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ADVANCED FLOW DIAGNOSTICS FOR AERONAUTICAL RESEARCH AFDAR

Deliverable D4.2

“Workshop on Advances of Optical Diagnostics in Combustion”

Partner DLR-K

Author Christian Willert (Ph.D.)

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Partnership:

Beneficiary number:	Beneficiary name	Beneficiary short name	Country
1 coordinator	Technische Universiteit Delft	TU Delft	NL
2	Centre National de la Recherche Scientific	CNRS	F
3	Deutsches Zentrum fuer Luft- und Raumfahrt e.V.	DLR	D
4	LaVision GmbH	LaVision	D
5	Universitaet der Bundeswehr Muenchen	UNIBWM	D
6	Universita Degli Studi di Napoli Federico II	UNINA	I
7	Stichting Nationaal Lucht- en Ruimtevaartlaboratorium	NLR	NL
8	Von Karman Institute for Fluid Dynamics	VKI	B
9	Institute of Thermal Physics	IOT	RU
10	Monash University	UNIMO	AUS

CONTENTS

1 Introduction

The objective of AFDAR is to develop, assess and demonstrate new image- based experimental technologies for the analysis of aerodynamic systems and aerospace propulsion components. The main development focus is on new three-dimensional methods based on Particle Image Velocimetry (PIV) to measure the flow field around aircraft components, and on the high-speed implementation of the planar PIV for the time-resolved analysis of transient/unsteady aerodynamic problems. The work also covers the simultaneous application of PIV-based techniques and other methods to determine aero-acoustic noise emissions from airframe and to improve combustion processes to lower NOx, CO_2 and soot emissions from engines.

In this context the primary intention of the AFDAR Workshop on Advances in Combustion Diagnostics was to address the advances of the PIV techniques in the area of combustion research, in particular in combination with other field measurement techniques. The main objective of the workshop was to provide the opportunity for exchange of up-to-date information on the numerous aspects of combined experimental field measurement techniques in combustion related research.

The AFDAR workshop was co-organized together with the annual DLR internal workshop on combustion diagnostics DIV ("Diagnostik in der Verbrennung"), the ninth in a series. This workshop commenced the day before the beginning of the AFDAR workshop in order to allow DLR participants to present confidential material not for public release. The DIV contributors were given the option to either present their work to the DLR internal audience or on the second day to the public audience of the AFDAR workshop. Of the 10 DLR contributions, six were given to the private audience of the DIV workshop and another four during the AFDAR workshop.

The workshop was funded in part by the EU-FP7 AFDAR project, an EU funded collaborative project for the development and application of *Advanced Flow Diagnostics for Aeronautical Research*. The support of the DLR is acknowledged for hosting the event and providing the necessary infrastructure.

C. Willert, L. Lange and J. Klinner

AFDAR Workshop Chairpersons

2 List of Participants

no.	Last name	First name	Title	Institute	Country
1	Arndt	Christoph	Mr.	DLR Institute of Combustion Technology	Germany
2	Astarita	Tommaso	Prof.	Universita di Napoli	Italy
3	Börner	Michael	Mr.	DLR Institute of Space Propulsion	Germany
4	Cardone	Gennaro	Prof.	Universita di Napoli	Italy
5	Cessou	Armelle	Dr.	CORIA, Rouen	France
6	Chikishev	Leonid	Dr.	Institute of Thermophysics (IOT)	Russia
7	Conzen	Tobias	Mr.	DLR Institute of Propulsion Technology	Germany
8	Diers	Olaf	Mr.	DLR Institute of Propulsion Technology	Germany
9	Doll	Ulrich	Mr.	DLR Institute of Propulsion Technology	Germany
10	Dulin	Vladimir	Dr.	Institute of Thermophysics (IOT)	Russia
11	Desgroux	Pascale	Prof.	PC2A - UMR CNRS	France
12	Enns	Andreas	Mr.	DLR Institute of Propulsion Technology	Germany
13	Fischer	Michael	Dr.	DLR Institute of Propulsion Technology	Germany
14	Freitag	Stefan	Mr.	DLR Institute of Propulsion Technology	Germany
15	Geigle	Klaus-Peter	Dr.	DLR Institute of Combustion Technology	Germany
16	Hassa	Christoph	Dr.	DLR Institute of Propulsion Technology	Germany
17	Heinze	Johannes	Dr.	DLR Institute of Propulsion Technology	Germany
18	Kirchheck	Daniel	Mr.	DLR Institute of Aeroynamics and Flow Technology	Germany
19	Klinner	Joachim	Mr.	DLR Institute of Propulsion Technology	Germany
20	Knapp	Bernhard	Mr.	DLR Institute of Space Propulsion	Germany
21	Koch	Uwe	Dr.	DLR Institute of Aerodynamics and Flow Technology	Germany
22	Köhler	Markus	Dr.	DLR Institute of Combustion Technology	Germany
23	Lecordier	Bertrand	Dr.	CORIA, Rouen	France
24	Lange	Lena	Mrs.	DLR Institute of Propulsion Technology	Germany
25	Meier	Ulrich	Dr.	DLR Institute of Propulsion Technology	Germany
26	O'Loughlin	William	Dr.	DLR Institute of Combustion Technology	Germany
27	Otterpohl	Ingo	Mr.	DLR Institute of Propulsion Technology	Germany
28	Peterson	Brian	Dr.	Technical University of Darmstadt	Germany
29	Renaud	Antoine	Mr.	CNRS - Ecole Centrale Paris	France
30	Saile	Dominik	Mr.	DLR Institute of Aeroynamics and Flow Technology	Germany
31	Scarano	Fulvio	Prof.	Delft University of Technology	Netherlands
32	Sender	Joachim	Dr.	DLR Institute of Space Propulsion	Germany
33	Stockhausen	Guido	Dr.	DLR Institute of Propulsion Technology	Germany
34	Strauss	Friedolin	Mr.	DLR Institute of Space Propulsion	Germany
35	Stützer	Robert	Dr.	DLR Institute of Space Propulsion	Germany
36	Tietz	Sebastian	Mr.	DLR Institute of Propulsion Technology	Germany
37	Voges	Heinrich	Dr.	LaVision GmbH	Germany
38	Willert	Chris	Dr.	DLR Institute of Propulsion Technology	Germany
39	Zimmer	Laurent	Dr.	CNRS - Ecole Centrale Paris	France

2.1 Participants Group Photo

Date taken: Oct. 16th, 2013 in the afternoon of 2nd day of Workshop (not all participants present)

3 Report on Workshop

3.1 Scope and Main Topics

Within the AFDAR project the combination of PIV with different image based combustion diagnostics has been demonstrated in representative combustion configurations at laboratory-scale. The experiments were aimed at verifying the feasibility to integrate and simultaneously operate PIV and spectroscopic imaging methods such as laser induced incandescence (LII) or planar laser induced fluorescence (PLIF). The recovered space-time correlated data promises to provide a more complete picture of the unsteady phenomena and demonstrates the concept of combined diagnostics to investigate new combustion strategies. Four main topics were addressed in Workpackage 4 of the AFDAR project:

- PIV and double OH Fluorescence imaging in a turbulent flame
- Joint PIV and LII measurements in a flame
- Combined stereo PIV and OH-Temperature PLIF measurements in lean premixed turbulent combustion
- PIV and chemiluminescence diagnostics for premixed swirling flames.

The workshop was opened to participation by non-AFDAR members providing them with the opportunity to share their up-to-date work in the area of image based combustion diagnostics.

3.2 Workshop

The workshop attracted 39 participants in total, mainly from Germany (29), five from France, two from Italy, one from the Netherlands and two participants from Russia. The scientific program consisted of eleven scientific presentations as well as three overview presentations, one on the AFDAR project and one introducing the hosting Institute of Propulsion Technology and one presenting the demands for optical measurement techniques in the context of combustor research and development.

The first day was focused on scientific presentations and closed with a dinner event in downtown Cologne. After two further presentations on the second day, a facility tour presented two combustor test facilities of the Institute of Propulsion Technology. The workshop closed around noon with a final discussion and summarizing remarks.

The workshop opened with an introductory presentation on the Institute of Propulsion Technology given by Dr. C. Willert providing an overview of the institute's mission of area of activity with focus on the role of the Department of Measurement Techniques within the institute. The following invited presentation by Dr. C. Hassa outlined the importance of laser optical measurements from the perspective of modern aero-engine combustor development and thereby put the workshop into a broader context. In essence laser optical diagnostics provide the physical insight into processes that conventional testing cannot provide, in particular when these diagnostics are applied at realistic operating conditions. The presentation by Dr. Hassa closed with an overview of the currently available optical combustion test facilities at the Institute.

Dr. A. Cessou of CORIA (Rouen, France) provided a summary of the activities within AFDAR WP4.1 relating to the combination of stereo PIV with double-pulsed laser induced fluorescence of the OH radical (OH-PLIF) in turbulent combustion with the intention of tracking flame propagation within a moving frame of reference, the latter being provided by the PIV technique. The first session closed with a contribution by Mr. A. Renaud of CNRS Ecole Centrale Paris (France) who described a combination of Mie scattering and PIV with chemiluminescence for the study of flame stabilization mechanisms on a laboratory scaled combustor.

The second session of the workshop focused on optical measurement techniques for sooting combustion conditions, commencing with a presentation by Dr. P. Desgroux of PC2A (Lille, France) who described the development and application of combined PIV with laser induced incandescence (LII) to provide both the velocity field and soot volume fraction in a turbulent jet flame. Similar work was then presented by Dr. K.P. Geigle of the DLR Institute of Combustion Technology (Stuttgart, Germany). In addition to flow field and volume soot fraction, simultaneous OH-PLIF was also applied to recover spatially resolved information on the reaction zone. This approach provides access to the "spatial correlation of soot clouds to the region of the primary reaction zone or to its immediate precursors." The final contribution of this session by Dr. C. Willert described methodologies of acquiring PIV recordings in highly luminescent flames on the basis of a dual sensor imaging configuration. This approach was necessary to cope with the fact that usual PIV imaging hardware leaves the sensor receptive to exposure while the first frame of the image pair is being read out.

The first afternoon session provided an overview on high-speed laser diagnostics as well as approaches aimed at volumetric data recovery. Mr. C. Arndt of the DLR Institute of Combustion Technology presented efforts for simultaneous measurement of mixture fraction, flow field, and flame-front position in a gas turbine model combustor at frame rates of 10 kHz. While fuel transport and mixing were visualized by acetone PLIF, flame position and reaction zones were captured using OH-PLIF and flow field data was provided using 2-C PIV. Measurements of the three-dimensional unsteady turbulent flow within lifted flame using tomographic PIV was presented by Dr. B. Peterson of TU-Darmstadt. An important finding of this work is that flame induced distortion of the particle image positions amounts to only about 0.10 pixels. This estimate was confirmed by similar work performed by Dr. L.M. Chikishev and his colleagues of the Institute of Thermal Physics from Novosibirsk (Russia). In their work they utilized high repetition rate tomographic PIV to study the unsteady motion of vortex structures in a turbulent lifted propane flame.

The final presentation of the first day of the workshop was given by Dr. V.M. Dulin of the IOT who presented post-processing approaches for high repetition rate PIV data. Both proper orthogonal decomposition (POD) as well as dynamic mode decomposition (DMD) were utilized to recover flow dynamics of a model swirl combustor operating at two different swirl rates which exhibit different modes of flame stabilization.

The second day of the workshop started off with a presentation by Dr. L. Zimmer of CNRS Ecole Centrale Paris (France) who highlighted discrepancies between velocity measurements of droplet velocities downstream of a swirl combustor as measured by PDA and various PIV analysis approaches. Differences of up to 20% were observed and attributed to the fact that PIV is biased toward the brighter and hence larger droplets. As a consequence spatial gradients and recirculation zone are not as well recovered by PIV as with PDA. The final presentation of the workshop was given B. Lecordier of CORIA (Rouen, France) who introduced a new PIV processing technique that is capable of recovering the local instantaneous laminar burning velocity of a stretched premixed flame with single pixel resolution. The performance of the technique was verified on well characterized "outwardly propagating spherical flames and used to investigate the propagation of laminar flames in stratified mixtures".

3.3 Facility Tour

During the later half of the morning of the second day featured a 1 ½ hour tour of two combustion facilities at the Institute of Propulsion Technology. The single sector facility (EDS) features a traversable vertical combustor test section that can be operated at up 20 bar with air preheating of up to 850K. Optical access to the 102 x 102 mm^2 test section is possible from three sides. A CO-LIF setup was installed at the time of the tour. The second facility, the HBK1, is a scaled up version of the EDS with approximately twice the mass flow allowing the investigation of unscaled lean injectors as well as multi-sector RQL combustion chambers. Optical diagnostics at this facility is provided by an integrated PLIF/LII system mounted on a dedicated traversing table. Alternatively, PIV and PDA can provide flow field and spatial distribution of droplet size, respectively. A variety of emissions sampling including SMPS (scanning mobility particle sizing) allows for the correlation of integral quantities with simultaneously acquired optical measurements.

3.4 Abstracts and Presentation Format

Participants contributed single page abstracts of their presentations, which can be found in the documents section of this deliverable.

Oral presentations of 20 minutes were given, each followed by a question answer session of 5 minutes. The presentation material itself was not collected.

3.5 Summary and Lessons Learned

With the exception of one representative from industry, the participants represented universities and research centers. Among the presentations given AFDAR partners gave roughly half.

Due to the rapid progress in imaging and laser technology both planar as well as volume resolving optical diagnostics for combustion related research has taken a considerable step forward in the last decade and the workshop provided an excellent snapshot of the current state-of-the-art. Four simultaneously occurring trends can be highlighted:

1. Laser optical methods are increasingly being applied in very demanding environments characterized by high pressure and high flame luminosity.
2. High-speed imaging and related post-processing methods provide a better understanding of combustion dynamics.
3. Volumetric (high-speed) imaging fills in where planar methods leave open questions or uncertainties.
4. The combination of the several optical techniques allows better correlation between different measurands, such as flow field and scalar quantities (soot, reactants, pollutants, etc.).

The AFDAR Workshop on Advances in Combustion Diagnostics was successfully performed at DLR in Cologne, with the participation of about 39 scientists from universities and research institutes from 5 different countries, presenting and discussing their experience and knowledge in state-of-the-art laser-based diagnostics for combustion research.

4 Workshop Documents

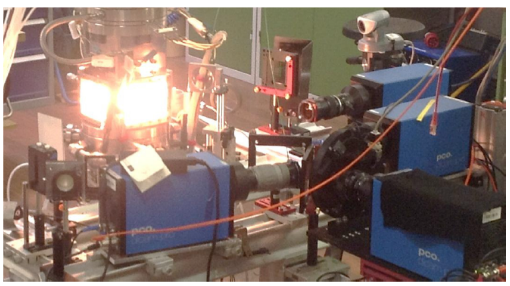
4.1 Announcement and Call for Contributions

Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

ADVANCED FLOW DIAGNOSTICS FOR AERONAUTICAL RESEARCH

First Announcement
AFDAR Workshop

Optical Diagnostics in Combustion



16-17 October 2013

DLR Institute of Propulsion Technology
51170 Köln, Germany

Organization

The workshop will be held over two days ending in the afternoon of the second day. A visit of DLR-Cologne's combustion facilities will be scheduled for the early afternoon of the second day, October 17th.

The event is co-organized with the annual DLR-internal workshop on combustion diagnostics, DIV9, which will commence on October 15th.

This workshop is open for all AFDAR partners and also non-AFDAR members in order to share their recent results on combustion related flow diagnostics. Due to space limitations the number of workshop attendees is limited to 35 people max., with priority given to AFDAR and DLR members.

Registration

Please fill out the attached registration form and indicate your (preliminary) title of contribution, if you are planning to give a talk at the workshop. A short abstract is much appreciated for the compilation of the workshop minutes.

Dead-lines and important dates

- Secure a hotel reservation as soon as possible
- Register by September 6th (Fax or email)
- Notice of acceptance by September 13th (by email)
- Provide brief abstract of intended presentations by October 7th (by email).

Accommodation

A total of 40 hotel rooms have been blocked under the reference "**DLR-DIV**" at the *Hotel zur Quelle* (www.hotelzurquelle.de, 84.00 € / night) and *Hotel Geisler* (www.hotel-geisler.de, 63.00 € / night). Please make sure to book well in advance as Cologne hosts numerous trade fairs and other large events throughout the year.

Hotel zur Quelle offers a shuttle bus for the morning transfer from the hotel to DLR. *Hotel Geisler* is serviced by public bus (Line 162) with regular transfers to and from DLR.

Organizer

Dr. Christian Willert
DLR, Institute of Propulsion Technology, Linder Höhe, 51147 Köln, Germany
e-mail: chris.willert@dlr.de
Tel: +49(0)2203 601-2308 Fax: +49(0)2203 64395

General

The objective of AFDAR is to develop, assess and demonstrate new image-based experimental technologies for the analysis of aerodynamic systems and aerospace propulsion components. The main development focus is on new three-dimensional methods based on Particle Image Velocimetry (PIV) to measure the flow field around aircraft components, and on the high-speed version of the planar technique for the analysis in time-resolved regime of transient/unsteady aerodynamic problems. The work also covers the simultaneous application of PIV-based techniques and other methods to determine aero-acoustic noise emissions from airframe and to improve combustion processes to lower NOx, CO_2 and soot emissions from engines.

In this context the workshop primarily addresses the advances of the PIV techniques in the area of combustion research, in particular in combination with other field measurement techniques. The main objective of the workshop is to provide the opportunity for exchange of up-to-date information on the numerous aspects of combined experimental field measurement techniques in combustion related research.

The AFDAR consortium is led by TU-Delft and consists of eight European partners including DLR as well as two non-European partners: the Institute of Thermal Physics (IOT SB RAS, Novosibirsk, RU) and Monash University (Melbourne, AUS). Three industries are involved in this work either as participant or contributing under subcontract and providing testing facilities.

For more information on AFDAR consult the website: **www.afdar.eu**

Scope and Main Topics

Within the AFDAR project the combination of PIV with different image based combustion diagnostics has been demonstrated in representative combustion configurations at laboratory-scale. The experiments were aimed at verifying the feasibility to integrate and simultaneously operate PIV and spectroscopic imaging methods such as laser induced incandescence (LII) or planar laser induced fluorescence (PLIF). The recovered space-time correlated data promises to provide a more complete picture of the unsteady phenomena and demonstrates the concept of combined diagnostics to investigate new combustion strategies. Four main topics were addressed in AFDAR:

- PIV and double OH Fluorescence imaging in a turbulent flame
- Joint PIV and LII measurements in a flame
- Combined stereo PIV and OH-Temperature PLIF measurements in lean premixed turbulent combustion
- PIV and chemiluminescence diagnostics for premixed swirling flames

Related contributions by non AFDAR partners are certainly welcome.

How to reach DLR Köln?

The DLR Köln (Cologne) site is located south-east of Köln, close to the Köln-Bonn airport (CGN).

Arrival by train

The local trains ("S-Bahn") S 12 or S 13 leave from Köln Hauptbahnhof (Hbf), Siegburg and Troisdorf. The local train S 13 also leaves from Köln/Bonn Airport. Daytime departures take place every 20 min for both trains so that there is a train every 10 minutes. Get off at the railway station "Porz-Wahn" and continue from there by KVB bus number 162, direction "DLR". See instructions "By bus" below.

Note: Tickets for local train routes must be purchased in advance. If you need a ticket, you can get one from the ticket vending machines (Zone 2A, 2.60 Euro).

Arrival by bus

To get to DLR Köln by bus, take the KVB bus number 162 from "Porz-Wahn" train station. The bus sign will show "DLR". Please be sure that you take the one saying "DLR" as there are different routes for bus number 162. Exit at the last stop and you have arrived at the main gate of the German Aerospace Center DLR Köln.

Arrival by taxi

Upon arrival at Köln Hauptbahnhof (Hbf) take a taxi to "Porz-Wahnheide, DLR". Taxi stands are located on both, the north and south exit of the station. Tell the driver to take you to "Porz-Wahnheide, DLR". The price will very much depend on daytime and traffic but from Cologne central station to DLR without any traffic jam it should not exceed 35 Euros.

A taxi transfer from Köln-Bonn airport to DLR takes about 10 minutes and should cost about 10 Euros.

4.2 Registration Form

AFDAR Workshop

Optical Diagnostics in Combustion

DLR-Köln, October 16th-17th, 2013

Registration form

To be sent to

Chris Willert
DLR Institute of Propulsion Technology
51170 Köln
Germany

Tel: 49 (0)2203 601 2308
Fax: 49 (0)2203 64395
Email: chris.willert@dlr.de
http : www.dlr.de/at/

Before September 30th 2013

Name: ______________________________ Title: ____________________

Organization:
____

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Address: ____

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Phone: ______________ Fax: ______________ Email: ______________________

Title of contribution (optional): ____

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Date of Arrival: ______________ Time: ________________

Date of Departure: ______________ Time: ________________

Signature: ____________________

4.3 Workshop Programme

Advanced Flow Diagnostics for Aeronautical Research

(AFDAR)

Workshop on Optical Diagnostics in Combustion

Location: **DLR Center Cologne, Bldg. 53 (Casino)**

Date: **16-17 Oct. 2013**

Agenda

Wednesday 16 Oct. 2013

08:30 Registration at the "Casino" (Bldg. 53)

09:00 Welcome and organisational infos on Workshop,
Brief introduction of the Institute of Propulsion Technology
C. Willert - DLR Institute of Propulsion Technology

09:30 The significance of advances in combustion diagnostics for aero engine research and development
C. Hassa - DLR Institute of Propulsion Technology

10:00 Simultaneous SPIV and double-pulse OH-PLIF for investigating turbulent flames
S. Grout , A. Cessou , C. Gobin, B. Lecordier - CORIA, Rouen

10:30 Joint time resolved PIV/CH* Measurements for the study of shape transistion in a turbulent spray flame
A. Renaud, L. Zimmer - CNRS - Ecole Centrale Paris

11:00 Coffee Break

11:30 Combined SPIV and laser induced incandescence measurements in a turbulent jet flame
K.H. Tran, S. Coudert, P. Desgroux, S. Grout, A. Cessou, B. Lecordier, J.M. Foucaut, M. Stanislas - PC2A and LML (Lille) and CORIA (Rouen)

12:00 Optical diagnostics in sooting flames
K.P. Geigle, W. O'Loughlin, M. Köhler, M. Stöhr - DLR Institute of Combustion Technology, Stuttgart

12:30 PIV-Measurements in highly luminescent flames
M. Schroll, C. Willert, J. Klinner, M. Beversdorff - DLR Institute of Propulsion Technology, Cologne

13:00 Lunch Break, DLR-Canteen

14:00 Introduction of AFDAR Project (*F. Scarano - TU-Delft*)

14:20 Multi-parameter high-speed laser diagnostics for simultaneous mixture fraction, flow field, and flame-front imaging in a gas turbine model combustor
C. Arndt, M. Stöhr, W. Meier - DLR Institute of Combustion Technology, Stuttgart

14:50 Towards volumetric imaging diagnostics in turbulent combustion
B. Peterson, A. Dreizler - Technical University of Darmstadt

15:20 Application of tomographic PIV to a lifted propane/air flame
D.M. Markovich, V.M. Dulin, M.P. Tokarev, L.M. Chikishev - Institute of Thermophysics (IOT), Novosibirsk

15:50 Coffee Break

16:10 Analysis of flow instabilities in a model swirl combustor from PIV data *D.M. Markovich, V.M. Dulin, M.P. Tokarev, L.M. Chikishev - Institute of Thermophysics (IOT), Novosibir*sk

16:40 (Title t.b.d.) - withdrawn
T. Reichel et al. - Technical University of Berlin

19:00 Workshop Dinner, Peters Brauhaus, Mühlengasse 1, 50667 Köln

Thursday 17 Oct. 2013

09:00 Investigation of the dynamics of spray combustion using time-resolved Mie scattering images
L. Zimmer, A. Renaud - CNRS - Ecole Centrale Paris

09:30 High resolution PIV technique in vicinity of reactive zones: Application to stratified combustion systems
E. Delangle, S. Balusamy, A. Cessou, B. Lecordier- CORIA, Rouen

10:00 Coffee break

10:20 Visit of DLR Test Facilities and Labs

12:30 Summarizing Remarks and Closure of Workshop

13:00 Lunch at DLR Canteen

4.4 Contributed Abstracts

The following pages contain one-page abstracts of the presentations given during the workshop.

Simultaneous SPIV and double-pulse OH-PLIF for investigating turbulent flames

S. Grout, A. Cessou, C. Gobin, B. Lecordier

CNRS UMR 6614- CORIA, Université et INSA de Rouen, 76801 BP- 12, St Etienne du Rouvray, France

Abstract: The purpose of this work is to associate SPIV and double exposure planar induced fluorescence (PLIF) of OH radical in order to investigate flame-turbulence interaction and unsteady behaviour of flames. Interactions of flames in highly tridimensional flows, like swirling flows, or transient behaviours of flames in high Reynolds turbulence cannot always be tracked by current kilohertz systems. The main idea of this work is to propose the combination of a stereoscopic PIV set-up with a double-pulse OH-PLIF set-up to access to the instantaneous motion of flames coupled with flow field, and this even in highly turbulent flows.

One SPIV device and two OH-PLIF devices are combined to perform simultaneous measurements of 2D-3C velocity field and double-pulse OH PLIF. The PIV apparatus consists of a dual-cavity frequency-doubled Nd:YAG and a pair of interline CCD cameras mounted equidistant from opposite sides at 90° and visualizing the laser sheet with a 45° angle of view. The double OH pulse set-up is composed of two frequency doubled dye lasers combined by a thin-film plate polarizer to accurately overlap the two UV laser sheets of around 200 µm in the investigation domain with the same constrains than a PIV laser. The SPIV and PLIF systems are synchronized to have the OH-PLIF and SPIV cameras both framing at 2 Hz, with the OH-PLIF and SPIV lasers operating at 10 Hz to ensure energy stability, and the first OH-PLIF laser is placed 2 µs after the first SPIV laser. A double side calibration grid is used simultaneously to calibrate the stereo-PIV technique (3 planes + self-calibration from particle images) and to measure the magnification factor and the mapping functions of the two ICCD cameras.

We have focused our investigations on the region of stabilization of turbulent jet flames flame in lifted regime near blow-out condition[1,2]. A burner has been conceived in collaboration with LML and PC2A teams[3,4] to be adapted to laser diagnostics and their combinations and to obtain well-defined inlet and boundary conditions suitable for providing detailed databases for modelling and simulation. In high Reynolds jet, the flame stabilizes in a region of established turbulence and within a large mixing layer. Thus the flame is submitted to 3D flow motion and large-scale structures leading to enlarged flame base fluctuations and to the sudden appearance of flame islands in the plane of the laser sheet. This flame configuration shows that double-pulse PLIF images provide a useful tool to describe the flame motion, in a flow field known by simultaneous PIV measurement.

The present work has demonstrated the capability to adjust the time delay between OH PLIF images between 0 to hundreds of µs, and allows us to consider the application of these simultaneous diagnostics in flames with strong swirling conditions, as those encountered in the field of aeronautics.

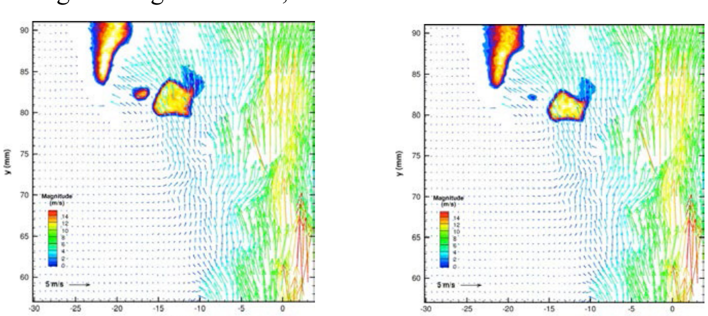

Fig. 1: Instantaneous couple of OH images overlapped to the velocity field with a time delay of 200µs

1 Maurey, C., A. Cessou, et al. (2000). Proceedings of the Combustion Institute **28**: 545-551

2 Cessou, A., C. Maurey, et al. (2004). Combustion and Flame **137**(4): 458-477

3 K.H. Tran, et al., "Combined measurements of velocity and soot volume fraction field in a turbulent jet flame", European combustion Meeting, ECM2013, in Lund, June 25-28, Sweden, 2013

4 K.H. Tran, S. Coudert, et al. , AFDAR Workshop on "Advances in Combustion Diagnostics", 16.-17. Oct. 2013

Joint time-resolved Mie scattering/CH* measurements for the study of shape transition in a turbulent spray flame

A. Renaud* , P. Scouflaire, S. Ducruix, L. Zimmer

CNRS, UPR 288 "Laboratoire d'Energetique moleculaire et macroscopique, combustion"
Grande Voie des Vignes, 92295 Chatenay-Malabry

Ecole Centrale Paris, Grande Voie des Vignes, 92295 Chatenay_Malabry

Abstract: To study the strategies of injecting fuels through different stages, a laboratory scaled combustor has been developed and runs at atmospheric pressure with dodecane as fuel. The fuel is injected through two co-swirling stages. The first, using a hollow-cone pressurized nozzle with 15% of air massflow rate is called the pilot stage. The second stage consists of a swirler in which 85% of the air flows and fuel is injected through 10 equally spaced holes of 0.3 mm diameter. Air is preheated at 433K and a typical air massflow rate of 43 g/s is used for the experiments. A staging parameter   is defined as being the ratio of the mass of fuel injected through the pilot stage to the overall mass of fuel.

In this research, the staging parameter is varied from low values (around =15%) to slightly higher values (up to =25%). At a specific moment, the flame has a sudden change in its shape, from lifted, stabilized in the chamber (figure 1) to V-shaped, stabilized inside the pilot (figure 2). The joint time-resolved measurements of Mie scattering of droplets and chemiluminescence images are used to understand the fine structure of the spray and the flame during the transition event. This transition happens in two steps: the flame first attaches to the injector and then widens into a V shape. The second step can happen a few seconds after the first one and the flame then remains in a tulip-like shape before widening. Synchronized time-resolved optical diagnostics allow for a precise monitoring of the flame and spray behaviour during the transition event and the metastable tulip state.

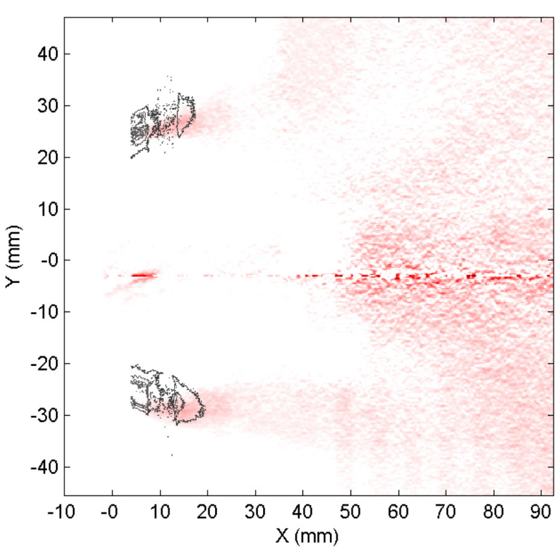

Figure 1. Abel-inverted CH* chemiluminescence and contours of Mie scattering intensity in the lifted state

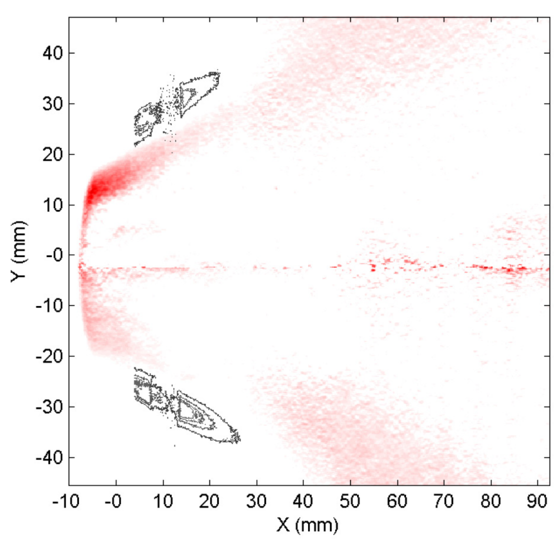

Figure 2. Abel-inverted CH* chemiluminescence and contours of Mie scattering intensity in the V state

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Combined measurements of velocity and soot volume fraction fields in a turbulent jet flame

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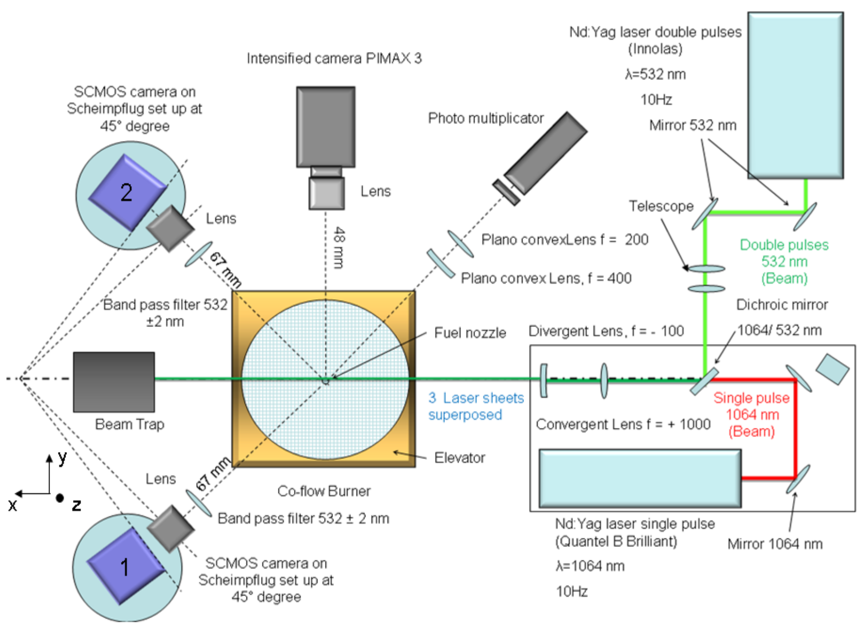
Abstract: The aim of this study is to develop advanced image-based diagnostics in sooting flames. Simultaneous combined velocity and soot volume fraction fields measurements in turbulent sooting flames are reported. Stereoscopic particle Image velocimetry (SPIV) technique has been combined with instantaneous laser-induced incandescence (LII) measurements in several turbulent sooting flames. To this aim, different strategies were applied to reduce the natural or laser-induced emission due to soot particles and PAH present in the flames. The combination capability of SPIV and LII techniques is validated on a model burner which consists of a circular nozzle of 3 mm inner diameter from which the fuel emerges. The fuel jet is surrounded by co-annular dry air flow of 400 mm in diameter in order to provide a homogeneous and controlled co-flow oxidizer. Four fuel mixtures of ethylene and methane have been considered in order to vary the soot concentration.

The PIV diagnostic associates two high-resolution sCMOS cameras (Lavision) to a double pulse Nd-Yag laser at 532 nm. The LII is performed at 1064 nm from a single pulse Nd-YAG laser and the LII signal is collected by an intensified camera (Roper Scientific - PIMAX 3) (Figure).



SPIV/LII Experimental optical set up

Statistical investigation is currently under investigation to determine the correlation between soot formation areas and the turbulent flow in the different flames. These combined data are very useful for a better understanding of soot formation in turbulent flames.

Optical Diagnostics in Sooting Flames

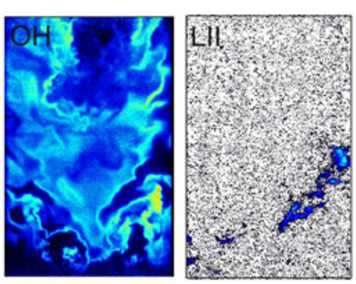
Klaus Peter Geigle, William O'Loughlin, Markus Köhler, Michael Stöhr

German Aerospace Center (DLR), Institute of Combustion Technology, Stuttgart, Germany

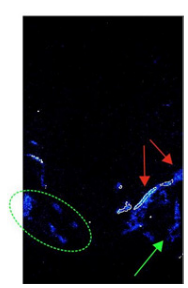
Abstract: Soot formation and oxidation in technical flames is still not fully understood. For improved understanding and to provide data for soot model validation we designed a burner exhibiting technical features as high turbulence, swirl and pressure. In addition, the combustion chamber enables the injection of additional air after two thirds of the flame height, mimicking cooling air as used in aero-engines or a lean combustion stage. The combustion chamber provides good optical access and is mounted into a pressure housing for operation up to 5 bars. The flames were operated with ethylene with thermal loads up to approximately 65 kW at different equivalence ratios, pressures or oxidation air flow rates. Laser-induced incandescence (LII) was applied separately for quantification and simultaneously with either OH planar laser-induced fluorescence (PLIF) or PAH PLIF. This allows for the spatial correlation of soot clouds to the region of the primary reaction zone or to its direct precursors. In addition, examples are shown for temperature histograms for two selected flames and a representative image pair of a recently acquired stereo PIV/LII combination.

Soot clouds typically exhibit strong gradients, appear very localized and unconnected and have a very intermittent behavior. Small soot filaments are mostly present in the conically shaped shear layer between inflowing fresh gases and the inner recirculation zone (irz) where hot exhaust gases and unburnt hydrocarbons are transported upstream towards the flame root. Soot is also visible inside the central part of the irz and downstream of it if no oxidation air is used. The main flame front, represented by steep OH signal gradients, occurs low in the flame and is strongly wrinkled. Contrary to the connected OH distributions present in the instantaneous images, PAH events have shapes more similar to the soot signatures, and are separated from each other. PAH either show up adjacent to soot or clearly separated from the closest soot structure; in the latter case soot is most probably formed elsewhere prior to being transported to the imaging plane.

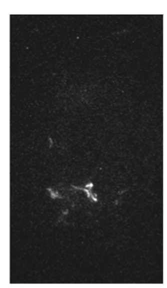
While OH is mainly present close to the fresh gas inflow for the studied rich flames without additional oxidation air, wrinkled OH signatures appear in the central and upper irz when oxidation air is switched on. Apparently, the oxidative influence reaches from the injection position significantly upstream, i.e. into the irz; the added oxygen directly reacts with the unburnt hydrocarbons which otherwise would lead to soot formation close to the above-mentioned shear layer and the irz. Consequently, flames with oxidation air do not show any soot in the central part of the irz. While the downstream portion of the inner recirculation zone is characterized by always hot temperatures (mean of 2000 K), the temperature drops exhibiting a wide distribution when oxidation air is added. Further insight is expected once the joint PIV/LII experiments are analysed.



OH-PLIF/LII image pair for rich flame with oxidation air. Signatures behave complementary, soot fits into gaps left in OH distribution.

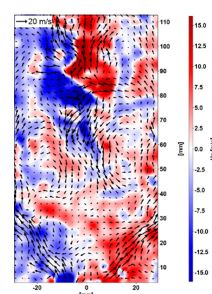


PAH PLIF in same flame; soot is labeled by isolines. PAH can occur either separated (green) or linked to soot (red).



LII image in intermediately rich flame

Raw image of PIV first pulse of top CCD camera.



3D velocity field. Color is indicative for out-of-plane-motion.

Particle image velocimetry measurements in highly luminescent flames

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Abstract: This contribution describes recent efforts leading toward the successful application of particle image velocimetry (PIV) in highly luminescent flames avoiding saturation of the second frame of commonly available double shutter PIV cameras, which is usually inevitable when using their interline-transfer CCD sensors. In order to characterize the performance of modern aero engine combustors in correlation with emissions data, laser optical diagnostics are extensively utilized in specifically designed pressurized test rigs with good optical access. While spectroscopic techniques provide information on fuel placement, reaction zone, temperature field among other quantities, flow field data is of equal importance in providing insight into the convective transport of reactants and their products. The method of choice in providing this flow field data is PIV. But the successful application of PIV in pressurized combustion imposes a variety of challenges. Among these, strong flame luminescence - mainly stemming from localized soot production and burn-off - cannot be sufficiently suppressed with narrow banded laser line filters and result in the saturation of the second frame of commonly available double shutter PIV cameras. A useable solution to this problem is a dual sensor setup as shown in Figure 1 splitting the optical path with a beamsplitter cube. By exposing each sensor separately in the sub-microsecond range saturation due to flame luminosity can be sufficiently reduced to allow reliable measurement in pressurized combustion. Several different swirl burners were investigated; each mounted inside pressurized single sector combustors (SSC), which are designed for the optical investigation of aero-engine combustors operating at realistic (flight relevant) conditions (Fig. 2).

Because of the beam splitter configuration and mechanical tolerances in the camera module along with the presence of a beam splitter in the optical setup necessitate an inter-sensor offset correction. After several iterations procedures for proper in-situ offset corrections could be established and ultimately allowed successful PIV measurements in highly luminescent environments.

Fig. 3 shows representative image obtained in the flow field of a pressurized combustion chamber with a swirl nozzle located near the middle on the lower edge and mean flow propagating from bottom to top. Exposure time of the sensor is 500ns while the laser light pulse has a duration of ~5ns. The image is characterized by four types of light scattering: (1) from the glass liner walls left on the left and right edges, (2) Mie scattering by the dense fuel spray immediately downstream of the fuel nozzle, (3) Mie scattering by the inert seed particles (1 µm porous silica spheres) and (4) Rayleigh scattering by soot particles in the fuel rich combustion zones. Due to their fine structure the soot patches serve as flow markers and be tracked with conventional PIV processing algorithms. The comparison of "flow" fields obtained with and without particles revealed that the soot patches do not adversely affect the velocity estimates provided by the seeding particles. Soot tracking therefore is a promising alternative when the particle image signal is lost in flows with higher soot fractions.

Figure 1: Dual sensor PIV camera system with a large aperture medium format lens and remote focusing

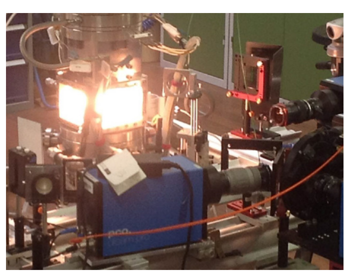

Figure 2: Pressurized single sector combustor operating at "moderate" fuel loading conditions

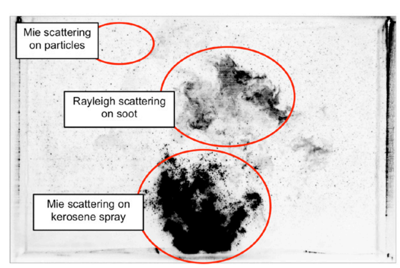

Figure 3: Single recording of the reacting flow field downstream of a kerosene swirl atomizer located at the bottom center at ~7 bar plenum pressure, CCD sensor exposure: 500 ns.

Multi-parameter high-speed laser diagnostics for simultaneous mixture fraction, flow field, and flame-front imaging in a gas turbine model combustor

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Abstract: Laser-based imaging techniques in combustion with frame rates in the kHz range have developed rapidly in recent years. Especially simultaneous measurements of multiple quantities, for example by the combination of planar laser-induced fluorescence (PLIF) of OH with particle image velocimetry (PIV), have broadened the insight into various combustion processes.

In this study, the dynamic processes in a gas turbine model combustor were studied by the simultaneous application of fuel tracer (acetone) and OH PLIF excited with a single dye laser and PIV at 10 kHz repetition rate. Of particular interest was the unsteady interaction of flow, fuel/air mixing and reaction. Fuel transport and mixing were visualized by adding 9 volume-% of acetone to the fuel flow. A very good tracer fluorescence yield has been achieved with this acetone seeding level. It was verified that the addition of acetone did not influence the flame characteristics. The dominant unsteady flow structure in the flow was a so-called precessing vortex core (PVC). The measurements clearly revealed, for instance, the influence of this helical flow instability on the fuel distribution. The PVC periodically passed through a region of largely unmixed air and fuel and caused a strong mixing. This zone of well-mixed fuel and air was then ignited by recirculated hot exhaust gas.

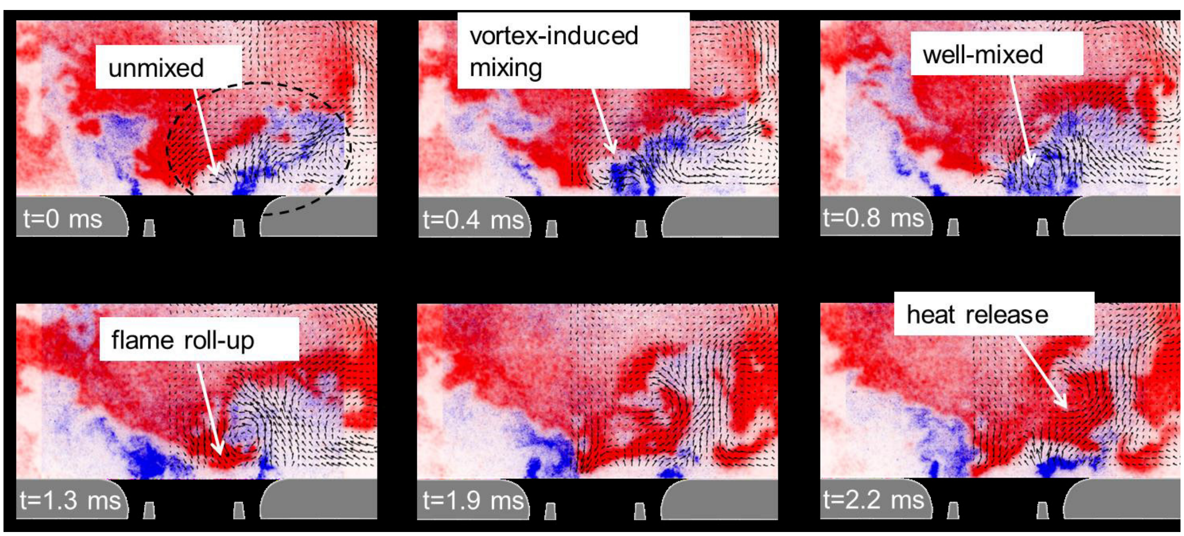

Fig.1: Vortex-Flame-Interaction and impact on the mixing: Fuel (blue) is mixed by a vortex with fresh air and transported to the flame root (represented by the interface of OH (red) with the inflow).

Towards Volumetric Imaging Diagnostics in Turbulent Combustion

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Technische Universität Darmstadt

Abstract: Worldwide consumption of petroleum-based fossil fuels and increasingly stringent emission regulations continue to motivate combustion scientists to improve fuel economy and reduce emission production within practical combustion systems. Laser-based diagnostics in combustion provide in-situ, non-intrusive measurements in practical combustion systems at high-spatial and temporal resolution. Sophisticated, well-designed diagnostics are capable to resolve details of the leading scalar and vector properties to investigate the mutual sub-processes in combustion. Emerging trends in the advancement of diagnostic equipment has allowed the possibility to measure transient, multi-component, and volumetric information within combustion systems of increasing complexity. The focus of the current research is to present some of the leading advancements in diagnostics within combustion systems. The first topic discussed is the development and application of tomographic particle image velocimetry (TPIV) within a turbulent lifted jet flame to measure the turbulent-chemistry coupling within a volumetric domain. The second topic presented focuses on the development of simultaneous dual-plane OH-LIF, stereoscopic PIV within an optical engine to resolve the 3D flame propagation within an optically accessible single-cylinder spark-ignition engine.

Details of the tomographic PIV setup are recognized in Weinkauff et al. (2013) *Exp. Fluids 54(12), 1-5*. The presentation focused on the peculiarities of TPIV within a flame environment. Particularly, the flame causes a local variant refractive index and beam steering, which can have large implications on particle reconstruction. Pixel disparity is the triangular offset of particles evaluated in sub-volumes to identify an individual particle for each detection system. Utilizing a volume self-calibration procedure to correct for image misalignment and distortion, the disparity level within the turbulent flame was less than 0.2 pixels, which was within the acceptable disparity limit of 0.4 pixels. Compared to the isothermal flow, the disparity level was 0.1 pixels greater, but showed great agreement when performing the volume self-calibration procedure for each individual dataset. Example images of the volumetric flow within the turbulent flame (shown in fig. 1) were presented and an outlook was given for future investigations of TPIV within several flame environments.

Details of the dual-plane OH-LIF, SPIV measurements were modeled after Trunk et al. (2013) *Proc. Combust. Inst. 34 3565-3572*. Measurements were performed in the engine as the engine operated at 800 RPM with stoichiometric isooctane-air mixtures. Images were acquired five crank-angle degrees after the onset of spark when less than 5% of the mixture was consumed. Measurements revealed individual contributions of local flow velocity and flame displacement speed on the overall transport of the flame surface and summarized the complex nature of flame development in engines.

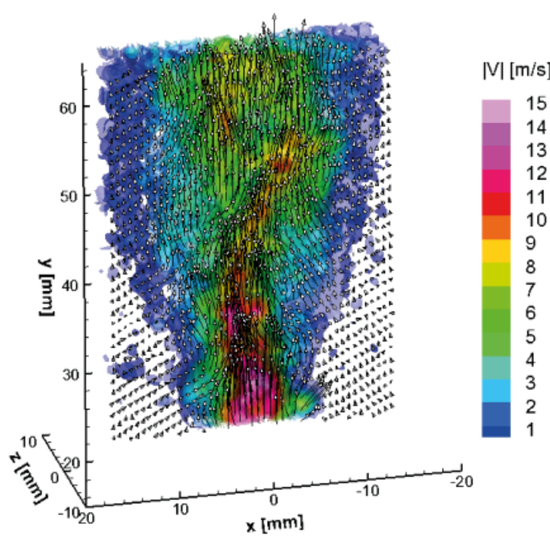

Figure 1: Instantaneous image of volumetric flow in a lifted jet flame from TPIV.

Application of tomographic PIV to a lifted propane/air flame

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Abstract: The influence of combustion on properties and dynamics of large-scale vortices below the lifted flame base and above is the aim of the present work. High-repetition tomographic PIV system is applied to study large-scale vortices in a non-reacting jet flow and lifted propane/air flame (the same configuration as in Abdurakipov et al. 2013). The nozzle diameter is 15 mm, bulk velocity of the air flow is 5 m/s. The flow is seeded by 1 μm TiO_2 particles. In the reacting flow, the fuel-rich mixture with equivalence ratio of 2.5 issued from the nozzle with the bulk velocity of 5.6 m/s. The flow with combustion represents several difficulties for tomographic PIV experiment such as non-uniform tracer particles concentration in space and soot luminosity, which reduces signal-to-noise ratio. It is concluded that tomographic PIV measurements can be fulfilled in the reacting gas flow by using a common configuration for high-repetition PIV systems (CMOS sensor, 10 mJ per laser pulse for the laser sheet with 6 mm thickness). The examples of subsequent 3D velocity snapshots obtained by tomographic PIV are presented in Figure below. The snapshots demonstrate that typical distance between the rolling-up vortices (below the flame onset) in the reacting flow is considerably shorter than in the non-reacting jet. The important feature seen from the snapshots is that the vortices in jet flow interact with each other with formation of smaller eddies, whereas in the reacting flow there is no interaction above the flame (in the domain considered), because their convection speed is increased by combustion.

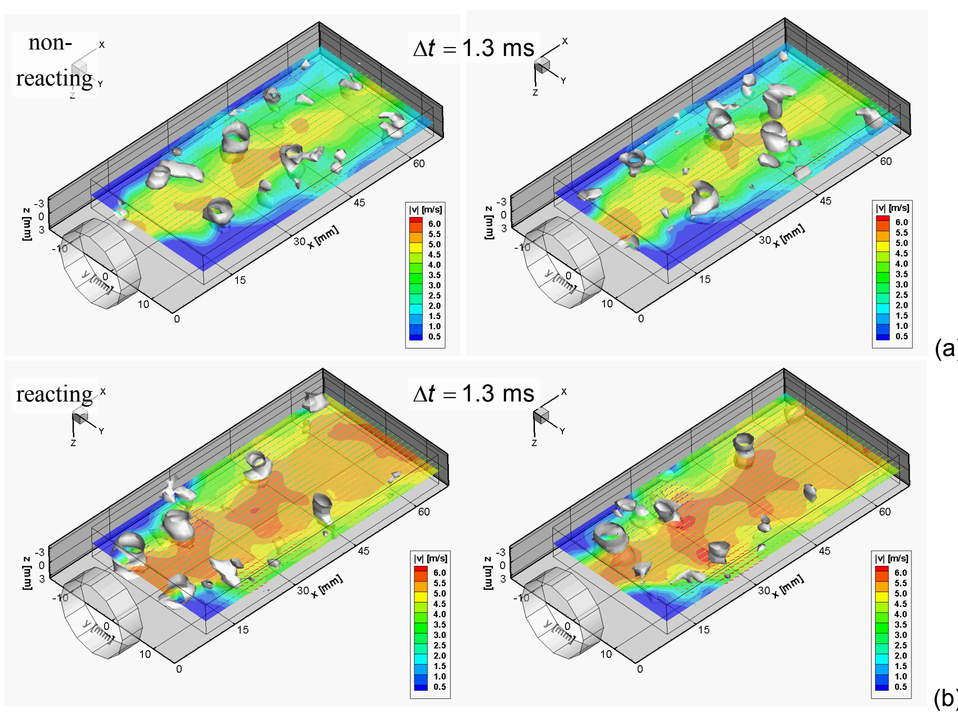

Figure - Subsequent snapshots of the instantaneous 3D velocity fields measured by Tomographic PIV for (a) non-reacting jet flow and (b) lifted propane/air flame. Velocity vectors and their magnitude are visualised for the central plane. The flame stabilisation height is about 20 mm

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Abdurakipov S.S., Dulin V.M., Markovich D.M., Hanjalic K. Expanding the stability range of a lifted propane flame by resonant acoustic excitation // Combustion Science and Technology 2013, published online DOI:10.1080/00102202.2013.828052

Analysis of flow instabilities in a model swirl combustor from PIV data

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Abstract: Thermo-acoustic instabilities in flames limit applicability of lean combustion technology for gas turbines. Nowadays time-resolved planar measurement techniques (such as PIV and PLIF) are used to investigate this phenomena. Phase-resolved analysis of oscillations is an often used approach to analyze unsteady 3D combustion. Moreover, response of swirling flames to external perturbations is of an interest to develop control strategies for combusting systems in confined geometries. In the present paper we report on performance of linear algebra tools, viz., POD and recently developed DMD (Schmid, 2010), to provide low-order models of reacting swirling flow dynamics from high-repetition PIV data. Lean methane/air swirling flames in a combustion chamber (open at the top) are the subjects of the study. High-repetition stereoscopic PIV measurements were carried out for the reacting and non-reacting flows. The study covers two typical swirl rates: low and high rates. A pronounced vortex breakdown takes place for the latter case with formation of a central recirculation zone and self-excited oscillations corresponding to precession of the swirling flow. In the former case, there is no global mode of flow precession, thereby allowing nearly axisymmetric oscillations in the corner recirculation zone. As can be seen from the time-averaged CH* images in the Figure below, both swirl configurations provide compact combustion zone. Besides, lean blow-off limits are quite similar for these flames. Noteworthy that at the same time, reverse flow in the case of low swirl is rather weak and appears to have a minor effect in stabilisation process.

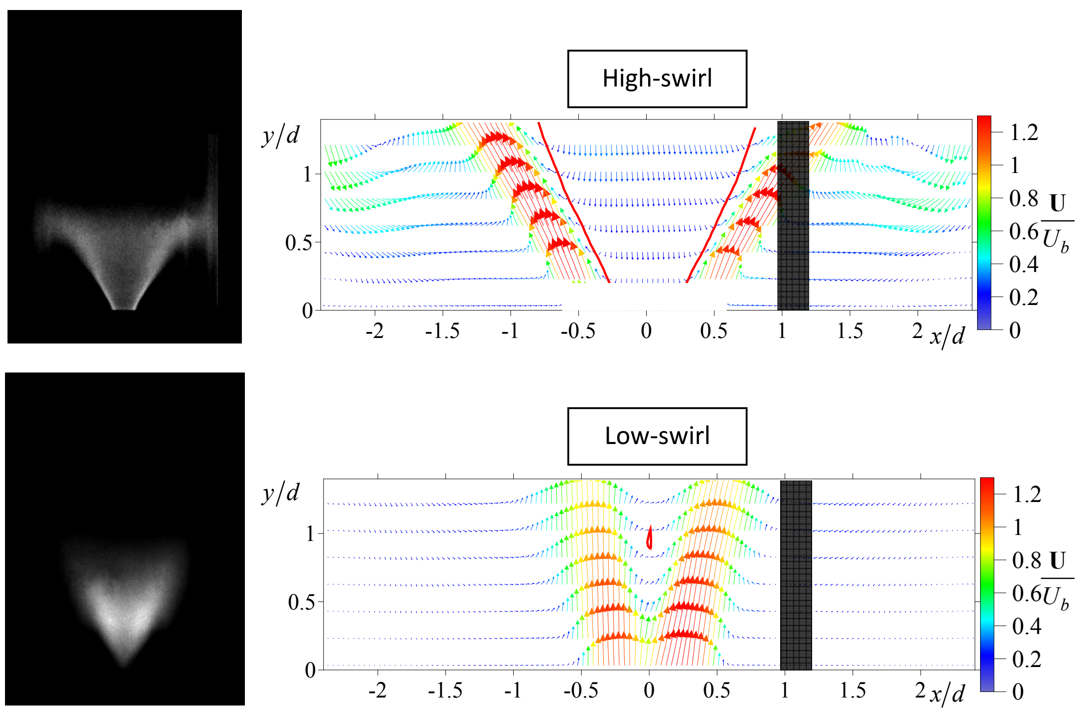

Figure - Time-averaged CH* chemiluminescence and velocity fields for (top) high- and (bottom) low-swirl fames. Diameter of the swirling nozzle outlet *d* is 15 mm, and the bulk velocity U_b of the methane/air mixture with equivalence ratio of 0.6 is 5 m/s

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Investigation of the dynamics of spray combustion using high-speed Mie scattering images

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Abstract To study the strategies of injecting fuels through different stages, a laboratory scaled combustor has been developed and runs at atmospheric pressure with dodecane as fuel [1,2]. In previous research, a helicoidal structure was found to exist in the combustion chamber and the dynamics of the spray and the flame was seen to change strongly with respect to this structure (see figure 1). One can see that positive fluctuations of Mie scattering are leading to positive fluctuations of fluorescence of the OH molecule. The space between the two quantities correspond to the gaseous fuel vapor.

This presentation focusses on the quantification of velocities of dodecane droplets. Whereas the final target is to have a complete description of the aerodynamic and combustion interactions, having access to the velocities of droplets will provide a better description of the helicoidal structure that exists in the combustor and the interaction between this structure, the spray and the flame stabilization mechanism. The measurements based on Mie scattering images will be used to evaluate those velocities. The true aerodynamic velocity field will be slightly different from the field obtained through droplets due to different Stokes number effects.

Different algorithms for the evaluation of Mie scattering data have been used and compared with PDA data at a distance corresponding to 15 mm from the entrance of the combustion chamber. Results obtained showed that conventional PIV based algorithms cannot catch the complete dynamics of the spray by about 20% in the absolute velocity as compared to PDA. Different algorithms, like optical flow approaches [3,4] showed a slightly different tendency. Whereas they could well capture the main velocity area, they failed in getting properly the recirculation zone (see figure 2(a)). This comes from the evaporation of droplets that lead to a very low signal. As far as transverse velocities are concerned, none of the imaging technique were able to catch the gradients as obtained by PDA (see figure 2(b)). A possible strategy to improve the results in the transverse velocity is to use a bigger time interval between two images, provided the droplets stay within the laser light sheet. In the future, the different algorithms tested will be used also in transverse planes and comparisons will be performed with PDA data. Finally, the best measurement strategy based on Mie scattering images will be proposed, certainly a joint cross-correlation / optical flow analysis.

Dynamic Mode Decomposition [5] is used with a combination of both the two components of the velocity and the Mie scattering intensity in the same matrix. This allows highlighting the interaction that exist between those two quantities as for some conditions, only the full matrix DMD lead to the description of an instability whereas only a DMD based on velocity or on Mie scattering intensities only did not lead to a specific mode.

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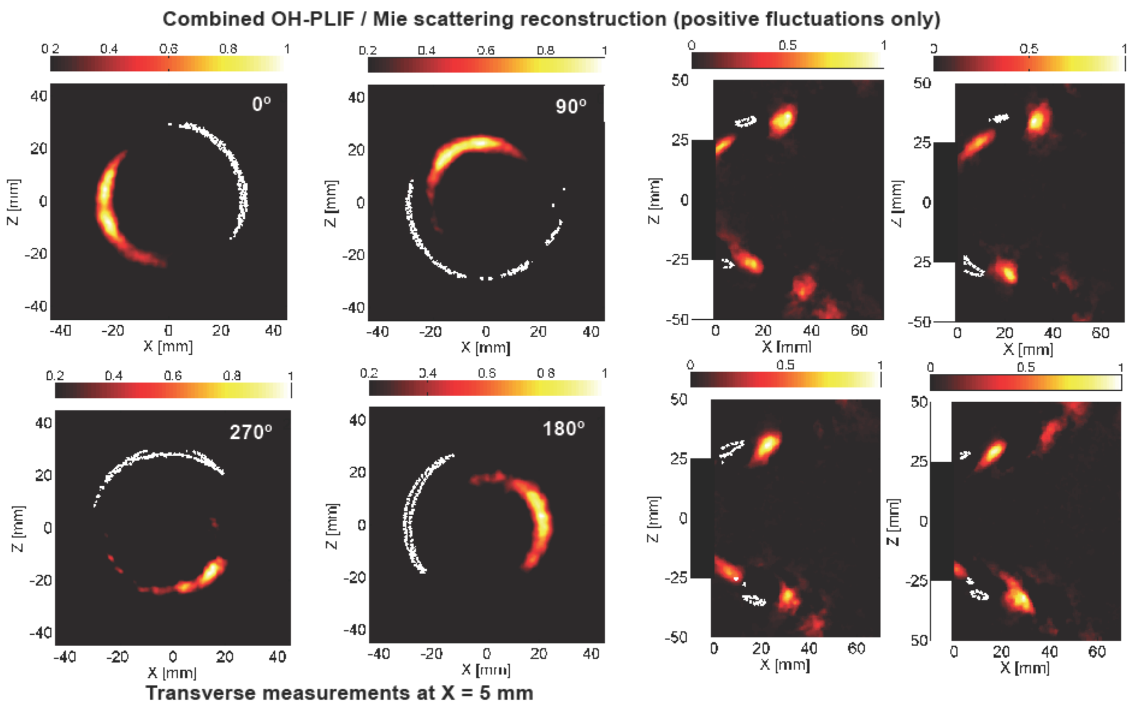

Figure 1. Influence of the helicoidal structure on the spray and on the flame dynamics

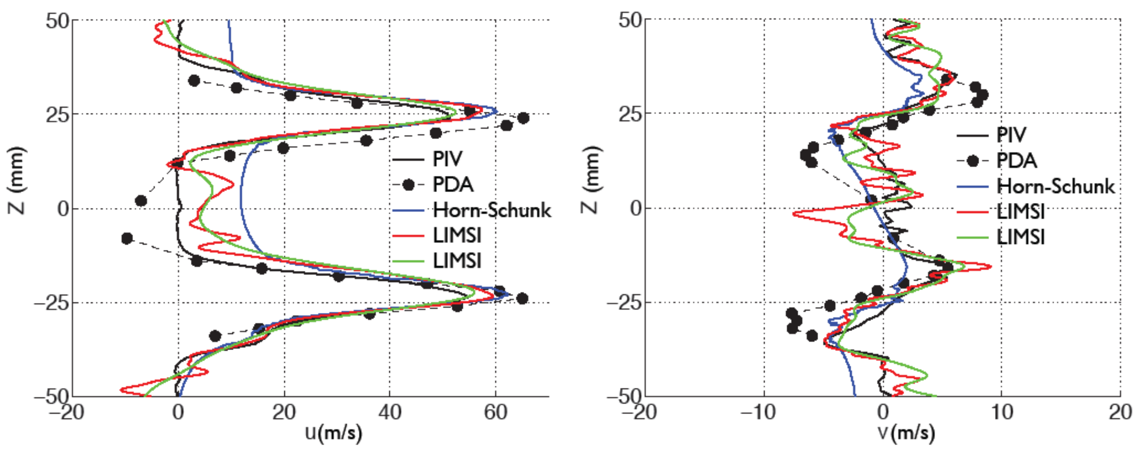

Figure 2. Comparisons between the different methods for the velocity measurements. Profiles extracted 15 mm from the exit of the swirler.

High resolution PIV technique in vicinity of reactive zones : Application to stratified combustion

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In the paper, a new experimental approach using PIV technique to measure the local instantaneous laminar burning velocity of a stretched premixed flame is presented. Up to now, from experimental techniques, this physical property was only accessible in average and the instantaneous interactions of flame with flow structures, mixture variations and walls could not be considered. In the present work, the local burning velocity is measured as the difference between the local flame speed and the local fresh gas velocity at the entrance of the flame zone. Two original methods are proposed to deduce these quantities from pair of particle images. The local flame speed is measured from the distance between two successive flame positions. For the flame localization, a new extraction tool combined with a filtering technique is proposed to access to the flame front coordinates with sub-pixel accuracy. The local fresh gas velocity near the flame front is extracted from the maximum of the normal velocity profile, located within 1 mm ahead of the flame front. To achieve the required spatial resolution, a new algorithm based on adaptive interrogation window scheme has been developed by taking into account the flow and flame front topologies.

The accuracy and reliability of our developments have been evaluated from the well-established configuration of outwardly propagating spherical flames [1] and used to investigate the propagation of laminar flame in stratified mixtures [2].

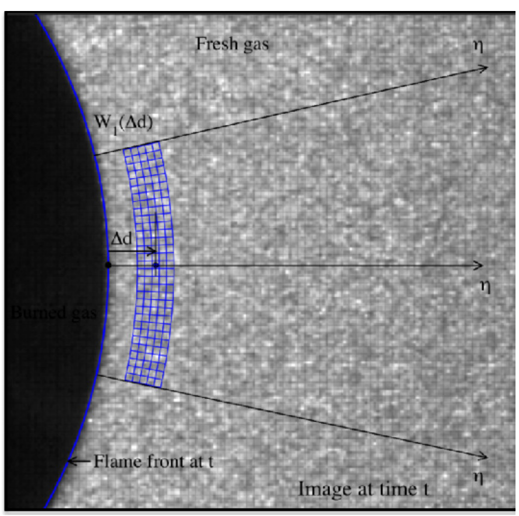

Fig. 1: Principle of measuring the fresh gas velocity near preheat zone of flame front from a stretched interogation window

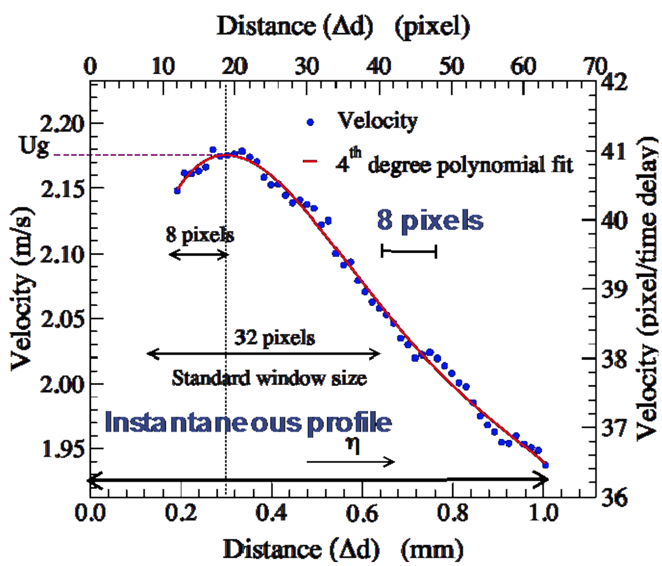

Fig. 2: Instantaneous profile of the normal component of fresh gas velocity in the first mm ahead the flame front

[1] Direct measurement of local instantaneous laminar burning velocity by a new PIV algorithm - Balusamy, S.; Cessou, A. & Lecordier, B. (2011) - *Experiments in Fluids* **50**, 1109-1121.2

[2] Laminar propagation of lean premixed flames ignited in stratified mixture - Balusamy, S.; Cessou, A. & Lecordier, B. (2013), *Combustion and Flame (In Press)*