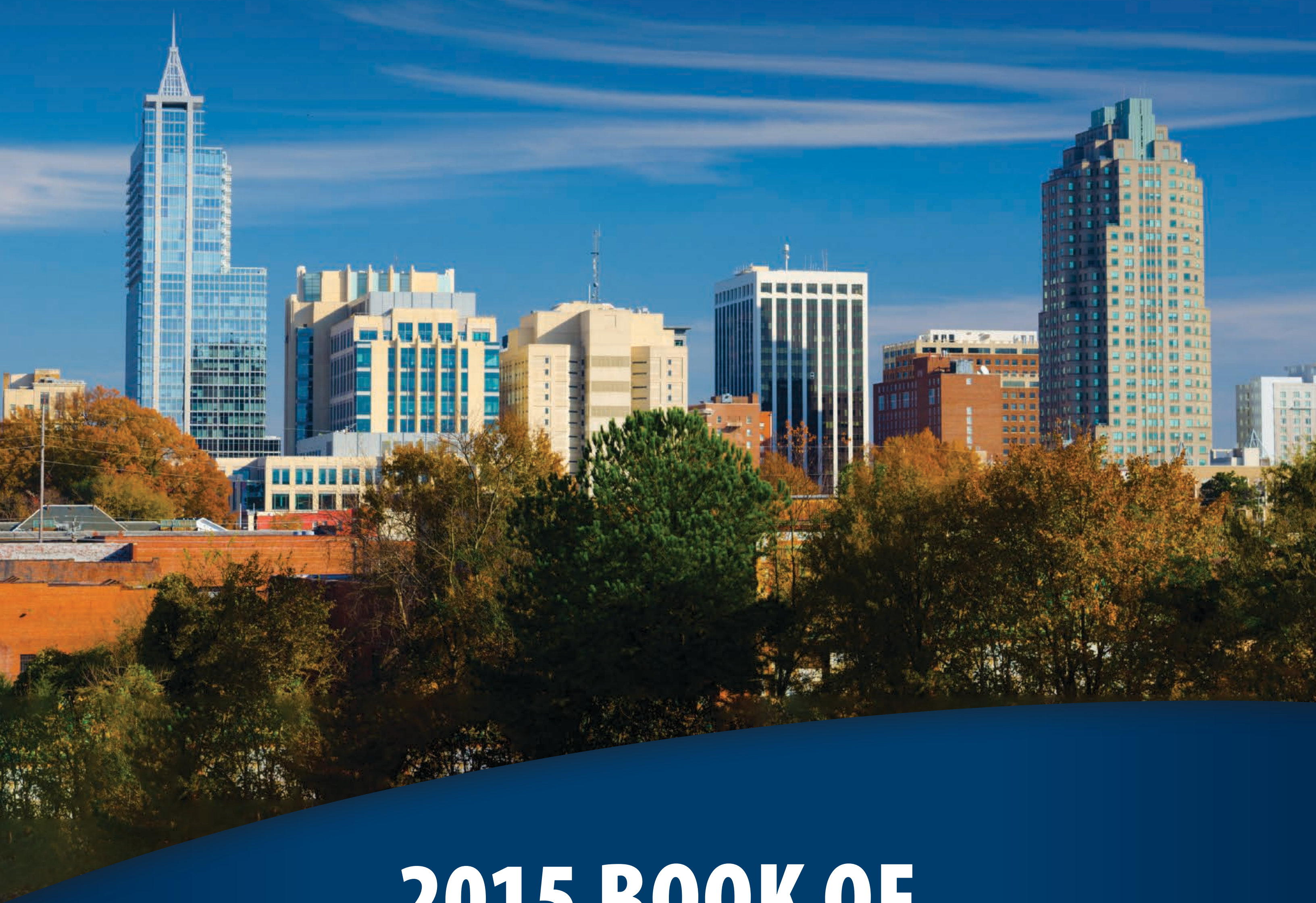
ILASS-Americas

Institute for Liquid Atomization and Spray Systems

27TH ANNUAL CONFERENCE



2015 BOOK OF ABSTRACTS

May 17 - 21, 2015 | Raleigh, NC

Sheraton Raleigh Hotel

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ILASS-Americas

Institute for Liquid Atomization and Spray Systems

ILASS-Americas

Institute for Liquid Atomization and Spray Systems

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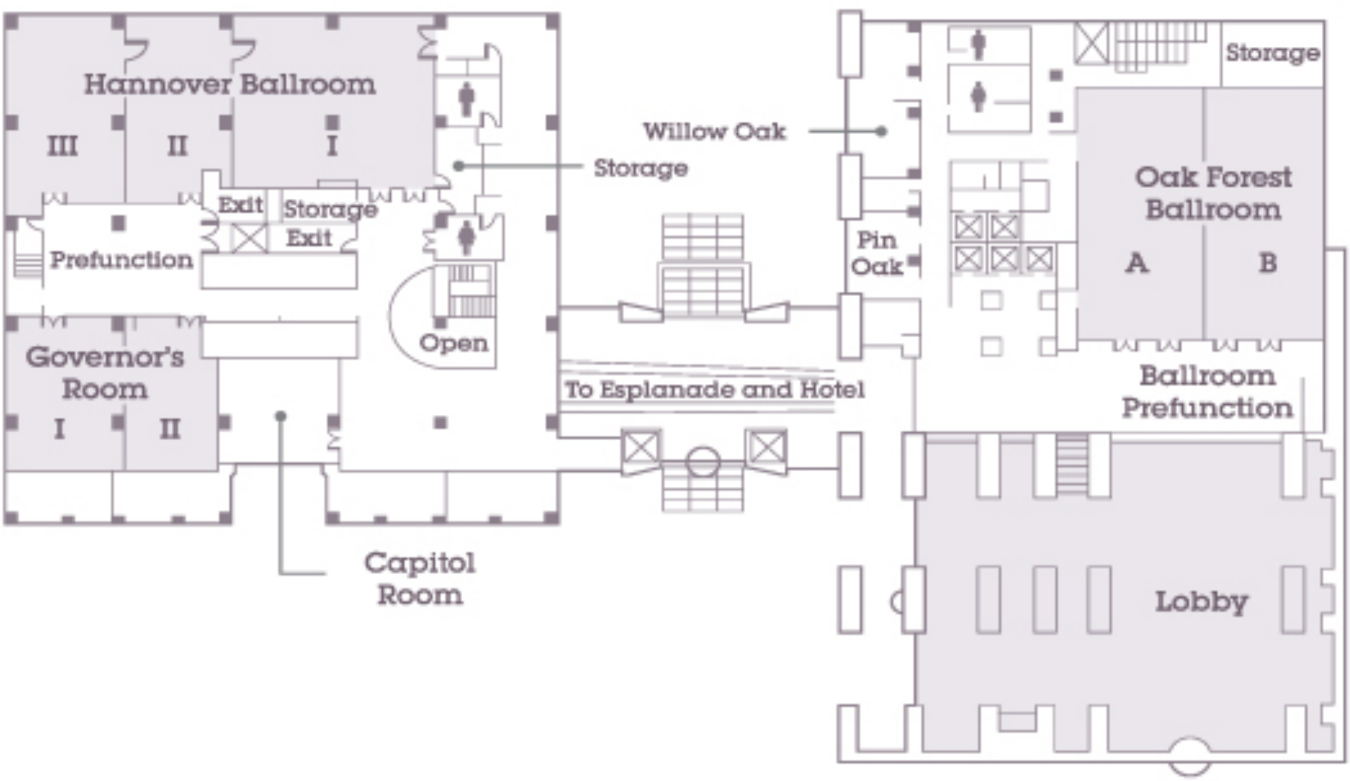
Conference Map

Exhibitors Room	Hanover Foyer
Welcome Reception	Hanover Foyer
Breakfast	Hanover Foyer
Keynote Presentation Room	Oak Forest A
Presentation Rooms	Oak Forest A & Governor's Room
Technical Committee Meetings	Oak Forest A & Governor's Room
Lunch	Oak Forest B



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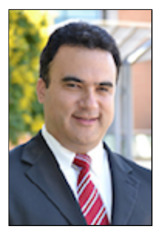

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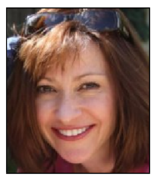

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ILASS-Americas
Institute for Liquid Atomization and Spray Systems

27th Annual Conference on Liquid Atomization and Spray Systems

ILASS 2015 is the 27th Annual Conference for North and South America. This conference, like its predecessors, provides a venue to meet and share recent developments in the field of atomization. Industrialists, researchers, academics, and students meet to discuss a variety of topics in areas including: theory, modeling, applications, and spray diagnostics. This year's conferences will feature a number of special sessions on focused topics.

Invited Sessions

- Spray & Liquid Breakup in Food Applications (Monday)
- 3D Imaging of Sprays
- Liquid Jets & Sprays in Crossflow
- Internal Nozzle Flow Modeling

General Topic Areas

- Instrumentation related to spray measurement including droplet size, velocity, impact, concentration, and patternation as well as film thickness, vapor concentration, and other parameters.
- Modeling of flow phenomena both inside and outside atomizers
- Design, operation, and performance of atomizers and spray systems
- Processes in which sprays are used such as spray reactors, spray dryers, humidifiers, spray coating, combustion, fire fighting, agricultural applications, medical applications, spray formations, and metal powder production.

Technical sessions at which state-of-the-art research, methods, and diagnostics are presented.

Manufacturer's exhibits showcasing the latest relevant instrumentation and hardware in the field.

Technical committees providing directed open discussions in areas of interest. All conference attendees are encouraged to attend.

Program Notes and Special Events

Registration will take place from 4-7 pm on Sunday in the Hanover Foyer

A Welcome Reception will take place from 6-7 pm on Sunday in the Hanover Room

A Panel Discussion on *Industrial Spray Applications: Critical Issues and Opportunities* will held Sunday evening after the welcome reception in the Governor's Room.

Exhibitors' Displays can be found from Sunday through Wednesday in the Hanover Room

Breakfast (Continental) will be served every morning from 7-7:45 am in the Hanover Room

Lunch will be served in Oak Forest B

The ILASS-Americas Annual Business Meeting will be held during lunch on Tuesday in Oak Forest B

Technical Committee Meetings will be held on Tuesday afternoon in Oak Forest A, Oak Forest B, and the Governor's Room. Conference attendees are strongly encouraged to join the technical committee discussions that math their interests. The meetings are open to all conference participants.

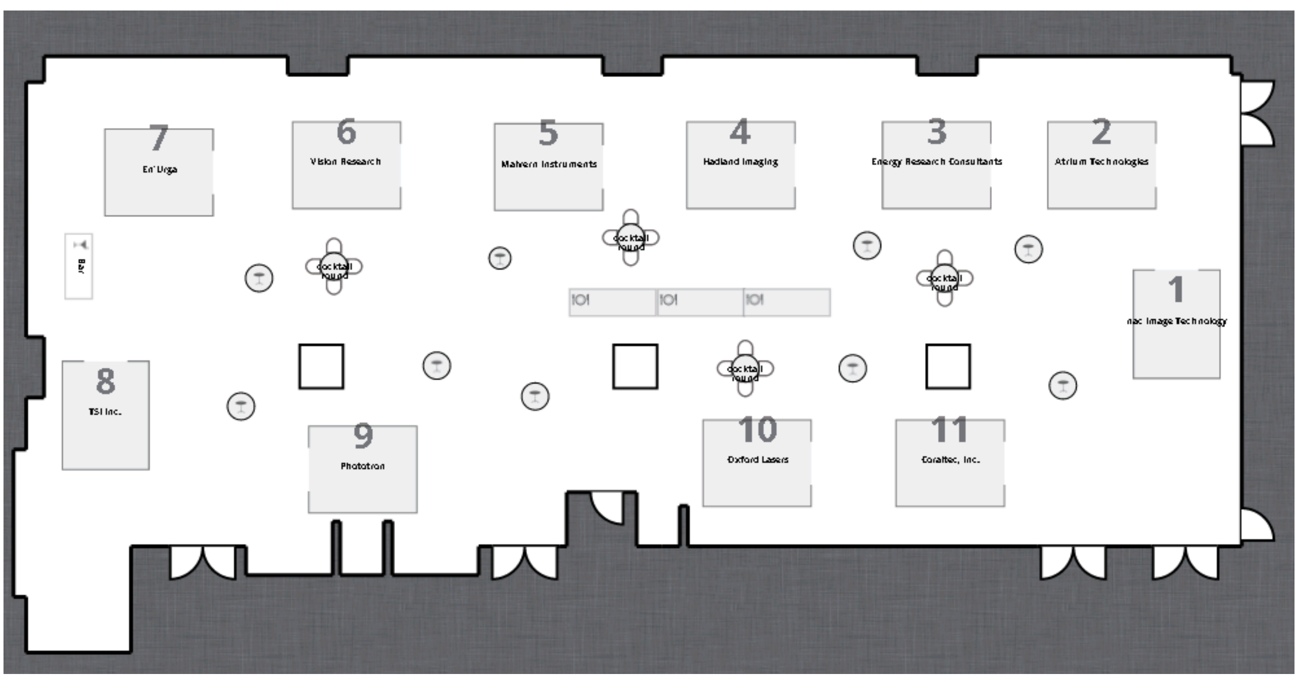
ILASS Service Awards will be presented at lunch on Tuesday in Oak Forest B. The Simmons Award and the Marshall Award will be presented for the best paper and best student paper from the previous year's ILASS-Americas conference.

Program changes will be announced every morning, posted at the Registration Desk, and noted on the schedule poster outside each presentation room.

Paper numbers & links are provided on each abstract page of the ILASS 2015 Book. When the link is selected from the PDF located on the media drive, these links will auto-open the respective paper from the media drive.

Exhibitors

There are eleven exhibitors at this year's conference. They offer an array of diagnostic instrumentation, services, and equipment. Specific details are outlined on the following profiles from each exhibitor. The exhibitors at this year's conference are:



470 Lakeside Drive, Unit C
Sunnyvale, CA 94085

Artium specializes in developing and manufacturing advanced particle characterization instruments for the spray community. We offer a broad range of instruments for measuring sprays, clouds, and aerosol droplets. Our **Phase Doppler Interferometry (PDI)** instruments are based on the light scattering interferometry principle which was **invented and developed by our scientists**. This technology has been developed and evaluated over the past 30 years and is acknowledged as the most reliable and accurate means for characterizing spray and aerosol droplet dynamics. Our goal over the past 15 years has been to further refine the method and its implementation to insure greater measurement reliability and accuracy while making the instruments much easier to use.

System automation (US Patent 7,564,564) has been one of our key goals. We have introduced advanced methods and algorithms **(US Patent 7,788,067)** to minimize the possibility for user setup errors even for the most complex measurement tasks**.** Advanced modern electronics and computers coupled with **software utilizing innovative signal processing algorithms** and validation strategies have resulted in significantly improved instrument performance even under the most difficult measurement conditions.

Our **newly developed flight probes designed for atmospheric cloud monitoring and aircraft icing research** have undergone significant testing in the field. Our flight probes are being flown by the **U.S. Navy CIRPAS** for their cloud research program and have produced significant data on cloud properties. Testing at the **U.S. Air Force Eglin Air Force Base McKinley Climatic Laboratory**, General Electric's aircraft engine icing facility, and in the **NASA Glenn Research Center Icing Research Tunnel (IRT)** proved our instruments are capable of making reliable and accurate measurements in these challenging environments.

Under our **U.S. Army SBIR Ph II program**, we developed PDI and high speed imaging (**HSI**) systems for helicopter icing research. The probes have been successfully tested on a **UH60 Black Hawk Helicopter** under the U.S. Army's helicopter icing research program. The high speed imaging (HSI) probe characterizes non-spherical particles (deformed droplets and mixed phase conditions). We have also developed a line of **TurnKey (TK)** systems, an integrated PDI probe suitable for in-spray use. Artium's other products include the LDV and Laser Induced Incandescence (LII) which is used for measuring soot (black carbon) emission from engine exhaust and in ambient air.

<u>**Contact Information**</u>
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CoralTec INC.

CoralTec Inc.

D30 line of spray sizers are developed, designed and manufactured by Coraltec Inc.

Coraltec Inc. was established with the vision to develop novel devices in the spray and nozzles industry. The company aims to serve the industry by developing and manufacturing diagnostics and testing devices for the industry as well as the academia and research centers.

The company is formed by a group of seasoned people in industry and international business along with highly qualified scientists and engineers. We develop our products with active collaboration of university researchers and academic institutions.

The mission of the company is to develop and manufacture testing devices which are ***Accurate, Reliable, User Friendly, Portable*** and yet ***very Affordable***. It should address the need of industry and academia for an easy to deploy device which can be used for frequent testing under different conditions.

Coraltec Inc. is heavily engaged in research and development to further enhance its leading edge technology. Headquartered in Toronto, Canada, it has a strong collaborative relation with top research institutes and universities throughout North America such as University of Toronto which enables it to continuously optimize its products and the processes it employs.

WEBSITE: **WWW.CORALTECNIC.COM** / **WWW.SPRAYSIZER.COM**

En'Urga Inc.[©]

Innovations in Quality Control

En'Urga Inc.

Company Description

En'Urga Inc. is the industry leader in customized optical diagnostic equipment for the most challenging factory floor application. En'Urga Inc. has over 20 years experience in optical diagnostics research, serving many Fortune 50 companies and Federal Government agencies.

En'Urga Inc. provides testing and consulting services for combustors, spray nozzles, heat sinks, and other engine related components. We specialize in characterizing sprays (drop sizes, spray patterns, drop surface areas, velocities, mass fluxes, etc.) in ambient as well as high-pressure conditions. En'Urga Inc. has developed standardized test protocols for GDI injectors, urea dosers, consumer sprays, and paint sprays. These standardized test protocols ensure that the quality of the nozzle that are used in these applications confirm to the highest standards possible.

En'Urga Inc. has several products in their portfolio. Our latest product is the "***SETXvue Tomography System"***. The ***SETxvue Tomography System*** provides tomographic mapping using soft X-Rays for a wide range of applications including spray characterization and flame structure determination in the automotive and aerospace industry as well as mass flux determination of particulates in the food and pharmaceutical industry.

En'Urga also markets "***SETScan Optical Patternator***", "***SPIvel Velocimeter***" and "***Spectraline Imaging Spectromete****r*".

The ***SETScan Optical Patternator"*** can obtain distribution of droplets in sprays or particles in particulate laden flows at a frequency of 10,000 Hz. The optical patternator is used for 100% quality of audit of nozzles in a wide variety of industries ranging from Aerospace to consumer products. Unlike laser sheet imaging patternators, the SETscan optical patternator provides quantitative information on various aspects of the spray such as spray angles, plume angles, % split in plumes, deviation, pitch, roll, and yaw angles. The SETscan patternator also provides the planar drop surface area density, the most useful quantity for ranking the performance of injectors for combustion and nozzles for spray drying.

The ***SPIvel Velocimeter*** provides full planar axial and radial velocities from high speed images obtained with any of the commercially available high speed cameras.

The ***Spectraline Imaging Spectrometers*** provides visible spectra from 0.3 to 1.1 microns at 40 KHz, and infrared spectra from 1.3 to 4.8 microns at 1.32 KHz. These are the fastest spectrometers available in the market. The Spectrometers are used to determine temperature and species concentration profiles in high frequency turbulent flames. These spectrometers are available with a range of accessories to enable hyper-spectral imaging and flame emission tomography.

All of En'Urga products can be leased or purchased from En'Urga Inc. More information can be obtained from our website at **www.enurga.com. E**mail us at **info@enurga.com**.

Energy Research Consultants (ERC) was founded in 1990 to fulfill a need for application of state-of-the-art experimental and numerical modeling tools to problems associated with energy generation and use. Projects which require fast and confidential answers via advanced research tools which are not otherwise readily available are addressed through experienced personnel and a fully equipped research laboratory. In addition, on site work can be accommodated. Both experimental and numerical studies are conducted for clients that are addressing mission oriented, time critical projects.

ERC has extensive experience with a wide variety of fluid dynamic, combustion, and spray system applications. In particular, ERC maintains expertise in the characterization of non-reacting and reacting flows such as those found in automotive combustion chambers and exhaust after-treatment systems, as well as those found in gas and spray-fired gas turbine combustion systems and industrial processes. The expertise ranges from the basic science of sprays, combustion, turbulent transport, and diagnostics to practical configurations in the area of gaseous fuel injection, liquid-fuel atomization, swirl, pollutant formation and control, and fuel/air mixing.

Specialized measurement services are offered to both commercial and government clients. Available spray diagnostics include Phase Doppler Interferometry, Laser Diffraction, Planar Liquid Laser Induced Fluorescence (PLIF with continuous and pulsed lasers with intensified CCD cameras), planar and global OH* LIF, optical patternation, particle image velocity, tunable diode laser spectroscopy, and high speed visualization. ERC has extensive experience applying these methods to wide array of customer systems. Other capabilities include CFD modeling, test facility development, and test plan development and execution using statistically designed experimental methods.

In addition to measurement services, ERC has also developed standalone design tools (for example, Advanced Spray Injection Phenomena Simulator--ASIPS; Flame Response Sensitivity Tool—FRST) and image analysis tools (for example, Automated Feature Extraction and Analysis Tool—AFEAT). ERC has also developed other products such as specialized imaging systems for inspection inside high temperature environments as well as coating system and particulate quality control. Gaseous and liquid fired burners are also available.

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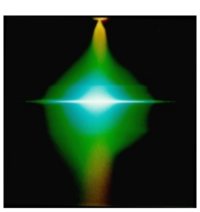
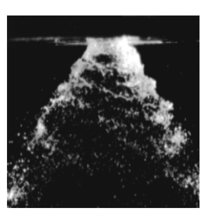


HADLAND IMAGING

CAMERAS • SYSTEMS • ACCESSORIES

Hadland Imaging is a High Speed Company in North America. We manufacture Intensifiers, Flight Followers and accessories, in addition to Representing Shimadzu HPVX, up to 10 mfps and Telops MWIR cameras, up to 90,000 fps. We also represent Xcitex post analysis software. We now have full sales/ service and support at our East and West Coast Offices. www.hadlandimaging.com

About Malvern Instruments

Malvern's materials and biophysical characterization technology and expertise enables scientists and engineers to investigate, understand, and control the properties of dispersed systems. From proteins and polymers in solution, particle and nanoparticle suspensions and emulsions, to sprays and aerosols, industrial bulk powders and high concentration slurries. Used at all stages of R&D and manufacturing, Malvern's instruments provide critical information that helps accelerate research and product development, enhance and maintain product quality and optimize process efficiency. They are used by industry and academia, in sectors ranging from pharmaceuticals and biopharmaceuticals to bulk chemicals, cement, plastics and polymers, energy and the environment. www.malvern.com

Material relationships

Spray particle and spray droplet size measurement

Incorporating over 35 years of experience in spray applications, Malvern Instrument's Spraytec laser diffraction system allows measurement of spray particle and spray droplet size distributions in real-time for more efficient product development of sprays and aerosols. It has been specifically designed to address the unique requirements for spray characterization and deliver robust, reproducible droplet size data. Spraytec:

- Measures across a wide size range (0.1 – 2000 microns) without requiring constant optics changes.
- Resolves rapid changes in droplet size over time, by measuring up to 10,000 measurements a second.
- Delivers accurate, concentration-independent results using a patented multiple scattering analysis.
- Characterizes wide spray plumes without risking optical contamination.
- Simply reveals the dynamic changes in spray particle size through its unique size history analysis software.

Contact Information

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Malvern's web site: www.malvern.com
Malvern's Interactive Learning Center: www.malvern.com/events

nac Image Technology has a proven track record of developing high quality, reliable products that satisfy specific high-speed imaging requirements for a multitude of applications including: Spray Analysis and PIV, Aerospace, Range and Ballistics, Manufacturing, Test and Design, Automotive / Transportation, and many more! nac Image Technology is the only manufacturer of high-speed camera systems that has dedicated itself to producing complete, integrated systems that have the ***most light sensitivity, the best image quality, the largest memory capacities, the smallest camera heads, the fastest download times and the most inclusive software packages in the industry***.

Since 1958 nac has been a pioneer in developing new uses for image technology and has gained a reputation for quality, experience and reliability! All nac products go through rigorous environmental testing and certification so you can be confident that your nac Camera System will be a valuable and reliable tool for years to come.

When it comes to reliable, high-quality, high-speed camera systems, make the proven choice with NAC and you'll ***see the visible difference.***

nac Image Technology
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Simi Valley, CA 93065
www.nacinc.com
Info@nacinc.com

Photron ILASS 2015 submission

Photron - High Speed Cameras for Slow Motion Analysis

Founded in 1974 to provide manufacturing, sales and service of professional film and video equipment and photo-instrumentation, Photron has been offering photo optics and electronic technologies to manufacturing industries, the medical field, film laboratories, major movie and television studios, as well as to the military worldwide for over forty years.

Key milestones include:

- In 1991 the Model 4540 was launched as the world's fastest commercial high-speed video system, operating at up to 40,500 frames per second. The 4540 was marketed for many years by the Kodak MASD company in both the Americas and Europe.
- The FASTCAM 1024 PCI was the first mega-pixel CMOS camera system for the PC, providing mega pixel resolution at one thousand frames per second (fps) and reduced resolution to over 100,000 fps.
- Photron's camera control software, Photron Fastcam Viewer (PFV), is award-winning freeware that enables easy control and replay of recorded imagery and includes a Software Developers Kit (SDK) with wrappers for both LabVIEW and MATLAB environments.
- Very short inter-frame times mean the Photron family of high speed cameras are ideally suited for particle image velocimetry (PIV) applications making us the number one choice for solving high speed fluidics problems.
- Our Data Acquisition (DAQ) module is compatible with the National Instrument USB series data acquisition modules to enable you to precisely synchronize and display external analog data, from load cells, accelerometers, etc., with the recorded high-speed video data.
- The FASTCAM SA-Z provides mega pixel resolution to 21,000 frames per second, (fps), and reduced resolution operation in excess of two million fps. The 12-bit CMOS sensor utilizes 20μm square pixels to provide genuine ISO 12232 light sensitivity of 25,000 ISO.
- The very compact and high-G FASTCAM Mini families of cameras encompasses two sensors;
    - 1.3 mega-pixels to 4,000 fps with 720 HD (1,280 x 720 pixels) to 6,250 fps.
    - 4 mega-pixel to just over 1,000 fps with 1080 HD (1,920 x 1,080) to 2,000 fps.
    - Top speeds, at reduced resolution of 800K and 80K fps respectively.

Photron's varied product range makes it the first choice for designers, manufacturers, R&D and test engineers to solve their most challenging motion problems. Whether it's testing a new product design or piece of equipment or trouble-shooting a high-speed production line, Photron's digital camera systems can capture thousands of high-resolution images for playback and analysis. And with the Photron FASTCAM Analysis (PFA) software, users can automatically track the motion of any point within a recorded sequence. Photron's continuing development of new state-of-the-art products shows our commitment to furthering research and development in the areas of digital imaging and motion analysis solutions.

Contact:
Email. image@photron.com
Web. www.photron.com
Phone. 800-585-2129 or 858-684-3555

9520 Padgett Street #110
San Diego, CA 92126-4446

TRUST. SCIENCE. INNOVATION.

TSI Incorporated in Shoreview, Minnesota provides a complete line of products for Spray diagnostic. They include Phase Doppler Particle Analysis (PDPA) system, time resolved Particle Image Velocimetry (TR-PIV) system, Global Patternation System, Global Sizing Velocimetry (GSV) system and Quantitative Flow Visualization systems. The different types of systems are used to characterize various aspects of the spray, from the precise measurement of the droplet velocity and size at a specific location to the global information of the ligament formation and breakup in the spray. Many of the systems are complementary to each other so that the complete diagnostic of the spray can be accomplished.

The PDPA system is a single point measurement technique which provides the simultaneous, accurate droplet velocity and size of the spray, with sampling rate up to 200,000 per second. The global imaging systems of TR-PIV, GSV and global patternation offer planar measurements of the spray illuminated by laser light sheet. PIV gives the velocity vector field of the spray with very high spatial resolution so that the flow structure can be analyzed. The GSV measures the simultaneous droplet velocity and size to allow the volume flux to be calculated. Global patternation is used to offer the researchers the behavior of spray angle and concentration distribution. Quantitative flow visualization using shadowgraph can be performed using either high resolution camera or high speed camera. Result from the high resolution camera can provide the detailed structure of the size of the droplets and ligaments. Using high speed camera, the evolution of the spray structure can be observed with high temporal resolution.

In addition product development and innovation are keys to TSI Fluid Mechanics group. We are continuously working on the state-of-the-art systems for better understanding of sprays. Please contact the Fluid Mechanics group of TSI or visit our booth in the conference.

About Vision Research

Vision Research is a leading manufacturer of high-speed digital imaging systems that are indispensible across a wide variety of applications including defense, automotive, engineering, science, medical research, industrial manufacturing, packaging, sports broadcast, TV production and digital cinematography. The Wayne, N.J.-based company designs and manufactures the most comprehensive range of digital high-speed cameras available today, all of which deliver unsurpassed light-sensitivity, image resolution, acquisition speed and image quality. Over the course of its 60+ year history, Vision Research has earned numerous awards in recognition of its innovations in high-speed digital camera technology and sensor design, including a technical Emmy and an Academy Award®. Vision Research digital high-speed cameras add a new dimension to the sense of sight, allowing the user to see details of an event ***when it's too fast to see, and too important not to***™. For additional information regarding Vision Research, please visit www.visionresearch.com.

Vision Research is a business unit of the Materials Analysis Division of AMETEK Inc., a leading global manufacturer of electronic instruments and electromechanical devices.

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Conference Schedule

ILASS-Americas
Institute for Liquid Atomization and Spray Systems

ILASS 2015 Schedule

Sunday, May 17

S 4:00-7:00 PM	**Registration**	*Hanover Foyer*
S 6:00-7:00 PM	**Welcome Reception with Exhibitors**	*Hanover Room*
S 7:00-8:30 PM	**Panel Discussion** **Industrial Spray Applications: Critical Issues & Opportunities** Moderator: M. Lightfoot, *AFRL* Panelists: R. Schick, *Spraying Systems Co.*; C. Lipp, *Lake Innovation*; K. Blakely, *Eli Lilly and Company*	*Governor's Room*

Monday, May 18

M 7:00-7:45 AM	**Breakfast with Exhibitors**	*Hanover Room*
M 7:45-8:00 AM	**Welcome & Opening Remarks**	*Oak Forest A*
M 8:00-9:00 AM	**Keynote Lecture** **Detailed Measurements of Spray Formation** Mark Linne, Chalmers University *Oak Forest A*	

	Experimental Methods & Instrumentation Chairs: M. Linne & K. Bade *Oak Forest A*	**Atomization Theory & Modeling I** Chairs: M. Trujillo & G. Agbaglah *Governor's Room*
M 9:05-9:30 AM	**Dynamic Ballistic Imaging: A Technique to Measure Acceleration in the Spray Formation Region** M. Rahm, Z. Falgout, D. Sedarsky, M. Linne *Chalmers University & University of Edinburgh*	**A Modeling Method for Impact & Impulse Dispersed Liquids: Alternative Transfer Criteria & Sensitivity Analysis** A. Brown, F. Pierce *Sandia National Laboratories*
M 9:30-9:55 AM	**Design Method for Optically Transmissive Nozzles for High-Pressure Experimental Fuel Injectors** Z. Falgout, M. Linne *Chalmers University*	**Investigating Traditional Atomization Theories with Highly-Resolved Simulations** S. Deshpande, S. Gurjar, M. Trujillo *University of Wisconsin Madison*
M 9:55-10:20 AM	**Validation of the Time-Shift Technique for Spray Characterization** W. Shäfer, S. Rosenkranz, C. Tropea *AOM-Systems GmbH & Technische Universität Darmstadt*	**Application of Interface Area Density Modeling to Define Spray Plume Boundary** Y. Wang, R. Grover, D. Schmidt, R. Diwakar, T.-W. Kuo *University of Massachusetts-Amherst & GM Global R&D*

M 10:20-10:35 AM **Break**

	Spray Characterization & Measurements I Chairs: V. McDonell & D. Duke *Oak Forest A*	**Atomization & Spray Simulations I** Chairs: M. Owkes & H. Gao *Governor's Room*
M 10:35-11:00 AM	**New Method of Liquid Atomization into Fine Droplets** M. Mezhericher, I. Ladizhensky, I. Etlin *Shamoon College of Engineering*	**Eulerian Two-Phase Flow CFD Simulation Using a Compressible and Equilibrium Eight-Equation Model** Y. Wang, R. Reitz *University of Wisconsin Madison*
M 11:00-11:25 AM	**Liquid Mixing in Doublet Impinging Jet Injectors Using X-Ray Fluorescence** B. Halls, T. Meyer, A. Kastengren *AFRL & Iowa State University & ANL*	**Detailed Numerical Study of Charge Mobility on Electrohydrodynamic Assisted Atomization** P. Sheehy, M. Owkes *Montana State University*
M 11:25-11:50 AM	**Study of Spray Distribution & Fuel Placement from a Novel Dual Phase Airblast Injector for Gas Turbine Combustor** J. Li, M. Hamza, U. Bhayaraju, S.-M. Jeng *University of Cincinnati*	**Impact of Droplet Injection Models in Numerical Simulations of Fire Suppression Systems** H. Gao, V. Sankaran, J. Snyder, J. Sheffel, M. Corn, M. Soteriou *UTRC*
M 11:50-12:15 AM	**Contrasting Atomization Performance of Biodiesel-Ethanol Mixtures in Air-blast and Pressure Swirl Nozzles** A. Silver, V. McDonell *University of California, Irvine*	**A Molten Solid Approach for Simulating Urea-Water Solution Droplet Depletion** S. Quan, M. Wang, S. Drennan, J. Strodtbeck, A. Dahale *Convergent Science, Inc.*

M 12:15-1:30 PM **Lunch** *Oak Forest B*

	Droplet Phenomena Chairs: M. Jog & G. Aguilar *Oak Forest A*	Automotive Sprays I Chairs: T. Fang & S. Parrish *Governor's Room*
M 1:30-1:55 PM	**Splashing of a Drop Impacting on a Thin Liquid Film** S. Rajendran, M. Jog, R. Manglik *University of Cincinnati*	**Jet-to-Jet Collision Studies of a Novel High-Pressure Two-hole Injector under Gasoline Engine Conditions** A. Moiz, L. Zhao, S.-Y. Lee, J. Naber, S. Barros, W. Atkinson *Michigan Technology University & Nostrum Energy LLC*
M 1:55-2:20 PM	**Computational Study of Heat Transfer from a Suspending Needle through Rayleigh-Marangoni Convection in an Evaporating Pendant Droplet** Srivathsan N., S. Bakshi *IIT Madras*	**Fluctuation Mechanisms in Single Hole Diesel Injectors** A. Swantek, D. Duke, C. Powell, A. Kastengren *Argonne National Laboratory*
M 2:20-2:45 PM	**Non-Newtonian Secondary Atomization in the Bag & Multimode Break up Regimes** J. Rocha, P. Sojka *Purdue University*	**Characteristics of Spray from a GDI Fuel Injector Using TRF Gasoline Fuel Surrogate** L. Wang, W. Roberts, T. Fang *North Carolina State University & KAUST*
M 2:45-3:10 PM	**Single Droplet & Droplet Train Impingement Pool Cooling** C. Ajawara, D. Banks, A. Cervantes, G. Aguilar *University of California, Riverside*	**Microscopic Observation of Miscible Mixing in Sprays at Elevated Temperatures & Pressures** J. Manin, L. Pickett, C. Crua *Sandia National Laboratories & University of Brighton*
M 3:10-3:25 PM	**Break**	
	Spray Applications Chairs: B. Van Poppel & K. Brown *Oak Forest A*	**Exp. Characterization of Atomization I** Chairs: L. Bravo & C. Genzale *Governor's Room*
M 3:25-3:50 PM	**SNCR Efficiency Study of Optimization of Spray Systems in CFB** F. Li, K. Brown, R. Schick, J. Shen *Spraying Systems Co.*	**High-Resolution Imaging of the Near-Nozzle Region of a Non-Reacting Spray** M. Tess, M. Kurman, L. Bravo, C.-B. Kweon *Army Research Laboratory*
M 3:50-4:15 PM	**Spray Analysis of an Electrostatic Atomization Nozzle with High Viscosity Vegetable Oils** P. Vesely, J. Shrimpton, F. Mashayek, R. Schick, M. Thenin *U. of Illinois at Chicago & U. Southampton & Spraying Systems*	**Transient Microscopy of Primary Atomization in Gasoline Direct Injection Sprays** H. Zaheer, C. Genzale *Georgia Institute of Technology*
M 4:15-4:40 PM	**Frequency & Bubble Size in CW Optical Cavitation** D. Banks, M. Daniels, C. Ajawara, G. Aguilar *University of California, Riverside*	**Characteristic Data for Primary Breakup & Spray Formation** D. Sedarsky, Z. Falgout, M. Rahm, M. Linne *Chalmers University*
M 4:40-5:05 PM	**Characterization of a Spray-Modifying Agricultural Adjuvant Using Multiple Diagnostic Techniques** L. Magidow, D. Bissell, A. Clark *Winfield Solutions, LLC & TSI Incorporated*	**Assisted Atomization of a Gas-Liquid Jet: Effect of the Volumic Gas Fraction in the Inner Jet on the Spray Characteristics** J.-C. Guillard, A. Cartellier, J.-P. Matas *Université Grenoble Alpes/CNRS, LEGI & CNES*
M 5:05 PM	**Evening at Leisure**	

Tuesday, May 19

T 7:00-7:55 AM	**Breakfast with Exhibitors**	*Hanover Room*
T 7:55-8:00 AM	**Opening Remarks**	*Oak Forest A*
T 8:00-9:00 AM	**Keynote Lecture** **High Fidelity Simulation of Spray Atomization for Aerospace Applications** M. Soteriou, UTRC	*Oak Forest A*

	Atomization & Spray Simulations II Chairs: M. Soteriou & G. Agbaglah *Oak Forest A*	**Spray & Liquid Breakup in Food Applications (Invited Session)** Chairs: F. Tanner & K. Feigl *Governor's Room*
T 9:05-9:30 AM	**High Resolution Numerical Simulations of Primary Atomization in Diesel Sprays with Single Component Reference Fuels** L. Bravo, D. Kim, M. Tess, M. Kurman, F. Ham, C. Kweon *Army Research Lab & Cascade Technologies Inc.*	**Production of Substructured Fat Systems by Co-Spraying of Two Different Fat(-Emulsions) with Very-Low Emulsifier Concentrations & Controlled Fat Polymorphism** P. Guillet, A. Kessler, E. Windhab *ETH Zürich*
T 9:30-9:55 AM	**High-fidelity Simulation of Liquid Fuel Atomization with Interface Evaporation** X. Li, M. Soteriou *UTRC*	**Viscoelastic Droplet Formation in a Microfluidic T-junction** O. Shonibare, K. Feigl, F. Tanner *Michigan Technological University*
T 9:55-10:20 AM	**Numerical Simulation of Air-Blast Atomization of a Liquid Layer** G. Agbaglah, J. McCaslin, O. Desjardins *Cornell University*	**Film Stabilization as Key Step of Atomization Process for Spray-Drying of Highly Concentrated Emulsions or Suspensions** M. Stranzinger *Nestlé Product Technology Centre*

T 10:20-10:35 AM **Break**

	Automotive Sprays II Chairs: L. Pickett & K. Bade *Oak Forest A*	**Spray & Liquid Breakup in Food Applications (Invited Session)** Chairs: F. Tanner & K. Feigl *Governor's Room*
T 10:35-11:00 AM	**Improvement of Spray Characteristics for Direct Injection Diesel Engine by Cavitation in Nozzle Holes** N. Tamaki, S. Minami, K. Nishikawa *Kindai University & Kobe University*	**Near Nozzle Analysis of a Liquid Filament under Rayleigh Breakup Conditions Created from Laminar Rotary Spraying of Oil-in-Water Emulsions** W. Case, F. Tanner, K. Feigl, E. Windhab *ETH Zürich & Michigan Technological University*
T 11:00-11:25 AM	**Effects of Cross-Flow & Ambient Pressure on Fuel Spray Injected by Hole-Type Nozzle for DISI Engine** M. Guo, R. Kishi, B. Shi, Y. Ogata, K. Nishida *University of Hiroshima & Beijing Institute of Technology*	**In-Nozzle Breakup Conditions for Emulsion Sprays** K. Feigl, A. Baniabedalruhman, F. Tanner, E. Windhab *Michigan Tech University & Swiss Federal Institute of Tech.*
T 11:25-11:50 AM	**Spray Characteristics of non-VCO, VCO, & Stepped-hole VCO Multi-hole Injectors** S. Parrish, R. Zink *General Motors Research & Development*	**Deformation & Breakup of Drops in Axisymmetric Flows & Comparisons with the Taylor Analogy Breakup Model** C. Liang, K. Feigl, F. Tanner *Michigan Technological University*

T 11:50-1:00 PM **Lunch** *Oak Forest B*
ILASS Americas Annual Business Meeting & Awards Presentation

	Spray Combustion Chairs: T. Fang & M. Oevermann *Oak Forest A*	**3D Imaging of Sprays (Invited Session)** Chairs: B. Halls & B. Scharfman *Governor's Room*
T 1:00-1:25 PM	**Turbulent Spray Combustion Simulations Based on a New Skeletal Mechanism for *n*-Dodecane** O. Samimi Abianeh, M. Oehlschlaeger, C.-J. Sung *Georgia Southern University & RPI & University of Connecticut*	**Three-Dimensional Synthetic Aperture Feature Extraction in Multiphase Flows** B. Scharfman, A. Techet *MIT*
T 1:25-1:50 PM	**Effects of the Direct-Injected Fuel Physical Properties under Early & Late Reactivity Controlled Compression Ignition (RCCI) Combustion** F. Chuahy, Y. Ra, S. Kokjohn *University of Wisconsin Madison*	**Single-shot 3D imaging of fuel injection in a Spark-Ignited Direct-Injected Gasoline Engine** H. Chen, P. Lillo, V. Sick *University of Michigan*
T 1:50-2:15 PM	**Effect of Pilot Fuel Injection on Diesel Spray Combustion in a Constant Volume Chamber** W. Jing, Z. Wu, W. Roberts, T. Fang *North Carolina State University & KAUST*	**Characterization of Drop Aerodynamic Fragmentation in the Bag & Shear Thinning Regimes by Crossed-Beam Two-View Digital In-Line Holography** J. Gao, D. Guildenbecher, K. Gabet Hoffmeister, J. Chen, P. Sojka *Johns Hopkins & Sandia National Lab. & Purdue*
T 2:15-2:40 PM	**Effect of Fuel Injection Quantities on Diesel Spray Combustion** W. Jing, Z. Wu, W. Roberts, T. Fang *North Carolina State University & KAUST*	**Demonstration of High Speed (20 kHz) Digital Inline Holographic (DIH) Imaging of a Multiphase Event: Drop Impact on a Thin Liquid Film** D. Guildenbecher, P. Sojka *Sandia National Laboratories & Purdue University*
T 2:40-3:05 PM	**Spray Characterization & Combustion Processes in a Constant Volume Chamber of Acetone-Butanol-Ethanol (ABE)** T. Lee, Y. Lin, A. Hansen, C.-F. Lee *UIUC & Tsinghua University*	**Viscous Drops Impacting Thin Liquid Surfaces: Experimental Quantification of Secondary Fragment Sizes & Velocities** D. Guildenbecher, C. Brooks, P. Sojka *Sandia National Laboratories & Purdue University*

T 3:05-3:20 PM **Break**

T 3:20-4:10 PM
Technical Committees
Spray Measurements & Instrumentation, *Oak Forest A*
Physics of Atomization, *Oak Forest B*
Rocket & Airbreathing Power Fuel Atomization & Industrial Combustion, *Governor's Room*

T 4:10-5:00 PM
Technical Committees
Diesel & Automotive Sprays, *Oak Forest A*
Computation & Modeling, *Oak Forest B*
Industrial & Agricultural Sprays, *Governor's Room*

T 5:00-6:30 PM **Free time**

T 6:30-9:30 PM **Group Dinner** *Jimmy V's*

Wednesday, May 20

W 7:00-7:55 AM — **Breakfast with Exhibitors** — *Hanover Room*

W 7:55-8:00 AM — **Opening Remarks** — *Oak Forest A*

	Liquid Jets & Sprays in Crossflow (Invited Session) Chairs: M. Herrmann & K.-C. Lin *Oak Forest A*	**Internal Nozzle Flow Modeling (Invited Session)** Chairs: R. Grover & D. Schmidt *Governor's Room*
W 8:00-8:25 AM	**Jet in Crossflow - Observations on Heterogeneous Liquid Behavior & Some Databases to Consider** V. McDonell *University of California Irvine*	**Validation of Cavitation Simulations in Submerged Nozzles** D. Duke, M. Battistoni, A. Swantek, N. Sovis, A. Kastengren, C. Powell, S. Som, D. Schmidt *Argonne National Lab. & U. of Perugia & U. Mass. - Amherst*
W 8:25-8:50 AM	**Response of Spray Formed by Liquid Jet Injected into Oscillating Air Crossflow** A. Sharma, J. Song, J. Lee *University of Cincinnati*	**Parametric Study Of Flashing Nozzles For Spray Characterization** S. Rachakonda, M. Moulai, D. Schmidt *University of Massachusetts Amherst*
W 8:50-9:15 AM	**Studies on Liquid Jets in Supersonic Crossflow** K.-C. Lin, C. Carter *Taitech Inc. & ARFL*	**CFD Modeling of the Nozzle Flow & Near-field Spray on ECN Spray B Injector** Q. Xue, M. Battistoni, S. Som *Argonne National Laboratory & University of Perugia*
W 9:15-9:40 AM	**Validation of High-fidelity Simulation of Liquid Jet Atomization in Crossflow** X. Li, M. Soteriou *UTRC*	**Steady State and Transient, Non-isothermal Modeling of Cavitation in Diesel Fuel Injectors** R. Salemi, R. McDavid, P. Koukouvinis, M. Gavaises, M. Marengo *Caterpillar & City U. London & U. of Brighton & U. of Bergamo*

W 9:40-10:00 AM — **Break**

	Liquid Jets & Sprays in Crossflow (Invited Session) Chairs: M. Herrmann & K.-C. Lin *Oak Forest A*	**Spray Characterization & Measurements II** Chairs: P. Sojka & D. Sedarsky *Governor's Room*
W 10:00-10:25 AM	**Jet in Crossflow Simulations using Fluent** M. Gale, M. Herrmann *Arizona State University*	**Comparison of JP-8 Sprays from a Hydraulically Actuated Electronically Controlled Unit Injector & a Common Rail Injector** M. Kurman, M. Tess, L. Bravo, C.-B. Kweon, C. Hershey *Army Research Lab & Army Materiel Systems Analysis Activity*
W 10:25-10:50 AM	**The Effect of Momentum Flux Ratio & Turbulence Model on the Numerical Prediction of Atomization Characteristics of Air Assisted Liquid Jets** M. Sami, M. Braun, V. Kumar *ANSYS Inc.*	**Non-Newtonian Impinging Jet Spray Formation at Low Generalized Bird-Carreau Jet Reynolds Numbers** N. Rodrigues, V. Kulkarni, J. Gao, J. Chen, P. Sojka *Purdue University*
W 10:50-11:15 AM	**Effects of Air-Assist on the Dynamics of a Liquid Fuel Jet-in-Crossflow at Elevated Temperatures & Pressures** Z. Tan, E. Lubarsky, O. Bibik, D. Shcherbik, B. Zinn *Georgia Institute of Technology*	**Spatially Resolved Drop Characteristics of Non-Newtonian Impinging Jet Sprays** N. Rodrigues, P. Sojka *Purdue University*
W 11:15-11:40 AM	**Discussion** Moderator: M. Herrmann	**Study of Sprays Generated by Impinging Liquid Jets from Unlike Doublet Injectors** H. Bower, S. Leask, V. McDonell *University of California Irvine*

W 11:40-12:30 PM — **Lunch** — *Oak Forest B*

	Atomization Theory & Modeling II Chairs: A. Kerstein & D. Jarrahbashi *Oak Forest A*	**Exp. Characterization of Atomization II** Chairs: M. Lightfoot & M. Mezhericher *Governor's Room*
W 12:30-12:55 PM	**Early Spray Development at High Pressure: Hole, Ligament, and Bridge Formations** D. Jarrahbashi, W. Sirignano, P. Popov, F. Hussain *University of California Irvine & Texas Tech University*	**Characterization of Flow Structures Inside an Aerated-Liquid Jet Using X-Ray Diagnostics** S. Peltier, K.-C. Lin, C. Carter, A. Kastengren *AFRL & Taitech Inc. & Argonne National Laboratory*
W 12:55-1:20 PM	**Direct Numerical Simulation of Surface Tension Effects on Interface Dynamics in Turbulence** J. McCaslin, R. Chiodi, O. Desjardins *Cornell University*	**Picosecond Ballistic Imaging of Ligament Structures in the Near-Nozzle Region of Diesel Sprays** J. Porter, S. Duran, T. Parker *Colorado School of Mines*
W 1:20-1:45 PM	**Numerical Study of the Interaction between Turbulence & Surface Tension using One-Dimensional Turbulence** A. Movaghar, M. Linne, M. Oevermann, A. Kerstein *Chalmers University*	**Core Length & Spray Width Measurements in Shear Coaxial Rocket Injectors from X-Ray Radiography Measurements** M. Lightfoot, S. Schumaker, S. Danczyk *AFRL & Argonne National Laboratory*
W 1:45-2:10 PM	**A Dual-Scale LES Subgrid model for Turbulent Liquid/Gas Phase Interface Dynamics** M. Herrmann *Arizona State University*	

W 2:10 PM **Conference Closes**

Keynote Abstracts

ILASS-Americas
Institute for Liquid Atomization and Spray Systems

Detailed Measurements of Spray Formation

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Abstract

Over time we have developed the ability to image optically the flow inside an injection system at somewhat more realistic pressures than before. High-speed shadowgraphy and/or micro-PIV can be applied to the interior flow (PIV for large injector passages) to characterize phenomena such as cavitation, flow dynamics and etc. Once the interior flow has been characterized it can be correlated with spray formation dynamics via multiple-pulse ballistic imaging (for dense sprays) or alternatively with long distance microscopy coupled to high speed imaging (for low optical density sprays). Imaging of the entire spray (non-vaporizing) is accomplished via high speed shadowgraphy, and droplet size distributions and velocities in two directions are characterized with phase Doppler interferometry. This suite of measurements is applied to describe the entire spray formation process, and we are investigating an array of sprays with the aim to develop a detailed database. This work begins by isolating each primary breakup process (e.g. turbulence, cavitation, swirl, shear etc.) and then combines them into mixed-mode sprays. When possible the work will be coupled to findings of DNS.

High Fidelity Simulation of Spray Atomization for Aerospace Applications

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Liquid fuel atomization by aerodynamic forces plays a critical role in the performance of combustion devices such as aeroengine combustors, augmentors, ramjets/scramjets and rockets. Ability to predict the behavior of liquid atomization has remained a challenge, however, due to the complexity of the multi-scale and multi-physics processes involved and the severe limitations of experimental techniques in quantifying its characteristics. This lecture will describe our efforts to advance the state of the art in modeling of this problem by focusing on first principles high fidelity simulation. The objective is to demonstrate the ability of this approach to yield predictive results for realistic problems. Our computational model employs state of the art algorithms such as the Coupled Level Set and Volume Of Fluid (CLSVOF) and the Ghost Fluid methods to accurately capture the evolution of the sharp liquid-gas interface. An embedded boundary method is used to deal with injector geometrical complexities. Adaptive Mesh Refinement (AMR) and Lagrangian droplet models are used to mitigate the cost of resolving the smallest flow scales. Optimization of code execution on massively parallel computational architectures will be briefly discussed. Simulation results will be presented for a range of problems of increasing complexity, starting from verification tests, then evolving to validation in the canonical problems of impinging liquid jets and liquid jet in cross-flow atomization, and finally ending with demonstration simulations in a realistic aeroengine injector. In each case, a discussion of key physics which is revealed in substantial detail by the simulations will be included. Finally, limitations inherent in the simulations and future research directions will be discussed.

Abstracts

ILASS-Americas
Institute for Liquid Atomization and Spray Systems

ILASS Americas 27th Annual Conference on Liquid Atomization and Spray Systems, Raleigh, NC, May 2015

Dynamic Ballistic Imaging: A technique to measure acceleration in the spray formation region

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[2]School of Engineering, University of Edinburgh, Edinburgh, UK

Abstract

There is a need to acquire quantitative data from the spray formation (primary breakup) region of atomizing sprays. Such data would increase understanding of the dynamics governing breakup and provide a means to validate computational codes. To probe this region, however, is very challenging. One reason is the droplet cloud that surrounds it. This cloud effectively scatters light at optical wavelengths and can thus prevent larger fluid structures in the interior from being probed. Ballistic imaging is a technique, often used in a trans-illumination scheme, designed to mitigate the effects of scattering from the droplet cloud with the use of specialized optical filtering techniques. The resulting ballistic images are composed of the fraction of the incident light that retains image information from inside the spray. Consequently, it can reveal larger fluid structures and interfaces from the interior of this region and thus provide information on primary breakup. In this paper we discuss the implementation of a ballistic imaging system capable of acquiring three ballistic images in rapid succession with a well-defined time separation. Using image correlation velocimetry techniques on the image triplet, two dimensional velocity and acceleration fields of the primary breakup region can be obtained.

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A Modeling Method for Impact and Impulse Dispersed Liquids: Alternative Transfer Criteria and Sensitivity Analysis

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Abstract

A method has been previously described for predicting impact and impulse dispersion of contained liquids that employs SPH solid mechanics predictions to initialize Lagrangian/Eulerian fluid mechanics simulations. The coupling algorithm is based on a dimensionless length scale that defines the temporal exchange between the two codes. Previous work has identified grounds for formulating additional criteria to the coupling algorithm that will help create a more continuous transfer of mass and energy between the codes when performing these analyses. A new criterion is proposed based on a critical dimensionless energy formulated from a model for the surface and kinetic energy of binary pair systems of SPH particles. A model for the break-up of drops upon surface impact has recently been implemented in the SIERRA fluid mechanics code used for this work. The importance of this model to the quantitative results of relevant scenarios is not known, and is also explored herein.

Five scenarios simulated in the past exhibiting a variety of conditions provide the context for a sensitivity analysis that is used to quantify the importance of the new algorithms. The new dimensionless energy transfer criterion and the impact break-up model are of varying significance depending on the scenario. The effect of the impact break-up model is most significant for scenarios where the prediction of aerosol sized particles is important. The predictions are not particularly sensitive to the critical dimensionless energy parameter, however the dimensionless energy model exhibits a modest effect on the coupling. Data are needed to quantitatively validate these methods.

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Design Method for Optically Transmissive Nozzles for High-Pressure Experimental Fuel Injectors

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Abstract

Nozzle-orifice flow and cavitation has an important effect on primary breakup of sprays. As a result, a number of studies in recent years have used injectors with optically transmissive nozzles to allow simultaneous observation of the in-nozzle orifice flow and spray break-up, so that the influence of cavitation on primary breakup can be examined directly. There are also several studies which focus exclusively on observing cavitating nozzle orifice flows. Many of these studies use injection pressures scaled down from realistic injection pressures for modern fuel injectors, resulting in significantly lower Reynolds numbers than the industrial applications of interest and ultimately limiting the usefulness of their results. A relatively small number of studies have shown results at or near the injection pressures used in real systems. Unfortunately, neither the specifics of the design of the optical nozzle nor the design methodology used is explained in detail in these papers. Here, a methodology demonstrating how to prevent failure of a finished design made from commonly used optically transmissive materials will be explained in detail, and a description of a new design for transparent nozzles which minimizes size and cost will be shown. The design methodology combines Finite Element Analysis with relevant materials science to evaluate the potential for failure of the finished assembly. Finally, test results from this design and plans for the next design iteration will be discussed.

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Investigating Traditional Atomization Theories with Highly-Resolved Simulations

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Abstract

Atomization of a liquid sheet is studied using simulations based on a Volume of Fluid (VoF) method. Our aim is to evaluate the primary atomization models, which are often used in Lagrangian-Eulerian simulations–a prominent spray simulation method. The models assume that growth of sinuous unstable waves on the sheet causes its breakup and use linear theory to predict the wavelength [Dombrowski & Johns 1963; Senecal et al. 1999]. With respect to this, we address two points: (1) applicability of linear theory to instability prediction, and (2) relevance of this prediction to sheet breakup. To this end, a more general linear analysis considering capillary, viscous and boundary layer is performed using Orr-Sommerfeld (OS) theory. The VoF and OS simulations agree well for the 2-phase mixing layer problem. These disturbances, however, do not cause sheet breakup, and this contrasts prior linear theories. The structures which eventually do lead to breakup are shown to be two to three orders of magnitude greater than the ones predicted from linear instability analysis and emerge well beyond the initial linear regime.

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Validation of the Time-Shift Technique for Spray Characterization

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Abstract

The present study focuses on a comparison between the phase Doppler technique and the time-shift technique. This comparison is made using a water spray generated by a full cone nozzle. Drop size distributions, drop velocity distributions as well as correlations between size and velocity are analyzed at given positions in the spray. Despite minor differences, good overall agreement between results obtained by the phase Doppler technique and the time-shift technique is found. Additionally, the reasons leading to differences between the techniques have been identified and discussed. Finally, the potential of the time-shift technique is demonstrated by the characterization of sprays generated from non-transparent liquids.

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Application of Interface Area Density Modeling to Define Spray Plume Boundary

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Abstract

This study is devoted to the application of a predicted flow quantity called “interface area density” for Eulerian CFD simulation of two-phase flows. The interface area density (denoted as “Σ”) is defined as the liquid-gas interface area per unit volume in order to describe local sub-grid distribution of the two phases in any CFD cell. Transport equation for Σ is discussed. It is shown that a line-of-sight integration of Σ through the simulated spray plume offers a reasonable estimate of the optical thickness, which is a measure of the light intensity reduction due to light scattering on the interface. A procedure to define spray plume boundary based on the CFD results of Σ is proposed. Simulation results using the new definition are compared with experimental results of a gasoline spray injected from a single-hole nozzle.

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New Method of Liquid Atomization into Fine Droplets

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Abstract

Liquid atomization is useful in many applications, such as engineering, science, pharmaceutics, medicine, forensics and others. Fine micron and sub-micron droplets have developed surfaces offering high heat and mass transfer rates combined with increased bioavailability. Traditional liquid-atomization methods and devices like various types of nozzles, rotating discs, droplet generators and nebulizers are well-known and have been extensively studied. Some other methods like microfluidic nozzle and flash-evaporation atomizer have recently been reported. In the present research, an innovative methodology and a new device for atomization of liquids have been developed, and patent application has been submitted. The main advantages of the invention are simplicity, low cost, versatility in generating micron and submicron droplets, ability to obtain narrow droplet-size distributions, working in wide range of liquid viscosities and densities, absence of clogging, ability to achieve high atomization capacities, suitability for pharmaceutical and biological materials, and environmental friendliness. The new liquid-atomization method exploits the physical phenomenon of disintegration of thin liquid films into fine micron and submicron droplets. In several tested prototypes, bubbles were generated within a liquid and their shells have been subsequently destroyed by applying a mechanical impulse (pressure of a compressed air) once the bubbles came over the liquid surface. The main characteristics of the generated spray have been experimentally measured by means of the laser diffraction technique under various conditions for each prototype. One of the prototypes demonstrated the minimum arithmetic and Sauter mean droplet diameters of 1.48 μm and 2.66 μm under the 2.2 l/h of droplet flow rate for 3.5 bar pressure of atomizing air. The results of performed studies demonstrate that the proposed methodology of generation of fine droplets can be perspective for many practical applications.

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Eulerian Two-Phase Flow CFD Simulation Using a Compressible and Equilibrium Eight-Equation Model

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Abstract

This study focuses on Computational Fluid Dynamics (CFD) simulation of liquid-gas two-phase flows with applications to high-speed fuel injection processes in automotive engines. Assuming both liquid and gas phases to be continua, Eulerian transport equations are used to describe the mass, momentum and energy conservation laws for each phase. Thermodynamic properties of the fluids are modeled with compressible Stiffened Gas Equations of State that are coupled with the conservation laws. It is assumed that the interactions between the two phases result in mechanical, thermal and phase equilibrium controlled by relaxation processes. Numerical methods for the governing equations are presented, and critical numerical issues, such as the positivity of the liquid and gas phase volume fractions, are discussed in detail. Robustness of the CFD code is examined using several test problems involving very steep pressure gradients. These include a shock tube problem, a shock-bubble interaction problem, and submerged and non-submerged injected liquid jet problems.

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Liquid mixing in doublet impinging jet injectors using x-ray fluorescence

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Abstract

X-ray fluorescence is used to quantify the path-averaged liquid mass distribution of two different fluids in a doublet impinging jet spray. Measurements are made at the Advanced Photon Source at Argonne National Laboratory using a narrowband x-ray beam to ensure that the absorption cross-section of the excitation beam is independent of the path-length within the spray and the energy range well separated from the fluorescence spectrum. The synchrotron x-ray source furthermore generates a focused x-ray beam for measurements with micron-scale spatial resolution. To distinguish the two fluids within the mixing zone, each fluid is doped with a separate metal-salt tracer and fluorescence is collected with a photon-counting energy-resolved detector to distinguish the signal from each fluid. Attenuation measurements are collected simultaneously for calibration purposes to relate the fluorescence signal to mass distribution. A parametric study is conducted to investigate the mixing behavior at various conditions of the impinging jet spray, including the effects of injector angle, and Re.

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Detailed numerical study of charge mobility on electrohydrodynamic assisted atomization

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Abstract

Electrohydrodynamics (EHD) has the potential to greatly enhance liquid break-up of atomizing flows. For many relevant engineering flows, including liquid fuel injection, the charge mobility timescale (time for charges to relax to interface) is similar in magnitude to the charge convection timescale (relevant flow time), which leads to a non-trivial electric charge distribution. This distribution within the liquid fuel may enhance atomization, the extent to which is dependent on the ratios of these timescales, which can be controlled through the rate of charge mobility. However, there is limited understanding of the degree of this dependency due to the challenges of measuring electric charge density experimentally and transporting the discontinuous electric charge density in numerical simulations.

In this work, a computational approach for simulating two-phase EHD flows is used to investigate the amount charge mobility influences the resulting atomization quality. The computational approach is second-order, conservative, and is used to consistently transport the phase interface along with the discontinuous electric charge density and momentum. Using this method, multiple two-dimensional test cases are simulated with varying amounts of charge mobility that highlight its effect on the atomization efficiency of a liquid jet. Namely, a case designed to match the physical experiment conducted by Shimpton and Yule (J. Atom. Sprays, 2001), a case with increased charge mobility, and a case with significantly more charge mobility. Comparison of these cases shows the importance of charge mobility on atomization and suggests that increasing charge mobility leads to larger concentrations of electric charge density, increased Coulomb force, and ultimately improved break-up during the atomization process.

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Study of Spray Distribution and Fuel Placement from a Novel Dual Phase Airblast Injector for Gas Turbine Combustor

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Abstract

A novel airblast injector is designed for gas turbine combustors. Unlike standard pressure swirl and prefilming/non-prefilming air blast atomizers, the novel injector has a porous stainless steel tube with 7 μm porosity. The porous tube is used to inject the fuel between two air streams. The advantage of such an injector is that it can increase the surface area of contact between the fuel and air by forming a thin liquid sheet along the circumference of the tube which will enhance the distribution the fuel more effectively, and produce a fine spray at engine idle conditions. The injector can also be used to inject simultaneously both liquid and gaseous fuels. An experimental approach is adopted in the present study to characterize initially the spray and fuel placement emanating from this injector. The fuel injector consists of two streams of air, viz. through inner section of the tube and another swirling stream merging downstream of the tube. Jet-A fuel is injected through the surface of the porous tube. Due to the permeability of the tube, a thin liquid sheet is produced along the tube which is atomized by the inner airstream by surface stripping of the liquid sheet. Further, a secondary breakup occurs downstream of the tube. The swirl vane angle and air split are selected to increase the amount of air through the tube and enhance the atomization. Flow visualization studies show a hollow conical spray. Patternator tests are carried out to study the fuel distribution and symmetry of the spray. The results show a hollow cone spray with asymmetric distribution of volume flux. Spray characterization is further carried out with PDPA at selected operating conditions. The measured SMD shows that the atomization is reasonably good with wide fuel placement downstream of the atomizer at atmospheric conditions.

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Impact of Droplet Injection Models in Numerical Simulations of Fire Suppression Systems

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Abstract

Water-mist based fire suppression relies on a combination of spray penetration to the fire source and evaporation of fine droplets to suppress and control the fire. CFD tools can be used to simulate the complex dynamics of water-mist transport and evaporation to understand the effectiveness of a given spray head in fire suppression tests. While droplet transport models are reasonably mature, injection models for droplets issued from a nozzle are mostly empirical. A new spatially-resolved injection modeling approach is proposed here that utilizes the correlation between drop size, velocities, and volume-flux as a function of spatial position to define initial conditions at the injection plane. This approach is compared to validation measurements and with a conventional approach that prescribes a set of mean initial conditions at the injection plane. Results compared with available experimental data clearly show that the solution accuracy is considerably degraded when the spatial information of the droplets is not included in the boundary conditions. In addition, inclusion of gas entrainment effects improves the predictions considerably. At larger distances from the nozzle all the models yield similar drop size and velocity data since the droplets lose most of their initial momentum to the gas phase. However, further evaluation of the effects of many other parameters, such as grid resolution, turbulence model, and number of Lagrangian particles, is needed to represent the spray and will be the focus of future work.

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Contrasting Atomization Performance of Biodiesel-Ethanol Mixtures in Air-blast and Pressure Swirl Nozzles

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Abstract

As a means to help combat climate change, it is sought to have renewable fuels replace conventional petroleum in gas turbine systems without major modifications. This paper discusses a plan to experimentally investigate the macroscopic and microscopic atomization behavior of B99 biodiesel, ethanol, and a series of blends between the two in order to create a balanced fuel that compromises neither atomization quality nor its thermodynamic properties. Two atomizer configurations are employed so as to provide a broader precursor to the combustion performance in various types of gas turbines. The experimental spray apparatuses consists of a plain air-blast atomizer and a hollow cone pressure swirl nozzle. Multiple flow rates for each fuel are tested in order to simulate meeting gas turbine control strategies for controlling both power output and mass flow rates. For this study, a Phase Doppler Particle Analyzer system will be employed to gain information on drop size, SMD, velocity, and volumetric flux distribution across the spray plume. A Phantom high speed camera will also be used to gather high speed cinematography of the sprays for use in observing breakup characteristics and providing additional insight.

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A Molten Solid Approach for Simulating Urea-Water Solution Droplet Depletion

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Abstract

Engine emissions regulations today have essentially required the use of NOx reduction aftertreatment systems for on and off-road diesel engines. Injection of Urea-Water Solution (UWS) into the exhaust system is a promising approach to reduce nitrogen oxides (NOx) emitted from diesel engines. The detailed understanding of the depletion process that converts UWS to corresponding gases is essential for designing an efficient UWS injection based SCR systems. In this work, we implemented a reliable numerical model into CONVERGE to simulate the depletion of UWS droplets. A multi-component droplet spray injection model is used for injecting UWS droplets. The time rate of change of the droplet radius due to water evaporation is modelled by the Frossling correlation, while the time rate of change of the droplet radius due to urea decomposition is computed using an Arrhenius correlation. A heat transfer equation between the drop and the gas phase is used to model the heat balance during the evaporation and/or decomposition. This model was validated against a number of numerical and experimental results with good agreement. The model results show excellent agreement with the trend observed in experiments for urea-water solution droplet evaporation, i.e. water evaporation dominates during the early stage while urea decomposition plays significant role at the late stage when the droplet temperature is high, is very well predicted.

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Splashing of a Drop Impacting on a Thin Liquid Film

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Abstract

When a drop impinges on a thin layer of liquid, there are one of three outcomes: a prompt splash, or a delayed splash, or deposition on the liquid film. Prompt splash occurs at the instant of drop impact, whereas delayed splash occurs with the breakup of the liquid film of the crown at or beyond the maximum expansion of the crown. An experimental and analytical investigation on the onset of delayed splash is reported in this paper. Experiments are carried out with varying drop sizes ranging from 3.5 mm to 5.2 mm and altering the impact velocity from 1 m/s to 3 m/s. Four different liquids are used to study the effect of liquid properties on the phenomena of splashing. A high speed digital camera Hi-D cam – II version 3.0 – (NAC Image technology) is used to capture the phenomena of splashing. The threshold of splashing is found to be related to drop size, impact velocity, liquid properties and thin film thickness. Experimental analysis shows the significance of inertial, viscous and capillary forces in determining the splash/no-splash (or deposition) boundary. The effects of liquid properties and flow parameters on demarcating splash/no-splash regimes are discussed in the paper.

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Jet-to-Jet Collision Studies of a Novel High-Pressure Two-hole Injector under Gasoline Engine Conditions

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Abstract

Collision of liquid jets near the nozzle orifice is obtained in a novel two-hole colliding-jet style direct-injection (DI) injector. This jet-to-jet collision produces liquid breakup that is fundamentally different from how traditional fuel injectors operate, opening avenues for applications in internal combustion engines to achieve improved atomization. In this work, a non-reacting spray study is performed using a 2-hole colliding jet injector with gasoline fuel under temperature-pressure (T-P) conditions corresponding to 30°, 60°, and 90° BTDC of a spark-ignition gasoline engine. The engine-like conditions were generated in a constant-volume high pressure-temperature pre-burn type combustion vessel. Also, Computational Fluid Dynamics (CFD) work has been performed using a Eulerian-Lagrangian modelling approach, after experimental validation in the CONVERGE-CFD code. Experimental work of the colliding jets has been performed through analysis of penetration lengths, and overall spray structure while using this data for CFD code validation, wherever possible. The Eulerian-Lagrangian model predicts the spray characteristics reasonably well. The experiments show overall better spray characteristics for the conditions of 60° BTDC and this finding is supported by the CFD work as well.

Computational study of heat transfer from a suspending needle through Rayleigh-Marangoni convection in an evaporating pendant droplet

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Abstract

The effect of suspender on the heat transfer in an evaporating microliter pendant droplet is studied numerically. Suspended pendant droplet from a needle serves as the easiest way to evaluate and compare evaporation rates of fuel droplets. However, this suffers from the intrusive effect of the suspender which is not present in the case of a free droplet. This study attempts to study this effect numerically. Steady state simulations are performed in an axisymmetric domain consisting of the needle and the droplet. Buoyancy-driven and Marangoni convection are included in the fluid domain and along the surface of the droplet respectively. The flow and energy equations are solved considering the exact shape of the droplet at a certain instance of evaporation using a commercial CFD package, ANSYS FLUENT 14.0. The surface temperature is prescribed from the measured data for the evaporation of pure liquid ethanol droplet (diameter ~ 3 mm) suspended using a hollow, flat-tip steel needle (length 120 mm and inner radius 2.6 mm) evaporating under atmospheric conditions inside a cubical chamber. The calculated heat transfer rates at the droplet surface from the simulation compare well with the experimental values.

(Keywords: Droplet evaporation, suspender, Marangoni convection)

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Fluctuation Mechanisms in Single Hole Diesel Injectors

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Abstract

Recently, single shot measurements at Argonne National Laboratory's Advanced Photon Source have provided insight into the nature of fluctuations resulting from shot-to-shot variations in single-hole diesel injectors. These shot-to-shot variations represent incoherent fluctuations in the mass of the fuel in the path of the beam, and are indicative of stochastic spray atomization and mixing. Fluctuations have spatial and magnitude dependencies on injection pressure, ambient pressure, and, to a lesser degree, nozzle hole size. In the current work, we perform a proper orthogonal decomposition (POD) analysis during the steady spray of these same single shot data to complement the previous analysis. POD analysis decomposes a set of potentially correlated mass data into components which are uncorrelated to all other modes. This serves to indicate regions of the spray with coherent, repeatable fluctuations (though not necessarily in phase from shot to shot). Shot-to-shot variation analysis indicates that incoherent/stochastic fluctuations are strongest several millimeters (> 2-5 mm) downstream of the nozzle. In contrast, the POD analysis reveals that the coherent, although much smaller in magnitude, fluctuations occur in the region very near to the nozzle (< 2 mm). Several conditions are investigated and a simplistic physical description is explored. We lastly examine the shot-to-shot variation in mean mass during the steady spray at a single spatial location near to the nozzle exit. These values are observed to have significant trends with diameter, rail pressure, and ambient pressure.

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Non-Newtonian Secondary Atomization in the Bag and Multimode Break up Regimes

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Abstract

Secondary atomization of shear thinning non-Newtonian liquids in the bag and multimode breakup regime was studied. Rheology for these fluids was controlled by varying amounts of Ashland's Carboxymethylcellulose (CMC-7MF or CMC-7HF) polymers, and deionized water. Three solutions having various cross model parameters were formulated. Secondary atomization was achieved using a continuous jet setup. For videos, a Vision Research Phantom v7.1 high speed camera was utilized to collect images at more than 4500 fps, which typically yielded more than 100 frames for each breakup event. Post processing was performed using in-house written MATLAB code. The max cross stream dimension at initiation time was obtained and compared to literature. Also, at the bag breakup event, max rim diameter, max bag length, and vertical displacements were acquired. The maximum cross stream dimension was found to be practically liquid invariant, while bag breakup times, vertical displacements, and transition Weber numbers were found to have liquid viscosity dependencies. Also, transition effects from bag to bag-N-stamen were identified in relation to max bag length and max rim diameter.

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Characteristics of Spray from a GDI Fuel Injector Using TRF Gasoline Fuel Surrogate

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Abstract

Characterization of the spray angle, penetration, and droplet size distribution is important to analyze the spray and atomization quality of fuel injectors. In this paper, the spray structure development and atomization characterization of a gasoline direct injection (GDI) fuel injector was investigated. The experimental setup included a fuel injection system, a high-speed imaging system, and a droplet size measurement system. Spray images were taken by using a high speed camera for spray angle and penetration analysis. Sauter mean diameter, Dv(10) , Dv(50), Dv(90), and particle size distribution were measured using a laser diffraction technique. The fuel injection event was synchronized with the instruments for high-speed imaging and droplet size measurements by using a pulse generator. The fuel used is a gasoline surrogate fuel, called toluene reference fuel (TRF). Fuel under 100 bar (10 MPa) pressure was injected into ambient atmospheric pressure (1 atm) and temperature (298 K). The injection process is very consistent and the spray angles are consistently near 96º during the relatively stable stage. The front edge of the spray remains relatively flat during the spray process at the early stage. The spray front penetration speed has a peak of 66 m/s, then decreases until the end of the injection and stays relatively stable. The Sauter mean diameter (SMD) shows a decrease with the increase of the horizontal distance from measuring center at the axis of the nozzle to the spray edge. The particle size with time and the time-averaged particle size are also analyzed and discussed.

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Single Droplet and Droplet Train Impingement Pool Cooling

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Abstract

The cooling behavior of an impacting single droplet and train of droplets on a heated substrate (T = 60^{o}C) for various pool conditions is explored. The effects of several variables such as impact velocity (1-4 m/s), droplet diameter (4.8 mm), pool depth (0-34 mm), and impact frequency (0.5-32 Hz) on the cooling dynamics are explored. A fast response RTD embedded at the surface of the substrate allows for temperature measurement below the droplet impact. A high speed video camera recorded the dynamics of cavity formation and collapse upon impact with the pool surface. Droplet diameter and impact velocity were also measured using the high speed video. The instantaneous heat flux and net heat extraction at the surface were obtained using a finite-time step integration of Duhamel's theorem.

Heat transfer appears to be maximized within an intermediate region of impact Weber number for the single droplet impacts. At this intermediate Weber number range, the impact crater almost reached the pool bottom, suggesting that cold droplet fluid made contact with the substrate, maximizing the cooling effect. Outside this intermediate region of Weber number, the heat flux appears decrease. At the higher Weber number range, cold droplet fluid is pushed away from the measurement point once the cavity reaches the substrate. Below the optimal range of Weber number, the droplet does not enter the crater formed by the previous droplet, preventing it from reaching the substrate. For a train of droplets, there seems to be several regions where the heat flux is further reduced due to collision of droplet with emerging jet.

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Microscopic observation of miscible mixing in sprays at elevated temperatures and pressures

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Abstract

Recent visualization of n-dodecane delivered from a diesel injector into environments above 60 bar and 900 K performed at Sandia National Laboratories suggested a reduction in surface tension as droplets and ligaments were no longer detectible via back-illuminated microscopy. In the current study, improvements in optical microscopy are implemented to overcome much of the optical distortion present at these harsh conditions, leading to greater measurement resolution. The measurements show that the classical atomization and vaporization processes do shift to one where surface tension forces diminish with increasing pressure and temperature. Key indicators of "miscible mixing" include a deformation of liquid structure under minimal shear from surrounding gas velocities as well as indications that both large-scale turbulent motions and local molecular diffusivity simultaneously drive the mixing between fluids of different densities. A new fundamental finding of this study is that the transition to miscible mixing does not occur instantaneously when the fluid enters the chamber at a given temperature and pressure where miscible mixing is observed. Rather, the large, cool liquid structure that was just injected exhibits surface tension at first, and then, after time surrounded by the hot ambient and other fuel vapor, undergoes a transition to miscible mixing.

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SNCR Efficiency Study of Optimization of Spray Systems in CFB

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Abstract

High-level Nitrogen oxides (NO_x) released to the atmosphere cause health and environmental hazards. Conventional power plants are required to have NO_x emission control systems to abide by local environmental regulations. Common post-combustion techniques include selective non-catalytic reduction (SNCR) or selective catalytic reduction (SCR) techniques. SNCR is a proven technology that can be implemented virtually without affecting existing industrial operations with low capital cost. SNCR is a method involving either aqueous ammonia or urea as the reagent injected into flue gas in the boiler/furnace within specific temperature range. This method commonly reduces the emission of NO_x by 30-50%. However, high reductions can be achieved by system optimization. Placement within the proper temperature window, distribution within the cross section and residence time of reagent significantly influence performance of an SNCR system. Therefore, spray lance and nozzle design is crucial for assurance of operating efficiency and ammonia utilization.

In this paper, an SNCR system in a circulating fluidized bed (CFB) boiler was studied with using Computational Fluid Dynamics (CFD) simulations, as it relates to spray technology. The simulation solves Navier-Stokes equations with heat and mass transfer using ANSYS Fluent SNCR model with Lagrangian multiphase models and species transport model. CFD was used to diagnose the gas phase behavior and thermal distribution, to determine optimal spray placement and maximum penetration. The focus of this work was the parameters of the injection, which were determined based on test data acquired through in-house laboratory equipment. Temperature profile, pollutant reduction, ammonia slippage and wall impingement were used from the CFD results to assist determining the best spray design to achieve the greatest efficiency.

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High-Resolution Imaging of the Near-Nozzle Region of a Non-Reacting Spray

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Abstract

High-fidelity computational fluid dynamics models of diesel sprays require validation from high-quality experimental data. In particular, detailed physical models of the initial breakup and atomization of a diesel spray require information on the droplet sizes and instability length scales. Depending on the atomization mode, the acquisition of such experimental data can be challenging because the relevant time and length scales test the resolution capabilities of modern imaging systems. This paper presents high-resolution backlit image data acquired in the near-nozzle regions of non-evaporating and non-reacting sprays of iso-paraffinic kerosene and n-dodecane fuels. The in-plane resolution of the image system was measured using a scanning edge technique to quantify the line spread function. The jets were issued from three different single axial-hole common rail diesel injectors into a quiescent, high-pressure environment at tip velocities ranging from 9–165 m/s. For the quasi-steady phase of the injection event, the Reynolds numbers ranged from 3,000–36,000 with an Ohnesorge number of 0.04-0.06, indicating the jets were in the second wind induced and full atomization breakup modes. The results provide detailed information about the structure of diesel sprays that may be used to validate CFD models.

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Spray Analysis of an Electrostatic Atomization Nozzle with High Viscosity Vegetable Oils

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Abstract

Oil coating applications can be found in various industries; such as the baking industry for pan coating and in manufacturing for stamping operations. Spraying oil by the traditional means of hydraulic and air atomization presents many issues, primarily, the mess and wasted material due to overspray and the high energy cost associated with heating and spraying with compressed air. In this study, soybean oil was sprayed via a charge injection, electrostatic atomization nozzle. The oil was sprayed at room temperature with enough pressure to produce the desired flowrates through the small orifice diameters tested. The primary focus of this study was to characterize the spray plume generated from the nozzle by experimental results acquired with an Artium phase Doppler interferometer (PDI), LaVision laser sheet imaging (LSI) and an Olympus i-Speed TR camera. These systems were used to measure the spray shape, size and distribution as well as droplet size and velocity. It was found that the electrostatic atomization nozzle produced a full cone spray pattern with a Sauter mean diameter of the droplets ranging from approximately 120 to 160 microns in the main spray plume and around 30 to 40 microns outside the spray plume.

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Transient Microscopy of Primary Atomization in Gasoline Direct Injection Sprays

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Abstract

Understanding the physics governing primary atomization of high pressure fuel sprays is of paramount importance to accurately model combustion in direct injection engines. The small length and time scales of features that characterize this process falls below the resolution power of typical grids in CFD simulations, which necessitates the inclusion of physical models (sub-models) to account for unresolved physics. Unfortunately current physical models for fuel spray atomization are based on significant empirical scaling because there is a lack of experimental data to understand the governing physics. The most widely employed atomization sub-model used in current CFD simulations assumes the spray atomization process to be dominated by aerodynamically-driven surface instabilities, but there has been no quantitative experimental validation of this theory to date. The lack of experimental validation is due to the high spatial and temporal resolutions required to simultaneously to image these instabilities, which is difficult to achieve. The present work entails the development of a diagnostic technique to obtain high spatial and temporal resolution images of jet breakup and atomization in the near nozzle region of Gasoline Direct Injection (GDI) sprays. It focuses on the optical setup required to achieve maximum illumination, image contrast, sharp feature detection, and temporal tracking of interface instabilities for long-range microscopic imaging with a high-speed camera. The resolution and performance of the imaging system is characterized by evaluating its modulation transfer function (MTF). The setup enabled imaging of GDI sprays for the entire duration of an injection event (several milliseconds) at significantly improved spatial and temporal resolutions compared to historical spray atomization imaging data. The images show that low to moderate injection pressure sprays can be visualized with a high level of detail and also enable the tracking of features across frames within the field of view (FOV).

Frequency and Bubble Size in CW Optical Cavitation

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Abstract

Cavitation induced by continuous wave laser (CWL) irradiation is a novel development with applications in fields including biomedicine, thermal management, and microfluidics. The use of continuous wave lasers, instead of pulsed lasers, creates differences in the cavitation phenomena. Perhaps most significantly, multiple cavitation events occur during the irradiation period. For applications involving repetitive cavitation events, e.g., microfluidic pumps or skin poration, control of the cavitation frequency is essential. The governing factor controlling the frequency of cavitation is the energy density, which is a product of the laser power and focus.

Using an 810 nm CWL and an absorptive copper nitrate solution, we present measurements of the frequency and bubble size for continuous-wave induced cavitation for a range of laser power (1-10 W) and a focal position that varies from the inner wall of the target cuvette to outside the cuvette opposite the driving laser. High speed video is used to record the bubble dynamics. To establish the frequency and bubble size, the spatial transmission modulation technique is used.

As intuitively expected, higher laser power is found to produce higher frequencies. However, at higher frequencies, the frequency becomes less consistent – there is a larger variation in the delay between bubbles. Small variations in concentration of solution are thought to be exaggerated by the increased irradiation, potentially triggering cavitation after a shorter delay than when lower power is used. There is an optimal focus position where cavitation occurs most frequently across the entire range of laser power. This focus is approximately half the nominal focal length of the lens, which is attributed to a thermal lensing effect as the laser heats the working liquid. As bubble frequency increases, bubble size tends to decrease. The shorter delay between bubbles provides less time for diffusion to heat the surrounding liquid, resulting in smaller bubbles.

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Characteristic Data for Primary Breakup and Spray Formation

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Abstract

In practical sprays, a range of instabilities and fluid phenomena actively contribute to spray formation, which is often discussed in terms of primary breakup occurring in regions near the nozzle orifice and secondary breakup beginning further along in the developing spray. A wide variety of breakup modes, spray structure, and droplet size distributions can often be observed for the same nozzle geometry under different flow and boundary conditions, depending on which instabilities grow to dominate the breakup interaction. Efforts to develop a more fundamental understanding of primary breakup require detailed observations in a variety of flow conditions that can isolate the effects of instabilities, e.g. cavitation, swirl, and turbulence intensity, and help delineate their interactions leading to different breakup modes. In this work we focus on single-hole pressure atomized sprays and introduce an experimental effort to understand flow conditions and breakup interactions in a well-characterized steady laboratory spray designed to reach a wide range of conditions relevant for fuel injection applications. A suite of complementary time-resolved diagnostics are applied to image this spray and fully characterize boundary conditions for the flow. High-speed shadowgraphy and micro-PIV measurements are used to capture the interior flow in the optically transmissive nozzle. Time-gated ballistic imaging (for dense regions) or long distance microscopy are applied to observe small-scale interactions, and high speed shadowgraphy is applied to image the full spray. In addition, phase Doppler interferometry is applied to provide point-wise statistics of droplet size and 2D velocity. This work outlines the capabilities of the spray system, introduces five of the characteristic flows and boundary conditions chosen for detailed study, and presents some preliminary experimental results.

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Characterization of a spray-modifying agricultural adjuvant using multiple diagnostic techniques

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Abstract

Stewardship of pesticides in crop production requires precise and effective application of agricultural sprays. Tank mix adjuvants are commonly added to pesticide mixtures to modify spray characteristics and improve performance. InterLock is an oil emulsion adjuvant used to reduce fine spray droplets and increase product deposition on plant surfaces. In this study, a variety of imaging-based diagnostic techniques were used to study the atomization process and downstream droplet characterization of an adjuvant spray, validated with laser diffraction sizing measurements. Test conditions represented typical spray application techniques used by many farmers in North America. Separately, InterLock at 0.31% v/v in a water solution, and water alone, were sprayed with a TeeJet AIXR11004 agricultural spray nozzle at 345 kPa. High resolution images were produced by a 29 million pixel PowerView Plus CCD Camera and high speed images were collected with a Phantom v711 CMOS camera. The adjuvant altered the spray pattern and atomization process versus water alone, and ultimately reduced small particle (<150 μm) concentration by 25–50%. The adjuvant solution had a higher average velocity and produced a wider spray angle. These diagnostic methods demonstrate the mechanisms by which a field-realistic nozzle and adjuvant combination that can be used for precision application of crop protection products, enabling farmers to optimize investments and minimize environmental impacts.

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Assisted atomization of a gas-liquid jet: effect of the volumic gas fraction in the inner jet on the spray characteristics

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Abstract

We study the assisted atomization of a two-phase jet. This situation is notably encountered during the start-up phase of cryotechnic engines where the gas flow rate fraction β of the inner jet decreases from unity (pure gas) down to zero (pure liquid). The key questions concern how the spray characteristics vary with β and/or the flow configuration in the inner jet. We have carried out air-water experiments for β ranging from 0 to 1 and for external gas velocities Ug_{ext} from 20 to 100 m/s. The physical mechanisms leading to atomization happen to be significantly altered when we vary β. First, the break-up length decreases with β. Second, the drop size at short distance from injection, which is mainly controlled by the external gas velocity at β=0, becomes less and less sensitive to Ug_{ext} as β increases. This trend indicates that new mechanisms control the drop production. An alternative process may be the following: as β increases, the inner two-phase jet configuration evolves as well as the scales of the liquid bridges change and may control the size of the drops produced by atomization. This scenario is supported by experiments showing that drop sizes are rather well correlated to the dimension of liquid bridges. In addition, the flapping phenomenon disappears with increasing β, in agreement with the initial break-up of the jet.

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High Resolution Numerical Simulations of Primary Atomization in Diesel Sprays with Single Component Reference Fuels

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A high-resolution numerical simulation of jet breakup and spray formation from a complex diesel fuel injector at diesel engine type conditions has been performed. A full understanding of the primary atomization process in diesel fuel injection has not been achieved for several reasons including the difficulties accessing the optically dense region. Due to the recent advances in numerical methods and computing resources, high resolution simulations of atomizing flows are becoming available to provide new insights of the process. In the present study, an unstructured un-split Volume-of-Fluid (VoF) method is employed to simulate the injection event with prescribed bulk inflow conditions. An axial single-hole ARL fuel injector was X-ray scanned at The Advanced Photon Source Facility from Argonne National Laboratory for this work to define the internal geometry. The working conditions correspond to orifice dimensions of 90μm fueled with n-paraffin (n-dodecane) and iso-paraffin (iso-octane) reference fuels for a detailed investigation of fuel specific mixing mechanisms. The spray releases into a quiescent chamber filled with 100% Nitrogen at ambient conditions at 20 *bar*, 300*K* with $6.9x10^4 < Re < 2.5x10^4$ and $5.4x10^4 < We < 1.25x10^5$ both with $Oh > Oh_{cr}$ setting the spray in the full atomization mode. The simulations provide detailed diagnostics in the optically dense region extending from $5 < x/d < 25$ jet diameters. The results provide insights on the effect of start-of-injection on the velocity and volume fraction fields for each fuel at a range of pressures. High resolution backlit imaged data in the near nozzle region recently acquired at the Army Research Laboratory are used to provide validation metrics for the spray breakup length and dispersion characteristics.

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Production of substructured fat systems by co-spraying of two different fat(-emulsions) with very-low emulsifier concentrations and controlled fat polymorphism

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Abstract

Novel fat systems can be obtained by simultaneous spraying of different fat fractions. In order to generate substructured fat powders, short-term stable emulsions are produced with low emulsifier concentrations. These emulsions have to be stable for a short time frame (only 1- 10 minutes) while being pumped from an in-line rotor-stator emulsification device to the spraying nozzle. These emulsions are then simultaneously with a lower melting oil phase sprayed into a liquid nitrogen cooled spray chilling tower and chilled to temperatures ranging from -40 to $10\circ C$ at very high cooling rates (20 80 K/s). Depending on the cooling rate applied, differences in the obtained polymorphic modification of the fat powder can be observed. These polymorphic modifications were analyzed by conventional and flash DSC in order to ensure high cooling rates which can be compared to the cooling rates observed in the spray chilling tower. By conventional spray chilling, fat powders with varying parameters (particles size, substructure, fat polymorphic modification) were generated. Co-spraying of two different melting fat fractions, continuous food fat systems could be obtained. The influence of product and process properties on the spray chilling process were investigated. Optimum injection locations of different fat fractions into the spray chilling tower were determined. The overall goal of this project is obtaining stable (polymorphic) food fat systems which can be applied in different food products.

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High-fidelity Simulation of Liquid Fuel Atomization with Interface Evaporation

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Abstract

Fuel "preparation" (atomization, evaporation and mixing of fuel with air) is critical to the performance of combustors encountered in aerospace applications, such as gas turbines, augmentors, scramjets and ramjets and rockets. Experimental study of liquid fuel atomization and evaporation in the high-temperature high-pressure environment has been rare due to its prohibitive difficulty and cost. Recently, high-fidelity direct numerical simulation has been shown as a promising alternative to gain physical insight of the injection, atomization, evaporation and mixing processes. Experimental validation of such simulations has been performed on far-field spray distribution as well as near-field atomization details. However, most of these simulations have been restricted to ambient conditions due to the complexity of evaporation algorithms and the unavailability of data at high-temperature and high-pressure. In this work, we develop a mass-conserving sharp-interface method to simulate fuel atomization and interface evaporation. The computational approach relies on the Coupled Level Set and Volume Of Fluid (CLSVOF) method to track/capture the evaporating liquid-gas interface. An additional evaporation velocity was constructed under the CLSVOF framework to evolve the interface without loss of mass/volume. The Ghost Fluid (GF) method is used for momentum, energy and species transport, and enables a sharp representation of discontinuity conditions across the liquid-gas interface and therefore an accurate computation of the evaporation rates. The approach is verified against analytical solutions for the Stefan problem. It is then compared with the standard droplet evaporation model represented by the D^2-law. It is also assessed for grid convergence in a planar evaporation case. Finally it is applied to the realistic problem of an evaporating liquid jet in crossflow exposed to high gas temperature. Results are contrasted against those from a simulation of the corresponding ambient condition problem to demonstrate the impact of evaporation on the flow characteristics.

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Viscoelastic Droplet Formation in a Microfluidic T-junction

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Abstract

The production of uniformly-sized droplets has numerous applications in various fields including the biotechnology and chemical industries. For example, in the separation of mixtures based on their relative absorbency, an optimal arrangement of monodispersed droplets in columns is desired for an effective separation. However, very few numerical studies on the formation of viscoelastic droplets via cross-flow shear are available, none of which have considered the case when the flow of the continuous phase is Couette. In this work, the effect of flow type and fluid elasticity on drop size and droplet formation dynamics was investigated in a viscoelastic-Newtonian system. Two-dimensional numerical simulations, using the Volume of Fluid (VOF) method within OpenFOAM, have been performed to predict the size and detachment behavior of a viscoelastic droplet in a Newtonian matrix. The results obtained show good qualitative agreement with experimental work. In both cases where the flow of the continuous phase is pressure-driven (P-flow) and plane Couette (C-flow), there was a decrease in drop size as the cross-flow shear rate increased. However, for a fixed average shear rate, the drop sizes generated in C-flow were found to be smaller than that in P-flow. It was also found that the influence of elasticity on drop size became accentuated as the cross-flow shear increased. An increase in elasticity was accompanied by a decrease in drop size.

Keywords: microfluidics, T-junction, viscoelasticity, Giesekus model, non-Newtonian fluid, satellite droplets.

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Numerical simulation of air-blast atomization of a liquid layer

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Abstract

Numerical simulations of a planar co-flowing air/water airblast atomization is performed using an in-house multiphase Navier-Stokes solver based on a semi-lagrangian geometric Volume of Fluid (VOF) method to track the position of the interface. This solver conserves mass and momentum exactly within each phase. Physical quantities, such as the liquid cone length, the maximum wave frequency and the spatial growth rate of the primary instability are computed at different spatial resolutions and compared with recent experiments. Excellent agreement with experiments is obtained when comparing the maximum frequencies at different values of the dynamics pressure ratio between the liquid and the gas. The present simulations are therefore reliable to capture the Kelvin-Helmholtz type instability mechanism which occurs in the streamwise direction. Turbulence in the gas phase and characteristics of the growth of the shear layer are further analyzed. The gas layer becomes unstable close to the interface between the liquid and the gas at downstream positions of the injector.

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Film Stabilization as key step of Atomization Process for Spray-drying of highly concentrated Emulsions or Suspensions.

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Abstract

Food industry applies spray-drying to achieve shelf-stable and fast reconstitutable powders for a variety of products, such as dairy, coffee, culinary and beverage products. The process of spray-drying converts emulsions, suspensions and other type of dispersions into powder. Spray nozzles create droplets, which are dried in hot air by evaporating water. The final powder quality, the final powder texture, the dryer process design, the drying efficiency and process economy, the operational safety, to name only a few characteristics, are directly linked to the spray quality and thus the atomization process. Drying efficiency and process economy are key cost drivers, which are triggered from product side by the product water content to be evaporated. Thus during spray-drying the aim is to atomize concentrate solids contents, as high as possible. A drawback for Dairy emulsions is, that concentrate viscosity increases exponentially with increasing solids of the liquid to be atomized. Single-phase atomization typically used in industry as most reliable technology by utilizing pressure-swirl atomizers has limitations in viscosity, resulting in air-core break down. Air-core variation and break-down cause liquid film variations and thus droplet size variations. The objective is to maintain uni-modal and polydisperse droplet size distributions. Therefore liquid film stabilization is key before atomization of highly concentrated emulsions or suspensions starts. This paper describes the features of single-phase pressure-swirl atomization, compares with other atomization technologies, describes the air-core break-down process, as well as dependence on process and material properties and limitations found in powder production processes, which are triggered by atomization. An experimentally found stability criterion based on the spray angle of the pressure-swirl atomizer explored in this study allows to correlate with the liquid film in the swirl-chamber of this type of atomizer.

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Improvement of Spray Characteristics for Direct Injection Diesel Engine by Cavitation in Nozzle Holes

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Abstract

Diesel engine is lifted in terms of high thermal efficiency, reduction of carbon dioxide. The purpose of this study is to develop of a direct injection Diesel nozzle, which is obtained high-dispersion spray inside a cylinder by strong disturbance of liquid flow due to cavitation phenomena and swirling flow inside the nozzle hole. Authors have high expectation of this developed injection nozzle with suitable for lean burn combustion. In this study, it was mainly researched that effects of inclination of nozzle holes of the atomization enhancement nozzle, which was designed and invented at previous in this study, on spray characteristics. As a result, it was clarified that spread of spray of the nozzle, which is dressed with round inlet cutting at inlet of the multi-hole nozzle, becomes large about 60 p.c. and Sauter mean diameter of 20 μm order are obtained compared with one of sharp inlet shape nozzle. Moreover, volumetric flow rate of Nozzle-R_{di} is obtained about 20 p.c. larger than sharp inlet sharp nozzle at all injection pressure regions. In general, although volumetric flow rate increases and improved by using the nozzle with round inlet cutting at inlet of the nozzle hole, spray characteristics becomes wrong rapidly. However, the atomization enhancement nozzle, which was designed and invented in this study, both spray characteristics and flow characteristics were improved. Furthermore, when the each nozzle holes of the multi-hole nozzle were inclined at 45 deg., spray angle becomes dramatically large about over 100 deg., spray characteristics were improved considerably.

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Near nozzle analysis of a liquid filament under Rayleigh breakup conditions created from laminar rotary spraying of oil-in-water emulsions

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Abstract

A liquid jet resulting from the laminar rotary spraying of an oil-in-water emulsion (O/W) with a viscosity on the order of 50 mPa s and a surface tension on the order 50 mN/m has been studied by means of a high-speed camera. The liquid flow rate and rotational speed of the rotary sprayer are tuned so that the liquid filament breaks up into droplets under Rayleigh breakup conditions. From the high-speed imagery we consider in detail the dominant forces, which define the shape of the liquid jet near the nozzle exit. We use the formation of Rayleigh disturbances as a tracing mechanism across multiple high-speed video frames to determine the role that rotational forces, surface tension, viscous forces and wind resistance play on the shape of the liquid filament as well as the formation of resulting droplets. From this analysis it is determined that rotational forces play the dominant role, thus resulting in a simplified parametric model of the liquid jet trajectory based on the Rossby number only. This model is compared to a previous model defined in the Frenet–Serret frame of reference and shown to be the same under simplifying assumptions.

Keywords: Rayleigh breakup; Rotary spray; Rossby number; High-speed camera.

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Effects of Cross-Flow and Ambient Pressure on Fuel Spray Injected by Hole-Type Nozzle for DISI Engine

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Abstract

Air flow in the combustion chamber of the direct injection spark ignition gasoline engine affects the spray significantly whatever in the stratified charge combustion mode or the homogeneous charge combustion mode. Cross-flow, which is a special and typical air flow in the combustion chamber of the DISI gasoline engine, was obtained by an atmospheric wind tunnel and a high pressure wind tunnel in this study. Those wind tunnels were designed to require the uniform cross-flows with various pressure, those surroundings are to simulate the cross-flows during the intake stroke in the homogenous combustion mode and the compression stroke in the stratified charge combustion mode in the DISI gasoline engine. Ethanol was injected by a hole-type nozzle into the cross-flow field. The injections were recorded by a high speed video camera with high frame rate. Droplet velocity distributions were tested by the PIV technique. The droplet sizes of the spray were measure using the Fraunhofer diffraction method. The cross-flow influences spray profiles distinctly, such as the spray distortion, changes of the vertical and horizontal penetrations. Additionally, the atomization of the spray can be enhanced by the cross-flow according to the droplet size measuring. The cross-flow owns the ability of blowing the broken droplets with low number density in the periphery into downstream, therefore the droplets with high number density in the central core require the opportunity to be exposed in the ambient gas. The exposed droplets with high vertical momentum could break due to the increasing of the aerodynamic force.

Keywords: Fuel spray, Direct injection gasoline engine, Cross-flow, Ambient pressure

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In-Nozzle Breakup Conditions for Emulsion Sprays

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Abstract

Simple and multiple emulsions have many applications in the food and pharmaceutical industries. Often these fluid systems are sprayed to produce powders, which enhance the shelf life and stability of the material. During the spraying process, it is important that the structure of the emulsion is maintained, both inside the nozzle and during atomization and secondary breakup. In particular, the dispersed phase drops should not break up or coalesce since this change of structure affects the material properties of the emulsion and powder. In this study, numerical simulations are used to investigate breakup conditions of drops in an emulsion within a spraying nozzle. The simulations are performed by solving a two-phase flow problem in the nozzle in which individual drops are tracked through the flow field. The flow, material and drop conditions under which drops break up are investigated. Of particular interest is the minimum, or critical, drop size for breakup along particle paths. The effect of the history of shear rates, and hence capillary numbers, experienced by a drop, the viscosity ratio, and the fluid rheology on critical drop sizes is determined. A version of the interFoam solver of the open source software, OpenFOAM®, is used as a basis for the simulations. The numerical algorithm employs the finite volume method for solving the mass and momentum conservation equations and a volume-of-fluid approach for capturing the fluid-fluid interface. Dynamic meshing is used to maintain a sufficiently refined mesh around a drop as it moves through the flow field.

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Spray Characteristics of non-VCO, VCO, and Stepped-hole VCO Multi-hole Injectors

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Abstract

This work examines the spray characteristics of three types of multi-hole injectors intended for use in direct-injection gasoline engines. The injectors investigated were a non-VCO type, a VCO type, and a stepped-hole VCO type. Of particular interest were the spray tip penetration, the individual spray plume angles, and the drop size characteristics. A variety of operating conditions were examined including, four ambient pressures, two fuel pressures, and two injector tip temperatures. Volume illumination imaging and phase Doppler interferometry were the primary measurement diagnostics employed in the study. The spray characteristics of the stepped-hole VCO injector were found to be significantly different than the standard VCO injector. In particular, the individual plume angles produced by the stepped-hole VCO injector were wider than those produced by the standard VCO injector.

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Deformation and Breakup of Drops in Axisymmetric Flows and Comparisons with the Taylor Analogy Breakup Model

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Abstract

The Taylor analogy breakup (TAB) model is used for the prediction of drop deformation and drop breakup in spray simulations conducted with CFD codes. This model assumes that a spherical droplet moving in a gas stream behaves like a forced, damped harmonic oscillator in which the forcing term is given by the aerodynamic drag, the damping is due to the liquid viscosity and the restoring force is supplied by the surface tension. The deformation equation is given in terms of the normalized drop deformation, and it is assumed that the droplet breaks up if this deformation exceeds a critical value. In this study, CFD methods are used to determine the conditions under which the TAB model is valid and develop a modified TAB model which predicts the deformation more accurately. A full 3D simulation is performed to justify the axisymmetric assumption. In order to keep the drop within the fixed computational domain, the location of the drop is adjusted in almost every time step. The results are compared with the TAB and the modified TAB models, including the critical deformation at which the drop starts disintegrating and the oscillation period. The results show good agreement with the modified TAB model. Further, the types of breakup are found to be in good agreement with experimental observations.

Key Words: drop deformation, drop breakup, Taylor drop oscillator

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Turbulent spray combustion simulations based on a new skeletal mechanism for n-dodecane

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Abstract

A study of turbulent spray combustion of n-dodecane was conducted using computational fluid dynamics simulations. We report a new skeletal mechanism based on the reduction of a detailed kinetic reaction mechanism for high pressure conditions (50-60 bar), temperatures from 750 to 2500 K, and a range of equivalence ratios from 0.5 to 1.5. The skeletal mechanism has 85 species and 266 reactions. The mechanism was implemented in a computational fluid dynamic code to model the combustion of n-dodecane in a high pressure (60 bar) and temperature (900 K) constant volume chamber. A dynamic structure turbulence model with fine mesh size was utilized. Both first-stage low-temperature combustion, or cool-flame, and second-stage high-temperature combustion were observed due to the decrease in the gas temperature surrounding the spray caused by the fuel evaporative cooling. The species mass fraction histories were studied numerically to find a correlation between first-stage and second-stage combustion and species consumption. Species mass fractions, combustion chamber pressure, and combusting n-dodecane vapor penetration histories were studied computationally, and the results were compared with experiments to find a numerical equivalent to the light-based activated OH chemiluminescence ignition delay experiment.

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Three-Dimensional Synthetic Aperture Feature Extraction in Multiphase Flows

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Abstract

Droplet and bubble detection and quantification (e.g., size, distribution, and velocity) in multiphase flows requires advanced three-dimensional (3D) imaging. Computational photography methods, such as light field imaging (LFI) and synthetic aperture (SA) refocusing, have been combined in an emerging method to resolve 3D flow fields over time. Image volumes of a scene are captured using a multiple CCD sensor array consisting of multiple cameras. SA refocusing techniques are applied to the raw camera array images, each with large depths of field, to obtain a stack of post-processed images with narrow depth of field. Simulations using the SA method show that it is possible to extract the centroids in 3D and radii of spheres found in a scene being imaged with simple back illumination. Raw images are binarized during preprocessing by detecting the circular borders of bubbles or droplets and removing all other information. This simplifies 3D feature detection in the stack of refocused images. Circles are detected in the refocused image volume at the actual centroid depth planes of the droplets; thus the scene can be reconstructed in 3D and the spheres can be tracked over time.

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Effects of the direct-injected fuel Physical Properties under early and late Reactivity Controlled Compression Ignition (RCCI) Combustion

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Abstract

An experimental and computational study was conducted to explore the effects of the physical properties of the high reactivity fuel in a Reactivity Controlled Compression Ignition (RCCI) combustion dual-fuel strategy. In all studies, methane was used as the low reactivity fuel. The effect of high reactivity fuel physical properties was investigated by comparing the results of engine experiments using two fuels with equal cetane numbers, but different boiling characteristics. The two fuels are 1) a certification grade Ultra Low Sulfur Diesel (ULSD) fuel with a cetane number of 45 and 2) a blend of 21% iso-octane and 89% n-heptane with a cetane number of 45. Computational fluid dynamics (CFD) modeling using the KIVA-3v code with a discrete multi-component evaporation model capable of capturing important physical property influences and a multi-fuel chemistry model capable of describing the chemical kinetics of single and multi-component fuels was used to assess the need to consider multi-component evaporation under RCCI operating conditions. It was found that the different boiling curves of the two fuels have significant effects on the combustion phasing at early injection timings, where combustion is kinetically controlled, and virtually no effect at late injection timings, where combustion is mixing controlled.

Single-shot 3D imaging of fuel injection in a Spark-Ignited Direct-Injected Gasoline Engine

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Abstract

There are currently large efforts being made towards improving internal combustion engine efficiency without degrading engine performance. To do so, advanced combustion strategies that require in-cylinder fuel/air mixtures to be prepared with unprecedented care and exactness are being implemented. Spray-guided stratified-charge (SGSC) operation is an example of one such strategy that offers high efficiency under light-load operation but requires precise fuel injector and combustion chamber design to ensure robust engine performance. Understanding the instantaneous mixture formation processes aids in the success of such strategies and is therefore an important goal for internal combustion engine research. Direct visualization via optical diagnostics remains one of the most powerful tools for gaining insight into in-cylinder mixing processes, such as liquid fuel spray break-up. Although substantial efforts have been made over the last few decades to develop and implement liquid fuel spray diagnostics in the challenging in-cylinder environment, such techniques have been almost exclusively 2D or too complex to be used regularly in design practices. Only now are practical, commercially available 3D visualization technologies beginning to mature to a level for which they can be adapted to perform in-cylinder diagnostics. Here we demonstrate the promise of using a single plenoptic camera technique for visualizing in-cylinder fuel sprays in 3D by imaging fuel spray development within an optically accessible SIDI engine that is operated under a variety of conditions relevant to conventional homogeneous-charge and SGSC engine strategies.

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Effect of Pilot Fuel Injection on Diesel Spray Combustion in a Constant Volume Chamber

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Abstract

Diesel spray combustion was studied by using pilot injection under conventional combustion condition in a constant volume combustion chamber. The condition of 1000 K ambient temperature and 21% O_2 concentration was used to provide a conventional spray combustion environment. A two-injection strategy was used, including a pilot injection and a main injection with the injection widths of 0.5 ms and 1.3 ms respectively. Two cases using a single injection strategy were also conducted in order to compare the effect of different injection strategies. High speed multi-band emission measurement was employed to visualize the flame development in terms of OH*, Band A and Band B obtained by using different narrow-band filters (wavelength is centered at 310 nm, 430 nm and 470 nm, respectively, with FWHM of 10 nm). The transient images show that there is a strong interaction of OH* between pilot injection and main injection while a weak connection is observed for Band A and Band B. A faster flame development can be found for the main injection combustion compared to the ones of other two single injections. The time resolved spatially integrated results show that the longest total combustion duration can be found in the two-injection strategy. Additionally, the main injection has both lower intensities and effective areas of three emissions compared to other two single injection strategies.
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Characterization of drop aerodynamic fragmentation in the bag and shear thinning regimes by crossed-beam two-view digital in-line holography

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Abstract

In our 2014 ILASS-Americas presentation we proposed a cross-beam, two-view digital in-line holography (DIH) configuration to quantify the size and velocity of fragments which are generated by the breakup of an ethanol drop in an air stream. There it was shown that the cross-beam configuration overcomes the depth of focus challenges in DIH and allows for accurate quantification of fragment size probability density functions, *pdf*(*d*), and size-velocity correlations. Here, the technique is applied to study the spatial and temporal evolution of these quantities for drops undergoing breakup in the bag and sheet thinning regimes. Reconstructed holograms quantitatively illustrate how drop and fragment position, morphology, size, and velocity vary with spatial position and time. In particular, the existence of a second peak in *pdf*(*d*) is shown to arise due to rim fragmentation in the bag breakup regime (We = 14). In addition, the velocities of the fragments show little correlation with size. In contrast, *pdf*(*d*) is always mono-modal for the sheet thinning case, likely due to the continuous breakup of the original drop core. In that case, the velocities of the smaller drops appear to exceed those of the larger drops. Finally, results show that the temporal behaviors of D_{10}, D_{30}, D_{32}, and MMD, as well as the ratio of MMD/D_{32}, can be dependent on time and We.

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Effect of Fuel Injection Quantities on Diesel Spray Combustion

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Abstract

Diesel spray combustion with different fuel quantities was investigated under conventional combustion conditions in a constant volume combustion chamber. Conventional combustion was achieved under 1000 K ambient temperature and 21% O_2 concentration. The injection duration was set at 0.5 ms, 0.8 ms, 1.0 ms, 1.5 ms and 2.0 ms corresponding to different fuel quantities. Different fuel injection quantities are related to the engine operation loads under certain conditions. High speed multi-band flame emission measurement was employed to illustrate the flame development. OH*, Band A and Band B were captured by different filters with wavelength centered at 310 nm, 430 nm and 470 nm, respectively, with FWHM of 10 nm. The transient images show that the appearance of OH* emission is farther to the nozzle compared to other emissions (Band A and Band B). OH* emission penetrates longer than other emissions at the end of combustion where OH* approaches near the wall region. The time resolved results show that higher emission increasing rate can be found under small fuel quantity for each emission. Maximum intensity of each emission can be reached as fuel injection width increases to 1 ms. The effective area of each emission shows a similar trend to the intensity. Additionally, effective areas of three emissions were compared under two different fuel quantities. Band A has the largest area while Band B and OH* have a similar area. OH* has a larger area at the end of combustion, especially for the case with a small fuel quantity.

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Demonstration of High Speed (20 kHz) Digital Inline Holographic (DIH) Imaging of a Multiphase Event: Drop Impact on a Thin Liquid Film

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Abstract

Digital in-line holography (DIH) is a laser based measurement technique that provides 3D quantification of a particle field, such as a spray. Most previous applications of DIH are limited to low-speed (10s of Hz or less) recording rates. In this work, we demonstrate what is believed to be one of the first applications of high speed DIH (20 kHz, 1024 × 1024 pixels) to a transient spray process. Analysis of the impact of a water drop on a thin film of water reveals that kHz DIH results in higher positional uncertainty compared to previous results using low-speed CCDs. However, the temporal resolution allows measured positions to be fit to smooth trajectories over a large number of frames. Consequently, for this application, kHz DIH produces overall 3D positional accuracy exceeding previous low speed DIH results with the added benefit of temporal resolution. Here, the technique is applied to study four impact Weber numbers ranging from 381 to 1160. Non-dimensional fragment diameters are shown to increase as a function of non-dimensional time, while the non-dimensional velocities decrease over time. The improved resolution of the temporal statistics provided here is expected to be beneficial for future model development and validation.

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Spray Characterization and Combustion Processes in a Constant Volume Chamber of Acetone-Butanol-Ethanol (ABE)

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Abstract

Butanol, in comparison with ethanol, has more similar properties of current transportation fuel. These means it has a potential of being a more suitable blend for use in diesel engines. Unfortunately, butanol has a high cost of production. Acetone-butanol-ethanol (ABE) is an intermediate product of the fermentation process of butanol production. By using ABE directly in diesel fuels instead of butanol, the separation and purification processes are eliminated. As a result, it has a potential for greatly decreasing the overall cost for fuel production. This could lead to a larger commercial use of ABE-diesel blends on the market. Research has been conducted over the past five years regarding spray and combustion processes of both neat ABE and ABE-diesel blends. The main focus of this paper is to review the efforts made in fundamental spray research under quasi-steady flow field environments provided by a high-temperature, high-pressure constant volume chamber. Heat release rates high-speed Mie-scattering images were acquired from in-cylinder pressure traces to characterize liquid spray penetration. Natural flam luminosity was also captured to depict spatial and temporal soot distribution. It is observed that the acetone content has a major influence in the combustion behavior of the ABE mixture. As the acetone content increases, the combustion phasing significantly advances. Butanol is able to compensate the advancing effect caused by acetone and ethanol. Additionally, butanol can increase the overall energy density of the mixture and as a result makes the properties of the mixture closer to that of diesel.

Key words: ABE, Acetone, Butanol, Ethanol, Diesel, Constant-Volume Chamber

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Viscous drops impacting thin liquid surfaces: experimental quantification of secondary fragment sizes and velocities

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Abstract

The impact of liquid drops onto thin liquid films has been studied for over a century, with hundreds of papers available in the literature. However, there have been relatively few quantitative investigations of the temporal evolution of fragment properties, and, to our knowledge, all such investigations have considered water as the test liquid. This is despite the fact that more viscous liquids have been shown to dramatically alter the breakup morphology. Motivated by this, the current study presents the results of an initial investigation to quantify the temporal history of the fragments produced by the impact of viscous drops onto liquid films. Fragments are quantified using kHz digital in-line holography (DIH), which is a laser-based diagnostic discussed in a companion article (Guildenbecher, D.R., and Sojka, P.E., *ILASS Americas 27th Annual Conference on Liquid Atomization and Spray Systems*, 2015). Test liquids include pure DI water and two relatively low concentrations of carboxymethyl cellulose salt (CMC-Na) in DI water, whose measured low-shear viscosities are 4.6 and 6.4 times that of pure water. Results show that increasing viscosity (decreasing Reynolds number) at constant impact Weber number may either: (1) suppress breakup of the crown and initiate the formation of a very fine micro spray from the ejecta sheet, (2) the crown may still break up but into larger fragments compared to the inviscid case, or (3) the crown may break up into fragments which are smaller compared to the inviscid case. The exact mechanisms which produce these varied changes in fragment sizes at decreasing *Re* are not well understood, and the results are further evidence of the richness of the physics of liquid splashing. Finally, it is noted that, at sufficient concentrations, CMC-Na solutions can display shear-thinning rheology. Nevertheless, at the relatively low concentrations considered here, the observed phenomena are believe to be attributable to changes in the Newtonian dynamic viscosity.

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Jet in Crossflow--Observations on Heterogeneous Liquid Behavior and Some Databases to Consider

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This panel presentation provides an overview of observations regarding the behavior of heterogeneous liquids upon injection as a plain jet into a crossflow.

Introduction

Most studies of liquid jet in crossflow in the literature focus on injection of pure subcooled liquids. Yet the behavior of heterogeneous liquids has become of interest as different operating conditions or injection strategies are considered. Examples include aerated jets for supersonic combustion [1], flashing jets for high heat sink applications [2], and injection of immiscible liquids for emissions control [3]. The presentation overviews these applications and summarizes the key results available for these "non-traditional" jet in crossflow problems.

Background

The characteristics of jet in crossflow have been studied for decades. Characteristics that are commonly reported include the liquid jet penetration into the crossflow which is generally obtained from imaging methods. Less frequently, information about breakup time of the liquid column is discussed as is the dispersion of the spray plume in the lateral direction. On less occasion, detailed measurements in the spray plume are presented as obtained by phase Doppler interferometry. The key design tools that have emanated from this work generally emphasis the jet penetration which has long been established to be a function of the liquid jet to crossflow momentum flux ratio, *q*:

$$q = \frac{\rho_L U_L^2}{\rho_C U_C^2} \qquad \text{Equation 1}$$

The penetration behavior in the direction normal to the crossflow, y, is often expressed in terms of the liquid jet orifice diameter, do and the downstream distance, x in a form such as:

$$\frac{y}{d_o} = A\, q^B \left(\frac{x}{d_o}\right)^C \qquad \text{Equation 2}$$

In some examples, the penetration is modified by terms such as viscosity or Weber number, but generally the form in Equation 2 appears to describe the penetration reasonably well. Is this form appropriate for heterogeneous liquid jet behavior?

Observations

Aerated jets have been studied in some details with particular application to fuel injection into a supersonic crossflow [1]. In this case, modifiers to the penetration were provided to account for the aeration and injection angle:

$$\frac{y}{d_o} = 0.99\,(1+sin\theta)^{1.8} q^{0.33} \left(\frac{x}{d_o}\right)^{0.37} (1+GLR)^{0.28}$$

Equation 3

Superheated jets or flashing sprays have had some recent study [2]. The majority of the results have been essentially qualitative in nature. The results shown in Figure 1 illustrate the challenge with interpretation of the jet under such conditions.

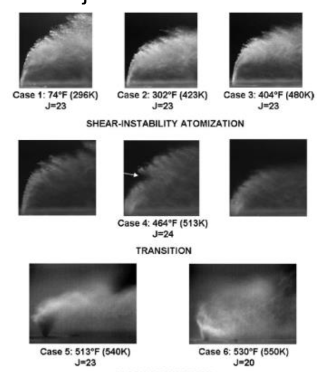

Figure 1. Examples of Flash Atomization Behavior of Superheated Fuel Jet Injected into a Crossflow.

Immiscible liquids have also received some attention in recent years. In this case it seems that penetration, at least, can be captured through the form of Equ.2 although the liquid density must be accurately considered. Also, while penetration can be captured, it is evident that the dispersion of the mixed liquid jet differs from that of the pure liquid [3].

a) DF-2 b) DF-2/Water

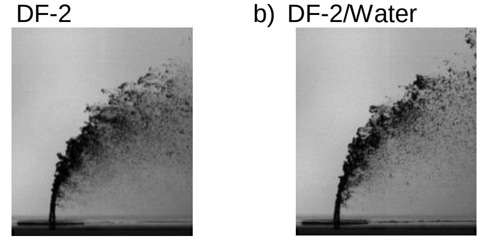

Figure 2. Behavior of pure DF-2 and DF-2/Water Emulsion (do = 0.72 mm; q = 48)

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Validation of Cavitation Simulations in Submerged Nozzles

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Abstract

Recent experimental and numerical studies of nozzle cavitation have revealed that dissolved non-condensable gases can play a substantial role in determining both the degree of cavitation and the morphology of the vapor field. These phenomena are currently not well understood, and are challenging to simulate. A wide variety of physical sub-models are used to model cavitation, yet the influence of non-condensable gases on the accuracy of these models has not yet been investigated, owing to the lack of available experimental data. To address this problem, new x-ray fluorescence measurements were performed at the 7-BM beamline of the Advanced Photon Source (APS) at Argonne National Laboratory. The fluorescence measurement was able to separate the contribution of dissolved gas and cavitation on the total line of sight void fraction. We consider the simplified case of a submerged cavitating nozzle with a sharp inlet and fixed diameter of 500 micron. Cavitation of a gasoline fuel surrogate was simulated with a compressible homogeneous relaxation model (HRM). Two implementations are considered, using Large Eddy Simulation to model turbulence in three-dimensional geometries. A range of conditions are considered, covering both incipient and strongly cavitating conditions, with and without dissolved gas in the fuel. A quantitative comparison between the simulations and line-of-sight x-ray measurements is made by projecting the volume fractions of cavitation vapor and non-condensable gas onto a plane. For the first time, both the concentration of dissolved gas in the fuel and the void fraction due to cavitation can be simultaneously validated.

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Response of Spray Formed by Liquid Jet Injected into Oscillating Air Crossflow

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Abstract

Experimental results on the characteristics of near-field (up to x/D=8) spray formed by a liquid jet injected into an oscillating air crossflow are presented. The modulation frequency is varied from 90 Hz to 450 Hz and the crossflow velocity (25-100 m/sec) and ambient pressure (2-3 atm) are systematically changed to investigate the spray response to modulated crossflow velocity over a range of crossflow Weber number (18, 60 and 175). Shadowgraph is used to visualize near field spray. The response of spray to modulated crossflow is characterized quantitatively in terms of upper penetration boundary and the corresponding change of momentum flux ratio is calculated based on an empirical correlation for upper penetration boundary. Spray response to modulated crossflow is found to depend on Weber number as well as modulation frequency.

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Parametric Study Of Flashing Nozzles For Spray Characterization

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Abstract

Spray characteristics like the drop size, number of droplets and the cone angle are crucial in the combustion process. Fine sprays can be effectively generated by means of flash boiling atomization. The spray characteristics and quality are significantly affected by the geometric, inlet and outlet conditions of the nozzle. In the current study, the flash boiling in nozzles was investigated utilising CFD as a tool with a thermal non-equilibrium model and a four component gasoline surrogate to predict the exit flow conditions and to develop correlations for determining the spray characteristics. In order to achieve this objective, a parametric study was undertaken on 2D axi-symmetric nozzles by varying the geometric aspects like the nozzle diameter, inlet corner radius and the aspect ratio along with the variation of injection and ambient pressures and temperatures, respectively with an aim to characterize the correlated data of the spray properties as a boundary condition for a downstream process. The effect of geometric factors, upstream and downstream conditions on the coefficient of discharge are discussed in the current work while the analysis of spray characteristics and its behavior will be undertaken in the future.

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Studies on Liquid Jets in Supersonic Crossflow

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ABSTRACT

Atomization of liquid fuel jets in supersonic crossflows has been one of the critical technology areas relevant to the development of high-speed air-breathing propulsion systems. In the early 70's and 80's, the majority of the studies on liquid jet in supersonic crossflows was motivated by NASA National Aero-Space Plane (NASP) program.[1,2] Plume trajectory, macroscopic structures, and droplet size distribution of liquid jets at various injection conditions and injector configurations were explored. Recently, the interest in developing liquid hydrocarbon-fueled air-breathing propulsion systems prompts renewed efforts in exploring the structures of liquid jets in supersonic crossflows. Advanced diagnostics, such as the phase Doppler Interferometry (PDI), high-speed imaging, holography, and PIV techniques, were utilized to investigate both plume and droplet properties.[3-5] In addition, approaches to enhance liquid atomization, such as the implementation of liquid aeration (or effervescent, or barbotage) technique, were recently evaluated.[5] The interaction between shock wave and liquid jet was also characterized.[6] In this talk, summary for recent research activities and major findings for liquid jets in supersonic crossflows will be presented.

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CFD Modeling of the Nozzle Flow and Near-field Spray on ECN Spray B Injector

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Abstract

It is important to understand the fluid dynamics inside the diesel injector and flow development in the nozzle due to their direct impact on the fuel-air mixing and combustion. This work uses a Eulerian approach and performs fully coupled simulations of the injector flow and near-field spray. This approach treats the liquid fuel and gas phases as a single mixture in the nozzle and near nozzle dense sprays. The liquid fuel mass fraction is transported with a model for the turbulent liquid diffusion flux using a Volume-of-Fluid method. The cavitation is modeled by the homogeneous relaxation model. A standard k-epsilon turbulence model is used with round-jet correction. The well-characterized ECN spray B injector is simulated under the x-ray radiography measurement conditions. The transient flow development and cavitation phenomena are analyzed in details. The effect of the needle motion on the flow and hole-to-hole variations is discussed. A comparison between the multi-hole injector and single-hole Spray A injector is also conducted.

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Validation of High-fidelity Simulation of Liquid Jet Atomization in Crossflow

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Summary

UTRC's past efforts to validate high fidelity simulation of liquid jet in cross flow at actual ambient experimental conditions are presented. One key reason why such validation is challenging is due to the numerical difficulties encountered by most high fidelity interface capturing algorithms at high density ratio. Results from two validation attempts are shown against two different experiments. These experiments are at similar physical conditions but one has much more detailed characterization of the boundary conditions and of the atomization near field. It is demonstrated that our computational model can stably produce high resolution solutions for both cases. More importantly, it is shown that high precision validation can only be achieved when the experimental information is comprehensive. When this is not the case, validation can only be partial/qualitative due to the ambiguity related to the incomplete definition of boundary conditions.

Steady State and Transient, Non-isothermal Modeling of Cavitation in Diesel Fuel Injectors

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Abstract

This paper describes preliminary results of non-isothermal CFD simulations of both single phase steady state flow at 5µm axial needle lift and two phase cavitating transient flow during a full injection cycle for three different diesel fuel injector designs. The CFD simulations are carried out under typical engine operating boundary conditions with variable fuel injector inlet pressure ranging from about 160 to 190MPa, a constant inlet temperature of 80°C and a typical constant outlet pressure of 10MPa. The non-isothermal CFD simulations, carried out using the in-house CFD code from City University in London (GFS), employ variable properties for diesel liquid as functions of both pressure and temperature. Additionally, the effects of viscous heating were taken into account in order to further improve the accuracy of the physics of the flow field within such fuel injectors. The paper provides a comparison of the variations of the coefficient of discharge and the temperature rise across each of the fuel injector designs during one full injection cycle. Furthermore the geometrical locations within the fuel injector, where the predicted cavitation might lead to erosion, are examined, while at the same time providing the novelty of outlining the likelihood of the occurrence of the flow boiling under the boundary conditions used.

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Jet in Crossflow Simulations using Fluent

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Abstract

In this work, a method is developed to simulate multi-phase flows using an industrial flow-solver as a mesh-infrastructure in conjunction with a high-fidelity refined level-set grid solver. A second-order consistent-rescaled momentum transport method is implemented, replacing the internal flow solver within the industrial package via user-defined functions. This method allows for high-density ratio, high-shear simulations when using level-set methods to track an interface. Using a refined overset Cartesian grid level-set solver, interface topology changes can be accurately described whilst reducing simulation costs. In addition, near-spherical liquid structures from the overset grid can be identified and transferred to the discrete-phase model as Lagrangian particles, providing coupling to secondary atomization models. The resulting method is a stable and cost-effective platform for simulating primary-atomization in an industrial setting. Jet-in-crossflow simulations are used to validate the proposed method.

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Comparison of JP-8 Sprays from a Hydraulically Actuated Electronically Controlled Unit Injector and a Common Rail Injector

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Abstract

JP-8 sprays from a hydraulically actuated electronically controlled unit injector (HEUI) and a common rail injector (CRIN) were investigated to compare the effects of the fuel delivery system on the spray behavior of the fuel. The fuel pressurization method between injectors is fundamentally different. The HEUI system utilizes engine oil to pressurize the fuel, whereas, the CRIN system pressurizes the fuel directly. To explore the different injection methods, rate of injection (ROI) experiments were initially conducted to measure shot-to-shot fuel quantity and rate of injection of both injector types. During the ROI experiments with the HEUI, the oil temperature and pressure was varied from 45°C to 90°C and 142-200 bar, respectively. In addition, the dwell time and rate shape of the HEUI was investigated to determine effects on injected fuel mass and rate of injection. Non-reacting spray experiments were performed in a high temperature (900 K), high pressure (60 bar) flow chamber to investigate the transient liquid penetration lengths of both injection systems. Ambient conditions of the flow chamber were chosen to represent typical conditions found in a compression-ignition engine and fuel injection pressures were 850, 1000, and 1200 bar. Results showed that an increase in oil temperature for the HEUI will increase the injected fuel mass. The CRIN injector system showed 4 times more precise control of injected fuel mass compared to the HEUI, and the CRIN showed less variations in the hydraulic delay. Comparing the plume to plume transient spray behavior of the two systems showed that more variations were present with the HEUI injector. However, the overall transient liquid penetration behavior was similar for both injection systems. Results of this study can be used to optimize the design of engines using JP-8 with hydraulic fuel injectors, thus improving fuel efficiency and power output.

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The effect of momentum flux ratio and turbulence model on the numerical prediction of atomization characteristics of air assisted liquid jets

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Abstract

The physical processes involved in a liquid jet breaking up are complex. Accurate prediction of such flows is computationally very expensive, as it involves transient LES modeling and VOF method to track liquid-gas interfaces. A relatively novel and easier approach to predict jet penetration was proposed by Vallet et. al [1], called Sigma-Y model. Lebas et.al.[2] later modified it into what is known as Omega-Y model. This modified form is implemented in this study using ANSYS FLUENT's user defined function approach. Steady state solver is used along with a user defined scalar to compute the interfacial area density transport equation. The liquid fraction is tracked via a species transport equation. A grid independence study is carried out for a fixed momentum flux ratio and results are compared with experimental data. Effect of momentum flux ratio and turbulence model on breakup length and droplet Sauter mean diameter is also investigated.

Keywords: CFD, Sprays, Modeling, Atomization

Non-Newtonian Impinging Jet Spray Formation at Low Generalized Bird-Carreau Jet Reynolds Numbers

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Abstract

Non-Newtonian impinging jet spray formation was experimentally investigated using two different grades of Carboxymethylcellulose (CMC) in de-ionized (DI) water (0.5 wt.-% CMC-7HF, 0.8 wt.-% CMC-7MF, and 1.4 wt.-% CMC-7MF). DI water was also used as a reference liquid. Experimental rheological data obtained using rotational and capillary rheometers was characterized using the Bird-Carreau model and a generalized Bird-Carreau jet Reynolds number $Re_{j,gen\text{-}BC}$ based on the Bird-Carreau model was used to correlate atomization behavior. The resulting spray was qualitatively and quantitatively studied using shadowgraphy. The general behavior exhibited by impinging Newtonian jet atomization was not observed when using non-Newtonian liquids; differences are ascribed to the shear thinning nature of the non-Newtonian liquids employed. Depending on $Re_{j,gen\text{-}BC}$ the observed spray patterns include: perforated sheet, ruffled sheet, tangled web, open rim, and ligament web. The experimentally measured maximum instability wavelength and sheet breakup length were observed to decrease with greater $Re_{j,gen\text{-}BC}$.

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Effects of Air-Assist on the Dynamics of a Liquid Fuel Jet-in-Crossflow at Elevated Temperatures and Pressures

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Abstract

Modern gas-turbines employ fuel-air mixers that utilize jet-in-cross-flow (JICF) fuel-injection to achieve rapid fuel-air mixing. In recent years, air-assist JICF has been investigated to improve the atomization and fuel-dispersion qualities of JICF. This paper describes an experimental investigation of the effects of air-assist upon the dynamics of JICF at elevated pressures and temperatures. In the investigation, the liquid Jet-A was injected through a wall-recessed orifice, while four slots surrounding the base of the recess supplied air streams that impinged on the jet at 45^o. Two arrangements of 10*kHz* high-speed Mie-scattering imaging were applied to capture the resulting spray plume: (1) simultaneous capture of the plume's integrated Mie-scattering from the top and side-views using a 2-camera system, and (2) capture of planar Mie-scattering across two different cross-sectional slices of the plume. A novel moments-based post-processing technique was applied to the 2-camera image-sets to obtain instantaneous center-of-gravity (*CG*) trajectories of the spray plume in 3-dimensional space, as well as the instantaneous dispersion pattern of the plume around the *CG*. From these, average and time standard-deviations of the CG and dispersions were calculated to investigate the static and dynamic properties of the JICF under different injection conditions. Similar statistics were also obtained from the cross-sectional images. From the instantaneous *CG* and dispersion values, the instantaneous spray plume can be reconstructed digitally in 3D, which serves as a useful visualization tool for engine designers, and facilitates the comparison of experimental results with CFD.

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Spatially Resolved Drop Characteristics of Non-Newtonian Impinging Jet Sprays

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Abstract

Phase Doppler Anemometry (PDA) was used to experimentally measure the spatially resolved spray characteristics of two non-Newtonian sprays produced by the impingement of a pair of liquid jets. The non-Newtonian liquids tested were water-based solutions of 0.5 wt.-% CMC-7HF (high molecular weight Carboxymethylcellulose) and 0.8 wt.-% CMC-7MF (medium molecular weight Carboxymethylcellulose). The like-on-like impinging jet doublet configuration was used in this investigation. Spatially resolved drop size and drop velocity measurements were obtained at the plane 5 cm downstream of the impingement point. Measurements were made up to 10 mm away from the centerline along the transverse axis in the plane of the sheet and up to 20 mm away from the centerline along the transverse axis in the plane normal to the sheet. Along both the axis transverse in the plane of the sheet and the axis transverse in the plane normal to the sheet, larger mean drop diameters and lower mean drop axial velocities were observed away from the centerline of the spray.

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Study of Sprays Generated by Impinging Liquid Jets from Unlike Doublet Injectors

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Abstract

This paper explores the application of optical diagnostics for the study of the structure of sprays generated by unlike doublet injectors. The cold-flow spray characteristics can be compared to corresponding hot-fire tests on prototype thrusters. A set of conditions, including differing injector impingement angles, were tested using high speed cinematography, laser diffraction, and a novel dual wavelength laser induced fluorescence system (DLIF). The DLIF system involved the development of appropriate dye/solvent mixtures that can be optically isolated through use of two excitation wavelengths and corresponding optical filters for isolating the fluorescence from the liquid stream from each of the two injectors. Additional analysis was required to assess the extent to which wavelength dependent scattering by the droplets impacted the relative intensity of the fluorescence from each stream. This was accomplished using calculated extinction coefficients from Mie scattering theory for each excitation wavelength combined with the measured size distribution from laser diffraction. The high speed cinematography captures the highly dynamic process induced by the impinging jets. The periodic nature of the atomization process for this type of injection strategy is clearly indicated and quantified in terms of dominant wavelengths and frequencies. High speed video is also used to quantify the resulting spread angle of the spray plume and the average spray breakup generated by the impingement. Additionally, the laser diffraction size distribution results indicated larger Sauter Mean diameters and volume distribution diameters for smaller impingement angles. The visualization results from the DLIF system indicated the effects of impingement angle on overall mixing of the two liquid streams. The results from the various optical measurement methods clearly demonstrate the strong dependence of the spray structure on impingement angle.

Keywords: Spray, atomization, measurement, drop size, imaging diagnostics

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Early Spray Development at High Pressure: Hole, Ligament, and Bridge Formations

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Abstract

Three-dimensional temporal instabilities, leading to spray formation, of a round liquid jet segment with co-axial gas flow at high pressure is studied by Navier-Stokes and level-set computations. Liquid-surface shape shows the development of smaller structures on the conical wave crests, i.e., lobes, holes, bridges, and ligaments. The gas-to-liquid density ratio, liquid Reynolds number (Re), and liquid Weber number range between 0.05 to 0.9, 320 to 5000, and 2000 to 230,000, respectively. At higher Re, lobes are longer and curve more at the crest edge with a regular formation of holes. The crest rims eventually tear, transforming the crest rims to ligaments. At higher gas densities throughout the Re range, the lobes are regular but shorter. The holes merge before the rims break to form ligaments. Consequently, liquid formations with both rim bridges and middle bridges are more common in this domain. In cases where both gas density and Re are lower, the well-ordered lobes are replaced by a more irregular corrugation with more wrinkles along the conical wave crest edge. Ligaments stretch from the lobes before holes form. The more viscous crests are thicker here explaining a delay in hole formation; still, the ligament extension is driven by pressure gradient rather than shear at the gas-liquid interface. In all cases, hole formation is correlated with hairpin and helical vortices; the perforations correlate with resulting fluid motion. Agreements with experiments are very good.

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Characterization of Flow Structures Inside an Aerated-Liquid Jet Using X-Ray Diagnostics

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Abstract

The present study examines the internal flowfield of aerated-liquid fuel injectors through X-ray radiography and fluorescence. An *inside-out* injector, consisting of a perforated aerating tube within an annular liquid stream, sprays into a quiescent environment at a fixed mass flow rate of water and nitrogen gas. The liquid and gas phases are doped with bromine and krypton, respectively, allowing discrimination between the phases through the respective X-ray fluorescence signals. For the present study, only the liquid mass distribution is examined. The injector housing is fabricated from beryllium (Be), which allows the internal flowfield to be examined (as Be has relatively low X-ray absorption). Time-averaged equivalent path length (EPL) and line-of-sight averaged density $\rho(y)$ reveal the formation of the two-phase mixture, showing that the liquid phase is concentrated primarily below the aerating tube. As the mixture travels down the nozzle, the liquid mass distribution becomes increasingly co-annular. However, the spray region rapidly transitions to a Gaussian shape after a distance of 0.25 mm. The location and size of the aerating orifices largely affects only the formation of the two-phase mixture, and any differences due to the aerating tube are negligible in the injector nozzle and spray region.

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Direct numerical simulation of surface tension effects on interface dynamics in turbulence

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Abstract

The interaction between turbulence and surface tension is studied through direct numerical simulation of a canonical multiphase flow. An initially flat interface is inserted into a triply periodic box of decaying homogeneous isotropic turbulence, simulated for a variety of turbulent Reynolds and Weber numbers on mesh sizes of 512^3 and 1024^3. Unity density and viscosity ratios are used in order to isolate the interaction between fluid inertia and the surface tension force. Interface height correlations and liquid volume fraction variance spectra are used to study the spatial scales of corrugations on the interface. A case with zero surface tension is first considered, yielding a passive interface that moves materially with the fluid. The power spectral density of the liquid volume fraction variance follows a κ^{-1} scaling, where κ is the wavenumber, which is consistent with dimensionality arguments. In the presence of surface tension, this corrugation spectrum follows a κ^{-1} scaling for large scales, but then deviates at a length scale wich corresponds to the critical radius. A spectral analysis of liquid volume fraction variance transfer is conducted, shedding light on the role played by surface tension in this process. Results will be used to deduce important ramifications for sub-grid scale models in large-eddy simulations of liquid-gas flows.

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Picosecond Ballistic Imaging of Ligament Structures in the Near-Nozzle Region of Diesel Sprays

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Abstract

Ligament formation in the near-nozzle region of diesel sprays was studied using high-speed shadowgraphy and picosecond ballistic imaging. Diesel and biodiesel surrogates, dodecane, methyl oleate, and methyl butyrate were injected at 147MPa injection pressure into air at temperatures from 25°C to 600°C and pressures from 100kPa to 2MPa. Simultaneous imaging of a single spray event with ballistic imaging and high-speed shadowgraphy demonstrated the advantages of ballistic imaging in capturing ligaments in diesel sprays. Ballistic images revealed a high propensity for long ligament formation in methyl oleate sprays compared to dodecane and methyl butyrate. A heated pressure vessel was used to image sprays at elevated temperature and pressure. When both the air temperature and pressure were increased, the length and frequency of ligaments dramatically increased. However, increases in temperature and pressure alone did not affect ligament formation. Finally, the length, orientation, and wavelength of observed ligaments are compared with recent numerical modeling results found the literature.

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Numerical study of the interaction between turbulence and surface tension using One-Dimensional Turbulence

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Abstract

The interaction between turbulence and surface tension is studied numerically using the one dimensional turbulence (ODT) model. ODT is a stochastic model simulating turbulent flow evolution along a notional one-dimensional line of sight by applying instantaneous maps that represent the effects of individual turbulent eddies on property fields. ODT has recently been used by the authors [1] to reproduce the main features of an experimentally determined regime diagram for primary jet breakup. ODT provides affordable high resolution of interface creation and property gradients within each phase, which are key for capturing the local behavior as well as overall trends.

In this paper we use ODT to investigate the interaction of turbulence with an initially plane interface. The notional flat interface is inserted into a periodic box of decaying homogeneous isotropic turbulence, simulated for a variety of turbulent Reynolds and Weber numbers. Unity density and viscosity ratios are used in order to study just the interaction between fluid inertia and the surface-tension force. Statistics of interface surface density and the two point autocorrelation function of phase index along the direction normal to the initial surface are obtained for future comparison with corresponding DNS data generated by other groups.

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Core Length and Spray Width Measurements in Shear Coaxial Rocket Injectors from X-ray Radiography Measurements

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Abstract

Shear coaxial injectors are so named because they rely on the shear between an outer low-density, high-velocity annulus and a high-density, low-velocity inner jet to atomize and mix a liquid and a gas. These sprays have an intact core near the injector and the high amount of light scattering its corrugated surface produces creates large optical densities. These high optical densities, in turn, make interrogation of the spray field in the intact core difficult. In combustion applications, such as rockets, this region is also the area of flame holding, and so is of primary importance in predicting combustion behavior. To overcome the problems of multiple scattering, the near-injector region was studied using x-ray radiography at Argonne National Laboratory's Advanced Photon Source. These results clearly show regions which correspond to changes in atomization behavior and can be used to quantify "core length" and understand more clearly what this term means. Three methods are explored to measure core length from x-ray radiography data and are compared to two-phase core length measurements from the literature. The core length non-dimensionalized by the inner jet diameter was found to scale with the momentum flux to the -0.66 power.

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A Dual-Scale LES Subgrid model for Turbulent Liquid/Gas Phase Interface Dynamics

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Abstract

Turbulent liquid/gas phase interface dynamics are at the core of many applications. For example, in atomizing flows, the properties of the resulting liquid spray are determined by the interplay of fluid and surface tension forces. The resulting dynamics typically span 4-6 orders of magnitude in length scales, making direct numerical simulations exceedingly expensive. This motivates the need for modeling approaches based on spatial filtering or ensemble averaging. In this paper, a dual-scale modeling approach is presented to describe turbulent two-phase interface dynamics in a large-eddy-simulation-type spatial filtering context. To close the unclosed terms related to the phase interface arising from filtering the Navier-Stokes equation, a resolved realization of the phase interface dynamics is explicitly filtered. This resolved realization is maintained on a high-resolution over-set mesh using a Refined Local Surface Grid approach [1] employing an un-split, geometric, bounded, and conservative Volume-of-Fluid method [2]. The required model for the resolved realization of the interface advection velocity includes the effects of sub-filter surface tension, dissipation, and turbulent eddies. Results of the dual-scale model are compared to recent direct numerical simulations of an interface in homogeneous isotropic turbulence [3].

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