicated by the presence of Coriolis forces, centrifugal-buoyancy forces, and secondary flows induced by the bends and anisotropies in the Reynolds-stresses. The dominant effects appear to be due to the *Coriolis forces* which are responsible for secondary flows directed from the leading to the trailing surface along the radially-outward flow passage and from the trailing to the leading along the radially-inward flow passage. These secondary flows (see Fig. 1b),

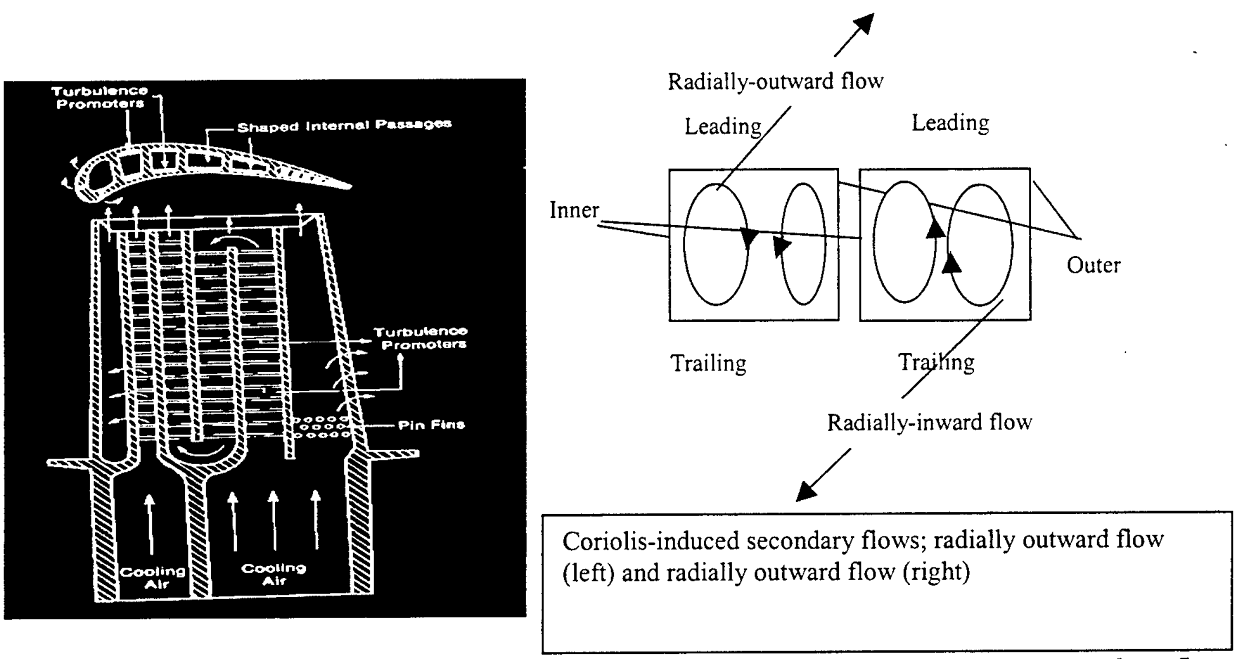


Figure 1: (a) Schematic of the cooling passages in a blade (b) Coriolis-induces secondary flows

produce a double-roll flow pattern, and destabilize the near-wall flow enhancing heat transfer along the trailing surface of the radially-outward flow leg and the leading surface of the radially-inward flow leg (see Wagner et al., 1991). Correspondingly, they stabilize the flow and degrade heat transfer along the leading surface of the radially-outward leg and the trailing surface of the radially-inward leg. A factor of 2 or greater in the Nusselt numbers between trailing and leading surfaces have been reported (Guidez, 1989; Han et al., 1993; Bons and Kerrebrock, 1998). The *bend-induced secondary flows* direct the flow from the inner-side wall to the outer side wall producing a two-roll flow pattern (Schabacker et al., 1998), and can considerably distort the Coriolis-induced secondary flow in the near-field following the bend. Heat/mass transfer measurements following the bend (*Hibbs et al., 1996*) have shown high heat transfer along the outer walls and low heat transfer along the inner wall (possibly associated with flow separation). *Centrifugal-buoyancy effects* are important at high rotation numbers, and can influence the surface heat transfer similar to those of mixed convection in asymmetrically heated channels (Wagner et al., 1991).

In the presence of ribbed turbulators, the flowfield is further complicated by the separated shear layer behind the rib, and by secondary flows that may be induced by the rib-inclination or by discrete broken-ribs. The rib-induced secondary flows are also likely to be influenced by the action of rotation.

The literature dealing with flow measurements under rotating conditions is extremely limited, due partly to the complexities associated with measurements in a rotating frame. Such measurements have been reported by Tse and Steuber (1997), Tse et al. (1994), Iacovides et al. (1998), Hsieh et al. (1997), Bons and Kerrebrock (1998) and Servouze (1998). However, these flow measurements have all been made with the instrumentation on the stationary frame, and only provide conditionally sampled data. Since the data at a specific point or plane is sampled for a short time interval during one revolution, and this process is repeated over many cycles, conditionally-averaged velocity, and the time-mean velocity can only be reliably obtained using this approach. Information on the mean turbulent stresses and higher order moments, needed for understanding the physical mechanisms of turbulent transport, and for developing suitable turbulence models for CFD, can not be accurately obtained using conditional sampling methods. Thus, time-resolved velocity measurements made with the instrumentation mounted on the rotating frame is necessary for accurately calculating the mean turbulent statistics. This is the primary objective of the proposed research.

Goals

The primary goal of the proposed research is to provide a detailed understanding of the flow and heat transfer mechanisms in a rotating coolant channel. A multi-pass smooth and ribbed rotating channel will be studied. For the measurements, a rotating facility is already available in the PI's laboratory (Fig. 1), and this facility has been used by the co-PIs to study heat transfer in the coolant channels with rotation (*Hibbs et al.*, 1996; *Eliades et al.*, 1999) and without rotation (*Hibbs et al., 1998; Hibbs et al., 1999*). Velocity and temperature measurements, and RANS computations in the stationary frame have also been reported by the PI (*Acharya et al. 1994, 1998*).

The velocity measurements proposed will include primarily Particle Image Velocimetry (PIV). These measurements will be done under conditions of rotation for Reynolds number, Rotation number and centrifugal buoyancy parameter relevant to gas turbine applications. A unique optical beam-transmission and receiving system, mounted on the rotating frame, will be employed, so that, time-resolved velocity data, and the associated heat transfer data can be obtained.

Current Experimental Facility

The current rotating facility (Fig. 2) is housed in the PI's laboratory, and the test section consists of a two-pass ribbed coolant channel mounted inside a pressure vessel. The test-section is located on a vertical arm that is connected to a hydraulically-driven hollowed shaft. The hollowed shaft is connected at both ends to rotating seals. Compressed air is delivered at one end of the hollow shaft, and is fed to the conditioning plenum upstream of the test section through rigid rubber tubing. Compressed air exiting from the test section is then delivered through a rubber tubing back to the hollow shaft and discharged through the other rotating seal. A dummy counter weight is placed diametrically opposite to the test section for load balancing. The entire rotating system is encased in an outer enclosure for safety and reduction of form drag.

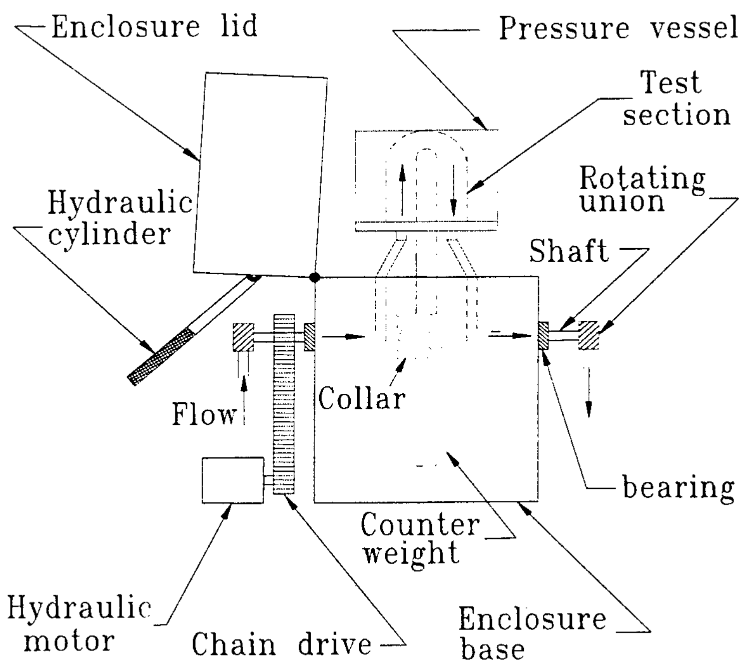


Figure 2 Rotating Channel Facility

The current facility can be driven to rotation numbers of around 0.5, and air handling capacity has been enhanced to reach Reynolds number as high as 10^6. Till this point, all measurements made in this facility have been mass-transfer (naphthalene-sublimation) measurements (*Hibbs et al., 1996, 1997, 1998, 1999; Chen et al., 1999; Eliades et al., 1999*), which as pointed out earlier, do not incorporate centrifugal buoyancy effects. This facility will be modified for the present research to accommodate velocity measurements on the rotating frame, and liquid-crystal measurements with cryogenically cooled air also on the rotating frame. Specific modifications to this facility are described later.

Measurements made on this facility, under rotational conditions, clearly indicate the dominant effects of Coriolis- and bend-induced secondary flows (*Hibbs et al., 1996; Eliades et al., 1999)*. For the smooth stationary channel, secondary flows generated by Reynolds-stress anisotropies were also noted to be important (*Chen et al., 1999)*.

Implementation of the Instrumentation for a Rotating Frame

Both local and field velocity measurements will be pursued. The former are necessary for obtaining statistically meaningful mean velocity and velocity correlation distributions, while the latter will provide both quantitative and qualitative insight of the velocity field on 2-D planes.

The field velocity measurements will help visualize instantaneous details of the flow that are very helpful in understanding the dynamics of the complex flows under study. Field velocity measurements will be obtained using Digital Particle Image Velocimetry. The velocity measurements will be performed in the rotating reference frame so that time-resolved data, without errors associated with shifting of the illumination plane or measurement location, can be obtained and used to compute the relevant statistics.

The principal obstacle in performing such measurements on a rotating frame stems from the necessity to transfer "information" to and from the rotating frame. This could be eliminated if it were possible to mount all of the instrumentation on the rotating frame. However, this is not feasible due to size, mass and strength limitations. Thus, the bulk of the instrumentation used in the proposed study will be on the stationary frame. Electrical signals are going to be transferred between the rotating and stationary frames through the use of slip rings. Optical signals will be transferred through a specially designed optical de-rotator.

Instantaneous planar measurements of the velocity field will be carried out by using a Digital PIV system. The principle of operation of PIV is well known and has been briefly described earlier. Almost all the hardware of the PIV system will be on the stationary frame as shown schematically in Figure 3. The pulsed laser source beams are going to be directed along the axis of rotation, through the hollow shaft, and to the measurement location by means of a periscope assembly with built-in, compact and ruggedized light sheet generating optics (a combination of spherical and cylindrical lenses) at the end. Two possible arrangements are shown in Figure 3. The first arrangement shown on the side view of Figure 3 allows for PIV on planes perpendicular to the main flow direction so that the cross-stream secondary flows, which are most relevant to this study, can be captured. The second arrangement shown on the front view of Figure 6 allows for PIV on planes parallel to the stream-wise direction so that the cross-flow jets can be captured. The illuminated plane images are going to be directed to a color CCD camera on the stationary frame through a periscope assembly and the use of a rotating triple-reflection prism which is also going to "de-rotate" the back-scattered light. The triple-reflection prism has been used as a de-rotator before by Lennemann (1969) for flow visualization between the vanes of rotating radial impellers. A similar image-reversal prism has also been employed by Fagan and Selbach (1984) for measurements between the rotating blades of axial flow fans, using their L2F Laser Velocimetry technique. The triple-reflection prism has the property of rotating an image by 180 deg if the prism is rotated by 90 deg.. Thus a rotating image can be made into a stationary one if the prism rotates at half the rotation speed of the image and in the same direction. The triple-reflection prism will be housed on a casing which will be rotated at half the speed of the test section through a 1:1 timing chain and 2:1 gear transmission as shown schematically in Figure 3. The images are going to be processed using commercially available software to render the instantaneous velocity vector field. An ensemble average of a number of images will render the mean flow field. Seed particles necessary for the application of PIV will be selected carefully depending on an estimate of the flow turbulence so that they have good frequency-response in the rotating environment. However, they will not be as small as those used for the LDV application due to resolution limitations. Micron-size Al_2O_3 particles are a good candidate as seed.

On the rotating frame the optical paths are going to be directed to and from the measurement location through the use of ruggedized periscope assemblies in combination with step-motor driven traverses. The traverses will be controlled either by a pre-programmed on-board mini-computer, or a computer on the stationary frame in combination with telemetry. The periscope assemblies and traverses will be supported on a lightweight, yet stiff, frame, which will be attached to the rotating shaft the test-section housing and counterbalance

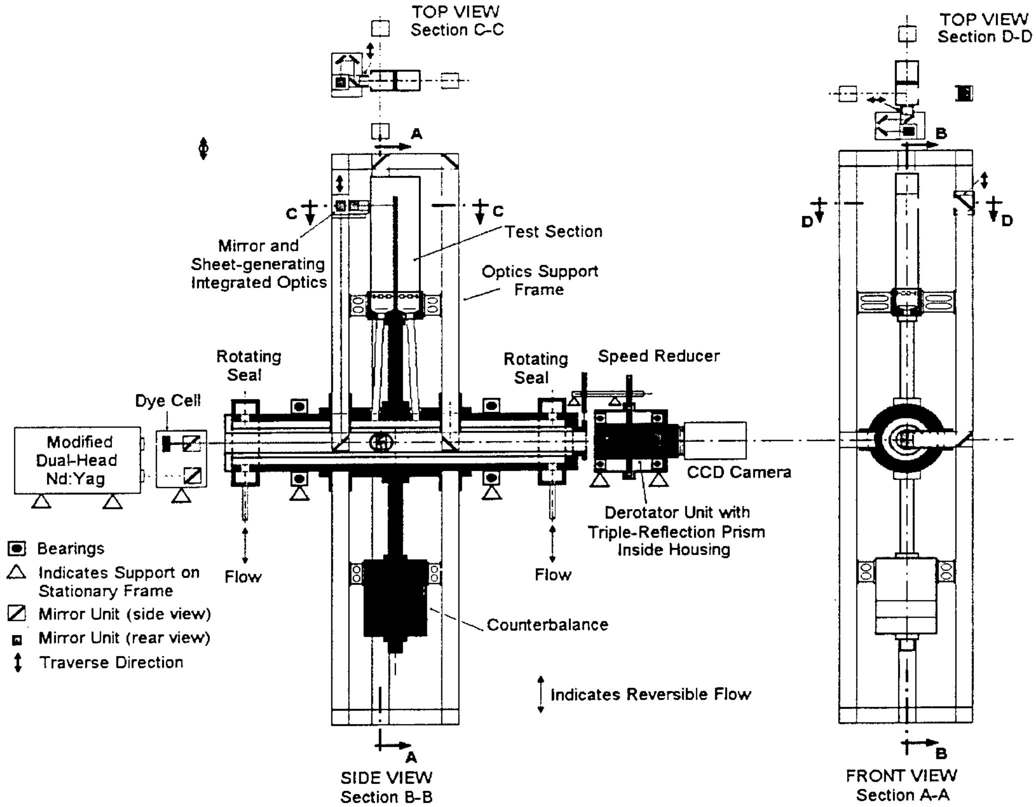


Figure 3: Implementation of two-color digital PIV on the rotating frame.

Achievements

The PIV system requested was acquired and all additional optical components necessary for the implementation of the PIV on the rotating frame have also been acquired. The engineering design of the schematic shown in Figure 3 has also been done. We are currently in the planning process for PIV measurements in a rotating frame. To allocate resources for such a venture, we have been looking for research funding, and currently have a proposal submitted to Dr. Beunter's program at AFOSR.

II. PIV Measurements in a Trapped Vortex Combustor

Introduction

The ongoing research deals with the fundamental issues pertaining to an improved concept of flame stabilization. In this concept, termed the Trapped-Vortex combustor(TVC), a circumferential cavity with a trapped vortex, into which secondary fuel and air is injected, provides the flame stabilization (Figure 4). Hot combustion products emanating from within the cavity get entrained into the main combustion zone thus providing ignition of the primary fuel/air mixture and the necessary flame stabilization mechanism. Stable combustion with Lean Blow Out (LBO) equivalence ratio limits as low as 0.005 have been obtained. However, very little is known about the important hydrodynamic and combustion mechanisms that are responsible for the improved behavior.

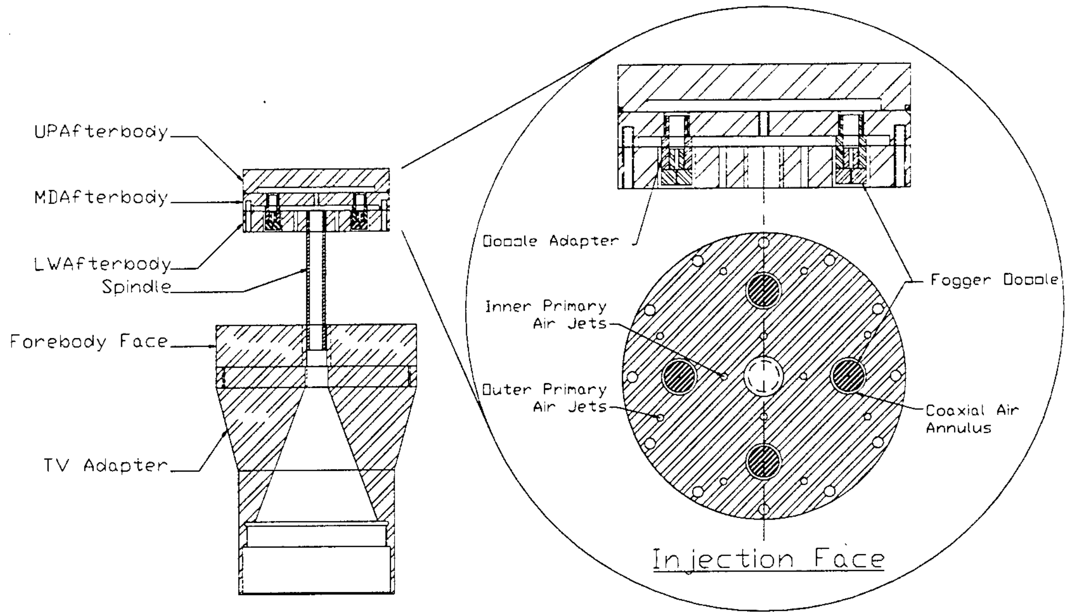


Figure 4: Schematic of the TVC Geometry

Despite the potential of the TV-concept, there are a number of problems. At high flow rates, the LBO equivalence ratio increases significantly. For cavity equivalence ratios less than 2, the efficiency drops rapidly. The maximum fuel efficiency is also associated with the maximum NOx. If the cavity is not sized correctly for the flow conditions, vortex shedding and/or dynamically varying cavity vortices can be obtained with resulting degradation in performance. Clearly significant improvements in the understanding of the flow and combustion mechanisms is needed for the optimal design of the TV combustor. This is the first goal of the ongoing research. In order to achieve this goal, detailed measurements of the velocity field are necessary, and the PIV system has been used in this regard. A number of these measurements have already been completed, and are described in the next section.

Distributed injection of fuel and air in the TV-cavity has the potential of improving mixedness. This is difficult to achieve with conventional injectors due to constraints of size and weight. However, with recent advances in high temperature MEMS fabrication, it is now possible to machine several injectors in a distributed fashion without size and weight penalties. Such distributed micro-injection has not been studied before, and atomization and combustion at micro-scales is not well understood. These fundamental issues must first be addressed before a rational design of a distributed injection system is possible. This is the second goal of the work. However, in order to understand the atomization and mixing in the microscales of interest, it is important to be able to measure the velocity field of the micro-injectors, and the PIV will be critical in this respect.

The third major goal of the research deals with the fundamental understanding and detection of events that can (1) degrade fuel efficiency, (2) lead to hot spots, local-fuel-rich regions and high NOx, and (3) lead to unstable or rough combustion and even blowout. Based on this understanding, control strategies that ameliorate the undesirable events will be developed. In the ongoing work, these control actions will be based on locally controlling or modulating the air injection through actuator-controlled injection ports along the combustor walls. Again an understanding of the fluid dynamics, through PIV measurements, is important in this work.

In what follows, we describe the PIV measurements made in the TVC using the PIV system acquired under the DURIP grant.

Experimental Setup

The TSI PIV system consists of a double-pulse Laser, a synchronizer box, camera-imaging system and processing software. The laser is the LASERPULSE™ integrated dual Nd:YAG laser system, 50mJ per pulse, 15 Hz. The laser beam is shutter-gated using a synchronizer that is programmed (through the Windows™-NT interface) to provide the appropriate laser energy, pulse separation and pulse duration for the best particle images of the flow field. Trigger signal outputs from the Synchronizer control the Nd:YAG laser pulsing sequence so that the laser pulses are located in the appropriate frame(s) in the camera. Double-pulsed images can be obtained in a single frame, or single-pulsed images on separate frames. A pair of PIVCAM 10-30 Cross/Autocorrelation CCD Camera (1024 x 1024 pixels, 30 frames/sec) with Stereoscopic PIV Assembly including Scheimpflug mounts collect the images. These images are analyzed with the INSIGHT ultrahigh resolution parallel processing software installed on a Pentium-based dual-processor computer system to obtain velocity distributions. The statistical method used to obtain velocity distribution is an cross-correlation technique to prevent any flow direction ambiguity.

The flow is seeded using sub-micron oil particles generated by a four-jet Laskin Nozzle. The nozzle has a pressure regulator so the concentration of particles in the flow may be controlled. Particles are introduced in a low-pressure region inside the combustor and then directed through the primary air delivery system to directly access the cavity.

Images were taken for confined non-reacting flow conditions. The confinement is obtained using a cast acrylic tube that was cut in halves; the halves were then cut on both sides and re-joined with two flat sections of acrylic. This prevents the laser beam from refraction if the beam is not perfectly aligned with the center of the tube. The back plane of the tube and the nozzle surface were painted black to eliminate the reflections of the laser sheet impinging on the body.

When all PIV data are obtained, a post-interrogation procedure is applied to check vectors for erroneous results, because the accuracy of PIV is adversely affected by noise. Once the experimental parameters are optimized, the number of remaining spurious vectors is low, less than 5 %. The filtering algorithm used is a comparative spatial procedure between each vector on the flow field with neighboring ones, called the "moving average". Additional validations such as the mean and STD calculations for a Hart correlation of 32 x 32 and sub-windowing of 16 x 16 were applied. Time-averaged results were also computed.

Results

Straight Injection Case

Velocity field was computed for different annular and primary air flow rates. Table 1 shows a summary of all the cases studied for both straight and swirl injection. The flow domain is outlined in Fig. 5 through 8. Repeated measurements showed that the center of the vortex oscillates around a determined location inside the cavity. For all conditions, the velocity field shows a strong recirculating flow that is expected for a toroidal vortex. The center of the vortex is located axially towards the forebody. The axial location of the vortex center did not appear to change significantly for different primary and annular air condition. However, the radial location of the vortex did change. It was observed that the center was pushed radially outwards when the air entrained at the downstream corner of the cavity was weaker than the primary air injection, more specifically, when it was weaker that the coaxial injection. The coaxial injection is the one that injects the more air into the cavity. Vectors pointing nearly straight down without been much affected by the flow at the top of the cavity are an indication that the coaxial injection is much stronger than the cavity flow. This type of behavior is shown in Fig. 5a.

The observations confirmed the theory established by Koening and Roshko (1965) that a stable vortex would be trapped inside the cavity when the stagnation point of the shear layer is located at the downstream corner of the cavity. For all the conditions, the annular air starts to turn around as it approaches the upstream face of the afterbody; then the flow stagnates at the corner. At the entrainment location part of the air that escaped the cavity is convected past the afterbody by the annular air; the rest re-entrains the cavity to sustain the constant feedback process of the trapped-vortex.

Table 1 Summary of Cases

	Primary Air							
	226 l/min		283 l/min		396 l/min		566 l/min	
Annular Air	Straight	Swirl	Straight	Swirl	Straight	Swirl	Straight	Swirl
1132 l/min (6 m/s)	**X**				**X**		**X**	
2265 l/min (11.5 m/s)	**X**		**X**		**X**		**X**	
2831 l/min (15 m/s)	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

The primary injection has to be such that reinforces the strength of the vortex and provides the necessary air for combustion. This appears to be the case for the multiple jet arrangement. As the ratio of coaxial jet to annular air velocities decreases eventually, the primary injection is overpowered by the entrained flow, deflecting the trajectory of the injection. This leads to dissipation of the injection before it reaches the face of the forebody. It also seems to be mixed into the recirculation zone and convected around the vortex center in a way that the vortex becomes stronger.

In general, the flow around the vortex center has a large axial velocity component well inside the forebody radius. The strength of the flow coming out of the cavity seems to greatly determine the entrainment of air in the cavity while the flow at the top controls the mixing and dissipation process. This process of constant feedback is the key to excellent stability of a TV combustor.

Swirl Injection Case

It has been suggested that by tilting the outermost array of jets by a certain angle it is possible to create a sufficiently strong tangential component of velocity. This tangential velocity creates a swirling motion around the spindle that is believed to provide additional mixing at locations midway fuel sprays. However, the injection must maintain the stability of the vortex from a combustion-performance point of view.

Figure 8 shows the effect of injection when the outermost array of jets has been tilted 30° in the tangential direction. Time-averaged results are presented for conditions described in Table 1. The background has been colored based on the tangential component magnitude introduced by the primary injection. Blue regions indicate flow moving towards the page (negative w) whereas red regions indicate flow coming out of the page (positive w). Regions at nearly zero or no tangential velocity are indicated by the color green. Observations showed that, at high primary air conditions, the location of the center of the vortex is greatly affected by the presence of a tangential component of velocity. At primary air flow rates of 566 l/min the vortex has been totally bulged towards the downstream corner of the cavity. Moreover, the center appeared stretched along almost two-thirds of the cavity and regions of negative tangential velocity cover almost all the cavity.

As primary air decreases the vortex center moves back inside the cavity and eventually conditions almost identical to those obtained for the straight injection are met. Furthermore, the tangential component of velocity introduced by the primary jets is no longer noticeable (Fig. 8d).

The introduction of the tangential component lead to strong azimuthal as well as radial interactions of the flow field. These interactions may be very useful to increase the exchange of heat and mass transfer throughout the cavity. A more homogenous flame can be obtained as a consequence of constant transport of species around and outside the cavity. Also, fuel may be conducted to regions never reached before with straight injection.

The velocity field suggests that swirl injection may promote a more stable combustion over a wider range of conditions. The incorporation of the tangential component of velocity would help sustaining the flame at higher power (higher primary air flow rate) conditions by promoting a more complete recirculation of hot products and radicals. And, when operated at lower power conditions (lower primary air) it would meet under the worst circumstances the results obtained with the first configuration (straight injection). Those results are by themselves very encouraging.

References

Acharya, S., Myrum, T. A., and Dutta, S., 1998, "Heat Transfer in Turbulent Flow Past a Surface-Mounted Two-Dimensional Rib", *ASME Journal of Heat Transfer,* **Vol. 120**, No. 3, pp.550-562

Acharya, S., Dutta, S., Myrum, T., and Baker, R. S., 1994, " Turbulent Flow Past A Surface-Mounted Two-Dimensional Rib", *ASME Journal of Fluids Engineering,* **Vol. 116,** No. 2, pp. 238-246

Bons, J. P., and Kerrebrock, J. L., 1998, "Complementary Velocity and Heat Transfer Measurements in a Rotating Cooling Passage with Smooth Walls," ASME Paper 98-GT-464.

Chen, Y., Nikitopoulos, D., Hibbs, R., Acharya, S., and Myrum, T., 1999, "Detailed Heat/Mass Transfer Distribution in a Ribbed Coolant Passage", *Intl. J. Heat Mass Transfer,* accepted, also in *ASME-International Mechanical Engineering Congress and Exposition (IMECE),* Atlanta, November 1996

Eliades, V., Nikitopoulos, D. E., and Acharya, S., "Detailed Mass Transfer Distribution in Rotating Two-Pass Ribbed Coolant Channels with Vortex Generators" *ASME-IGTI Intl. Gas Turbine Conference*, Indianapolis, June 1999

Fagan, W., and Selbach, H., 1984, "Laser 2 Focus Flow Measurements in the Absolute and Rotating Frame Inside the Blade Row of an Axial Flow Fan", Proceedings of the *2nd Int. Symp. on the Application of Laser Anemometry in Fluid Mechanics*, Lisbon.

Guidez, J., 1989, "Study of the Convective Heat Transfer in Rotating Coolant Channels," *ASME Journal of Turbomachinery*, Vol. 111, pp. 43-50.

Han, J. C., Zhang, Y. M., and Kalkeuhler, K., 1993, "Uneven Wall Temperature Effect on Local Heat Transfer in a Rotating Two-Pass Square Channel with Smooth Walls," *ASME Journal of Heat Transfer*, Vol. 115, pp. 912-920.

Hibbs, R., Acharya, S., Chen, Y., Nikitopoulos, D., and Myrum, T., 1996, "Heat Transfer in a Two-Pass Internally Ribbed Turbine Blade Coolant Channel with Cylindrical Vortex Generators", *ASME-International Mechanical Engineering Congress and Exposition (IMECE),* Atlanta, November 1996

Hibbs, R., Acharya, S., Chen, Y., and Nikitopoulos, D. E., 1997, "Mass/Heat Transfer in a Ribbed Coolant Passage with Cylindrical Vortex Generators: The Effect of Generator-Rib Spacing", *ASME-International Gas Turbine Conference,* 1997, Orlando

Hibbs, R., Acharya, S., Chen, Y., Nikitopoulos, D., and Myrum, T., 1998, "Heat Transfer in a Two-Pass Internally Ribbed Turbine Blade Coolant Channel with Cylindrical Vortex Generators", *ASME Journal of Turbomachinery*, **Vol. 120**, No. 4, pp. 724-734.

Hsieh, S., Chiang, M., and Chen, P., 1997, "Velocity Measurements and Local Heat Transfer in a Rotating Ribbed Two-Pass Square Channel with Uneven Heat Flux," ASME Paper 97-GT-160.

Iacovides, H., Jackson, D. C., Ji, H., Kelemenis, G., Launder, B. E., and Nikas, K., 1998, "LDA study of the Flow Development Through an Orthogonally rotating U-Bend of Strong Curvature and Rib Roughened Walls," *ASME Journal of Turbomachinery*, Vol. 120, pp. 386-391.

Koening, K. and Roshko, A., "An experimental study of geometrical effects on the drag and flow field of two bluff bodies separated by a gap," *J. Fluid Mech*., Vol. 156, 167, 1965.

Lennemann, E., 1969, "Secondary Flows in Rotating Passages", MS Thesis, University of Waterloo.

Schabacker, J., Bolcs, A., and Johnson, B. V., 1998, "PIV Investigation of the Flow Characteristics in an Internal Coolant Passage with Two Ducts Connected by a Sharp 180^{o} Bend," ASME Paper 98-GT-544.

Servouze, Y., 1998, "3D Laser Anemometry in a Rotating Cooling Channel," ASME Paper 98-GT-123.

Tse, D. G. N., Kreskovsky, J. P., Shamroth, S. J., and McGrath, D. B., 1994, "A Combined Experimental/Computational Study of Flow in Turbine Blade Cooling Passage, NASA Contractor report 4584

Tse, D. G. N., and Steuber, G. D., 1997, "Flow in a rotating Square Serpentine Coolant Passage with Skewed Trips," ASME Paper 97-GT-529.

Wagner, J. H., Johnson, B. V., and Kopper, F. C., 1991, "Heat Transfer in Rotating Serpentine Passages with Smooth Walls," *ASME Journal of Turbomachinery*, Vol. 113, pp. 321-330.

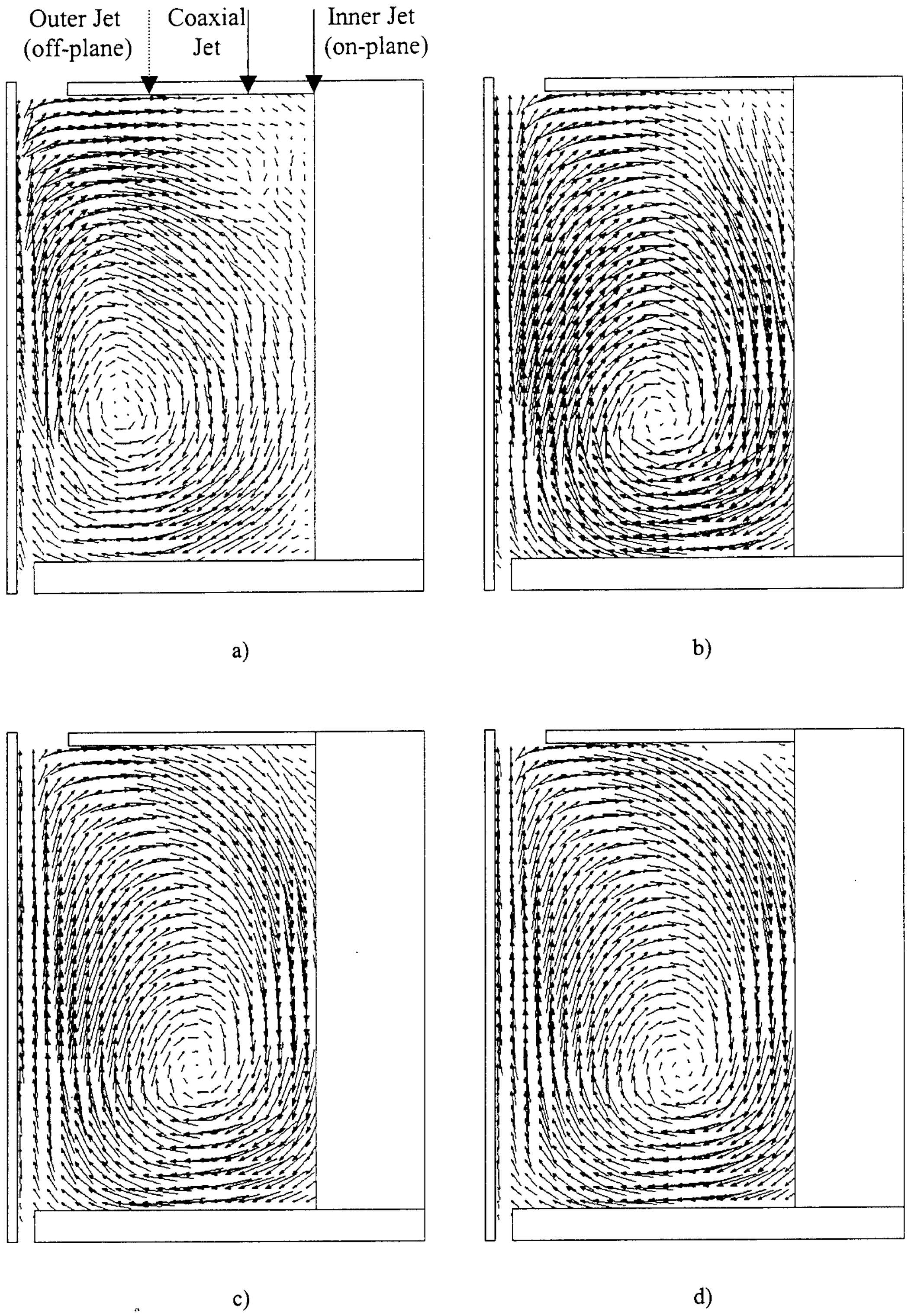


Fig. 5 Velocity Field for Primary Air Flow of a) 566, b) 396, c) 283, and d) 226 l/min (Annular Air= 2831 l/min)

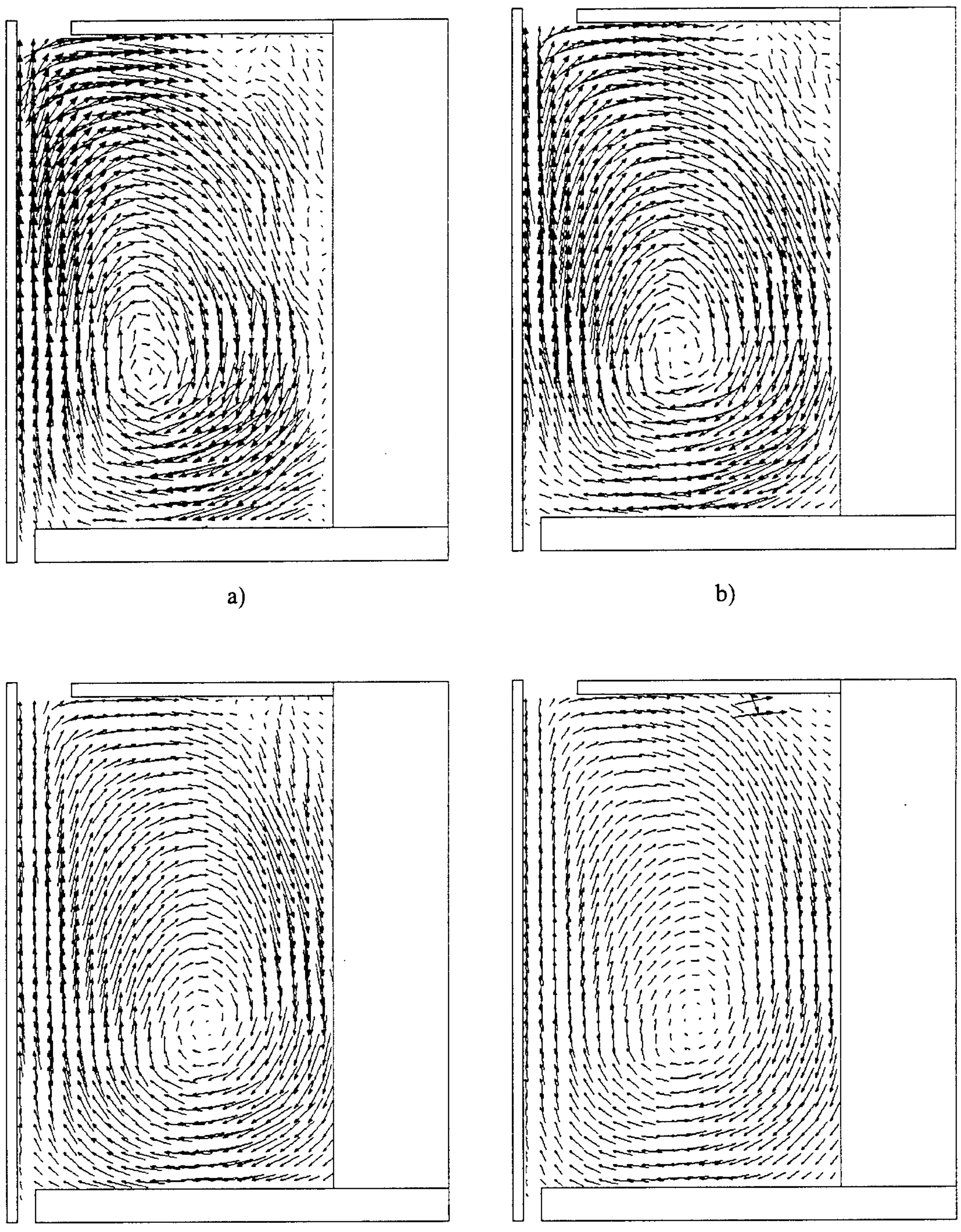


Fig. 6 Velocity Field for Primary Air Flow of a) 566, b) 396, c) 283, and d) 226 l/min (Annular Air= 2265 l/min)

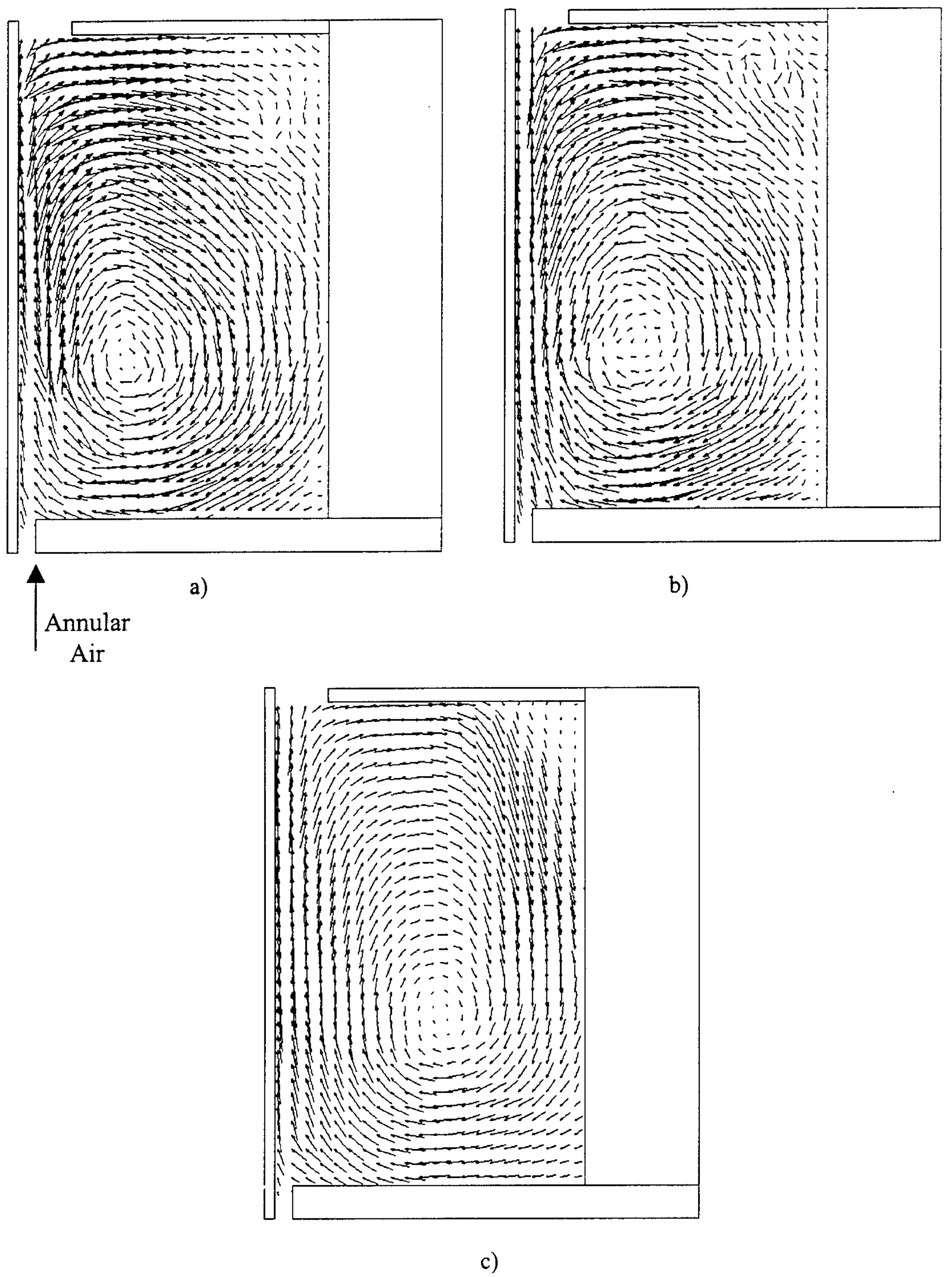
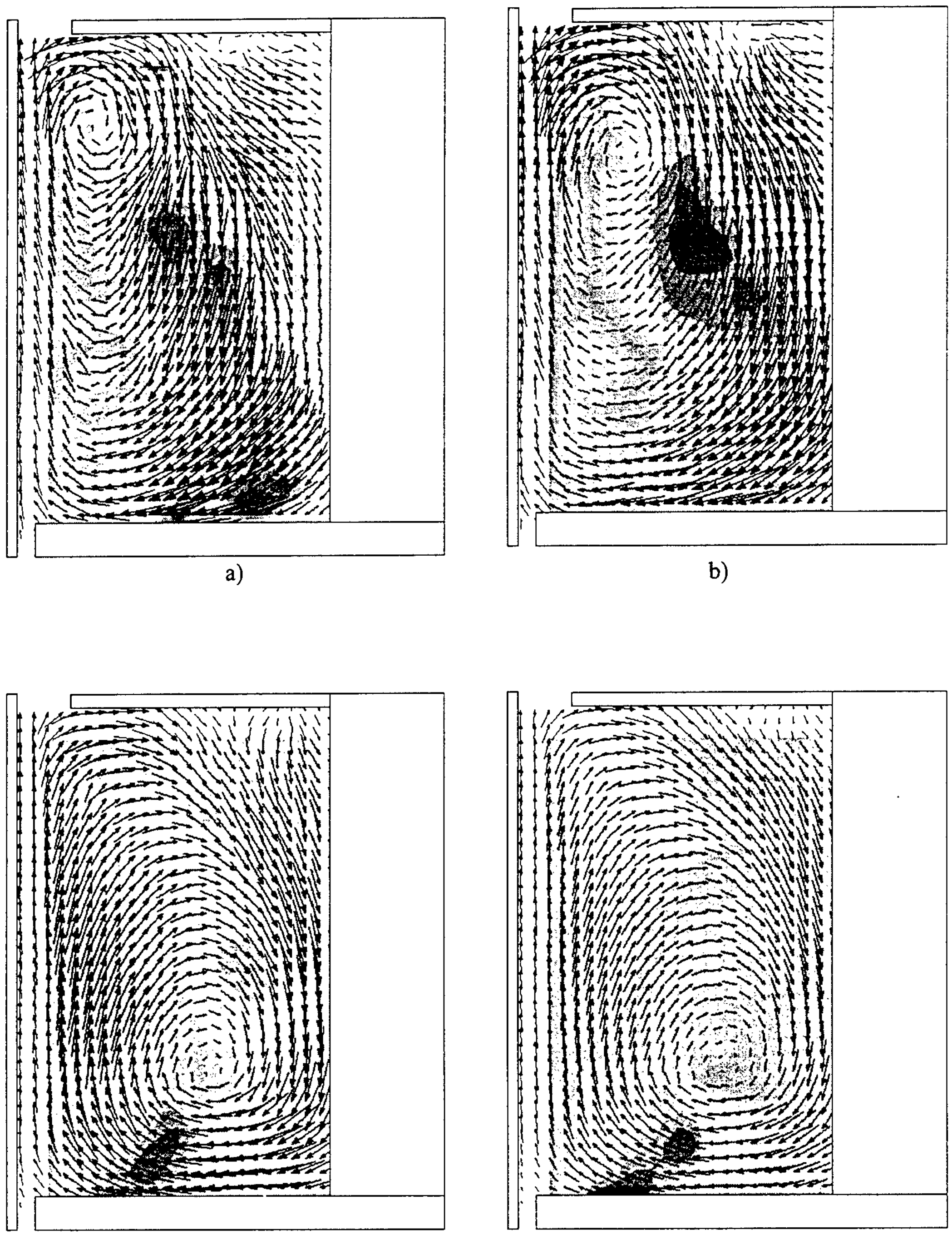


Fig. 7 Velocity Field for Primary Air Flow of a) 566, b) 396, and c) 226 l/min (Annular Air= 1132 l/min)



a) b) c) d)

Fig. 8 Velocity Field (Swirl Injection) for Primary Air Flow of a) 566, b) 396, c) 283, and d) 226 l/min (Annular Air= 2831 l/min)

Veon Wendy Civ AFRL/AFOSR

From: Smith, Gerald [smithg@onr.navy.mil]

Sent: Wednesday, August 14, 2002 1:48 PM

To: harry.haraldsen@afosr.af.mil; pkcontracting@AFOSR.AF.mil

Cc: Kelly, Michael

Subject: AFOSR Cash Management

Harry:

As promised, the attached spreadsheet contains two worksheets. The first worksheet is a list of all the SF 272's that has been input into our Toolbox database as of Monday for the reporting period ending 4/1/02 through 6/30/02. The second worksheet is one that reflects all AFOSR awards which will expire in 90 days and the cash on hand balance is at least 50% of the award obligation amount.

Caution: A brief check of the data shows we still have more work to do on updating our CAMIS records and tracking down missing reports.

We can provide you the first worksheet on a quarterly basis. The second worksheet is something that we would route internally to the ONR regional offices. The plan is the assigned Specialist will review the SF 272 and will contact the School to find out what is going on. The Grant Specialist will in turn contact the AFOSR Grants Officer and will recommend appropriate action like issue an NFE and/or defer the next option until the cash on hand balance is reduced.

A third report that we have developed is one where we compare SF 272 data where disbursements are not exceeding receipts. See sample web page attached.

This is a detailed description of how we are determining these awards are not passing the expected threshold:

Possible Problems:
The Total disbursements on the SF 272 reports are less than the total receipts as of the prior reporting period. The performer is not spending the money as fast as they are getting it. Following the expenditure rate formula established by the CBC for ONR Grants, the performers disbursement rate must match their receipts received. Part of the formula allows the performer a 3 month billing lag. Money received in month 1 should be spent in month 4.

Since SF 272 reports are typically submitted every 90 days, a simple rule of thumb is: If the Cash On Hand (Block 11j.) is more than the Total Receipts (Block 11d.) for a given report, the performer is failing the expenditure rate.

It is important to watch the trend of cash on hand to the disbursements reported on subsequent SF 272 reports. If the Gross Disbursements (Block 11e.) is more than the Total Receipts (Block 11d.), the award is trending down (a good thing). If the Gross Disbursements (Block 11e.) is less than the Total Receipts (Block 11d.), the award is trending up (a bad thing).

Possible Solutions:
These steps may include, but are not limited to:
1. Cautionary correspondence to the recipient and documentation in the award file, about the appearance of CM concerns.
2. Working with the issuing office and the recipient to adjust the payment schedules for future advances via award modification.
3. Requesting increasing levels of management attention and involvement for repeated or severe problems.
4. Invoking, or recommending of invoking, as appropriate, the enforcement provisions provided by OMB Circular A-110.

Your feedback on these reports is appreciated. We will be having training on Cash Management with the field offices via VTC from HQ on Sep 26th. We would like to take some time while we are there to demo these tools to you and your staff. How about the afternoon of Sep 25th?

As we also discussed yesterday, I will send to you in a separate e-mail the final version of the OCR report.

Lambert concurs with your suggestion that we move forward with what was agreed to in the MOU and not wait for the signed document. Please let me know if this OK.

I will follow up with you next week.

Regards,

Jerry

NOTE: AFOSR security systems scanned this email for malicious content. Do not open attachments from unrecognized senders.