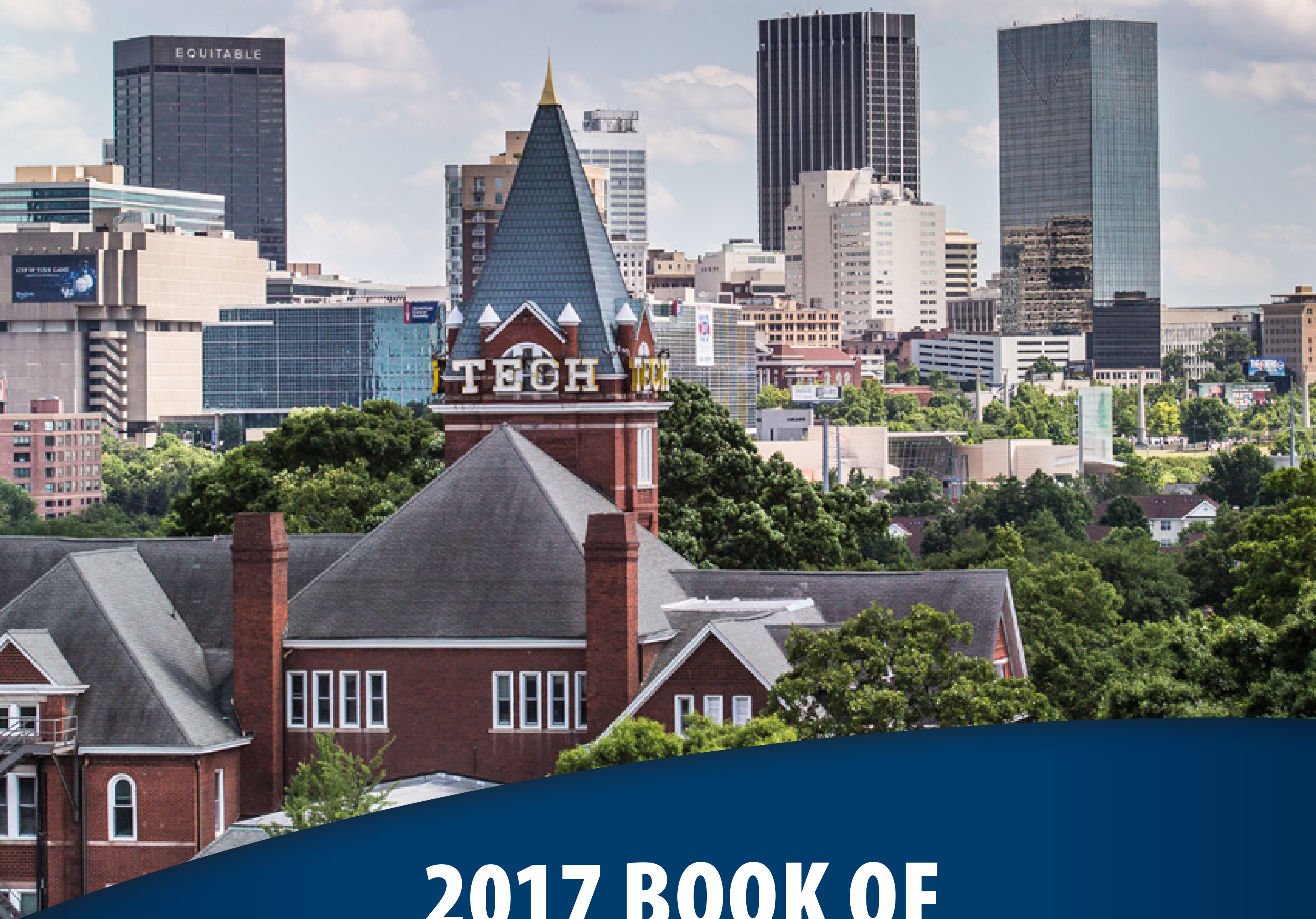
ILASS-Americas

Institute for Liquid Atomization and Spray Systems

29TH ANNUAL CONFERENCE



2017 BOOK OF ABSTRACTS

May 15 - 18, 2017 | Atlanta, GA

Georgia Institute of Technology

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ILASS-Americas

Institute for Liquid Atomization and Spray Systems

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CONVERGENT SCIENCE

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Conference Map

Exhibitors Room	Klaus Atrium
Welcome Reception	Klaus Atrium
Breakfast	Klaus Atrium
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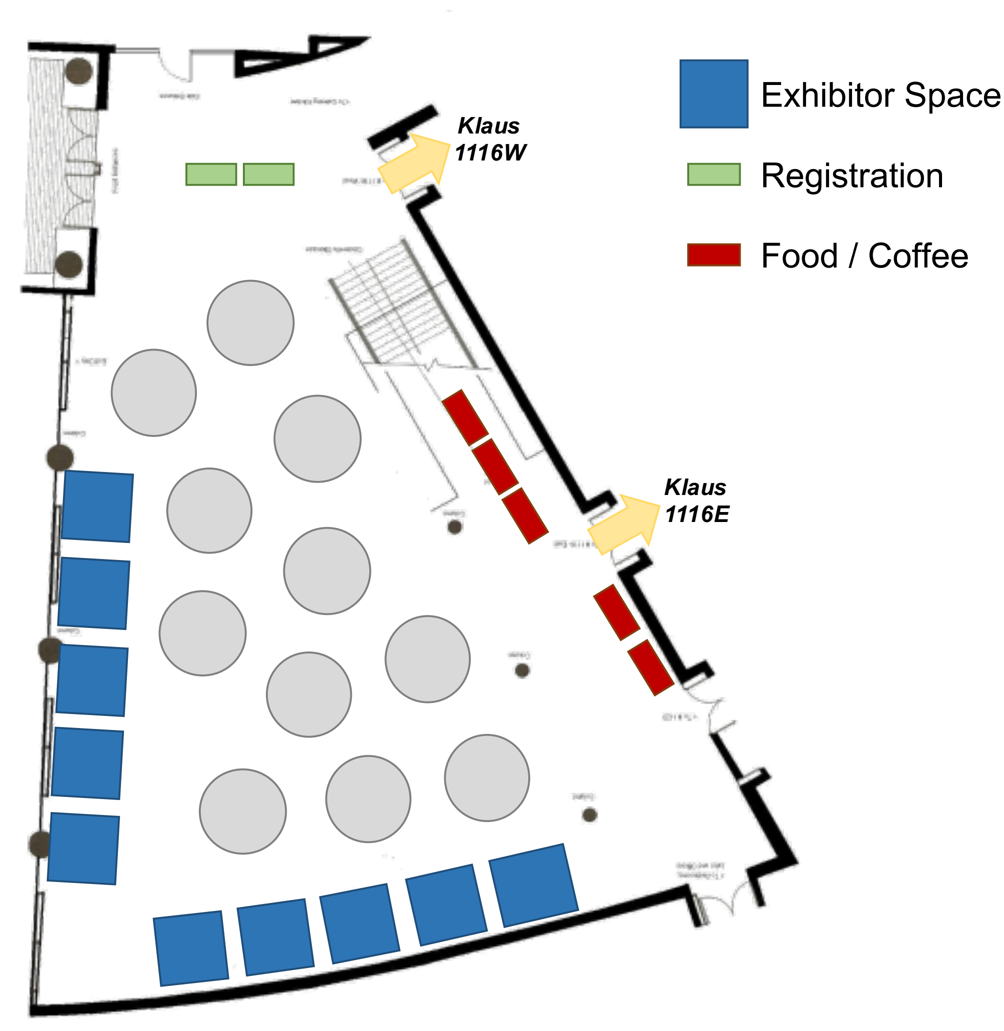
Presentation Rooms	Klaus 1116E or 1116W
Technical Committee Meetings .	Klaus 1116E or 1116W
Lunch	Klaus Atrium



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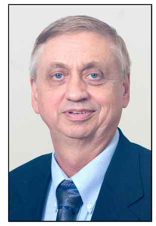

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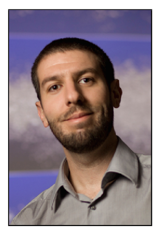

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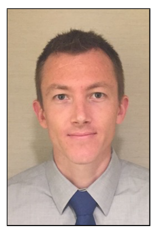

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ILASS-Americas

Institute for Liquid Atomization and Spray Systems

29th Annual Conference on Liquid Atomization and Spray Systems

ILASS 2017 is the 29th 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

- X-Ray Diagnostics of Sprays (Tuesday)
- Computational Methods for Atomization (Tuesday)
- Recent Advances in Spray Diagnostics I & II (Wednesday)
- Multiphysics Control of Spray Formation and Dispersion (Wednesday)
- Liquid Jets & Sprays in Crossflow (Wednesday)
- Turbulence Phenomena in Spray (Wednesday)
- Compressible Atomization (Thursday)
- Spray Image Analysis/3D Imaging (Thursday)

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 where 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 5-7 pm on Monday in the Klaus Atrium.

A Welcome Reception will take place from 5:30-7 pm on Monday in the Klaus Atrium.

Exhibitors' Displays can be found from Monday through Thursday in the Klaus Atrium.

Breakfast (Continental) will be served every morning from approximately 7-7:45 am in the Klaus Atrium (see program schedule for exact breakfast times).

Lunch will be served in the Klaus Atrium.

The ILASS-Americas Annual Business Meeting will be held during lunch on Wednesday in the Klaus Atrium.

Technical Committee Meetings will be held on Monday & Tuesday evenings in the Klaus Atrium, rm 1116E, and rm 1116W. Conference attendees are strongly encouraged to join the technical committee discussions that match their interests. The meetings are open to all conference participants.

A Poster Exhibition will be held Tuesday-Thursday in the Klaus Atrium.

A Tour of the Combustion Lab will be provided on Wednesday from 3-4:45pm.

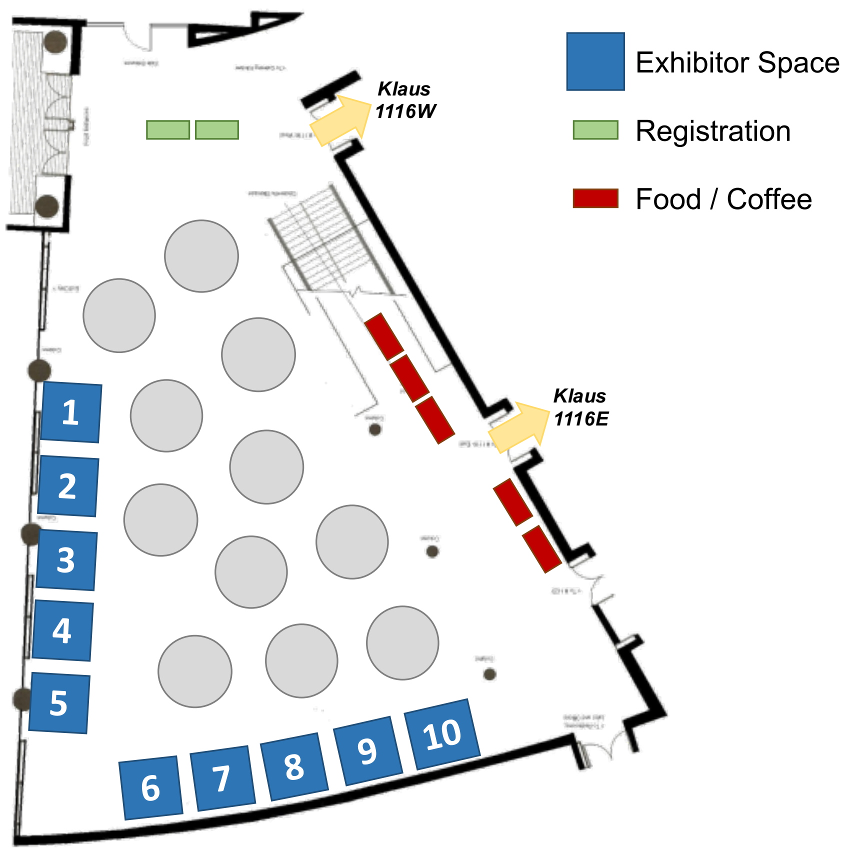
ILASS Service Awards will be presented at the Conference Banquet on Wednesday. The Simmons Award and the Marshall Award will be presented for the best paper and best student paper from the previous year's ILASS-Americas conference.

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 2017 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:



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 spray and gas fired gas turbine combustion systems and industrial processes. The expertise ranges from the basic science of liquid injection and sprays associated with a wide array of applications to study of complex practical configurations for atomization and spray formation, fuel/air mixing and combustion, swirl generation, and associated pollutant formation and operability performance and control.

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, liquid film thickness measurements, 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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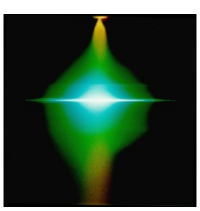
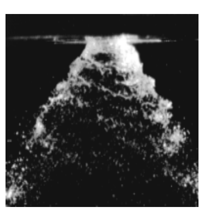
Email: Brown@ERC-Ltd.com Website: www.ERC-Ltd.com

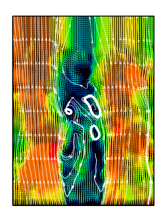


Phase Doppler Interferometry



High Speed Video

Reacting Spray Visualization



Particle Image Velocimetry

Revolutionizing high-speed camera technology

iX Cameras is a world-leading technology and product company specializing in the field of high-speed (slow motion) imaging. Based on proprietary innovative technologies, we design, build and sell cutting-edge ultra-fast cameras and software for a wide range of advanced scientific research applications. Our commitment to innovate and push the boundaries of high-speed video science is the reason we develop technically superior and easy-to-use products that our customers need to attain the highest scientific achievements and creativity. The innovation of our i-SPEED brand of cameras is backed by our world-class service and support teams, ensuring our customers' success.

Innovation built on our legacy
For over a decade, thousands of i-SPEED brand cameras were developed and sold by Olympus until the spinoff of the product development group in 2014. Today, the same heralded development team from Olympus, combined with new camera and software industry veterans, continues to design innovative state-of-the-art i-SPEED cameras under the iX Cameras name, always upholding the Olympus legacy of quality.

Scientists and Engineers in fluid dynamics and solid mechanics rely on measurements to make breakthroughs in applied research, technology development, and quality assurance.

Dantec Dynamics specializes in the development, manufacture and application support of measurement systems that acquire and analyze data of physical properties in fluids and in solid structures.

We deliver turnkey and customized solutions built on high-end laser optics, imaging, and sensor technologies. Our user-friendly software performs advanced data analysis and produces real-time results. Furthermore, we pride ourselves in providing our clients superior technical application support worldwide.

You gain accurate measurement results easily and quickly which help you accelerate the pace of discovery, innovation, quality control or NDT. Our distinct competence and experience in integrating measurement methods and technologies into the right solution for you, is unique.

Partnering with Dantec Dynamics helps you gain crucial knowledge from any test or measurement campaign.

Dantec Dynamics – Turn Measurements into Knowledge

En’Urga Inc.

Innovations in Quality Control

En’Urga Inc. is the industry leader in customized optical diagnostic equipment for the most challenging factory floor application. En'Urga Inc. has 20 years experience in optical diagnostics research, serving many Fortune 50 companies and Federal Government agencies. Our expertise in emission and absorption tomography in hostile environments enables measurement and control of varied processes in a wide array of industries. We specialize in research, design, development, calibration, and installation of instruments suitable for the measurement of temperatures, gas concentrations, emissivity, and particulate (liquid and powder) characteristics.

En’Urga Inc. currently has four products in their portfolio. The first product is the SETScan optical patternator. The 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 second product is the Spectraline imaging spectrometer. The Spectraline series of 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 highest speed 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.

The third product is the SPIvel velocimeter. 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 fourth product that En’Urga is introducing commercially this year 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.

All of En’Urga products can be leased or purchased from En’Urga Inc. 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. At En’Urga Inc., customer service and innovation are our primary goals.

UNDERSTANDING,
ACCELERATED

TSI Incorporated in Shoreview, Minnesota offers a complete line of products for spray diagnostics. Products include Phase Doppler Particle Analysis (PDPA) systems, Time-Resolved Particle Image Velocimetry (TR-PIV) systems, Global Patternation Systems, Global Sizing Velocimetry (GSV) systems and Quantitative Flow Visualization systems. These systems are used to characterize various aspects of a spray; from measuring droplet velocity and size at a specific location, to obtaining global information of the ligament formation, to identifying the breakup in a spray. Many of these systems are complementary to one other, helping the user to obtain the complete diagnostics of a spray.

The latest FSA9500/8500 series of processor is the newest development for our well renowned PDPA system for spray diagnostics. The new FSA series of processors offers the highest Doppler frequency input of more than 200 MHz and sampling rate of 1.5 GHz. The FPGA based processor is a complete system with the integrated color bar for optical signal input directly from the Phase Doppler receiver. The system also includes inputs for the OPR signal for periodic flows, external trigger signals and analog signals to be taken simultaneously with the velocity and size measurements.

The latest FSA processor is the most advanced and complete LDV/PDPA processor to provide you with the Power to do MORE for your spray diagnostic 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.phantomhighspeed.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.

100 Dey Road
Wayne, New Jersey 07470
sales@visionresearch.com

LaVision develops and sells integrated measurement systems for research and development in the areas of fluid mechanics, solid mechanics, microfluidics, liquid atomization, spray systems and combustion. Established over 25 years ago LaVision is the market leader in image based measurement systems and has sold systems and services into leading universities, companies and government labs worldwide. LaVision continues to strengthen its credibility in the field of fluid dynamics with its development of Tomographic PIV and Shake-The-Box Particle Tracking.

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Malvern offers many technologies for material and particle characterization, covering a wide range of industries.

ILASS attendees would be most interested in the **Spraytec,** a laser diffraction analyzer that provides droplet size distribution results. The Spraytec covers a size range from 0.1 micron to 2000 microns, and features a patented correction for multiple scattering that occurs in dense sprays. The Spraytec is IP65 rated so it can survive in harsh environments, such as spray chambers and wind tunnels. Data can be collected at speeds as fast as 10,000Hz, and is available immediately after the measurement. This 10,000 Hz is ideal for short pulse spray events such as DI injectors. Slower collection speeds can provide data output in real time. Data is output as a volume based distribution, and both Fraunhofer and Mie analysis are available. Typical output parameters include d10-d50-d90, %<10 microns, Span, and percent above/below specific size classes.

Malvern's Spraytec is available with many specialized accessories that make it extremely useful for wide angle sprays, pharmacuetical sprays, and consumer sprays.

Malvern is headquartered in Malvern, UK, with sales offices in most countries. In the US we are based in Westborough, MA. We look forward to your inquiries, and learning more about your spray application!

Joe Wolfgang | Product Manager, Diffraction, North & South America
Malvern Instruments | 117 Flanders Road, Westborough, MA 01581 US (based in Hopewell, NJ)
609-466-3929 / 609-273-8113 | Web **www.malvern.com**

Oxford lasers Inc.
As one of the most successful spin offs from Oxford University in 1977, Oxford Lasers have been at the forefront of laser technology for 40 years.
Through huge shifts in the industrial applications and technological requirements; from uranium enrichment in the 1980's to high speed imaging for the pharmaceutical market in the 2000's, Oxford Lasers adapted and brought new laser technology solutions to market. Proving their ability to invent solutions applied not just to laser technology, but to the business too.
Oxford Lasers continues to develop new systems and solutions. The substantial R&D department is involved in numerous UK & European research projects which enables them to keep to the forefront of laser micromachining and high speed imaging techniques and technologies.
Today, Oxford Lasers operates two divisions of the business; Imaging and Industrial, and have locations in America, France and the UK.

Imaging Division

Oxford Lasers Imaging Division offer laser systems, contract services, system rental, R&D and technical support for: High speed imaging, using high speed cameras, lasers and software to offer complete imaging solutions.

Oxford Lasers has significant experience within the field of spray characterisation, providing information on droplet size, droplet velocity and droplet shape. The VisiSize instrument range provides a range of capability to suit the different measurement challenges present in the field. Our VisiSize systems are not only Class 1 laser safe, but can range from portable systems right up to highly sophisticated systems that measure down to 2 microns and velocities up to 1500 m/sec. Even with high capability, the use of the VisiSize Software and maintenance of the laser system can all be learned in less than a day, allowing for several competent users.

Industrial Division

Oxford Lasers Industrial Division offer the full spectrum of fully automated Laser Micro-Machining Tools from Compact Laser Micromachining Tools; perfect for R&D and Pilot Production, through to Ultrafast Laser Micromachining Tools; utilising the highest precision industrial laser technology.

In conjunction with providing a significant range of Laser Micromachining Tools, Oxford Lasers Industrial Division also offer Subcontract Laser Micromachining Services. With nine in-house Laser Micromachining systems, capabilities include micro-drilling, milling, patterning, scribing and cutting in a vast array of materials from Metals to Glass and have covered over 10,000 niche applications across a variety of sectors.

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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. We have now introduced advanced particle imaging systems to allow easy and economic characterization of spray formation and drop size distributions. This method is also used for measuring aircraft icing sprays with mixed phase (liquid and ice) particles as well as large droplets that may be highly deformed.

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 based on the phase Doppler method and imaging have been designed for atmospheric cloud monitoring and aircraft icing research.** They 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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ILASS-Americas
Institute for Liquid Atomization and Spray Systems

Conference Schedule

ILASS-Americas 2017 Schedule

Monday, May 15

M 5:00-7:00 PM	**Registration**	*Klaus Atrium*
M 5:30-7:00 PM	**Welcome Reception with Exhibitors**	*Klaus Atrium*
M 7:00-8:00 PM	**Technical Committee Meetings** Diesel and Automotive Sprays Industrial, Agricultural & Biological Sprays Rocket & Airbreathing Power Fuel Atomization & Industrial Combustion	*Klaus 1116E* *Klaus 1116W* *Klaus Atrium*

Tuesday, May 16

T 7:00-7:45 AM	**Breakfast with Exhibitors**	*Klaus Atrium*
T 7:45-8:00 AM	**Welcome & Opening Remarks**	*Klaus 1116E-W*
T 8:00-9:00 AM	**Keynote Lecture** **A Multi-Fidelity Simulation Strategy for Rocket Injector Design Evaluation and Physics Extraction** Vigor Yang, Georgia Institute of Technology	*Klaus 1116E-W*
T 9:00-10:00 AM	**Plenary Session with Exhibitors** Chair: Lee Markle	*Klaus 1116E-W*

	Automotive Sprays I Chairs: S. Drennan & T. Fang *Klaus 1116W*	**Spray Applications** Chairs: V. Acharya & M. Somasi *Klaus 1116E*
T 10:10-10:30 AM	**Spray Characteristics of Multiple Fuels from a Gasoline Direct Injection Injector under Different Ambient Pressures** Z. Wu, L. Wang, J. Badra, W. Roberts, T. Fang *North Carlolina State University & Saudi Arabian Oil Company & King Abdullah University of Science and Technology*	**Numerical Analysis of the Flame Spray Process Applied to Nanoparticle Production** L. Buss, P. Bianchi Neto, H. Meier, U. Fritsching, D. Noriler *IWT Foundation Bremen & University of Blumenau & University of Bremen & University of Campinas*
T 10:30-10:50 AM	**Investigation of Spray Regimes for a Supercavitating Injector Geometry** D. Sykes, J. Gattoni, P. Yelvington *Mainstream Engineering Corporation*	**Spatial-Temporal Flow Dynamics Prediction in a Large Design Space via Data-Driven Method** Y. Chang, L Zhang, X. Wang, S. Yeh, S. Mak, C. Sung, C. Wu, V. Yang *Georgia Institute of Technology*
T 10:50-11:10 AM	**Study of Near-Cup Water Droplet Breakup of a Rotary Bell Atomizer Using Shadowgraph and High-Speed Imaging** J. Wilson, S. Grib, M. Renfro, S. Adams, A. Salaimeh *University of Kentucky & Ford Motor Company*	**Spray Characterization to Optimize Insecticide Performance** H. Jeon, D. Linscott, J. Schleier, M. Rushton, L. Gomez, M.Somasi *Dow AgroSciences LLC*
T 11:10-11:30 AM	**Break**	*Klaus Atrium*

Poster Exhibition *Tuesday - Thursday*	*Klaus Atrium*
Standardizing a Simplex Atomizer Andrew Thistle *Advanced Atomization Technologies*	**Analysis of Electrohydrodynamic Atomization using High-Speed Microscopy** William Doak, Paul Chiarot *SUNY Binghamton*

Tuesday, May 16

	Automotive Sprays II Chairs: D. Jarrabashi & D. Sykes *Klaus 1116W*	**X-Ray Diagnostics of Sprays (Invited Session)** Chairs: A. Kastengren & T. Meyer *Klaus 1116E*
T 11:30-11:50 AM	**Investigation on the Use of Unsteady Flamelet Modeling for Transient Diesel Spray Combustion Processes** S. Kim, D. Jarrahbashi, C. Genzale *Georgia Institute of Technology*	**Use of X-Ray Fluorescence for Multiphase Flow Applications** A. Kastengren *Argonne National Laboratory*
T 11:50-12:10 PM	**Demonstration and Validation of Urea Deposit Predictions on a Practical Mid/Heavy Duty Vehicle Aftertreatment System** Y. Sun, B. Vernham, S. Drennan *Isuzu Technical Center of America Inc. & Convergent Science Inc.*	**Exploration of Temporal and Time-Averaged Two-Phase Flow Structures Using X-Ray Diagnostics** K.-C. Lin, A. Kastengren, C. Carter *Taitech Inc. & Argonne National Laboratory & Air Force Research Laboratory*
T 12:10-12:30 PM	**Experimental Analysis of the Pollutant Emissions and Reaction Structure of a Diesel Spray Reacting in a High Temperature and Oxygen Reduced Environment** A. Colorado, J. Obando, A. García, A. Amell *University of Antioquia*	**X-ray Fluorescence Measurements of Hydraulic Flip in a Beryllium Nozzle** D. Duke, K. Matusik, N. Sovis, A. Kastengren, C. Powell *Monash University & Argonne National Laboratory*
T 12:30-12:50 PM	**Fuel Adhesion Characteristics of Flat Wall-Impinging Spray under DISI Engine Conditions** H. Luo, S. Uchitomi, K. Nishida , Y. Ogata, W. Zhang, T. Fujikawa *University of Hiroshima & Mazda Motor Corporation*	**High-Speed X-ray Fluorescence Measurements in an Impinging Jet Spray** B. Halls, J. Gord, A. Douglawi, N. Rahman, T. Meyer, A. Kastengren *Air Force Research Laboratory & Purdue University & Argonne National Laboratory*
T 12:50-2:00 PM	**Lunch**	*Klaus Atrium*
	Droplet Phenomena I Chairs: K. Feigl & J. Bennewitz *Klaus 1116W*	**Computational Methods for Atomization (Invited Session)** Chairs: M. Owkes & M. Trujillo *Klaus 1116E*
T 2:00-2:20 PM	**Measurement of the Burning Rate and Ignition Delay for Various Hydrocarbon Fuel Droplets Using Photothermal Ignition of Aluminum Nanoparticles** J. Bennewitz, A. Badakhshan, S. Schumaker, D. Talley *University of California Los Angeles & Engineering Research Corporation & Air Force Research Laboratoy*	**Importance of Curvature Length Scale for Accurate Predictions of Dynamic Interfaces** M. Owkes *Montana State University*
T 2:20-2:40 PM	**Oscillatory Behavior of Droplet Impacting on Hydrophilic Surface** F. Wang, T. Fang *North Carolina State University*	**Immersed Interface Method for the Direct Numerical Simulation of Air-Blast Primary Atomization** I. Lagrange, A. Orazzo, D. Zuzio, J.-L. Estivalèzes *ONERA the French Aerospace Laboratory*
T 2:40-3:00 PM	**The Effects of Different Surface Wettabilities on Droplet-Dry Substrate Impact Outcomes** M. Owen, M. Jog *University of Cincinnati*	**A Volume of Fluid Dual Scale Approach for Modeling Turbulent Liquid/Gas Phase Interfaces** D. Kedelty, J. Uglietta, M. Herrmann *Arizona State University*
T 3:00-3:20 PM	**Observation of the Coating Process in Spray Coating** J. Huang, Z. Yuan, S. Gao, J. Liao, M. Eslamian *University of Michigan-Shanghai Jiao Tong University Joint Institute*	**The Benefits of High-Order Interface Advection Schemes?** M. Trujillo, D. Ryddner, L. Anumolu *University of Wisconsin-Madison*
T 3:20-3:40 PM	**Computational Study of the Effect of Shear-Thinning Viscosity on Drop Behavior in Nozzle-Type Contraction Geometries** K. Feigl, A. Baniabedalruhman, F. Tanner, E. Windhab *Michigan Technological University & Yarmouk University & ETH Zurich*	**Numerical Simulations of Shock Waves, Gas Bubbles and Liquid Droplets** E. Johnsen, S. Beig *University of Michigan*
T 3:40-4:00 PM	**Break**	*Klaus Atrium*

Tuesday, May 16		
	Droplet Phenomena II Chairs: M. Eslamian & J. Michael *Klaus 1116W*	**Experimental Methods & Instrumentation** Chairs: I. Mastikhin & R. Padilla *Klaus 1116E*
T 4:00-4:20 PM	**Shear Driven Motion of a Liquid Drop on a Smooth Rigid Substrate** P. Seiler, I. Roisman, S. Matthes, C. Tropea *Technical University Darmstadt*	**Surface Tension Measurements of Mixtures at Elevated Pressures** R. Padilla, M. Lightfoot, S. Dancyzk *University of California Los Angeles & Air Force Research Laboratory*
T 4:20-4:40 PM	**Drop Impact onto a Hot Surface: Heat Transfer in the Nucleate Boiling Regime** J. Breitenbach, I. Roisman, C. Tropea *Technical University Darmstadt*	**Tomographic Reconstruction of Scattering Phase Function of Droplet in an Urea Injector** J. Lim, J. Green, Y. Sivathanu *En'Urga Inc.*
T 4:40-5:00 PM	**Multicomponent Droplet Breakup During Heated Wall Impact** A. Chausalkar, S.-C. Kong, J. Michael *Iowa State University*	**Ultra-Short Pulse Off-Axis Digital Holography for Imaging the Core Structure of Transient Sprays** M. Minniti, A. Ziaee, J. Trolinger, D. Dunn-Rankin *University of California Irvine & MetroLaser Inc.*
T 5:00-5:20 PM	**Simulation of Single Diesel Droplet Evaporation and Combustion Process with a Unified Diesel Surrogate** Q. Wang, C. P. Chen *University of Michigan-Shanghai Jiao Tong University Joint Institute*	**Magnetic Resonance Imaging with Prepared Magnetization: Application to a Near-Nozzle Region of a Flat Spray** I. Mastikhin, K. Bade, S. Ahmadi *University of New Brunswick & Spraying Systems Co.*
T 5:20-5:40 PM	**Interaction of Burning Droplets in a Linear Stream** N. Kumar,S. Sahu *Indian Institute of Technology Madras*	**Simultaneous Flame, Spray, and Flow Imaging in a High Pressure Swirl Combustor** H. Ek, I. Chterev, N. Rock, H. Ozogul, B. Emerson, T. Lieuwen, N. Jiang, J. Roy, J. Gord *Georgia Institute of Technology & Spectral Energies LLC & Air Force Research Laboratory*
T 5:40-6:40 PM	**Technical Committee Meetings** Spray Measurements & Instrumentation — *Klaus 1116E* Physics of Atomization — *Klaus 1116W* Computation and Modeling — *Klaus Atrium*	
T 6:40 PM	**Evening at Leisure**	

Wednesday, May 17

W 7:00-7:55 AM	**Breakfast with Exhibitors** *Klaus Atrium*	
W 7:55-8:00 AM	**Opening Remarks** *Klaus 1116E-W*	
W 8:00-9:00 AM	**Keynote Lecture** *Klaus 1116E-W* **Atmospheric Clouds: Droplets Evolving by Condensation and Collisions within Turbulent Flows** Raymond Shaw, Michigan Technological University	
	Recent Advances in Spray Diagnostics I (Invited Session) Chairs: D. Guildenbecher & M. Paciaroni *Klaus 1116W*	**Internal and Near Nozzle Behavior** Chairs: M. Sami & R. Torelli *Klaus 1116E*
W 9:10-9:30 AM	**Recent Advances in Spray Diagnostics Using X-rays** T. Heindel *Iowa State University*	**Internal Nozzle Flow Simulations of Gasoline-Like Fuels under Diesel Operating Conditions** R. Torelli, S. Som, Y. Pei, Y. Zhang, M. Traver *Argonne National Laboratory & Aramco Research Center-Detroit*
W 9:30-9:50 AM	**Recent Advances in Spray Diagnostics at the AFRL** J. Gord, B. Halls, S.Roy, T. Meyer, A. Kastengren *Air Force Research Laboratory & Spectral Energies LLC & Purdue Univeristy & Argonne National Laboratory*	**Comparison of Theoretical and Experimental Diesel and Biodiesel Internal Flow and Spray Characteristics** S. Yu, B. Yin, H. Jia *Jiangsu University*
W 9:50-10:10 AM	**Advances in the Phase Doppler Method for Dense Spray Measurements** W. Bachalo, G. Payne, C. Sipperley, K. Ibrahim *Artium Technologies Inc.*	**In-Nozzle Flow Investigations of Marine Diesel Injectors** R. Balz, A. Schmid, D. Sedarsky *Winterthur Gas and Diesel Ltd. & Chalmers University of Technology*
W 10:10-10:30 AM	**Development of Novel Diagnostic Techniques to Characterize Spray Flows Pertinent to Aircraft Icing Phenomena** H. Hu *Iowa State University*	**Primary Atomization of a Simplex Nozzle in an Eulerian-Lagrangian Framework** M. Sami, Rohitkumar Sonawane, V. Kumar *ANSYS Inc.*
W 10:30-10:50 AM	**Break** *Klaus Atrium*	
	Recent Advances in Spray Diagnostics II (Invited Session) Chairs: D. Guildenbecher & M. Paciaroni *Klaus 1116W*	**Multiphysics Control of Spray Formation and Dispersion (Invited Session)** Chairs: O. Desjardins & D. Bodony *Klaus 1116E*
W 10:50-11:10 AM	**Sub- and Supercritical Phase Diagnostics Using Filtered Rayleigh Scattering Methods** J. Estevadeordal, A. Cross, N. Jiang *North Dakota State University & GE Research & Spectral Energies*	**X-Ray Observations in the Spray Near-Field Using Synchrotron X-Rays** T. Heindel, D. Li, T. Morgan, J. Bothell, A. Aliseda, N. Machicoane, A. Kastegren *Iowa State University & University of Washington & Argonne National Laboratory*
W 11:10-11:30 AM	**Multi-Beam Illumination for Coping with Dense Sprays Using Imaging** W. Bachalo, G. Payne, K. Ibrahim, R. Karami *Artium Technologies Inc.*	**Experimental Characterization of a Canonical Coaxial Gas-Liquid Atomizer** N. Machicoane, A. Aliseda *University of Washington*
W 11:30-11:50 AM	**Quantitative, Bias-Corrected Measurements of Droplet Position, Size and Velocity with Digital In-line Holography** Y. Chen, D. Guildenbecher *Sandia National Laboratories*	**An Exploration of Initial Destabilization During Air-Blast Atomization Using 3D Simulations** R. Chiodi, L. Vu, O. Desjardins *Cornell University*
W 11:50-12:10 PM	**Uncertainty Characterization of Particle Location Using a Plenoptic Camera** E. Hall, D. Guildenbecher, B. Thurow *Auburn University & Sandia National Laboratories*	**Pairwise Interaction Extended Point-Particle (PIEP) Model for Droplet-Laden Flows: Towards Application to the Mid-Field of a Spray** G. Akiki, K. Liu, S Balachandar *University of Florida*
W 12:10-12:30 PM	**Inter-Plume Velocity Measurements to Understand Spray Collapse when Varying Injection Duration or Number of Injections** P. Sphicas, L. Pickett, S. Skeen, J. Frank *Imperial College London & Sandia National Laboratories*	**Advances in Adjoint-Based Methods: Application towards Multiphase Systems** S. Bidadi, M. Banks, D. Bodony *University of Illinois at Urbana-Champaign*

Wednesday, May 17		
W 12:30-1:40 PM	**Lunch** ILASS Americas Annual Business Meeting *Klaus Atrium*	
	Liquid Jets & Sprays in Crossflow (Invited Session) Chairs: M. Herrmann & K.-C. Lin *Klaus 1116W*	**Turbulence Phenomena in Sprays (Invited Session)** Chairs: O. Kaario & F. Tanner *Klaus 1116E*
W 1:40-2:00 PM	**Temporal Evolution of Liquid Jets in Supersonic Crossflows** K.-C. Lin, M.-C. Lai, T. Ombrello, C. Carter *Taitech Inc. & Wayne State University & Air Force Research Laboratory*	**Proper Orthogonal Decomposition Analysis of The Engine Combustion Network "Spray A"** H. Kahila, O. Kaario, A. Wehrfritz, V. Vuorinen *Aalto University*
W 2:00-2:20 PM	**Validation of a Compressible Interfacial Flow Solver Using Jet in Crossflow** W. Hagen, D. Garrick, M. Owkes, J. Regele *Iowa State University & Montana State University*	**Effects of Subgrid-Scale Dispersion Modeling on Large-Eddy Simulation of Non-Evaporative and Evaporative Diesel Sprays** C.-W. Tsang, C. Rutland *University of Wisconsin-Madison*
W 2:20-2:40 PM	**High-Fidelity Simulations of High-Viscosity Liquid Jet Atomization in Crossflow** X. Li, H. Gao, M. Soteriou *United Technologies Research Center*	**Numerical Study of the Interaction between Turbulence and Surface Tension Using One-Dimensional Turbulence** A. Movaghar, M. Linne, M. Oevermann, R. Chiodi, O. Desjardins, A. Kerstein *Chalmers University of Technology & University of Edinburgh & Cornell University & Kerstein Consulting*
W 2:40 PM	Bus Transport to NARA Campus *pick-up in back of Klaus Bldg.*	
W 3:00-4:45 PM	**Break & Snacks** **Tour of the Combustion Lab** *NARA Campus*	
W 4:45 PM	Bus Transport to Renaissance Hotel *pick-up at NARA Campus*	
W 5:00-5:30 PM	**Break** *Hotels*	
W 5:30 PM	Bus Transport to the Park Tavern *pick-up at Renaissance Hotel*	
W 6:00-7:00 PM	**Cocktail Reception** *Park Tavern*	
W 7:00-9:00 PM	**Conference Banquet** **Awards Presentation** *Park Tavern*	
W 9:00 PM	Bus Transport back to Hotels (*Drop-offs: Renaissance, Courtyard and Regency Suites*)	

Thursday, May 18

Time	Klaus 1116W	Klaus 1116E
R 7:00-8:00 AM	**Breakfast with Exhibitors** *Klaus Atrium*	
	Atomization Theory, Analysis & Modeling Chairs: K. Matusik & P. Khare *Klaus 1116W*	**Compressible Atomization (Invited Session)** Chairs: J. Regele & B. Bornhoft *Klaus 1116E*
R 8:00-8:20 AM	**Analysis of Near-Field Spray Behavior with Highly-Resolved Simulations** S. Gurjar, M. Trujillo *University of Wisconsin-Madison*	**Numerical Simulation of Aerated-Liquid Injection with Various Nozzle Designs** B. Bornhoft, K.-C. Lin, J. Edwards *Taitech Inc. & North Carolina State University*
R 8:20-8:40 AM	**Frequency Behavior of the Large Scale Instability in Assisted Atomization of a Liquid Jet** A. Delon, J.-P. Matas, A. Cartellier *Grenoble Alpes University & University of Lyon*	**Characterization of Secondary Atomization in Compressible Crossflows** D. Garrick, W. Hagen, J. Regele *Iowa State University*
R 8:40-9:00 AM	**Modeling and Numerical Study of Primary Breakup under Diesel Conditions** A. Movaghar, M. Linne, M. Herrmann, A. Kerstein, M. Oevermann *Chalmers University of Technology & University of Edinburgh & Arizona State University & Kerstein Consulting*	**Aerodynamic Breakup of Liquid Metal in a Shock-Induced Crossflow** M. Arienti, Y. Chen, J. Wagner, D. Guildenbecher *Sandia National Laboratories*
R 9:00-9:20 AM	**Numerical Study of Stochastic Particle Dispersion Using One-Dimensional-Turbulence** M. Fistler, D. Lignell, A. Kerstein, M. Oevermann *Chalmers University of Technology & Brigham Young University & Kerstein Consulting*	**Modeling and Simulation of Diesel Injection at Transcritical Conditions** P. Ma, M. Ihme, L. Bravo *Stanford University & Army Research Labratory*
R 9:20-9:40 AM	**Modeling the Dense Spray Regime Using an Euler-Lagrange Approach with Volumetric Displacement Effects** P. Pakseresht, S. Apte *Oregon State University*	**Numerical Study of Liquid Jet Atomization in Supersonic Crossflows** O. Desjardins, M. Natarajan, M. Kuhn *Cornell University*
R 9:40-10:00 AM	**Modeling the Influence of Nozzle-Generated Turbulence on Diesel Sprays** G. Magnotti, K. Matusik, D. Duke, B. Knox, G. Martinez, C. Powell, A. Kastengren, C. Genzale *Georgia Institute of Technology & Argonne National Laboratory*	**A Volume-of-Fluid Sharp Interface Method for Simulating the Interaction of Shocks with Immiscible Interfaces** K. Kannan, D. Kedelty, M. Herrmann *Arizona State University*
R 10:00-10:20 AM	**Break** *Klaus Atrium*	
	Spray Characterization & Measurements I Chairs: K. Bade & L. Pickett *Klaus 1116W*	**Spray Image Analysis/3D Imaging (Invited Session)** Chairs: Benjamin Halls & A. Kastengren *Klaus 1116E*
R 10:20-10:40 AM	**Experimental Investigation of Spray Characteristics of High Reactivity Gasoline and Diesel Fuel Using a Heavy-Duty Single-Hole Injector, Part I: Non-Reacting, Non-Vaporizing Sprays** M. Tang, J. Zhang, T. Menucci, H. Schmidt, S.-Y. Lee, J. Naber, T. Tzanetakis *Michigan Technological University & Aramco Research Center-Detroit*	**Voids, Bubbles, Holes, and Complex Three-Dimensional Spray Structures Revealed by High-Speed X-ray Imaging** T. Meyer, N. Rahman, A. Douglawi, C. Radke, B. Halls, J. Gord, A. Kastengren *Purdue University & NASA-Johnson Space Center & Air Force Research Laboratory & Argonne National Laboratory*
R 10:40-11:00 AM	**Experimental Investigation of Spray Characteristics of High Reactivity Gasoline and Diesel Fuel Using a Heavy-Duty Single-Hole Injector** J. Zhang, M. Tang, T. Menucci, H. Schmidt, S.-Y. Lee, J. Naber, T. Tzanetakis *Michigan Technological University & Aramco Research Center-Detroit*	**Dynamic Measurement of Liquid Sheet Formed by Two Low-Speed Impinging Jets via Partial Coherent Interferometry** W. Shang, J. Chen *Purdue Univeristy*

Thursday, May 18

	Spray Characterization & Measurements I (Continued)	Spray Image Analysis/3D Imaging (Continued)
R 11:00-11:20 AM	**On the Effects of Liquid Viscosity on the Spray Characteristics of Spray Dry Nozzles** K. Bade, R. Schick *Spraying Systems Co.*	**Fragment PDF(D)s for Drops Impacting a Thin Liquid Surface** L. Yao, J. Chen, P. Sojka, D. Guildenbecher *Purdue University & Sandia National Laboratories*
R 11:20-11:40 AM	**Characterization of Flame Sprays Generated by an Air-Assisted Atomization Nozzle** U. Fritsching, F. Meierhofer *University of Bremen & Foundation Institute of Materials Science Bremen*	**Size-Velocity PDFs for Drop Fragments Formed via Bag Breakup** C. White, G. Sondgeroth, W. Shang, L. Yao, J. Chen, P. Sojka, D. Guildenbecher *Purdue University & Sandia National Laboratories*
R 11:40-12:00 PM	**Quantification of Sauter Mean Diameter in Diesel Sprays Using Scattering-Absorption Extinction Measurements** G. Martinez, G. Magnotti, B. Knox, C. Genzale, K. Matusik, D. Duke, C. Powell, A. Kastengren *Georgia Institute of Technology & Argonne National Laboratory*	**Size-Velocity PDFs for Drop Fragments Formed via Multi-Mode Breakup** G. Sondgeroth, C. White, W. Shang, L. Yao, J. Chen, P. Sojka, D. Guildenbecher *Purdue University & Sandia National Laboratories*
R 12:00-1:00 PM	**Lunch and Drawing for Prizes** *Klaus Atrium*	
	Spray Characterization & Measurements II Chairs: U. Fritsching & E. Lubarsky *Klaus 1116W*	**Atomization & Spray Simulations** Chairs: M. Arienti & D. Schmidt *Klaus 1116E*
R 1:00-1:20 PM	**The Effect of Doublet Injector Orifice Geometry on Spray Characteristics** S. Leask, V. McDonell *University of California Irvine*	**An Analysis for the Convergence of Stochastic Lagrangian/Eulerian Spray Simulations** D. Schmidt, F. Bedford *University of Massachusetts & Siemens Product Lifecycle Management Software Inc.*
R 1:20-1:40 PM	**Size-Velocity PDFs and Dynamic Sheet Profiles for Impinging Jet Atomizer-Produced Sprays** S. Denker, B.Gutman, C. White, W. Shang, J. Chen, Paul E. Sojka, D. Guildenbecher *Purdue University & Sandia National Laboratories*	**A Finite Particle Approach for the Simulation of Multiphase Flows** E. Wenzel, S. Garrick *University of Minnesota*
R 1:40-2:00 PM	**Hydrodynamics of Precisely Controlled Droplet Train Impinging upon a Liquid Film** T. Zhang, J. Muthusamy, J. Alvarado, A. Kanjirakat, R. Sadr *Texas A&M University and Texas A&M University-Qatar*	**Planar Liquid Sheet Breakup Mechanisms, Time Scales and Length Scale Cascade** A. Zandian, W. Sirignano, F. Hussain *University of California Irvine & Texas Tech University*
R 2:00-2:20 PM	**Experimental Study of Twin-Fluid Jet-in-Crossflow at Jet-Engine Operating Conditions** Z. Tan, E. Lubarsky, O. Bibik, D. Shcherbik, B. Zinn *Georgia Institute of Technology*	**Explaining the Planar Liquid Jet Atomization via Vortex Dynamics** A. Zandian, W. Sirignano, F. Hussain *University of California Irvine & Texas Tech University*
R 2:20-2:40 PM		**Primary Atomization of a Liquid Dodecane Jet Using the Ghost-Fluid Method** K. Satheesh, S. Hemchandra *Indian Institute of Science Bangalore*
R 2:40-3:00 PM		**Evaluation of Spray/Wall Interaction Models under Conditions Related to Diesel Engines with a Hybrid Breakup Model** W. Qi, W. Zhang, P. Ming *Harbin Engineering University*
R 3:00 PM	**Conference Closes**	

Keynote Abstracts

ILASS-Americas 29th Annual Conference on Liquid Atomization and Spray Systems, Atlanta, GA, May 2017

Keynote Lecture

A Multi-Fidelity Simulation Strategy for Rocket Injector Design Evaluation and Physics Extraction

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Abstract

This lecture will address a multi-fidelity simulation strategy for rocket injector design evaluation and physics extraction. An interdisciplinary research will be presented for the development of an efficient and robust capability to understand, analyze, and predict the flow and flame dynamics of injectors for contemporary rocket engines. The effort requires extensive knowledge in supercritical combustion, reduced-basis modeling (emulation), statistics, uncertainty quantification, and machine learning. Recent breakthroughs in modeling and data analytics techniques are utilized to substantially improve the modeling capabilities at all levels. New techniques will be discussed to address issues specific for physics extraction and design evaluation of a complex system. The effect of all known parameters (e.g., design attributes and operating conditions) on injector behaviors will be surveyed effectively and efficiently, with practical turn-around times.

The integrated approach starts with LES-based high fidelity modeling and simulations of injector dynamics. Reduced-basis models and emulation then leverages the database established by LES for a physics-based data assimilation. Stochastic-based extraction of physics from complex flowfields provides faithful and interpretable representations of underlying mechanisms. Feature extraction techniques are incorporated into a spatio-temporal surrogate model built upon machine-learning techniques such as Gaussian process (GP) regression. Combined with statistical methodologies and control theories, these techniques allow for an efficient survey of flow evolution and flame dynamics. Data-driven quantification of the transfer function between the identified mechanisms will be achieved.

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ILASS-Americas 29th Annual Conference on Liquid Atomization and Spray Systems, Atlanta, GA, May 2017

Keynote Lecture

Atmospheric Clouds: Droplets Evolving by Condensation and Collisions within Turbulent Flows

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Abstract

Atomized liquids exist in a multitude of applied and natural systems, and while each application may have unique aspects, some aspects are universal. Perhaps one of the most widely encountered examples of a liquid aerosol is an atmospheric cloud. Kindergarteners sketch their cauliflower-shaped outlines and daydreamers envision their evolving figures. But, zooming in, we know that warm clouds (warm meaning those that contain no ice) consist of a dispersion of water droplets and that relevant cloud properties like brightness and precipitation efficiency depend on various moments of the particle size distribution. The evolution of the droplet size distribution takes place primarily by water vapor condensation (and evaporation) and by droplet coalescence (and breakup). Parallels with measurement and theoretical challenges facing the ILASS community therefore abound, and some of them will be illustrated here.

How droplet diameter changes with time due to condensation or evaporation, given a known water vapor concentration and temperature, is basically a solved problem. The challenge comes when one considers competition between droplets residing in spatially and temporally varying water vapor concentration and temperature fields constantly mixed by turbulence. Take as an example the seemingly simple question, how does a droplet size distribution respond when dry air from outside a cloud is entrained? Some fraction of the condensed water mass will evaporate in order to reach a new equilibrium state (that is, assuming that the entrained air is not so dry that all of the liquid evaporates). But consider that the evaporation could proceed in any number of scenarios between these two extremes: On the one hand, all droplets could evaporate by the same amount, causing the size distribution to shift to smaller size, but maintaining a constant number concentration; On the other hand, some subset of the droplets could evaporate completely, leaving the remaining droplets unchanged, thereby reducing the number density but keeping the mean diameter constant. These two limits have become known, respectively, as homogeneous and inhomogeneous mixing, and can be understood as limiting values of a cloud version of the Damkoehler number. That is, a ratio of a turbulent mixing time and a cloud droplet–thermodynamic response time. These concepts lead to intriguing, yet counter-intuitive implications, such as entrainment and evaporation eventually promoting the growth of some subset of droplets that eventually spur the onset of precipitation.

Ultimately, precipitation in warm, ice-free clouds, is thought to require that droplets begin to collide and coalesce in order to form large drops with appreciable fall speeds within reasonable times. Here, turbulence again rears its head. Calculating a geometric collision rate for droplets falling in a quiescent flow already is not a simple problem, and extending this to the turbulent case is considerably more challenging still. Water droplets have a mass density about 1000 times that of air, so under sufficiently turbulent conditions they tend to preferentially concentrate into regions of high strain or low vorticity. Furthermore, even droplets on a geometric collision course will not necessarily collide due to microhydrodynamic interactions, the adjusted rate being expressed usually as a collision efficiency. Adding electric charge makes the problem still more complex. Finally, once precipitation is developed, the problems of spontaneous and collision-induced drop breakup may become relevant for predicting a raindrop size distribution. Knowing the shape of that distri-

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Abstracts

Spray Characteristics of Multiple Fuels from a Gasoline Direct Injection Injector under Different Ambient Pressures

Zengyang Wu[1], Libing Wang[1], Jihad A. Badra[2], William L. Roberts[3], Tiegang Fang[1,*]
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King Abdullah University of Science and Technology
Thuwal, Saudi Arabia

Abstract

This study explores the spray characteristics of light naphtha (LN), primary reference fuel (PRF) and neat gasoline under different ambient pressures with GDI fuel injector. Gasoline (E10) (AKI (anti-knock index) = 87) used in this study was obtained from three different local gas stations to account for the variation of fuel properties. The AKI is an average of the research octane number (RON) and the motor octane number (MON). Naphtha is a less processed petroleum stream with gasoline-like boiling range. Normally, the naphtha fuels have lower octane number (research octane number ~65) than normal gasoline. PRF is a gasoline surrogate mixture comprising iso-octane and n-heptane. PRF95, the blend of 95% iso-octane and 5% n-heptane by volume, was used in this study as a surrogate for high-octane gasoline. Five different ambient pressure conditions were selected from 1 bar to 10 bar. The spray is visualized using a high-speed camera with Mie-scattering technique. The spray structure, spray angle, spray penetration length and spray front fluctuation are discussed. The result shows that higher ambient pressures generally lead to larger spray angle for all three fuels. Neat gasoline always has the largest spray angle at each ambient condition, while the spray angle of PRF95 is the smallest. For each fuel, spray penetration length and spray penetration velocity decrease with increasing ambient pressure. All three selected fuels have similar penetration length and penetration velocity under each ambient pressure condition. A two-stage spray front fluctuation distribution is remarked for all three fuels. Stage one begins from the start of the injection and ends at 450 µs to 500 µs ASOIT with slow fluctuation increasing for all ambient conditions. The spray front fluctuation increases rapidly to a certain level and then becomes stable in stage two.

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Numerical Analysis of the Flame Spray Process Applied to Nanoparticle Production

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[3] Department of Particles and Process Engineering, University of Bremen, Germany
[4] DEPro Department of Process Engineering, University of Campinas, Brazil

Abstract

Nanomaterials can be synthesized using different processes and techniques. Flame Spray Pyrolysis (FSP) has become a versatile and scalable process for synthesizing nanometer-sized metal oxide powders. In general lines, there are two ways to perform studies to find the best set-up. One way is performing experiments and the other method is through numerical simulations. Experimental studies of FSP processes are very well developed, but the mathematical modeling still has some gaps. The development of models to simulate the flame sprays and the formation and growth of nanoparticles is intrinsic since the input parameters are connected to the characteristics of nanoparticles. The use of computational fluid dynamics techniques is a way to achieve an optimal configuration of reactor design and operational conditions. Within the FSP process for nanoparticles synthesis, the effects of the enclosure and co-flow injection on the spray flame structure and on the nanoparticle properties were investigated by means of numerical simulations. A mathematical model was carried out considering two-way coupling between the gas and liquid phases. For the combustion reaction modeling, Eddy Dissipation Concept (EDC) model is employed, considering the droplet vaporization effects, chemical reaction mechanisms, and chemistry-turbulence interactions. A population balance equation (PBE) model is implemented to analyze growth and sintering of nanoparticles and the particle deposition on the reactor walls is considered. Numerical results are compared with experimental data to validate the model and to study the potential influence of significant parameters on the FSP process. With 6.667 L/s of co-flow gas, the temperature profile inside the reactor is similar than the open reactor configuration (with natural gas entrainment) and the primary particle size diameter is around 10 nm. By decreasing the co-flow gas, strong recirculation zones and particle deposition on the wall are observed. Large (nano-sized) particles are produced by decreasing the co-flow gas to 0.667 L/s. In this situation, the temperature increases considerably and strong recirculation zones and vortex regions inside the reactor are observed, resulting in larger primary nanoparticles diameters.

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Investigation of Spray Regimes for a Supercavitating Injector Geometry

D. M. Sykes*, J. M. Gattoni, and P. E. Yelvington

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Abstract

Downsized, boosted, high-speed diesel engines are pushing common-rail diesel injector technology to the limits of manufacturability. This study examines an alternative supercavitating geometry that adds a second large-diameter section to the end of a conventional hole-type geometry. This geometry creates a rapid expansion that promotes controlled cavitation within the nozzle and discourages nozzle-to-nozzle interactions. Several supercavitating nozzle prototypes have been fabricated and tested in a spray chamber with high-speed imaging to determine the effect of geometry, fluid properties, and operating conditions on the spray morphology. Dodecane, used for the majority of the testing as a diesel surrogate, was supplied at high pressures (up to 6.92 MPa) to the nozzle and issued into a pressurized chamber (up to 860 kPa at 25 °C) to generate sprays. Our previous studies had shown that the droplet size for this geometry can be 15.5% lower than conventional geometries. In the present study, an idealized supercavitating geometry was incorporated in a transparent nozzle to allow visualization of both internal flow field and external spray. Spray angle for the supercavitating geometry was observed to be up to six times larger compared to conventional geometries, and the spray angle was controlled primarily by the dimensionless cavitation index. Changes in spray angle were correlated to flow phenomena inside of the nozzle geometry. Also, it was found that the discharge coefficient for the supercavitating geometry is significantly larger than for the conventional geometry.

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Spatial-temporal flow dynamics prediction in a large design space via data-driven method

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Abstract

This is an interdisciplinary study combining machine-learning techniques, statistics, and physics analyses. To develop a robust propulsion system efficiently, understandings of underlying physics, coupling, and conflicting of the design parameters are significantly important to achieve the optimal design. The large eddy simulation (LES) technique has been widely used to simulate flow physics and combustion characteristics inside rocket engines for decades; however, it consumes great amount of time and resources, which is impractical for design purposes. The purpose of this work is to predict spatial-temporal flowfields using data-driven surrogate model in a short turnaround time. Our previous study has demonstrated a novel design strategy based on the Kernel-smoothed proper orthogonal decomposition (KSPOD) for the swirl injector design. The instantaneous flow dynamics in swirl injectors were well predicted in a small geometry range via kriging based weighting function from design matrix. To further discuss the capability of the emulator for the instantaneous turbulent flow dynamics, the current work extends the design method to a large design space across RD-0110 and RD-170 engines. Overall, the emulator captures most of the flow dynamic details. It also well predicts the performance measurements such as the liquid film thickness and the spreading angle. At the same time, the turnaround time for evaluating a new design point is reduced significantly compared with other algorithms and the resultant CPU time is over 2,000 times shorter than that in the LES simulation.

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Study of Near-Cup Water Droplet Breakup of a Rotary Bell Atomizer Using Shadowgraph and High-Speed Imaging

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Abstract

Rotary bell atomizers are used as the primary means of paint application by the automotive industry due to their high paint transfer efficiency and enhanced surface finish quality. They utilize high rotational speed of a serrated cup to provide primary atomization of the liquid, and shaping air to provide secondary atomization and to transport the subsequent droplets. In order to better understand the fluid breakup mechanisms involved in this process, an optical setup involving shadowgraph high-speed imaging was used to image the edge of a serrated rotary bell at speeds varying between 5,000 and 10,000 RPM and at a water flow rate of 250 ccm. A multi-step image processing algorithm was also developed to differentiate between ligaments and droplets during the primary atomization process. The results of this experiment showed higher bell speeds resulted in lower ligament and droplet formations. Additionally, both ligament (ranging from 40-400 μm) and droplet (ranging from 40-200 μm) hydraulic diameters formed bimodal distributions. Velocity and associated hydraulic diameter statistics were also calculated for the various cases using particle tracking velocimetry. It was found that droplet velocities did not vary with hydraulic diameter, but did vary slightly with RPM, indicating that the droplets were more driven by the rotational speed of the bell than the ligaments, whose velocities are more dependent on other factors such as liquid flow rate.

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Spray Characterization to Optimize Insecticide Performance

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Abstract

Efficacy of crop protection products can be affected by a variety of variables chief among which is spray coverage on the target substrate. Generally speaking, increasing coverage for insecticides via fine droplet sprays leads to better efficacy and lower application rates. However, finer droplets are prone to physical drift through the air, which in turn could lead to off-target crop injury, in the case of herbicides, or runoff leading to a less-than-optimal environmental profile. Therefore, it is critical to characterize the spray tank mix to determine the effect of application conditions (nozzle type, height, pressure, wind, etc.) and the formulation composition (dynamic surface tension, evaporation time, contact angle, etc.) for optimal performance with minimal drift potential. In this work, a generic framework will be presented to understand the key parameters affecting product activity for an insecticide formulation. Under this framework, several agrochemical spray tank mixes were characterized by contact angle, droplet evaporation time, and spray droplet size spectrum in laboratory conditions. These data were then correlated with greenhouse efficacy trials on cotton aphids. Our studies showed that droplet contact angle and evaporation time have the greatest influence in controlling cotton aphids using the example formulation. On the other hand, efficacy was not influenced significantly by the use of low drift nozzles. The technique presented in this work will enable options to optimize efficacy via tank mix adjuvants in combination with specific application conditions to minimize spray drift.

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Investigation on the use of unsteady flamelet modeling for transient diesel spray combustion processes

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Abstract

This study seeks to explore the use of unsteady flamelet modeling in the numerical simulation of steady-state flame development and combustion recession in a chemically reacting diesel spray following an end-of-injection transient. The heterogeneous mixture formation in sub-grid scale and turbulence-chemistry interaction are modeled with the use of a Representative Interactive Flamelets (RIF) model. The RIF model has been incorporated with a Eulerian Particle Flamelet Model (EPFM) approach that employs multiple flamelets to leverage the unsteady flamelet history. The results are compared against a first-order moment method, i.e. Well-Stirred Reactor (WSR) model. The simulations have been performed with a Reynolds Averaged Navier-Stokes (RANS) framework incorporated within the commercially-available CFD code, CONVERGE. The present study demonstrates the prediction capability of two combustion models, and characterizes the predicted ensemble-averaged turbulent mean scalars in comparison to experimental observations from the Engine Combustion Network (ECN). Detailed analysis of simulations employing varying number of flamelets in the RIF-EPFM approach reveal some artificially induced combustion instabilities that manifest as an oscillatory behavior of the flame lift-off length. This instability is found to be alleviated by properly tracking flamelet scalar-dissipation-rate history; i.e. further increase of flamelets attenuate the oscillations in reaction zone. Moreover, it is shown that the use of flamelet model better captures the experimentally observed end-of-injection combustion, so-called combustion recession in terms of ensemble-averaged turbulent mean quantities of reaction zone.

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Use of X-Ray Fluorescence for Multiphase Flow Applications

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Abstract

X-ray measurements have been used for decades to examine optically inaccessible multiphase flows. These diagnostics have relied on absorption to provide contrast for measurements. Over the past twenty years, as synchrotron x-ray sources have been applied to multiphase flow measurements, other contrast modalities have been used, including phase contrast and small angle scattering. Over the past six years, x-ray fluorescence has been explored to provide measurements unavailable with other contrast modalities. This paper will provide a description of x-ray fluorescence and its application to multiphase flow measurements. A brief overview of the potential of the technique and future directions for measurements will also be described.

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Demonstration and Validation of Urea Deposit Predictions on a Practical Mid/Heavy Duty Vehicle Aftertreatment System

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Abstract

Urea-SCR systems have become required equipment on mid/heavy duty diesel on and off road vehicles to reduce NOx emissions. These systems have proven effective at reducing NOx over a wide range of operating conditions. However, design changes related to reducing the size to modern compact Urea/SCR systems and lower exhaust temperatures have increased the possibility of urea deposit formation. Urea deposits result when urea in films and droplets undergoes undesirable secondary reactions that produce by-products such as Ammelide, Biuret and Cyanuric Acid (CYA). These by-products are difficult to decompose and will build up forming a solid deposit that can reduce aftertreatment system performance by decreasing overall mixing, lowering de-NOx efficiency and increasing pressure drop. Avoiding or mitigating urea deposits is a primary design goal of modern aftertreatment systems. This paper presents CFD simulation approaches to urea deposit predictions using both simple urea decomposition containing only thermolysis and hydrolysis for deposit risk analysis and detailed urea decomposition scheme with 12 reactions to identify actual urea deposit formations in the exhaust system. The paper will present the application of both of these urea decomposition approaches on a practical Isuzu aftertreatment system and compared against experimental data. The experimental data encompass a variation in Diesel Emission Fluid (DEF) flow rate, exhaust gas temperatures and flow rate, that all formed liquid films but only a subset for solid deposits. Urea de-posits form where films exist in a deposit forming temperature window so it is critical to accurately predict the temperature of the urea/water film. Conjugate Heat Transfer (CHT) is used with advanced splashing and film evaporation models to correctly predict the film temperature. Wall film properties are used to identify risky deposit formation region. The locations and conditions identified as being at risk for deposit formation agree well with the experimental data. The next step was to include detailed multi-step urea decomposition mechanism to predict the actual formation of urea decomposition by-products that make up urea deposits. A modified two-liquid evaporation model was used with the detailed decomposition mechanism to capture the proper evaporation rate of water for film predictions. The detailed urea decomposition approach was validated against fundamental experiments for single drops, sprays, spray-wall interactions that are also presented. Finally, the detailed decomposition approach was applied to the Isuzu case and good agreements with experimental data were achieved.

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Exploration of Temporal and Time-Averaged Two-Phase Flow Structures Using X-Ray Diagnostics

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Abstract

Time-averaged and temporal structures of the two-phase flows within the nozzle of an aerated-liquid injector were experimentally explored with synchrotron x-ray diagnostics, including pathlength-integrated and confocal x-ray fluorescence and x-ray high-speed imaging. A beryllium nozzle with a constant passage diameter was fabricated to mate with an aerated-liquid injector featuring the outside-in aerating scheme. Water and nitrogen were doped with x-ray fluorescent elements at low concentrations to facilitate the x-ray diagnostics. The present study shows that the two-phase flows inside the nozzle section exhibit an annular-like flow pattern, while the aerating gas is distributed in a Gaussian-like pattern. Axial distributions of the average liquid density, gas density, and liquid velocity were also explored by integrating the line-of-sight properties over several cross-sectional areas and axial locations within the nozzle section. For the first time on these sprays, a confocal x-ray fluorescence measurement was carried out with a polycapillary x-ray optic to spatially resolve the cross-sectional mass distributions within the near field of various discharged plumes. Plume separation phenomena were readily observed in both liquid and gas plumes. High-speed imaging shows that large-scale structures are mainly present in the plenum section and can be aerodynamically stretched into fine structures near the nozzle exit.

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Experimental Analysis of the Pollutant Emissions and Reaction Structure of a Diesel Spray Reacting in a High Temperature and Oxygen Reduced Environment

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Abstract

The experimental burner used in this study consists of an optically accessible chamber that confines a central spray of diesel issuing into a flow of oxidant gas at high temperature and reduced concentration of oxygen (O_2<12%); those settings simulate the conditions of the flameless combustion regime, also known as colorless combustion, high temperature air combustion (HiTAC) or MILD combustion. In flameless mode, the reactions take place at conditions above the self-ignition temperature of the fuel, thus an ignition source is not necessary as the oxidant flow is purposely maintained above this temperature. With flameless combustion, there is no flame front, no visible flame, no UV or ionization detection, and no noise or roar. The emissions of CO, NO_x, soot and UHC are abated to very small residual values. The combustion products of a fully premixed natural gas burner located upstream of the spray nozzle are used to keep the chamber above the self-ignition temperature and as the oxidant flow for the diesel spray. The oxygen concentration of the flow used for burning the diesel spray is controlled by varying the excess of air of a natural gas premixed burner. The temperatures of the combustion products before the diesel injector, the internal walls, and the exhaust after the diesel reactions are measured with a set of thermocouples. Various levels of oxygen concentration in the oxidant are assessed (4 and 12 % O_2, by volume). The reaction structure of the diesel spray under variable oxidant composition and temperature is visualized using OH* chemiluminiscence; also the effect of the hot co-flow on the emissions of NO_x, CO, and UHC is measured using on-line gas analyzers.

Keywords: Diesel spray; flameless; low-NO_x; OH*; soot.

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X-ray Fluorescence Measurements of Hydraulic Flip in a Beryllium Nozzle

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Abstract

Spray nozzles with constant or diverging diameters are known to be subject to the phenomenon of hydraulic flip, where the fluid detaches from the nozzle wall prior to exiting the nozzle. This can have a significant impact on atomization; it is well established that hydraulic flip can substantially increase the breakup length of a jet. Geometric cavitation inside the nozzle often occurs under similar conditions to those that produce a flipped jet. The interactions between these phenomena are not fully understood. Hydraulic flip is challenging to study, particularly in round nozzles. Changes in refractive index between the nozzle wall material, ambient gas, and liquid make it very difficult to obtain good optical access at the nozzle exit plane. Strong geometric dependence and hysteresis in onset conditions makes it difficult to extend observations in rectangular nozzles to the axisymmetric case. It is also difficult to measure the difference between a void generated by cavitation inside the nozzle, and displacement of the liquid due to encroachment of the ambient gas. In this paper, we demonstrate a novel X-ray fluorescence experiment to study hydraulic flip in an X-ray transparent beryllium nozzle with diameter 330 µm and length 2 mm. The ambient gas was doped with 3% krypton and time-averaged measurements of krypton fluorescence allowed the volume fraction of ambient gas to be quantitatively measured both inside and outside the nozzle. A polycapillary X-ray optic was used to allow the detector to observe only a small portion of the focused 15 keV X-ray beam where it intersected the nozzle. We found that for a fluid with a vapor pressure much lower than the back pressure, the ambient gas can travel as far upstream as the nozzle inlet lip due to stabilized flow separation and displacement of cavitation voids.

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Fuel Adhesion Characteristics of Flat Wall-Impinging Spray under DISI Engine Conditions

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Abstract

The direct injection is a very attractive technology for improving fuel economy and engine performance in gasoline engines. However, it is difficult to avoid the spray impingement of fuel on the combustion chamber wall and piston head, which is a possible source of hydrocarbons and soot emission. This work investigated the spray and impingement on a flat wall by a mini-sac injector with a single hole. Different ambient pressures and injection pressures were investigated. The evolution of the impinging spray was obtained by the Mie scattering method. The spray tip penetration and vortex height under different conditions were discussed. The bottom view of the fuel film was acquired by the Refractive Index Matching method. The fuel film mass, area, and thickness under different conditions were compared. The SMD and velocity of droplets were measured by the microscopic imaging method. The effects of injection pressure and ambient pressure on SMD, velocity, and fuel film were investigated. The effect of droplets behaviors on adhered fuel film mass are obtained.

Keywords: DISI engine, Spray, Wall impingement, Fuel film, SMD

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High-Speed X-ray Fluorescence Measurements in an Impinging Jet Spray

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Abstract

A high-speed x-ray fluorescence measurement technique is developed to quantify the path-integrated liquid–liquid mixing in an impinging jet spray. Mixing is inferred from the amount of each liquid present along the x-ray beam. Measurements are made at the Sector 7 bending magnet beamline at the Advanced Photon Source located at Argonne National Laboratory. The x-ray beam is spatially focused to 5×6 μm^2, and spectrally filtered to 15±0.2 keV. The 15 keV beam excited sodium bromide doped into the spray and PIN diodes collected the fluorescence signal (captured orthogonally to the x-ray beam to minimize scatter) and the transmission signal. Two Reynolds numbers are investigated and measurements are performed with the x-ray beam perpendicular to the liquid sheet and parallel to the liquid sheet. Two measurements, for each condition, are performed with the tracer doped in one jet to determine the mixing and doped in both jets for calibration and normalization. The accuracy and precision of the measurements are quantified and the limitations of the technique are discussed. This manuscript has been cleared for public release by the Air Force Research Laboratory.

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Measurement of the Burning Rate and Ignition Delay for Various Hydrocarbon Fuel Droplets using Photothermal Ignition of Aluminum Nanoparticles

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Abstract

Combustion of a wide range of hydrocarbon fuel droplets has been achieved through photoignition (PI) utilizing sub milligram of aluminum nanoparticles (Al NPs). For diesel fuel, a reliable ignition was made possible by mixing a solid oxidizer with the Al NPs. PI offers a fast (<5 ms) gasless reaction, a high ignition temperature (>2000 K), and a relatively short total ignition duration (80-200 ms). Droplets with a diameter of 1.4±0.1 mm were suspended from a 0.15 mm quartz fiber, then ignited through PI and in a few cases with a Ni-Cr heating wire. The burning rate constant *K* for ethanol, heptane, n-dodecane, kerosene (RP-2), Fischer−Tropsch synfuel (FT), and diesel #2 was found to be 0.83±0.01, 0.95±0.01, 0.90±0.01, 0.77±0.02, 0.99±0.01 and 0.71±0.05 mm^2/s, respectively. PI also allows the evaluation of ignition delays via high-speed imaging of the luminous flame. Ignition delays as short as 50 ms were observed, which are much smaller than those achieved by conventional ignition methods at atmospheric pressure (>400 ms). The dramatically shorter ignition delay may be explained in part by the extremely fast local heating effect (estimated to exceed 10^5 K/s) and the high burning temperature of Al NPs in the vicinity of the droplet.

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Importance of curvature length scale for accurate predictions of dynamic interfaces

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Abstract

The curvature of a gas-liquid interface is directly proportional to the surface tension force and a large amount of work has created many numerical approaches to compute this curvature. However, the analysis of these methods has historically been performed with static test cases with the goal of improving the accuracy of the curvature calculation. In this work, we show that for dynamic interfaces the accuracy is not as important as the length scale the curvature is computed on. For example, when the temporal evolution of a standing wave is computed it is found that second- and fourth-order height function methods perform similarly to each other. This is a surprising results because the fourth-order method is significantly more accurate for computing the curvature of the static wave. We hypothesize that the curvature scale relative to the velocity scale which creates interface perturbations is the important characteristic of the curvature scheme. To test this hypothesis further, we developed a numerical method to compute curvatures that allows the length scale to be varied and analyze the behavior of the scheme over a range of curvature scales. We demonstrate that the curvature scale does control the accuracy of the interface dynamics and identify an optimal curvature scale. These results provide insight into considerations for future interface curvature calculation methodologies and demonstrate that static test cases are not adequate to predict how methods will perform when applied to realistic dynamic problems.

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Oscillatory Behavior of Droplet Impacting on Hydrophilic Surface

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Abstract

Droplet impacting on a solid substrate with medium Weber number usually exhibits obvious oscillatory behavior during the post-impact process, in terms of droplet spread and thickness variation. Investigation of this behavior can effectively help predict the evolution of spread factor, which is of high interest in many applications (ink-jet printing and pesticide spraying), and evaluate the roles of inertia, viscous forces and surface tension in droplet impact dynamics. In this work, water droplets of different sizes (0.2~1.7 mm) with varying impact velocities (0.9~3.9 m/s) were dropped from a piezoelectric droplet generator onto a polished, smooth aluminum surface. The instant droplet-surface interaction process was captured by a high-speed video camera at 10,000 frames per second and with a spatial resolution higher than 20 pixel/mm. MATLAB® was employed to detect the droplet profile, extract the oscillation frequency and calculate other droplet parameters for further analysis. Droplet impact images (side view and tilted view), and temporal evolution of droplet spread and thickness were provided in this paper. Damped oscillation phenomenon was well displayed by the variation of spread and thickness factor under $We<120$. Irregularities were found in the oscillation curve of thickness factor for droplets with $We>40$, which was further explained by the independent motion of the central lamella and the surrounding rim. It was found that the oscillation frequency of spread factor and thickness factor were nearly the same and an empirical equation was obtained to correlate the oscillation frequency with fluid properties. Proposed damped harmonic oscillator model is successful in predicting the oscillatory behavior in the experimental results.

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Immersed Interface Method for the Direct Numerical Simulation of air-blast primary atomization

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Abstract

Many two-phase Direct Numerical Simulations of atomization process mostly focus on the interaction between the liquid main body and the airflow. However, the characteristics of the injector internal flow may strongly affect the atomization process. Two main approaches allow the proper simulation of the whole injector system. The first involves using unstructured body-fitted meshes. The second one, employed here, is to include an irregular geometry in structured Cartesian meshes with an Immersed Interface Method (IIM). We propose an incompressible projection method for the resolution of two-phase Navier-Stokes equations to simulate atomization devices. A second-order IIM has been adapted to a Level Set/Volume-of-Fluid (CLSVOF) method. A new velocity advection algorithm has been used [1] for ensuring mass and momentum conservation in presence of large density ratios and gas shearing characterizing the considered flows. The irregular domain is defined by means of a second Level Set function in order to get a sharp representation of the interface. The presence of the solid implies the enforcement of wall boundary conditions at the solid interface. The no-slip boundary condition on the velocity is handled on the viscous term using a Ghost-Cell formalism. The resulting Neumann boundary condition for the pressure is directly taken into account in the discretization of the Poisson equation by defining a fluid fraction function over the cell faces. A special treatment adapted to the CLSVOF method is employed for the jump conditions on the pressure field due to the surface tension in the triple-point cells, where both the solid and the liquid-gas interfaces are present. The method has been validated on some academic test cases. Then, it has been used to simulate the primary atomization of a two-dimensional liquid sheet considering a simplified air-blast injector system. The main macroscopic behaviors of the liquid sheet have been compared with the relative experiments.

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The Effects of Different Surface Wettabilities on Droplet-Dry Substrate Impact Outcomes

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Abstract

Evaporation of chemicals can result in fumes in the air. In work environments where they could be inhaled, these can pose negative short term or long term health effects. Splashing of a droplet after impacting a dry surface can result in formation of small liquid particles which may evaporate in air. To minimize and better control this fully in future situations, understanding properties the enable or enhance to splash is important. To this end, the relationship between wettability and the behavior of secondary droplets has been computationally investigated in this paper using OpenFOAM. Computational results are validated against experimental measurements reported in the literature. Then test cases of droplets of diameters between 1-3 mm and impact velocities between 1.5-3.5 m/s with varying surface tensions, densities, and kinematic viscosities are run. Dynamic contact angles between the substrate and impinging droplet range between 20 and 150 degrees while the Reynolds number varies from 1800 to 14000, the Weber number ranges from 590 to 731, and Ohnesorge number is from 0.002 to 0.01. Resulting predicted splashing behaviors such as coronas and fragments are described. The predicted patterns of secondary droplet formation are charted. Explanations for the predicted outcomes are offered.

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A Volume of Fluid Dual Scale Approach for Modeling Turbulent Liquid/Gas Phase Interfaces

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Abstract

In atomizing flows, the properties of the resulting liquid spray are determined by the interplay of fluid and surface tension forces. The resulting flow and interface 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 contribution, advances to a dual-scale modeling approach (Herrmann, 2013) are presented to describe turbulent two-phase interface dynamics in a large-eddy-simulation-type spatial filtering context. Spatial filtering of the governing equations introduces several sub-filter terms that require modeling (Toutant et al., 2008). These include terms associated with sub-filter acceleration, transport, viscous effects, and surface tension. Instead of developing individual closure-models for each of the terms associated with the phase interface, the proposed dual-scale approach uses an exact closure by explicitly filtering a fully resolved realization of the phase interface. This resolved realization is maintained on a high-resolution over-set mesh using a Refined Local Surface Grid approach (Herrmann, 2008) employing an un-split, geometric, bounded, and conservative Volume-of-Fluid method (Owkes and Desjardins, 2014). The advection equation for the phase interface on this DNS scale requires a model for the fully resolved interface advection velocity. This velocity is the sum of the LES filtered velocity, readily available from the LES approach solving the filtered Navier Stokes equation, and the sub-filter velocity fluctuation that has two contributions. The first is due to sub-filter turbulent eddies, the second is due to sub-filter surface tension forces. We propose four different methods to reconstruct the sub-filter turbulent eddy fluctuation velocity using the fractal interpolation approach of Scotti & Meneveau (1999). Results of the dual-scale model are compared to recent direct numerical simulations of a phase interface in homogeneous isotropic turbulence (McCaslin and Desjardins, 2015).

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Observation of the Coating Process in Spray Coating

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Abstract
Spray coating is a facile coating and deposition process with numerous existing and emerging applications. However, it is a stochastic process comprising impingement of many droplets, which upon impact on a heated substrate may dry individually or coalesce first to make a thin liquid film and then dry to make a thin solid film. There is very limited knowledge on how this process occurs; therefore in this work, high speed imaging is used to visualize the spray coating process. Two model solutions including food-dye with properties similar to those of water, and PEDOT:PSS, a polymeric solution, are sprayed onto glossy paper and regular glass substrates. Substrates are kept at room temperature and elevated temperature of 80 °C. In some cases, a vertical ultrasonic vibration is imposed on the substrate to study its effect on the coating process. In conclusion, it is observed that the spray coating process is highly random and stochastic. A higher substrate temperature results in better coating process. Imposed vibration in the case of glossy paper substrates results in better droplet spreading and a more uniform coating, whereas in the case of glass substrate results in droplet "walking" on the substrate. Further systematic study is required to better understand the process.

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The Benefits of High-Order Interface Advection Schemes?

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Abstract

Recent numerical methods for implicit interface transport are generally presented as enjoying a higher order of spatial-temporal convergence when compared to classical methods or less sophisticated approaches. However, when applied to test cases, which are designed to simulate practical industrial conditions, a significant increase in error is observed in higher-order methods, whereas the less sophisticated method maintains a smaller growth in the error norms. This provides an opportunity to understand the underlying issues which causes this decrease in accuracy in both types of methods. As an example we consider the Gradient Augmented Level Set method (GALS) and a variant of the Volume of Fluid (VoF) method in our study. Results show that while both methods do suffer from a loss of accuracy, it is the higher order method that deteriorates to a greater degree. The implication is a significant reduction in the performance advantage of the GALS method over the VoF scheme. Reasons for this lie in the behavior of the higher order derivatives, particular in situations where the level set field is highly distorted.

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Computational Study of the Effect of Shear-Thinning Viscosity on Drop Behavior in Nozzle-Type Contraction Geometries

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Abstract

Emulsions are encountered in many manufacturing processes in the food and pharmaceutical industries. To enhance its shelf life and stability, emulsions can be sprayed to produce powders. During the spraying process, the structure of the emulsion should be 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 contraction domain representing a spraying nozzle. The simulations are performed by solving a two-phase flow problem in the contraction domain, where individual drops are tracked through the flow field. A modified version of the interDyMFoam solver of the open source software, OpenFOAM, is used as a basis for the simulations. The droplet phase is taken to be a Newtonian fluid, while three different fluids are taken for continuous phase: a Newtonian fluid and two shear-thinning non-Newtonian fluids with different degrees of shear-thinning. The focus is on the effect that a shear-thinning viscosity has on the breakup conditions, in particular the critical drop size and critical capillary number. It is found that along a given streamline, there is a non-monotonic behavior in the critical drop size as the degree of shear-thinning increases. This is due in part to the decreased shear stresses and in part to the increased viscosity ratio as shear-thinning increases.

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Numerical simulations of shock waves, gas bubbles and liquid droplets

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Abstract

In problems ranging from cavitation erosion to shock-induced droplet break-up, compressible flow features such as shock and rarefaction waves interact with gas-liquid interfaces. The extension of shock capturing, the established numerical approach to accurately represent shock waves, is not straightforward for gas-liquid flows. We present an interface-capturing approach capable of accurately and robustly representing shock waves and high-density-ratio material interfaces, without generating spurious pressure or temperature errors at material discontinuities. Our spatial scheme is high-order accurate in smooth regions and nominally non-dissipative in that high-order discontinuity capturing is applied only at sharp gradients detected by a discontinuity sensor. We use this approach to investigate the collapse of gas bubbles near solid surfaces and the break up of liquid droplets by the passage of a shock wave.

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Shear driven motion of a liquid drop on a smooth rigid substrate

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Abstract

Shear driven drop motion on rigid substrates is a phenomenon relevant to various applications, e.g. process engineering, multiphase transport, printing, furthermore it determines the process of ice accretion or vehicle soiling. The drop motion on a wall is governed by the forces associated with the substrate wettability, viscous forces in the drop and the driving aerodynamic forces. Prediction of the conditions for incipient drop motion and the estimation of the drop translational velocity is a challenging task, since the problem is three-dimensional and time dependent. In order to gain a better physical understanding of this phenomenon, an extensive experimental data basis is required. In the present study, the motion of a water drop placed on the wall of a turbulent, two-dimensional Hagen-Poiseuille flow is investigated. Time-resolved drop profiles and the three-phase contact line are visualized with shadowgraphy and video recordings. At constant velocity of the airflow, the incipient drop motion is determined for varying parameters: drop volume, surface wettability, air velocity. Finally, an empirical model for the average drop velocity as a function of the gas velocity gradient is developed.

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Surface Tension Measurements of Mixtures at Elevated Pressures

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Abstract

An experimental study has been conducted to determine the effects of high pressures on the surface tension of H_2O-N_2 and MeOH-CO_2. The motivation for this work is operations at high pressure and temperature, such as diesel and rocket engines. At high pressures and temperatures the system moves towards its thermodynamic critical point. The interfacial behavior as liquid moves towards this critical condition is not well understood. To examine the interface behavior, an experiment was developed to measure surface tension at different pressures. The experimental setup consists of a pool of either water and methanol placed inside a pressure vessel whic was pressurized with N_2 or CO_2, respectively. Capillary waves are created on the liquid surface using a metal rod that is attached to a speaker and excited via a function generator. Diffused light illuminates the liquid and waves are captured with a digital camera. Waves are observed in MeOH-CO_2 below 5 MPa and as the critical pressure was approached the solubility of CO_2 into methanol increased and contributed to lowering the amplitude of the waves. Surface tension decreased significantly in MeOH-CO_2 compared to H_2O-N_2 due to the increased solubility and the widening of the interface region due to nearing the critical point of MeOH-CO_2. Experimental challenges in making surface tension measurements in these conditions are also discussed.

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Water drop impact onto a hot surface: heat transfer in the nucleate boiling regime

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Abstract

Outcomes from an isothermal drop impact without phase change onto a solid surface (rebound, deposition or splash) are determined by the impact parameters, liquid material properties, substrate morphology and wettability. However, if a drop impacts onto a hot surface additional effects arise, for example, Marangoni flow, nucleate or film boiling, evaporation, or temperature dependent fluid properties. By varying the surface temperature the phenomena of drop impact can be changed significantly. Various thermodynamic and hydrodynamic regimes can be observed and constitute the basis of the current study.

The main subject of this experimental study is the characterization of the hydrodynamic outcome of a single drop impact onto a hot surface. Drop impact phenomena have been observed and characterized using a high-speed video system. The impact parameters and the surface temperature have been varied. The observations lead to a classification of impact outcomes into several thermodynamic regimes (evaporation, nucleate boiling, transitional boiling, and film boiling) and hydrodynamic impact regimes (drop deposition, drop rebound, and drop breakup). The contact time of the impinging drop on the surface has been measured for the nucleate boiling regime and a model for this time and for the heat flux from the substrate to the drop has been proposed. Comparison of model predictions to existing literature data is good.

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Tomographic Reconstruction of Scattering Phase Function of Droplet in an Urea Injector

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Abstract

Mie theory relates scattering phase function of droplets to the size distribution. Line of sight scattering intensity distributions of the droplets were measured at 30 degree off the incidence angle using a modified SetScan optical patternator. A reconstruction algorithm for local scattering phase function was developed and theoretically validated. The reconstructed scattering phase function provides the first moment of the PDF of drop size distribution, and can be used to estimate the spatial distribution of Sauter Mean Diameter (SMD) of the droplets. The SMD distribution in a pressure atomizer was estimated from the local scattering phase function was validated against 2-D grid scan of PDPA measurements At higher pressure condition, the local scattering phase functions are more uniform than the distribution at lower pressure condition. The SMD distribution from the scattering phase function agrees well with the PDA measurement when the shape of PDF of drop size distribution is maintained.

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Multicomponent droplet breakup during heated wall impact

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Abstract

The regimes of single droplet breakup behavior during wall impact are critical to the prediction and optimization of fuel vaporization and mixing in combustion systems. These impacts often take place at elevated wall temperatures and at significant impact velocities resulting in a wealth of physical phenomena. In this paper, regimes of droplet impact, breakup, and rebound were characterized during heated wall impact. Mixtures of n-heptane and n-decane were used to represent low and high boiling point fuel components, respectively. Surface temperatures were varied from 27 to 300 °C for Weber numbers ranging from 20 to 664 across a range of mixing ratios of n-heptane and n-decane to represent low and high boiling point fuel components, respectively. The droplet impact events were observed with high speed imaging. Results include the comparison of impact sequences identifying the transitions between film vaporization, nucleate boiling, and film boiling as functions of both Weber number and surface temperature. Qualitative imaging results were used to identify regimes of impact as a function of the ratio of n-heptane and n-decane. For high Weber number, the transition to film boiling were observed at temperatures below the Leidenfrost point for pure n-decane droplets. At these conditions, secondary droplet formation measurements during prompt splashing and film boiling breakup provides droplet sizing and its number.

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Ultra-short Pulse Off-axis Digital Holography for Imaging the Core Structure of Transient Sprays.

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Abstract

A single-shot Ultra-short Pulse Off-axis Digital Holography (UPODH) system is used to successfully image microscopic details of fuel injection phenomena that are hidden from view by a dense cloud of droplets surrounding the near nozzle region. The experiment approximates the optically dense conditions typical of fuel injection in modern diesel engines. Under these conditions an outer layer of small droplets can hide a core of larger droplets or liquid ligaments; this core is inaccessible to most imaging techniques due to multiple-scattering in the outer layer. These conditions are mimicked by intentionally surrounding a core spray with a fine mist. The mist has a SMD of 4.28 microns. The core spray comes from driving water, with pressure ranging from 10 to 200 PSI, through single orifices of 0.1 and 0.3 mm diameter. The system shows nearly opaque transmissivities as low as $6x10^{-6}$. Transient phenomena, such as sheets of liquid becoming ligaments and their further break up into small particles are easily visible even when surrounded by the opaque mist with an optical density (OD) of 12. Holographic reconstruction allows these phenomena to be clearly observable in 3D, and a planar resolution of 30 microns is achieved. The 3D capability allows UPODH to bring into focus small particles and ligaments at different depth planes, even several millimeters apart.

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Simulation of single diesel droplet evaporation and combustion process with a unified diesel surrogate

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Abstract

Real diesel fuel is composed of hundreds to thousands of components and is not suitable for multi-dimensional spray combustion simulations. Besides, the diesel spray combustion process involves both thermo-physical (heating and evaporation) and chemical (ignition and combustion) process. Therefore, unitizing a surrogate fuel with only a few representative components that can accurately capture both physical and chemical properties of real diesel fuel is essential for diesel spray combustion calculations. To this end, we have recently developed a "unified" surrogate that can simultaneously mimic the physical properties, distillation curve and combustion characteristics (ignition delays and laminar flame speeds) of a real diesel fuel. The developed surrogate has four representative components C_9H_{12}(1,2,4-trimethylbenzene), $C_{10}H_{18}$(trans-decalin), $iC_{16}H_{34}$ (heptamethylnonane), and $C_{16}H_{34}$ (n-hexadecane) from the hydrocarbon groups of linear paraffins, cyclo-paraffins and aromatics with mole fraction: 0.262/0.065/0.365/0.319. The purpose of this study is to use this surrogate to study a single diesel droplet's heating/evaporation and ignition process and compare the simulation results to experimental data. In this study, the recently developed discrete multicomponent modeling methodology with finite thermal and mass transfer rate was used to perform the single liquid droplet's heating, evaporation and ignition process. A detailed chemical kinetics of 352 species with 13264 reactions is used for ignition prediction. Comparisons are then made among surrogate droplet simulation results with experimental data. Our proposed multi-components surrogate model gives good prediction for both heating/evaporation and ignition delay times when compared with single diesel droplet's experimental data.

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Magnetic Resonance Imaging with prepared magnetization: application to the near-nozzle region of a flat spray

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Abstract

Magnetic Resonance Imaging (MRI) is a non-invasive, 3D imaging modality where a sample is magnetized inside a homogeneous magnetic field, and then excited and detected with a radiofrequency (RF) probe in the presence of a magnetic field gradient to encode an element of spatial information, with the process repeating until the 3D dataset is acquired (total imaging time: sec – min). Its usefulness for medical, biological and materials studies is primarily based on its flexibility: its signal intensity can be sensitized to a wide variety of physical and chemical parameters. This is usually achieved by so-called "preparation techniques" which involve a combination of RF pulses, magnetic field gradient pulses, and time delays, which are followed by the detection stage ("readout"). Typical timescales for the preparation are in the milliseconds-to-seconds range. This represents a challenge if one studies fast-moving flows: the measurement must have a characteristic measurement time short enough to enable the detection while the sample is still inside the RF probe (typically several cm long). We had recently showed an application of MRI inside the nozzle and the near-nozzle regions of a flat spray. In this work, we applied a short-timescale preparation and detection approach to sprays. A flat narrow-angle spray from a ceramic nozzle was reliably imaged over the 5 cm-long RF probe. The following image sets were acquired: density maps, Time-of-Flight maps, and T1rho-sensitized maps. The latter activate sensitivity to local periodic motions, and can be of interest for studies of atomization in the near-nozzle region.

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Interaction of Burning Droplets in a Linear Stream

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Abstract

In the present paper, linear streams of periodically generated mono-dispersed fuel (ethanol) droplets are investigated under ambient conditions. The purpose is to study convective interaction of burning droplets, and the role of surrounding air turbulence on combustion of interacting droplets. Droplet measurements (size, and separation distance) are obtained by Shadowgraph technique. In addition, long exposure flame visualization images are also recorded. Experiments are performed for different initial droplet sizes and inter-separation distances. Each case is considered with and without droplet stream burning corresponding to pure evaporation and combustion of droplets, respectively. The results show that interaction of neighboring droplet vapor clouds significantly reduces the evaporation rate of burning droplets within the stream in comparison to that of a freely falling isolated droplet, which can be predicted by the d^2-law. Thus, smaller distance parameter (normalized droplet separation) results in smaller evaporation coefficients of interacting droplets. The distance parameter also influences the flame length since smaller the droplet spacing higher is the vapor accumulation, and so, longer is the flame. Far downstream, combustion of droplets promotes droplet collision and coalescence. Droplet combustion experiments are also performed with in a box of turbulence, which can generate at the center of the box nearly zero-mean turbulent flow field at required turbulent intensity. Preliminary results are presented. Experiments based on a suspended droplet at the center of the box identified non-stationary flame around the droplet when surrounding air turbulent intensity is high, which may even lower the evaporation rate of the droplet. Interaction of the flame surrounding the droplet stream and the turbulent air flow field was found to lead to collision and coalescence of droplets such that the overall effect of burning on droplet size is not significant in comparison to pure evaporation of droplets.

Keywords

Mono-sized droplets, Droplet burning rate, distance parameter, Flame length, Isotropic Turbulence

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Simultaneous Flame, Spray, and Flow Imaging in a High Pressure Swirl Combustor

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Abstract

This paper presents measurements of the simultaneous flame position and flow velocity in a high pressure, liquid fueled combustor. Liquid fuels injected in swirling flows are commonly used in gas turbines, but data collection and analysis pose a challenge in the two-phase, reacting flow field, particularly when operating at high pressure. Measurements in a liquid fueled, swirl combustor were performed using simultaneous, high speed stereo-PIV, OH-PLIF and fuel-PLIF. The OH and fuel fluorescence were separated, and regions of liquid fuel, OH and liquid fuel+OH were identified during data reduction. The measurements were taken at elevated pressures to visualize the gaseous and liquid flow field, heat release region and fuel spray distribution. This paper extends work in a prior paper by analyzing the sensitivity of the physical locations of these regimes to the processing approach.

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Recent Advances in Spray Diagnostics using X-rays

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Abstract

Liquid sprays play a key role in many engineering processes (e.g., food processing, coating and painting, 3D printing, fire suppression, agricultural production, combustion systems, etc.). Spray characteristics can easily be assessed in the mid- and far-field regions, well after liquid sheet breakup and droplet formation, using various optical/laser diagnostic techniques. The conditions in the near-field region can influence mid- and far-field characteristics; however, near-field measurements are extremely challenging because the spray in this region is typically optically dense where optical/laser diagnostics are ineffective. This paper will present the advantages and challenges of using X-rays to characterize the near-field region of a spray. X-rays produced with tube sources and synchrotron sources will be discussed. Using tube-source X-rays, 2D radiographic movies are possible showing qualitative spray information. The 2D radiographs can also provide quantitative measurements of the spray equivalent path length (EPL) in the near-field region. Tube sources can also provide X-ray computed tomography imaging that can produce time-average 3D density (mass distribution) maps of the spray. X-rays from synchrotron radiation provides a high-flux and/or monochromatic X-ray beam that can be used to provide high spatial and temporal resolution of the spray, but is more challenging to implement than using a common tube source. Various examples of these X-ray imaging techniques will be discussed.

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Internal Nozzle Flow Simulations of Gasoline-Like Fuels under Diesel Operating Conditions

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Abstract

Spray formation in internal combustion engines with direct injection is strictly correlated with internal nozzle flow characteristics, which are in turn influenced by fuel physical properties and injector needle motion. This paper presents a series of 3D simulations that model the in-nozzle flow in a 5-hole mini-sac diesel injector. Two gasoline-like naphtha fuels, namely full-range and light naphtha, were tested under operating conditions typical of diesel applications and were compared with n-dodecane, selected from a palette used as diesel surrogates. Validated methodologies from our previous work were employed to account for realistic needle motion. The multi-phase nature of the problem was described by the mixture model assumption with the Volume of Fluid method. Cavitation effects were included by means of the Homogeneous Relaxation Model and turbulence closure was achieved with the Standard k-ε model in an Unsteady Reynolds-Averaged Navier-Stokes formulation. The results revealed that injector performance and propensity to cavitation are influenced by the fuel properties. Analyses of several physical quantities were carried out to highlight the fuel-to-fuel differences in terms of mass flow rate, discharge coefficients, and fuel vapor volume fraction inside the orifices. A series of parametric investigations was also performed to assess the fuel response to varied fuel injection temperature, injection pressure, and cross-sectional orifice area. For all cases, the strict correlation between cavitation magnitude and saturation pressure was confirmed. Owing to their higher volatility, the two gasoline-like fuels were characterized by higher cavitation across all the simulated conditions. Occurrence of cavitation was mostly found at the needle seat and at the orifice inlets during the injection event's transient, when very small gaps exist between the needle and its seat. This behavior tended to disappear at maximum needle lift, where cavitation was absent for all fuels. Differences in mass flow rate between the naphtha fuels and n-dodecane were measured and ascribed to the different densities of the three fuels. Nevertheless, they were found to be smaller than expected, owing to the lower viscosity of the gasoline-like fuels. This beneficial influence of the lower viscosity was shown to be less effective at higher temperature, where the relative viscosity differences decreased.

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Recent Advances in Spray Diagnostics at AFRL

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Abstract

Recent advances in diagnostic development have been made in the area of spray and droplet research at the Air Force Research Laboratory at Wright-Patterson Air Force Base. These developments have occurred in four key areas: ballistic imaging; vapor–droplet imaging; high-speed synchrotron measurements; and three-dimensional tomographic imaging. A novel approach to extend the range of ballistic imaging for dense sprays by varying the time-gate duration has been developed and demonstrated in scattering media. Vapor–droplet imaging and differentiation has been achieved though tailored-quenching fluorescence lifetime emission. High-speed synchrotron measurements have been extended to "white beam" imaging of mass distribution and mixing in dense sprays and high-speed fluorescence to measure mixing near the nozzle exit. Two imaging systems have been developed to capture the three-dimensional mass distribution fields in dense and dilute sprays. An x-ray system with two sources and two detectors has been developed and tomographic spray measurements have been performed. A laser-based system with a single laser and single detector coupled to a quad-scope has been employed to make 3D droplet LIF measurements in a dilute spray. These accomplishments will help pave the way for future discoveries in spray research and spray model validation.

Comparison of Theoretical and Experimental Diesel and Biodiesel Internal Flow and Spray Characteristics

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Abstract

The internal flow in nozzle and macroscopic spray characteristics of diesel and biodiesel are investigated by employing a validated numerical model and a laser-based Mie-scattering technique. The results indicate that diesel exhibits larger mass flow rate and the orifice exit average velocity than biodiesel. Also, the diesel consistently produced higher intensity of cavitaiton and turbulence kinetic energy, confirming that diesel fuel can boost the naissance of caivtation and the turbulence disturbance inside the orifice. Meanwhile, the cavitaiton intensity and the turbulence kinetic energy increase dramatically as the injection pressure increases, and also the caivtation domain is constant with the domain of high turbulence kinetic energy. Furthermore, the radial velocity for diesel is significantly higher than biodiesel at the same injection pressure, and also the radial velocity increased as the injection pressure increased. Moreover, biodiesel fuel, in spite of longer spray tip penetration, shows narrower spray cone angle when compared to diesel under the same injection pressure, due to the higher surface tension and viscosity for biodiesel with weaker aerodynamics and the caivtation intensity and turbulence kinetic energy in the orifice，and also the smaller radial velocity at the nozzle exit, which in turn contribute to narrow the spray cone angle for biodiesel.

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Advances in the Phase Doppler Method for Dense Spray Measurements

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Abstract

Phase Doppler Interferometry (PDI, PDA, PDPA) continues to be one of the most useful spray measurement instruments since its invention in 1980. A key limitation to PDI has been the requirement that only one droplet passes the measurement volume at a given time. This limits the maximum particle number density that the instrument can reliably measure, based on random arrivals. Coincident particle occurrences also introduce the probability of underreporting values such as number density, volume flux, and volume-based statistics.

In this paper we present a new approach to capturing and analyzing PDI signals that allows for multiple droplets in the measurement volume at the same time. Existing signal processing systems rely on analog and/or digital Doppler burst signal detection that are reliable when coincident arrivals of particles at the probe volume are limited. However, under high number density conditions, these signal detection systems can remain active during several particle arrivals and accept this information as a single event only to be rejected later or to produce a faulty measurement. A new signal processing approach has been developed that allows for capturing long burst records that can contain multiple Doppler signals. New processing algorithms use this extended record and partition signals into sub-records which are then processed for the individual droplet signals. This approach enables recovery of individual measurements that would have been lost with conventional phase Doppler signal processors.

Results when measuring a monodisperse droplet stream which has a known droplet generation rate with a large measurement volume (guaranteeing multiple droplets at the same time) are presented to show the method can recover the full data rate in contrast with conventional systems. Additional results from measurements in a dense spray are compared with a simple sampling tube to show recovery of the volume flux and number density in challenging environments.

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In-Nozzle Flow Investigations of Marine Diesel Injectors

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Abstract

Injector geometries of large marine two-stroke diesel engines differ extensively from configurations typically used in diesel engines for automotive applications. In marine engines, the fuel enters the combustion volume radially, supplied by multi-hole injectors with asymmetrically positioned orifices facing in similar directions. Due to this setup, the nominal direction of the orifice group is also eccentric with respect to the central axis of the injector. Experiments have shown that the sprays formed by this arrangement are asymmetric with respect to the axis at each orifice. These strong deviations can lead to wall wetting which increases fuel consumption, emissions, component temperatures and contributes to loss of lubrication at the cylinder wall. In order to investigate the in-nozzle flow and how it affects the spray morphology in this design, experiments were carried out using transparent nozzles at injection pressures and air densities of up to 50 MPa and 35 kg/m^3, respectively. The experiments were performed with diesel fuel in a newly built ambient temperature spray chamber which was designed to cope with significant spray backsplash. The results discussed here were generated using an orthogonally arranged 0.75 mm diameter mono-hole injector which matches the hole size and geometry used in large marine two-stroke diesel engines. High-speed shadowgraphy using a far-field microscope was applied to visualize cavitation within the nozzle during the complete injection process. These imaging results are used to compute statistical evaluations of cavitation in the nozzle over a range of conditions.

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Development of Novel Diagnostic Techniques to Characterize Spray Flows Pertinent to Aircraft Icing Phenomena

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Abstract

In the present study, the progresses made in our recent efforts to develop novel diagnostic techniques to characterize spray flows pertinent to aircraft icing phenomena are reported. A novel molecular tagging technique is introduced at first to achieve simultaneous measurements of droplet size, flying velocity and transient temperature of in-flight liquid droplets in spray flows. For the molecular tagging measurements, a pulsed laser is used to "tag" phosphorescent 1-BrNp·Mβ-CD·ROH triplex molecules premixed within liquid droplets. After the same laser excitation pulse, long-lived laser-induced phosphorescence is imaged at two successive times within the phosphorescence lifetime of the tagged phosphorescent triplex molecules. While the sizes of the droplets are determined quantitatively based on the acquired droplet images with a pre-calibrated scale ratio between the image plane and the object plane, the displacements of the in-flight droplets between the two images are used to estimate the flying velocities of the droplets. The simultaneous measurements of the transient temperatures of the in-flight droplets are achieved by taking advantage of the temperature dependence of phosphorescence lifetime, which is estimated from the intensity ratio of the acquired phosphorescence image pair of the in-flight droplets. A novel digital image projection (DIP) technique is also introduced to achieve quantitative measurements of the film thickness distributions to quantify the dynamic impingement of water droplets onto solid surface with different impact velocities. The DIP technique is based on the principle of structured light triangulation in a fashion similar to stereo vision technique, but replaces one of the cameras in the stereo impair with a digital projector. Based on the time-resolved DIP measurements, the time evolution of the droplet shapes in the course of the dynamic impact process, i.e., the spreading, receding, and oscillating of the impinging water droplets, under different impact velocities are revealed clearly and quantitatively.

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Primary Atomization of a Simplex Nozzle in an Eulerian-Lagrangian Framework

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Abstract

Accurate modeling of primary atomization requires transient interface tracking models like the VOF method as well as an LES-type turbulence closure. These are expensive computational models when applied to capture the entire spray region. In this study, we look at a new workflow whereby the interface tracking is applied only in the near nozzle region where the jet is intact and a Lagrangian approach is used to introduce droplets in regions where the spray is dilute. The approach, known as Euler Lagrangian Spray Atomization (ELSA) is applied to several test cases and results are compared with measured data. Here we apply this method to a Simplex Nozzle. Several user-defined functions are used to calculate the dilute regions, apply in-situ particle injection and post process droplet data using ANSYS FLUENT CFD code. The spray angle and droplet size distribution are presented.

Keywords: CFD, Sprays, Modeling, Atomization

Introduction

Primary atomization is a key area of research as the nozzle internals and flow parameters can have a wide variety of effects of the generated drop sizes and spray patterns. The ability to predict spray features with accuracy and speed with lower costs is very much desired by the nozzle manufacturers and research groups. Several approaches are used starting from very simple single phase interface area capturing technique (e.g. Sigma-Y and Omega-Y) to direct numerical simulations, DNS. Within this spectrum, there are methods such as ELSA and VOF-Lagrangian that provide the accuracy at a lower cost than more sophisticated but computationally intensive methods.

The main difficulty in analyzing primary atomization is that there is a range of length scales in the body of the spray. Final sizes are very small and can be appropriately tracked using Lagrangian approaches; however, the same approach does not capture the near nozzle blobs of liquid. In this near-nozzle region, one needs a eulerian model to capture the liquid-gas interface. Hence, an Eulerian description for modeling the flow near the nozzle and a Lagrangian procedure for tracking a large number of droplets in the sparse zone of the spray is the recommended approach. This understanding has led to the formulation of hybrid approaches which suitably transition from an Eulerian description in the near-nozzle region to a Lagrangian description in the sparse region away from the nozzle. Two such models namely ELSA model and VOF-Lagrangian model have gained substantial popularity in the past decade. The ELSA model has its roots in the Σ-Y model [1], which derives its popularity from being able to work with a RANS based turbulence model and still possessing the ability to give a reasonable estimate of relevant quantities such as penetration, spray half angle and mean diameter. The VOF-Lagrangian hybrid approach using ANSYS Fluent (also referred to as VOF-DPM approach in [2], [3], [4]) on the other hand relies heavily on the accurate prediction of the liquid-gas interface near the nozzle. To achieve that it is extremely important to either perform a detailed analysis using DNS or at least work with an LES-based turbulence model. However, with a suitable algorithm to identify spherically shaped isolated liquid structures one can quickly transition to a Lagrangian description from the Eulerian VOF lump. This relaxes the constraint on the mesh requirement imposed by DNS or LES in the large sparse region of the spray containing many tiny droplets.

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Sub- and Supercritical Phase Diagnostics using Filtered Rayleigh Scattering Methods

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Abstract

Filtered Rayleigh scattering (FRS) methods are investigated for unambiguous imaging and property measurement of gas/vapor/liquid/supercritical phases, their transitions, and their interactions in multiphase flows occurring in harsh environment conditions such as those encountered in high pressure combustors. Simple sprays, non-reacting fuel mixing combustors, and liquid nitrogen (LN_2) jets in sub- and supercritical crossflows were studied. A standard two-dimensional (2D) laser system including a 10 Hz Nd:YAG laser, a ICCD camera, and a Iodine filter was the primary diagnostic. A high speed (100 kHz) burst laser with Intensified CMOS camera system was also utilized in preliminary testing in atmospheric sprays for its time-resolved capability and its spectral purity.

For large particle and droplet phase diagnostics, laser scattering from the region of interest was captured using CCD or CMOS cameras in a variety of arrangements similar to traditional Mie scattering methods such as particle image velocimetry and also by de-tuning the frequency in FRS to allow a prescribed amount of light leakage through the molecular filter absorption lines. For gas and supercritical phase measurements, laser Rayleigh scattering from molecules in the volume of interest is captured with intensified CCD or CMOS cameras. By adding a molecular filter, FRS can filter out reflections from surfaces and Mie scattering from droplets and particles while transmitting the tails from the spectrally shifted molecular signals due to Doppler shift, molecular Brillouin scattering, etc., that yield a measurement related to the molecular number density.

This study sought to decouple jet-in-crossflow mixing from combustion in engine-relevant conditions as an aid to CFD validation. Filtered Rayleigh Scattering (FRS) was used to visualize the mixing process; by slightly de-tuning the laser seeding frequency, both the liquid and gaseous phases were simultaneously detectable by Mie and Rayleigh scattering, respectively. This included the observation of droplets. Liquid nitrogen (LN_2) was used as a surrogate for jet fuel, since Jet-A's critical point is quite close to its autoignition point. To aid processing of the 2-D FRS images into quantitative temperature and density data, the crossflow was composed of pure nitrogen. Ultimately, this data will be used to validate CFD simulations in the supercritical regime, adding new capabilities to next-generation combustor nozzle design tools.

In these nitrogen tests, single substance nitrogen was injected into the crossflow as a liquid or compressed liquid at high pressures, and allowed to reach a gaseous or supercritical state within the test section's crossflow. A large difference was observed between sub- and supercritical LN_2 jets. Subcritical jets demonstrated classic shear breakup of the column into droplets; supercritical jets had significantly shorter penetration and consisted of a dense core from which pockets of dense supercritical fluid emerged upwards and downstream. At the near-critical (but still subcritical) condition of Pr=0.97, jet behavior was much closer to supercritical than subcritical, although some droplets were observable and the core/column penetration was further downstream.

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X-ray Observations in the Spray Near-Field using Synchrotron X-rays

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Abstract

The ability to control spray formation and dispersion is extremely important to many spray applications such as combustion systems, coating and painting methods, 3D printing processes, and fire suppression designs. The ultimate outcome of our ONR Multidisciplinary University Research Initiative (MURI) project is to demonstrate multiphysics control of liquid sprays issuing from airblast atomizers through the novel integration of advanced diagnostics and the application of data- and simulation-driven model reduction in easy-to-implement control algorithms. Some of the advanced diagnostics used in this project to better understand spray formation include: (1) 2D X-ray radiography and 3D X-ray computed tomography obtained from common tube X-ray sources, and (2) high-speed 2D radiographic movies and detailed 2D density projections from high intensity white beam and focused beam radiography from a synchrotron X-ray source. All of these techniques will focus on imaging the near-field region of the spray. This paper will provide initial X-ray spray imaging observations that were recently recorded using the Advanced Photon Source (APS) at Argonne National Laboratory.

Initial high-speed X-ray images from an airblast atomizer are presented, where the inner liquid flow is laminar (Re_l = 1000) and the outer air flow is turbulent (Re_g = 16,700), with and without gas swirl. Radiographic movies of the atomizer show a very dynamic near-field region, including bag formation and stable air bubble formation inside liquid drops. When air swirl is added, the liquid stream is very unstable near the nozzle exit. A discussion of the quantitative measures that can be acquired from the qualitative white beam images and focused beam radiographic measurements will also be provided. Eventually, these data will be compared to near-field simulations performed at Cornell University and to mid-field measurements completed at the University of Washington – Seattle using an identical flow system.

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Multi-Beam Illumination for Coping with Dense Sprays Using Imaging

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Abstract

Rapid development of high quality digital cameras and low cost diode lasers that can be pulsed at durations as short as 10 nanoseconds is making imaging an attractive means for measuring sprays. An advantage of imaging methods is their ability to record detailed information on the particle morphology. Unfortunately, the method has been generally limited to relatively dilute sprays when attempting to measure drop size distributions. Under spray formation conditions wherein imaging systems have superior performance in terms of dealing with various liquid structures including droplets, the out-of-focus objects will obscure the objects within the field of view.

An approach for mitigating these problems is to use multiple light sources or a single extended light source that converges to the sample volume. In the present approach, we use six or more diode lasers beams that converge to produce relatively incoherent illumination at the sample volume. Lasers have the advantage of producing collimated light that can be projected over larger distances.

In this proposed paper, the method and experiments on the effectiveness of this approach in allowing imaging of dense sprays will be described. Imaging glass beads on glass slides at different layer positions along the optical paths provided an adequate simulation of a dense spray. Comparisons were made for single beam and multiple beam imaging to show the advantages of the method. Relatively dense sprays have been measured using single beam and multiple beam illumination to provide a comparison of the capabilities of the approach.

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Experimental characterization of a canonical coaxial gas-liquid atomizer

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Abstract

Break-up of a liquid jet by a high speed coaxial gas jet is a frequently-used configuration to generate a high quality spray. Despite its extended use in engineering and natural processes, the instabilities that control the liquid droplet size and their spatio-temporal distribution in the spray are not completely understood. Fundamental understanding of the mechanisms that dominate ligament formation and break-up in the liquid, as well as those that determine the differential transport of droplets in the spray can provide quantitative design and analysis tools for spray engineering. Additionally, detailed understanding is necessary to achieve spray control, in which the break up can be actuated to provide certain preferred droplet size distribution, and the dispersion of droplets from the spray axis can be influenced with acoustic or electric forces to achieve a desired spatial distribution.

We present an experimental study of a canonical coaxial gas-liquid atomizer. The liquid injection rate is fixed at a speed of 0.5 m/s (Reynolds number $Re_l = 1000$), while the coaxial gas jet Reynolds number is varied over a wide range $8 \times 10^3 < Re_g < 2 \times 10^6$. The resulting droplet sizes distribution is measured using PDPA in the mid-field region, after the break-up of all fluids ligaments is completed and droplets are spherically-shaped. Data on droplet distribution inside the spray is compared with high-resolution particle-laden DNS from our collaborators at U. Florida. The break-up process and the spray development are also characterized in the close-field region using high-speed imaging. These data sets are complemented with X-ray measurements and liquid-gas interface dynamics capturing numerical simulations of the spray shape and void fraction, presented by our collaborators at Iowa State University and Cornell University. This work is part of a large-scale project funded by an ONR MURI to provide feedback control of sprays.

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Quantitative, Bias-Corrected Measurements of Droplet Position, Size and Velocity with Digital In-line Holography

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Abstract

Digital in-line holography (DIH) is a laser diagnostic technique that can be used to measure particle sizes, velocities and positions in sprays and other multiphase flows. Understanding the biases, error sources and limitations of DIH are critical to designing processing algorithms and making accurate quantitative measurements. Here, work focuses specifically on the biases which arise whenever there is a non-constant correlation between particle size and particle velocity. Due to the limited data throughput of digital sensors, one often has to choose between high-temporal resolution with a limited spatial resolution (image pixel count) or high-spatial resolution with limited temporal resolution. As shown here, when particle sizes are sampled in space with insufficient frame rates for particle tracking through time, the measured particle size distribution is biased toward particle sizes classes which travel slower and reside within the field-of-view longer. Such biases due to size-velocity correlations have been previously reported for many spray diagnostics and are shown here to be equally applicable to DIH. Using simulations and experiments, corrections are proposed and validated which reduce these biases using a measurement of the mean particle size to velocity correlation. Finally, it is proposed to combine a high-spatial resolution measurement with a simultaneous temporally resolved measurement. As demonstrated here, this allows for a relatively large particle size dynamic range, which is corrected for size-velocity biases.

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An Exploration of Initial Destabilization During Air-Blast Atomization using 3D Simulations

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Abstract

A multidisciplinary university research initiative (MURI), funded by the Office of Naval Research, has been formed to computationally and experimentally explore actively controlling atomization. Before active control strategies can be devised, the key parameters to target must be chosen, requiring a fundamental understanding of how the liquid-gas interface destabilizes. We first study the air-blast atomization of a planar liquid layer using three-dimensional simulations. With this configuration, we will present results showing the effect of the dynamic pressure ratio on both the longitudinal and transverse interface instability frequencies. Flow statistics will be presented, demonstrating the intimate relationship between turbulence and interfacial waves that extend into the high-speed gas coflow. We will then move on to three-dimensional simulations of the cylindrical air-blast atomization flow configuration central to our MURI project and compare our results to corresponding experiments performed at the University of Washington and Iowa State University. Specifically, we will be comparing the liquid-gas interface location to shadowgraphs and radiographs captured in the experiments, as well as mean liquid volume fraction obtained with X-ray tomographic measurements.

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Uncertainty Characterization of Particle Location Using a Plenoptic Camera

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Abstract

Plenoptic imaging is an emerging 3D diagnostic technique that can be applied in the analysis of a variety of flows including the measurement of particle size and location in multiphase sprays. A plenoptic camera uses a microlens array to collect both angular and spatial information about the incoming light rays. This can be manipulated in post processing to provide a 3D representation of a scene from a single snapshot. Due to the recent rapid development of plenoptic imaging, it has become critical to experimentally determine uncertainty and the resulting measurement limitations. Here a static particle field is translated to provide known displacements. These known displacements are compared to measured displacement values, corrected using a recently developed calibration technique, to provide a measure of the uncertainty in particle location. Trends are determined as functions of the magnification of the system as well as of the location of the particle within the measured volume, and results are compared to theoretical resolution limits. As expected, data indicate that measurement precision improves with increasing magnification and is well correlated with the theoretical depth of focus. On the other hand, the variation of measurement accuracy as a function of optical depth reveals trends that are not yet fully understood and more work is warranted.

Pairwise Interaction Extended Point-Particle (PIEP) Model for droplet-laden flows: Towards application to the mid-field of a spray

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Euler-Lagrange (EL) methodology is the common approach used to simulate the collective dynamics of a very large number of dispersed droplets in the mid region of a spray. Traditional point-particle models used in these EL simulations assume the force on a droplets to depend only on mean Reynolds number and volume fraction. This approximation ignores interactions among the droplets at the microscale and therefore significantly under-predicts fluctuations in droplet velocity and feed-back forces, resulting in incorrect mesoscale structures and macroscale dispersion. This study introduces a new extended point-particle force model that attempts to rigorously account for the hydrodynamic influence of the neighboring droplets. The model computes the drag and lift forces, and heat/mass transfer on each droplet by accounting for the precise location of few surrounding neighbors. A pairwise interaction is assumed to superpose the perturbation fields induced by each neighbor and the Faxén form is used to obtain the forces and heat transfer. The model is tested for the cases of a random array of stationary and freely sedimenting particles. The ultimate objective if our ONR Multi-University Research Initiative (MURI) project is to demonstrate multiphysics control of liquid sprays. The talk will also present on-going effort at simulation of mid-field region of a spray where a turbulent inflow of gas with a dispersed distribution of droplets is specified. While first generation simulations will employ standard point-particle models, the goal is to employ the PIEP model and to firmly establish the role of droplet-droplet interaction in such dense droplet-laden flows.

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Inter-plume velocity measurements to understand spray collapse when varying injection duration or number of injections

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Abstract

The collapse or merging of individual plumes of direct-injection gasoline injectors is of fundamental importance to engine performance because of its impact on fuel-air mixing. However, the mechanisms of spray collapse are not fully understood. The purpose of this work is to study the effects of injection duration and multiple injections on the interaction and/or collapse of multi-plume GDI sprays. High-speed (100 kHz) Particle Image Velocimetry (PIV) is applied along a plane between plumes to observe the full temporal evolution of plume-interaction and potential collapse, resolved for individual injection events. Supporting information along a line of sight is obtained using Diffused Back Illumination (DBI). Experiments are performed under simulated engine conditions using a symmetric 8-hole injector in a high-temperature, high-pressure vessel at the "Spray G" operating conditions of the Engine Combustion Network (ECN). Longer injection duration is found to promote plume collapse, while staging fuel delivery with multiple, shorter injections is resistant to plume collapse.

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Advances in adjoint-based methods: application towards multiphase systems

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Abstract

A Multidisciplinary University Research Initiative (MURI), funded by the Office of Naval Research, has been formed to computationally and experimentally explore the potential for actively controlling atomization. Control strategies incorporating nozzle design and injection scheduling, electrostatics, and acoustics are being considered and their optimal, in some sense, application is sought. However, typical methods for optimal control are not available for multiphase systems because, primarily, of the lack of sensitivity information available through the adjoint, or dual, system to make balanced truncation models and optimal control techniques possible. Adjoint-based methods efficiently use the sensitivities of trajectories of dynamical systems with respect to system inputs and parameters to make control decisions and to construct reduced-order models. In the context of continuum mechanics, the development and application of adjoint methods has focused on single phase systems. In this talk we detail updates to adjoint-based methods for multiphase systems, including data-based estimation of adjoint operators and application of adjoint sensitivities to multiphase flows.

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Temporal Evolution of Liquid Jets in Supersonic Crossflows

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Abstract

Temporal evolution and structures of both pure- and aerated-liquid jets injected into a Mach 1.94 crossflow environment were explored with high-speed shadowgraph imaging and phase Doppler particle analysis (PDPA). Water and nitrogen at the desired flow rates were injected through an aerated-liquid injector equipped with an exchangeable nozzle adaptor. The nozzle configuration with a constant-diameter passage was selected for liquid delivery at two intrusion depths from the tunnel floor. It was found that formation and propagation of protrusion structures located on the windward side of the initial spray columns, generated by either pure- or aerated-liquid jets, play important roles in initial liquid column breakup and eventual plume formation. In a pure-liquid jet, the protrusion structure is generated from surface wave growth on a solid liquid column and typically propagates downstream at a lower speed. In an aerated-liquid jet, the protrusion structure is generated from the thin liquid film of the spray cone and propagates downstream at a higher speed, due to the higher plume penetration. The intrusion injector can enhance plume penetration with respect to the nozzle exit plane. Spray penetration heights were also measured from the average shadowgraph images for correlation development. PDPA measurements show that the injected liquid mass is mainly distributed within a kidney-shaped domain located near the periphery of the plume, which is above the penetration heights characterized by the shadowgraph images.

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Proper Orthogonal Decomposition Analysis of The Engine Combustion Network "Spray A"

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Abstract

In the present paper the large eddy simulation (LES) results of the reacting Engine Combustion Network (ECN) Spray A case at three different fuel injection pressure levels (50, 100 and 150 MPa) are analysed by the proper orthogonal decomposition (POD). The LES results are validated against experimental data in terms of the liquid and vapour penetration and average radial mixing field. Consistently for all injection pressures, the POD analysis indicates a dominant helical mode, containing 10 - 12 % of the fluctuation energy, in the proximity of an approximately 50 nozzle diameter (4.5 mm) long laminar potential core of the spray. The analysis implies that the coherent modes are mostly related to the fuel spray regions where the initial turbulence transition, evaporation, mixing, and first low-temperature reactions occur. The helical structure is similar to previous gas-jet studies, presented in the literature. Furthermore, reconstruction of the flow field from the most energetic POD modes shows that the most dominating instability mechanism in the current simulations is via transverse oscillations. The degree of realism with respect to the turbulence transition location and discovered instability mechanism in the current LES framework is discussed in detail. Furthermore, the sufficiency of the grid resolution of 62 µm is also reviewed and additionally, the implications of the analysis result are linked to the spatial location of the low-temperature reactions prior to ignition.

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Validation of a Compressible Interfacial Flow Solver Using Jet in Crossflow

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Abstract

An important aspect of scramjet development is characterizing liquid jet atomization in supersonic crossflow under startup conditions. Numerical simulations may be used to better understand the flow behavior. To this end, an interface reconstruction approach extended from a Tangent of Hyperbola for INterface Capturing (THINC) reconstruction scheme for use with the five-equation model has been developed. Coupled with a Harten-Lax-van Leer-Contact (HLLC) Riemann solver–modified to include the effects of surface tension–this method maintains the thickness of the gas-liquid interface throughout the simulation without impacting the underlying conservation of the scheme. The atomization of a liquid jet in subsonic crossflow is simulated and validated against experimental results to ensure the relevant flow physics are captured accurately. A qualitative analysis of the overall flow structure and quantitative comparisons to measured values of liquid jet atomization are performed, including: surface wavelengths, penetration height, and jet trajectory. After examining the subsonic case, a liquid jet in supersonic crossflow is simulated to demonstrate the strength of the method for compressible atomization applications.

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Effects of Sub-Grid Scale (SGS) Dispersion Modeling on Large-Eddy Simulation (LES) of Non-Evaporative and Evaporative Diesel Sprays

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Abstract

Performance of the sub-grid models accounting for the effects of unresolved motions on Diesel spray dispersion was tested. The models predict the SGS dispersion velocity used for calculating the slip velocity in Lagrangian-Eulerian LES spray models. Discussion was made on the effects of different model formulations and model constants on the simulations of the constant-volume Engine Combustion Network non-evaporative and evaporative "Spray-A". It was found that the SGS dispersion models have profound impact on the prediction of the spatial distribution of liquid mass. Neglecting the SGS dispersion model results in the under-predicted width of the lateral projected liquid mass density profiles. Also, the prediction of the projected liquid mass density is sensitive to the two model constants determining the SGS dispersion velocity magnitude and turbulence time scale. On the other hand, the predictions of gas-phase velocity profiles, fuel vapor mass fraction profiles, vortex structures, and liquid penetration are insensitive to different SGS dispersion model setups. The primary reason for this is that the motion of high-momentum liquid blobs in the near-nozzle region leading to air entrainment and subsequent gas jet development is little influenced by the SGS dispersion. The SGS dispersion is more critical in determining the motion of droplets having small inertia.

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High-Fidelity Simulations of High-Viscosity Liquid Jet Atomization in Crossflow

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Abstract

Atomization of extremely high viscosity fuel is of interest for applications such as alternative fuels, and altitude relight with extremely cold fuel. In these applications, the fuel-air viscosity-ratio can be orders of magnitude higher than the conventional scenario, outside the applicability of the atomization regimes established in the literature. While detailed atomization measurements usually face grand challenges, high-fidelity numerical simulations offer the advantage to comprehensively explore the atomization details in this new regime. In this work, a previously-validated high-fidelity first-principle simulation code HiMIST is utilized to simulate liquid jet atomization in crossflow in the high viscosity-ratio regime. A Coupled Level Set and Volume-of-Fluid (CLSVOF) interface capturing approach combined with Adaptive Mesh Refinement (AMR) for enhanced simulation efficiencies is used to perform a parametric study in the Ohnesorge number (*Oh*) and Weber number (*We*) space. A wider range of liquid viscosity (*Oh*=0.004 to 2) than literature reports is explored. Direct comparisons between present study and previously published low-viscosity jet in crossflow results are performed. The effects of viscous damping and slowing on jet penetration and ligament formation/breakup are investigated. Near-field decrease and far-field increase in jet penetration with increasing *Oh* are observed, mostly consistent with the literature reports. The detailed simulations elucidate a distinctive *edge-ligament-breakup* dominated process with long surviving ligaments for the higher *Oh* cases, as opposed to a two-stage column-stripping/column-breakup process for the lower Oh counterparts. The trend in the *We* dependence of penetration is reversed as *Oh* increases.

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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 planar 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 isolate 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 the CTFLab at Cornell University.

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Analysis of Near-Field Spray Behavior with Highly-Resolved Simulations

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Abstract

Highly-resolved simulations (2D and 3D) of liquid injection into a quiescent gas environment are presented for a range of injection speeds from 20 m/s to 100 m/s. The main findings show that the near nozzle part of the spray, which extends from the jet orifice location to approximately 70 to 100 diameters downstream is characterized by three distinct regions. In the first region, the surface of the jet undergoes interfacial perturbations and breakup; however, the internal liquid core remains intact. In the second region, the entire jet breaks up, which leads to the characterization of this part of the domain as the primary atomization zone. Besides the creation of relatively large amounts of interfacial area, this zone is distinguished by a huge increase in the momentum coupling between the gas and liquid phases. In the final region, both phases merge into an equilibrium state, where the average velocity difference between phases becomes considerably small, and the atomization process largely subsides. The momentum coupling between both phases is further analyzed using an analogous 3D two-phase shear layer configuration, where the interaction between both phases can be more conveniently isolated. Under this configuration, an approximate closed form expression for the phasic velocities is obtained, which explicitly shows the relation between interfacial area and the three distinct atomization regions. Validation exercises and numerical resolution issues are also discussed.

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Numerical Simulation of Aerated-Liquid Injection with Various Nozzle Designs

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ABSTRACT

Aerated-liquid injection, or 'barbotage', or effervescent, is considered one of the injection schemes capable of delivering well-atomized sprays. By creating two-phase mixtures upstream of the injector nozzle, aerated-liquid injectors increase the production of smaller droplets needed for fast vaporization. Recent advances in experimental techniques using synchrotron x-ray diagnostics have allowed for the increased development of both quantitative and qualitative data in the near field and internal structure of these injectors. The present effort conducts highly resolved numerical simulations of two-phase flow within 'outside-in' aerated injector designs using sharp interface-capturing techniques. The 'outside-in' design injects nitrogen from an outer plenum chamber into a co-flowing liquid stream. Various injector nozzle designs are compared to determine the flow conditions at the nozzle exit. Data obtained through x-ray radiography and fluorescence techniques are used to validate current computational simulations. The effects of grid refinement and volume-fraction smoothing within the surface tension model are used to study the levels of mixing and break-up within the liquid as it exits the injector nozzle.

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Frequency behavior of the large scale instability in assisted atomization of a liquid jet

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Abstract

In assisted atomization, a liquid jet stripped off by a fast gas stream produces fine drops at small distances downstream injection (Marmottant and Villermaux [1], Hong et al. [2], Varga et al. [3]). Yet, the incoming liquid stream is never fully atomized by stripping alone: the jet that remains at the end of the intact length experiences large scale lateral motion and breaks further downstream into droplets significantly larger than those due to stripping. The origin of these large-scale instabilities and the scaling of the flapping frequency with control parameters remain quite controversial. Indeed, the flapping frequency is found to linearly increase with the gas velocity (e.g. Arai and Hasimoto [4], Lozano et al. [5]), but there is no agreement on the influence of the injector geometry including the gas vorticity thickness at injection which is a key parameter of the shear instability involved in the stripping process (Marmottant et al. [1], Matas et al. [6], Fuster et al. [7], Matas [8]). To clarify this question, experiments have been undertaken that span a wide range of flow parameters (liquid velocities from 0.17 to 1.4 m/s, gas velocities from 10 to 140m/s) and injector geometries (5 to 20 mm liquid diameters, 1.8 to 24 mm gas thicknesses). Flapping occurred for all conditions, and its frequency was found to be independent of the axial downstream position. Two quite different regimes have been identified. In the first regime, the flapping frequency increases with the gas velocity. Using stability analysis, we show that this regime is driven by the asymmetric shear instability so that the frequency scales as the gas velocity divided by the gas vorticity thickness at injection. In the second regime, the flapping frequency no longer varies with the gas velocity, a behavior not mentioned in the literature. In that case, the frequency scales as the liquid velocity over the liquid jet radius. The first regime is shown to occur when the wavelength associated with the shear instability is larger than the jet radius. Conversely, the second regime occurs when the expected shear-instability wavelength becomes too small compared with the jet radius: in the latter case, the system prefers to amplify a larger scale, comparable with the jet size. A quantitative criterion for this boundary is suggested based on experimental evidence and inspired from stability analysis results.

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Characterization of secondary atomization in compressible crossflows

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Abstract

To better understand the breakup behavior of water columns in supersonic flows, a range of Weber numbers are investigated for two shock Mach numbers consisting of either subsonic or supersonic post-shock conditions. The effects of compressibility, surface tension, and molecular diffusion are included. Fluid immiscibility is maintained with an interface sharpening scheme. In the subsonic case, a number of different breakup modes are observed with a strong dependence on the Weber number and provide good correlation with experimental observations, validating the approach. In the supersonic case, significantly less variation in the breakup behavior was observed across the same range of surface tension forces. In both cases, water columns at lower Weber numbers exhibit lower drag coefficients but less variation in the drag coefficient as a function of the Weber number is observed in the supersonic case.

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Modeling and numerical study of primary breakup under diesel conditions

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Abstract

In this work we numerically study primary atomization of a round turbulent liquid jet injected into stagnant air in a high pressure chamber under diesel like conditions. The simulations are carried out by applying the One-Dimensional Turbulence (ODT) approach for primary breakup as recently proposed by [1]. ODT is a stochastic model simulating the evolution of turbulent flow along a notional 1D line of sight. By resolving all scales, ODT provides high resolution at interface and property gradients within each phase with afordable computational cost, which are key to capturing the local behavior of the breakup process and at the same time allows simulations at high Reynolds and Weber numbers. We investigate the capabilities of the model to predict primary droplets statistics in a case which is relevant to conditions typically encountered in combustion engines. Due to the lack of detailed experimental data for droplet statistics from primary breakup only, the Direct Numerical Simulation (DNS) study of Herrmann(2011) [2] is used for comparison. The main results are presented in form of droplet size and velocity distributions.

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Aerodynamic Breakup of Liquid Metal in a Shock-Induced Crossflow

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Abstract

Although the atomization of liquid jet in crossflow has been extensively studied, there are substantially fewer studies on liquid metal breakup resulting from shock-induced crossflow. Liquid metals have unique properties, such as high density, high surface tension, and the ability to form oxide skins on the surface, that make their accurate simulation a challenge. In this paper, the breakup modes of a column of liquid in a shock-induced crossflow are evaluated for Galinstan, a room-temperature liquid metal alloy, and for water, used as reference. The low reactivity of Galinstan allows us to concentrate on the hydrodynamics effects due to surface tension and inertia while ignoring parameters such as yield stress and fracture toughness of the metal. Simulations are carried out with a multiphase compressible flow solver coupled to interface capturing, CLSVOF, and are compared with experimental measurements and visualization from the multiphase shock tube facility at Sandia. A matrix of two-dimensional simulations is first presented where the breakup morphology is classified by increasing the incident shock from M=1.04 to M=1.23 (corresponding to a Weber number between 8.1 and 267 for water and between 4.7 and 26.8 for Galinstan). A trend is observed where the breakup mode transition for Galinstan occurs at a lower Weber number than for water. To understand the role of three-dimensional effects in determining the breakup mode, preliminary results of simulations of a segment of liquid column in crossflow are discussed at the transition between the vibrational and the bag breakup mode.

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Numerical study of stochastic particle dispersion using One-Dimensional-Turbulence

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Abstract

A stochastic model to study particle dispersion in a round jet configuration using the one-dimensional-turbulence model (ODT) is evaluated. To address one of the major problems for multiphase flow simulations, namely computational costs, the dimension-reduced model is used with the goal of predicting these flows more efficiently. ODT is a stochastic model simulating turbulent flow evolution along a notional one-dimensional line of sight by applying instantaneous maps which represent the effect of individual turbulent eddies on property fields. As the impact of the particles on the carrier fluid phase is negligible for cases considered, a one-way coupling approach is used, which means that the carrier-phase is affecting the particle dynamics but not vice versa. The radial dispersion and axial velocity are compared with jet experimental data as a function of axial position. For consistent representation of the spatially developing round jet, the spatial formulation of ODT in cylindrical coordinates is used. The investigated jet configuration has a nozzle diameter of 7 mm and Reynolds numbers ranging from 10000 to 30000. The flow statistics of the ODT particle model are compared with experimental measurements for two different particle diameters (60 and 90 µm), thereby testing the Stokes number dependence predicted by ODT.

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Modeling and Simulation of Diesel Injection at Transcritical Conditions

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Abstract

The need for improved engine efficiencies has motivated the development of high-pressure combustion systems, in which operating conditions achieve and exceed critical conditions. Associated with these conditions are large thermodynamic gradients and strong variations in transport properties as the fluid undergoes mixing and phase transition. Accurately simulating these real-fluid environments remains a main challenge. Different modeling approaches have been employed, which can be categorized as diffused and sharp interface methods. The objective of this study is to examine the diffused interface method for simulating diesel-fuel injection at conditions related to the supercritical regime. To this end, a recently developed compressible real-fluid solver for transcritical conditions is employed. Simulations of an ECN-relevant diesel-fuel injector are performed and predictions for instantaneous and statistical flow-field results are compared against available measurements. It is expected that results from this analysis will be useful in identifying limitations of current modeling techniques and in improving physical and numerical models for high-pressure injection systems.

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Modeling the Dense Spray Regime Using an Euler-Lagrange Approach With Volumetric Displacement Effects

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Abstract

Modeling of a dense spray regime using an Euler-Lagrange approach is challenging because of local high volume loading. A cluster of droplets, that are assumed subgrid, can lead to locally low void fractions for the fluid phase. Under these conditions, spatio-temporal changes in the fluid volume fractions should be considered in an Euler-Lagrange, two-way coupling model. This leads to zero-Mach number, variable density governing equations. Using pressure-based solvers, this gives rise to a source term in the pressure Poisson equation and a non-divergence free velocity field. To test the validity and predictive capability of such an approach, a round jet laden with particles is investigated using Direct Numerical Simulation coupled with point-Particle based model and compared with available experimental data for a particulate turbulent round jet with $Re_j = 5712$. Standard force closures including drag, lift, Magnus effect, pressure, added mass as well as viscous torque acting on each individual particle are employed in the Point-Particle based model. In addition, volume displacement effects due to the presence of solid particles or liquid droplets, which is commonly neglected in the standard two-way coupling, are taken into account in both continuity and inter-phase momentum transfer to accurately capture the underlying structure of particle-turbulence interactions. Prediction results are in well agreement with the corresponding experiment.

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Numerical Study of Liquid Jet Atomization in Supersonic Crossflows

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Abstract

Compressible fuel injection is a critical process in the operation of scramjet engines, but a challenging area for experimentation. Accurate numerical simulations based on first principles can help elucidate the limiting physics in these flows and provide guidance for engineering design. However, most computational studies of liquid jet atomization so far have been conducted in an incompressible setting. While a variety of accurate and robust simulation techniques have been developed for atomization, their transfer to the realm of compressible flows presents major challenges. In this work, we combine a recently developed, unsplit volume-of-fluid technique (VOF) with second order accuracy (Owkes and Desjardins, J. Comp. Phys. 2014) with a fully conservative finite volume compressible flow code that solves discontinuous equations for the density and energy of each phase. To maximize computational performance with atomizing flows in low supersonic conditions, we employ an implicit equation for pressure, following Kwatra et al. (J. Comp. Phys. 2009), allowing us to avoid any acoustic CFL limitation. We then use this multiphase compressible flow solver to simulate a liquid jet in supersonic crossflow studied experimentally at the Air Force Research Laboratory. Qualitative comparison with experimental results and mesh convergence properties are discussed.

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Modeling the Influence of Nozzle-Generated Turbulence on Diesel Sprays

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Abstract

The physical mechanisms governing spray breakup in direct injection engines, such as aerodynamic-induced instabilities and nozzle-generated cavitation and turbulence, are not well understood due to the experimental and computational limitations in resolving these processes. Recent x-ray and visible extinction measurements have been conducted with a targeted interest in the spray formation region in order to characterize the distribution of droplet sizes throughout the spray. Detailed analysis of these measurements shows promise of yielding insight into likely mechanisms governing atomization, which can inform the improvement of spray models for engine computational fluid dynamic (CFD) codes.

In order to investigate potential atomization mechanisms, we employ a joint experimental and computational approach to characterize the structure of the spray formation region using the Engine Combustion Network Spray D injector. X-ray tomography, radiography and ultra-small angle x-ray scattering measurements conducted at the Advanced Photon Source at Argonne National Laboratory quantify the injector geometry, liquid fuel mass and Sauter mean diameter (SMD) distributions under non-vaporizing conditions. Diffused back-illumination imaging measurements, conducted at the Georgia Institute of Technology, characterize the asymmetry of the spray structure. The selected range of injection pressures (50 – 150 MPa) and ambient densities (1.2 – 22.8 kg/m^3) allow for the influence of aerodynamic forces on the spray to be studied in a controlled and systematic manner, while isolating the atomization process from the effects of vaporization. In comparison to high ambient density conditions, the spray is observed to be more asymmetric at low ambient density conditions. Although several mechanisms may cause asymmetries in the nozzle exit flow conditions and ultimately the spray distribution, irregularities in the internal nozzle geometry were identified, suggesting an increased sensitivity of the spray structure to internal nozzle surface finish imperfections at such conditions. The presence of these asymmetries may influence the ability to interpret line-of-sight measurements and their derived SMD values and trends from a single viewing angle of the spray. With this consideration in mind, the measured local sensitivities to ambient density suggest that for ambient densities less than 2.4 kg/m^3, aerodynamic effects are likely suppressed, allowing the influence of turbulent-induced breakup to be isolated. In concert with the experimental measurements, we utilize three-dimensional, CFD Lagrangian-Eulerian spray simulations in CONVERGE to evaluate the details of the predicted spray structure. In particular, we compare measured and predicted sensitivities of the SMD distribution to changes in injection and ambient conditions from three different atomization models, namely Kelvin Helmholtz (KH), KH Aerodynamics Cavitation Turbulence (KH-ACT), and the newly developed KH-Faeth hybrid model. While none of the existing hybrid spray models were able to replicate the experimentally observed sensitivities, it was found that the scales characterizing the KH-Faeth model show promise of capturing the experimentally observed trends if the effects of secondary droplet breakup are neglected. These results inform recommendations for future experiments and computational studies that can guide the development of an improved spray breakup model.

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A volume-of-fluid sharp interface method for simulating the interaction of shocks with immiscible interfaces

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Abstract

Many applications of atomization occur in flows involving Mach numbers beyond the range that can be modeled using low-Mach number incompressible formulations. In this contribution we present advancements to a hybrid tracking capturing scheme using an in-cell-reconstruction technique based on the method originally proposed by Smiljanovski (1996) for deflagration waves coupled to a volume-of-fluid volume tracking method. The resulting method is applicable to compressible flows that involve the interaction of shocks with phase interfaces. The new approach uses either a second-order wave propagation algorithm by LeVeque (2010) or a flux based formulation and avoids the need for small time steps by using cell face aperture averaged wave, respective flux updates of the volume averaged states of cells containing the phase interface. The method is a sharp interface method in that it maintains the phase interface as a discontinuity in the continuum limit by reconstructing the liquid and gas states from cell average values using the jump conditions across the phase interface and the geometric information provided by the volume-of-fluid method. The performance of the method is demonstrated on a range of test cases.

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Experimental Investigation of Spray Characteristics of High Reactivity Gasoline and Diesel Fuel Using a Heavy-Duty Single-Hole Injector, Part I: Non-Reacting, Non-Vaporizing Sprays

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Abstract

Recent trends in the transportation energy sector indicate that demand for middle distillates, such as diesel, will increase due to growing commercial traffic in emerging economies. In contrast, demand for light distillates, such as gasoline, is projected to decrease due to fuel economy regulations imposed on passenger vehicles. Therefore, market forces suggest that fuels within the gasoline property range may become an attractive alternative for the heavy-duty commercial transport sector if they can be ignited and combusted as efficiently and robustly as diesel with additional emission benefits. Prior experimental work on a production 14.9 L heavy-duty engine demonstrated that high reactivity gasoline (RON 60, CN 34) can burn in a conventional mixing-controlled combustion mode with similar brake fuel efficiency and lower soot emissions than diesel at a given engine-out NO_x level. The emissions benefit was attributed to the high volatility and low aromatic content of the gasoline-like fuel. The current study is aimed at investigating the single-plume non-reacting, non-vaporizing spray characteristics of the gasoline-like fuel compared to ultra-low-sulfur-diesel (ULSD) under heavy-duty engine relevant conditions. Another companion study (Part II) focuses on the spray characteristics of non-reacting, vaporizing sprays. The measurements provided here are intended to elucidate the dominant physical and chemical processes behind previously observed engine performance differences and to provide validation data for spray models used in combustion system development. The experiments were carried out in an optically accessible constant volume combustion chamber using a production heavy-duty injector fitted with a single-hole nozzle. A wide range of charge gas densities (10.3-166.5 kg/m3) and injection pressures (100 – 250 MPa) were considered at a fixed temperature of 323 K in order to represent heavy-duty engine relevant, non-evaporating conditions. The spray injection process was characterized using high speed videos at 25,000 frames per second (fps) to capture the entire field of view, and 100,000 fps to capture initial spray development details within the vicinity of the nozzle tip. Results show that the high reactivity gasoline produces a wider spray dispersion angle and slower spray penetration rate compared to ULSD which is consistent with enhanced air entrainment and potentially, gasoline vaporization. The observed differences were further analyzed using existing spray correlations for non-reacting, non-vaporizing sprays and related to the properties of the fuels considered.

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Voids, Bubbles, Holes, and Complex Three-Dimensional Spray Structures Revealed by High-Speed X-ray Imaging

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Abstract

X-ray radiographic imaging was performed at rates of 20–120 kHz to reveal complex, three-dimensional structure in an atomizing spray as a function of time during primary and secondary breakup. This was enabled by upgrades to the 7BM beamline of the Advanced Photon Source at Argonne National Laboratories that allowed synchrotron white-beam x-ray radiography with spatial resolution of 65–12 microns, respectively. A series of experiments were conducted to interrogate a swirl-coaxial rocket injector operating with water and nitrogen at various flow rates to simulate liquid oxygen and gaseous methane, respectively. Analysis of the time evolving flowfield reveals complex three-dimensional structures such as non-spherical droplets, droplets with multiple voids, ligaments with complex honeycomb structures, liquid sheets with stable bubbles, and the development of rim structures due to hole initiation and growth. The images of x-ray attenuation enable quantitative analysis of the internal liquid structure, including void sizes and liquid path length through droplets and ligaments. The complex three-dimensional flow structures provide new information on the mixed-phase (gas-liquid) distribution leading to inhomogeneities in the liquid phase during primary and secondary breakup. This approach is compared with efforts to use high-speed imaging with multiple x-ray tube sources for three-dimensional tomographic imaging.

Experimental Investigation of Spray Characteristics of High Reactivity Gasoline and Diesel Fuel Using a Heavy-Duty Single-Hole Injector, Part II: Non-Reacting, Vaporizing Sprays

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Abstract

Future projections in the transportation energy sector indicate that fuels within the gasoline property range may become attractive alternatives for the heavy-duty commercial market. Prior experimental work on a production heavy-duty engine demonstrated that high reactivity gasoline (RON 60, CN 34) could operate in a conventional mixing-controlled combustion mode with similar efficiency and lower soot emissions than diesel at a given engine-out NOx level due to its high volatility and low aromatic content. This study is aimed at investigating the single-plume non-reacting, vaporizing spray characteristics of high reactivity gasoline compared to ultra-low-sulfur-diesel (ULSD). A companion study (Part I) focuses on the characteristics of non-reacting, non-vaporizing sprays. The experiments were carried out in an optically accessible constant volume combustion chamber using a single-hole injector. A wide range of charge gas densities (10.3- 41.7 kg/m^3), temperatures (800-1200 K), and injection pressures (100-250 MPa) were tested to represent heavy-duty engine relevant conditions. A hybrid Mie scattering and shadowgraph technique was implemented using a high-speed camera to capture images at 60,000 frames per second and determine vapor dispersion angle, vapor penetration, and liquid length of the vaporizing sprays for both fuels considered. Results indicate that the high reactivity gasoline has similar vapor penetration compared to ULSD (within 5%). Although the vapor penetration of the two fuels is similar, the vapor dispersion angle is as much as 20% wider for the gasoline-like fuel in comparison to ULSD at a given operating condition. The liquid length of the gasoline-like fuel is 50% shorter than ULSD, which is consistent with the difference in volatility between fuels.

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Dynamic Measurement of Liquid Sheet Formed by Two Low-Speed Impinging Jets via Partial Coherent Interferometry

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Abstract

This work presents a new technique, Partial Coherent Interferometry, for measuring the dynamic liquid sheet formed by two impinging jets. This technique enables non-intrusive measurement and resolves the thickness distribution. An impinging liquid sheet is generated from two alike impinging jets with a 45-degree impinging angle. An optical interferometer and a laser with calibrated partial coherence are used to record an interference pattern by passing one branch of the two optical paths through the impinging sheet. By examining both the phase and the intensity of the recorded interference pattern, the absolute thickness distribution of impinging sheet is measured. The same technique can be applied to measure the thickness distribution of other thin liquid films.

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On the effects of liquid viscosity on the spray characteristics of spray dry nozzles

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Abstract

Spray dry nozzles represent a notable portion of industrial nozzles, and are typically used to generate a dried powder from a liquid or slurry. From a spray technology perspective, these nozzles are identified as hydraulic atomization nozzles that operate at high pressures in order to generate relatively small droplets with controlled distributions. In this study, nozzles which are used for spray drying in areas such as the Dairy, Food, Pharmaceutical, and Chemical industries, are characterized and analyzed over a range of operating conditions. For this effort, water-based mixtures with viscosities of 1-1000 cP are investigated with various nozzle types (Swirlchamber, Slotted Core, and Whirlchamber) using a Phase Doppler Interferometer instrument to acquire drop size, velocity, and number density measurements. Traditionally difficult measurements due to high spray density, these detailed results across each spray plume provide insight on the spray characteristics over the range of operating conditions. It is found that among the tested nozzle types, *i*) the spray characteristics with the SV SprayDry® nozzle change the least with viscosity, *ii*) the SB SprayDry nozzle has much more uniform characteristics across the spray pattern with the higher viscosity fluid than with water, and *iii*) the WhirlJet® SprayDry nozzle produces the widest spray pattern and the largest droplets.

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Fragment pdf(d)s for drops impacting a thin liquid surface

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Abstract

The impact of liquid drops onto thin liquid films has been studied for decades. However, there are few reports of fragment *pdf(d)s*. Motivated by this, the current study presents fragment *pdf(d)*s formed after drop impact. The first sampling time is chosen to be the initial observance of fragments. The second sampling time is either when the crown begins to collapse so that no additional fragments are formed, or immediately prior to the formation of crown-generated fragments. The third sampling time exists only in the case of crown fragment formation and is the point at which the crown begins to retract. In all cases, fragments are quantified using kHz digital in-line holography (DIH). DI-water was the only liquid used during these early studies.

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Characterization of flame sprays generated by an air-assisted atomization nozzle

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Abstract
Many technical spray applications involving evaporation and subsequent chemical reactions require narrow and distinct droplet size distributions to allow stable process conditions and a consistent product outcome. Hence, the type of atomizer unit is of major importance. Air-assisted nozzles have been previously applied in spray flame processes and also in flame spray pyrolysis (FSP), one of the most versatile and scalable methods for nano-powder manufacturing. In particular, a mixture of liquid fuel and organometallic precursor (fed through a capillary tube) is atomized by gaseous oxygen (fed through a coaxially surrounding outlet) and simultaneously ignited resulting in a flame spray. Gas velocity and temperature distribution along the centerline are supposed to be determining the size and crystallinity of the solid nanoparticles. In this study, the atomization and spray characteristics of an air-assisted nozzle, previously utilized in a laboratory-scaled FSP reactor, are investigated at burning and non-burning conditions. Different flow liquid and dispersion gas flow rates, dispersion gas pressures (above and below critical conditions of 0.9 bar) and compositions (oxygen/nitrogen) are carried out by means of optical measurement techniques. Liquid ethanol is fed with flow rates from 3-21 mL/min through a concentric capillary tube of an air-assisted atomizer and is dispersed by oxygen gas (5 L/min) into a fine spray that is characterized at non-burning and burning conditions. Optical characterization such as high speed camera (HSC) and longtime exposure imaging (LTI), laser sheet imaging (LSI), phase Doppler anemometry (PDA) are used to determine the droplet formation, size, velocity and flame shape.

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Size-velocity *pdf*s for Drop Fragments Formed via Bag Breakup

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Abstract

Digital-inline holography (DIH) was used to measure size probability distribution functions, *pdf*(d), for fragments formed via bag breakup. A MatLab script was used to reconstruct drop fragmentation dynamics, from which fragment sizes, as well as velocities (and accelerations), can be extracted. Results, which demonstrate bi-modal fragment size distributions, are reported in terms of Weber and Ohnesorge numbers for the ranges $13<We<30$ and $0.002<Oh<0.45$. Physical explanations for the presence of the two-and three-peaked size distribution are presented. The data will be useful to those modeling sprays in gas turbine engines, pharmaceutical tablet coaters, and spray dryers.

Quantification of Sauter Mean Diameter in Diesel Sprays using Scattering-Absorption Extinction Measurements

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Abstract

Quantitative measurements of the primary breakup process in diesel sprays are lacking due to a range of experimental and diagnostic challenges, including: high droplet number density environments, very small characteristic drop size scales (~1-10 μm), and high characteristic velocities in the primary breakup region (~600 m/s). Due to these challenges, existing measurement techniques have failed to resolve a sufficient range of the temporal and spatial scales involved and much remains unknown about the primary atomization process in practical diesel sprays. To gain a better insight into this process, we have developed a joint visible and x-ray extinction measurement technique to quantify axial and radial distributions of the path-integrated Sauter Mean Diameter (SMD) and Liquid Volume Fraction (LVF) for diesel-like sprays. This technique enables measurement of the SMD in regions of moderate droplet number density, enabling construction of the temporal history of drop size development within practical diesel sprays. The experimental campaign was conducted jointly at the Georgia Institute of Technology and Argonne National Laboratory using the Engine Combustion Network "Spray D" injector. X-ray radiography liquid absorption measurements, conducted at the Advanced Photon Source at Argonne, quantify the liquid-fuel mass and volume distribution in the spray. Diffused back-illumination liquid scattering measurements were conducted at Georgia Tech to quantify the optical thickness throughout the spray. By application of Mie-scatter equations, the ratio of the absorption and scattering extinction measurements is demonstrated to yield solutions for the SMD. This work introduces the newly developed scattering-absorption measurement technique and highlights the important considerations that must be taken into account when jointly processing these measurements to extract the SMD. These considerations include co-alignment of measurements taken at different institutions, identification of viable regions where the measurement ratio can be accurately interpreted, and uncertainty analysis in the measurement ratio and resulting SMD. Because the measurement technique provides the spatial history of the SMD development, it is expected to be especially informative to the diesel spray modeling community. Results from this work will aid in understanding the effect of ambient densities and injection pressures on primary breakup and help assess the appropriateness of spray submodels for engine computational fluid dynamics codes.

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Size-velocity *pdfs* for Drop Fragments Formed via Multi-mode Breakup

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Abstract

Digital-inline holography (DIH) was used to measure size probability distribution functions, *pdf*(*d*), for fragments formed via multi-mode breakup. A MATLAB script was used to reconstruct drop fragmentation dynamics, from which fragment sizes, as well as velocities (and accelerations), can be extracted. Results, which demonstrate multi-modal fragment size distributions, are reported in terms of Weber and Ohnesorge numbers for the ranges $30<We<50$ and $0.002<Oh<0.45$. Physical explanations for the presence of the two-and three-peaked size distribution are presented. The data will be useful to those modeling sprays in gas turbine engines, pharmaceutical tablet coaters, and spray dryers.

The Effect of Doublet Injector Orifice Geometry on Spray Characteristics

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Abstract

Doublet injectors have been studied parametrically in past work focusing on, for example, orifice length to diameter ratio, impingement angle, and injection velocity. The effect of orifice geometry has been comparatively under-studied although it has a significant impact on the impinging jet stream dynamics. Few works have been presented since the inception of orifice geometry studies for doublet injectors, yet the findings on the effectiveness of non-circular orifices have been acknowledged since the 1970's. Of particular promise is the use of rectangular orifices. Many initial drawbacks of non-circular orifices have since been remedied, for example, the precise design and manufacture of the orifice shapes. Yet little work has been done recently to affirm the benefits of rectangular geometries. As a result, the present study examines the effect of changing orifice geometry of doublet injectors on the resulting spray characteristics. Circular geometries are compared to rectangular orifices of varying aspect ratio. The effect of the orifice geometries on Sauter mean diameter, span, fuel and oxidizer mixing, and spray velocity vector fields are characterized for various test conditions. Injection velocity and impingement angle were varied to provide results for different cases. Data were collected at four downstream locations using multiple laser diagnostic systems to provide spray-averaged results. The results indicate affirms that improved mixing efficiency can be achieved through using rectangular orifices over circular orifices. Finer atomization can also be produced through the use of rectangular orifices, but greater droplet size non-uniformities can be present. The rectangular jet streams show greater stream instability compared to circular jet streams, possibly due to the axis-switching phenomenon, which can lead to increased mis-impingement for rectangular orifices depending on the conditions and impingement distance.

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An Analysis of the Convergence of Stochastic Lagrangian/Eulerian Spray Simulations

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Abstract

This work derives how the convergence of stochastic Lagrangian/Eulerian spray simulations depends on the number of computational parcels. A new, simple formula is derived that can be used for managing the numerical error in two or three dimensional computational studies. For example, keeping the number of parcels per cell constant as the mesh is refined yields an order one-half convergence rate in transient spray simulations. First order convergence would require a doubling of the number of parcels per cell if the cell size is halved. Second order convergence would require increasing the number of parcels per cell by a factor of eight. The results show that controlling statistical error requires dramatically larger numbers of parcels than have typically been used, which explains why convergence has been so elusive.

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Size-Velocity PDFs and Dynamic Sheet Profiles for Impinging Jet Atomizer-Produced Sprays

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Abstract

The specific link between the impinging jet sheet dynamics and the drop size and velocity pdfs is currently unknown. This study begins to fill in the gaps through use of high speed shadowgraphy and digital inline holography (DIH). High speed shadowgraphy was first used to gain a qualitative understanding of sheet evolution and breakup. DIH was then applied to determine fragment size-velocity pdfs. Both types of data were obtained at several jet Reynolds (*Re*) and Weber (*We*) numbers. Results are discussed in terms of the dominant physical mechanisms observed in the time-resolved, two- or three-dimensional, two – or three-component shadowgraph or holographic images.

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A Finite Particle Approach for the Simulation of Multiphase Flows

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Abstract

The simulation of multiphase flows presents challenges related to accuracy and affordability, particularly for practitioners in industrial settings where computational time is a significant constraint. In response to the need for improved multiphase models, we present a coupled Eulerian-Lagrangian multiphase methodology called the Lagrangian volume of fluid. In this method, Lagrangian phase-identifying particles seeded throughout the computational domain define the local phase, interface geometry, and surface tension force, while the Navier-Stokes equations are solved on an Eulerian mesh. The finite particle method is used to compute the interfacial geometry and surface tension on the Lagrangian particles as a function of their volume of fluid values and spatial distribution. Unlike other methods, the approach is free of remeshing and retains identical Lagrangian domain mass conservation (independent of resolution). Breakup and coalescence occur without explicit modeling, allowing for the capture of primary and secondary atomization. We present the method and apply it to the simulation of multiphase mixing layers and the capillary breakup of droplets to illustrate physical realizability and to demonstrate its sensitivity to numerical parameters including particle number density. Eulerian mass conservation errors are shown to be less than 0.02% for temporal mixing layers undergoing sheet breakup. Conservation errors in laminar capillary breakup are greater, ranging between 1.5% and 2.5%, which is attributable to interpolation errors near merging characteristics. The inherent Lagrangian domain mass conservation and sub-grid scale resolution provided by the phase-identifying particles makes the approach a promising foundation for large eddy simulation.

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Hydrodynamics of Precisely Controlled Droplet Train Impinging upon a Liquid Film

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Abstract

In this study, hydrodynamics of a single droplet train impinging upon a liquid film has been investigated experimentally and numerically. A piezo-electric droplet generator was used to produce mono-dispersed droplets with the ability to control droplet properties, such as droplet diameter, droplet velocity and droplet Weber number. A high speed camera was used to capture the droplet-induced crown propagation dynamics and the morphology of the droplet-induced liquid film. The liquid film thickness within the impingement zone was measured using a laser beam based on the Total Internal Reflection principle. Results show that high frequency droplet train impingement leads to an ultra-thin liquid film (about 12 µm) within the impingement zone. Results also reveal that Weber number of droplets plays a significant role in the morphology of droplet-induced crown and liquid film. Numerically, ANSYS-Fluent was employed to simulate the droplet impingement process using Volume of Fluid model Coupled with Level Set method (CLS-VOF). The dynamic mesh adaption technique was used in the simulations, which was capable of capturing the propagation of droplet-induced crown with time dependent high spatial and temporal resolutions. A good agreement was reached between experimental and numerical data in terms of droplet-induced crown diameter and number of cusps. Velocity distribution within the propagating droplet was determined numerically. Results show that the radial velocity within the propagating droplet always vary linearly with radial position. In summary, results to date have elucidated the hydrodynamic characteristics of droplet train impingement both experimentally and numerically.

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Planar Liquid Sheet Breakup Mechanisms, Time Scales, and Length Scale Cascade

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Abstract

The temporal, three-dimensional instabilities on a planar liquid sheet are studied using Direct Numerical Simulation and the level-set and volume-of-fluid interface tracking. Three breakup mechanisms are distinguished at early breakup, which are well categorized on a gas Weber number (We_g) versus liquid Reynolds number (Re_l) diagram. At low Re_l and low We_g, liquid lobes stretch directly into ligaments. Thick ligaments and large droplets occur in this zone. With increasing Re_l at high We_g, the breakup mechanism manifests hole formation. Breakup is initiated with lobe thinning and perforation, leading to formation of bridges and then ligaments. At lower Ohnesorge number (Oh) and higher Re_l, hole formation is prohibited at early breakup. The lobes are corrugated; thin ligaments result from corrugation stretching. These mechanisms are relatively independent of the jet configuration - seen in both planar and circular liquid jets. The characteristic times for the hole formation and the ligament stretching differ - the former depending on surface tension and the latter on liquid viscosity. In the transitional region, both characteristic times are of the same order. Using the local radius of curvature of the surface and the local cross-flow coordinate of the spray surface, two series of PDFs are obtained over a wide range of length scales. The radius PDF shows that, with increasing We_g, the average curvature increases, the number of small droplets increases, and cascade occurs at a faster rate. The other PDF shows the spray expansion, with the spray angle being larger at higher We_g, higher density ratios, and lower Re_l.

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Experimental Study of Twin-Fluid Jet-in-Crossflow at Jet-Engine Operating Conditions

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Abstract

Designs for numerous future jet-engine fuel-injector make use of a flow configuration called the "Twin-Fluid Jet-in-Crossflow (TF-JICF)", where fuel is injected as a jet that is atomized by both co-injected and crossflowing combustor air. TF-JICF injectors theoretically improve combustor performance and durability compared to existing plain-jet JICF injectors. However, experimental studies of TF-JICF are very sparse. Furthermore, the "standard model" of TF-JICF that was adopted by earlier studies is increasingly showing discrepancy with emerging data. We conducted an investigation to resolve this discrepancy by experimentally characterizing the TF-JICF produced by a single injector across extremely wide ranges of conditions (i.e., crossflow Weber number =175-1050, crossflow pressure P_{cf} =1.8-9.5*atm*, momentum-flux ratio J=5-40 and air-nozzle dP =0-150% of P_{cf}). These covered the conditions used to develop the standard model, recently studied conditions where discrepancies were found, and high-density conditions that are found only in jet-engine combustors. Consequently, the investigation found a spectrum of new TF-JICF spray characteristics, as well as an unusual non-monotonic relation between spray penetration and air-nozzle dP. Based on these observations, we propose that TF-JICF is comprised of four regimes with different sets of dominant spray-formation mechanisms. Certain regimes are beneficial towards jet-engine fuel-injectors while others are counter-productive. Critically, the proposed four-regime understanding of TF-JICF is also consistent with all experimental data to date. In this new understanding, the TF-JICF standard model was found to be applicable only to the highest dP regime, contrary to their early applications across all operating conditions.

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Explaining the Planar Liquid Jet Atomization via Vortex Dynamics

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Abstract

The 3D, temporal instabilities on a planar liquid jet are studied using DNS with level-set and volume-of-fluid surface tracking methods. The λ_2 method has been used to relate the vortex dynamics to the surface dynamics at different stages of the jet breakup, e.g. lobe formation, thinning and perforation, ligament formation, stretching, and tearing. The breakup character depends on the flow Ohnesorge number (Oh) and gas-to-liquid density ratio. At high Reynolds number (Re) and high Oh, hairpin vortices form on the braid and overlap with the lobe hairpins, thinning the lobes, which puncture to form holes and bridges. The bridges break, creating one or more ligaments that stretch and break into droplets by capillary action. At low Oh and high Re, lobe stretching and thinning is hindered due to the high surface tension and splitting of the primary Kelvin-Helmholtz (KH) vortices, inhibiting early hole formation. Corrugations form on the lobe edges, induced by the split vortices, and stretch to form ligaments. At low Re, the breakup process moves from hole formation to direct stretching as Oh is decreased. The Kelvin-Helmholtz (KH) vortices depart from the liquid surface, with reduced influence on rolling and thinning of the lobes. As the vortices turn streamwise, they squeeze the lobes from both sides and shape them into thick ligaments. Streamwise vortex stretching and baroclinicity are the main causes of streamwise vorticity generation, resulting in three-dimensional instabilities at high and low density ratios, respectively. The gas-to-liquid viscosity ratio does not significantly affect the breakup process and time scales.

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Primary atomization of a liquid dodecane jet using the Ghost-fluid method

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Abstract

Atomization of liquid jets in IC engines and gas turbines is essential for efficient mixing of fuel and air. A key hurdle to understanding the physical mechanisms controlling the breakup of liquid jets in practical injectors has been the difficulty associated with making reliable flow-field measurements in the dense spray region using currently available experimental techniques. As such physically realistic CFD simulations of the primary atomization process provide one possible route to improving current understanding of the fundamental physics in this area. This paper presents the results from primary atomization simulations of an n-Dodecane jet. The simulation conditions have been chosen to match those of the 'cold' Spray A defined by the Engine Combustion Network. These simulations have been performed by using a numerical approach in which the evolution of liquid and gas flows are solved using distinct instances of a solver for each phase and matching conditions across the interface are captured using the Ghost-fluid method. Reasonable agreement for the jet penetration length from the simulation with experimentally measured estimates from the ECN database is observed.

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Evaluation of Spray/wall Interaction Models under Conditions Related to Diesel Engines with a Hybrid Breakup Model

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Abstract

The spray atomization process and the spray/wall interaction play a fundamental role on the mixture formation process, which greatly influences the combustion process and the exhaust emissions. However, due to the complex nature of the process, the mechanism is not yet completely understood. A numerical approach is proposed in this paper. The modified FVM (Finite Volume Method) method is used to solve fluid flow equations and numerical simulations are performed with the in-house software GTEA (General Transport Equation Analysis).To model the spray atomization for diesel engines, four breakup models including the Taylor Analogy Breakup (TAB), Cascade Atomization and Drop Breakup (CAB), Kelvin-Helmholtz Rayleigh-Taylor (KH-RT) and a new hybrid breakup (Hybrid) were evaluated. Based on the experiment results, the prediction accuracy of four breakup models was assessed in terms of spray penetration and spray shapes. The results indicate the Hybrid model shows good predictions in all aspects. To model the interaction between the spray and wall, three interaction models including the O'Rourke and Amsden (OA) model, Bai and Gosman (BG) model and Zhang and Jia (ZJ) model were evaluated, and validated by the experimental data from recent under the conditions related to diesel engines. The validations of these interaction models focus on the penetrations, including the spray radius and spray height. The results indicate the ZJ interaction model better agreements with experiment data.

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Poster Abstracts

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Poster

Standardizing a Simplex Atomizer

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Abstract

Advanced Atomization Technologies has designed a standard atomizer to provide a typical aerospace simplex atomizer geometry to the research community. The intent of the program is to mirror the Engine Combustion Network (ECN). With a single geometry, research across institutions will be easily compared and built upon. The atomizer design has a flow number of 3.7 and an air circuit with a swirler that can be removed for optical line of sight to the atomizer. Preliminary program details are explained and future state of standardizing gas turbine atomization devices is discussed.

Keywords: Advanced Atomization Technologies, Parker standard atomizer, simplex atomizer, standard atomizer

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Poster

Analysis of Electrohydrodynamic Atomization using High-Speed Microscopy

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Abstract

Atomization of a diesel micro-jet is achieved via an electrohydrodynamic charge injection process. Our atomizer is comprised of a grounded nozzle housing and an internal probe, concentric with the emitting orifice, that is held at high electric potentials ranging from 1–10 kV. A pressurized reservoir at 5–40 psi drives the fuel at a desired flow rate through the 100 micrometer diameter nozzle orifice. The fuel fills the cavity between the high voltage probe and the nozzle housing as it passes through the atomizer. Diesel fuel (a dielectric) impedes the transport of electrons from the probe to the nozzle housing and advects some of this charge. Therefore, after exiting the orifice, the fluid jet will possess a high electric charge density. Once it is ejected from the atomizer, induced electromagnetic forces drive a kink instability during jet breakup and imparts droplet velocity components normal and perpendicular to the axis of the atomizer. This results in the formation of a conically-shaped spray plume. The magnitude of the jet charge density, which governs the quality of the atomization, is dictated by several factors: intrinsic fuel properties, such as molecular composition and viscosity, fuel flowrate, stand-off distance, surface quality of the probe and the nozzle housing, and magnitude of the applied potential. In this study we investigated the jet breakup and spray characteristics as a function of these parameters. Our primary interest is in the process that dictates the jet breakup within the first few hundred micrometers of the emitting orifice. Several mechanisms have been observed: electrospray breakup, capillary breakup, and mixed breakup. We characterize the electrohydrodynamically-assisted breakup of the fuel jet through the use of high-speed microscopy and image processing. The images are combined with the measured charge density and environmental factors to provide a better understanding of the electrohydrodynamic breakup phenomena.

Keywords: Diesel, dielectric, atomization, electrohydrodynamics, electrospray, droplets, charge injection

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