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14. ABSTRACT Modern rockets operate at supercritical pressures with respect to propellants. There is a need to understand mixing and combustion beyond liquid and gas states. Shear coaxial injectors are a common choice for cryogenic liquid rocket engines. Interactions of transverse acoustics with an injector's own modes and mixing need to be understood in terms of combustion instability. There is a need to understand the differences in response to pressure and velocity nodes. There is a need to understand what non-dimensional numbers capture the mixing of typical injectors, and to characterize how geometry affects mixing. In this presentation, relevant physics of shear coaxial jets are explored; highlights from literature review are listed; and experimental set-ups are described.					
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1

Coaxial Injectors Subjected to External Acoustics

Ivett Leyva

**Students (current and past): Sophonias Teshome,
Juan Rodriguez, Jeff Graham**

Co-advisors: Doug Talley, Ann Karagozian

October 20, 2011

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Statement of need



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- **Modern rockets operate at supercritical pressures with respect to the propellants**
- **Need to understand mixing and combustion beyond liquid, gas states**
- **Shear coaxial injectors are a common choice for cryogenic liquid rocket engines**
- **Interactions of transverse acoustics with injector's own modes and mixing needs to be understood for combustion instability**
- **Need to understand differences in response to pressure and velocity nodes**
- **Understand what non-dimensional numbers capture the mixing of typical injectors**
- **Characterize how geometry affects mixing**





Relevant physics of shear coaxial jets



1. Transverse Acoustic mode from chamber/siren

— $f=f(c, \text{geometry})$

2. Acoustic modes for outer and inner jets

— $f \sim c/2L$ – 2 speeds of sound up and downstream

3. Wake resulting from inner post thickness

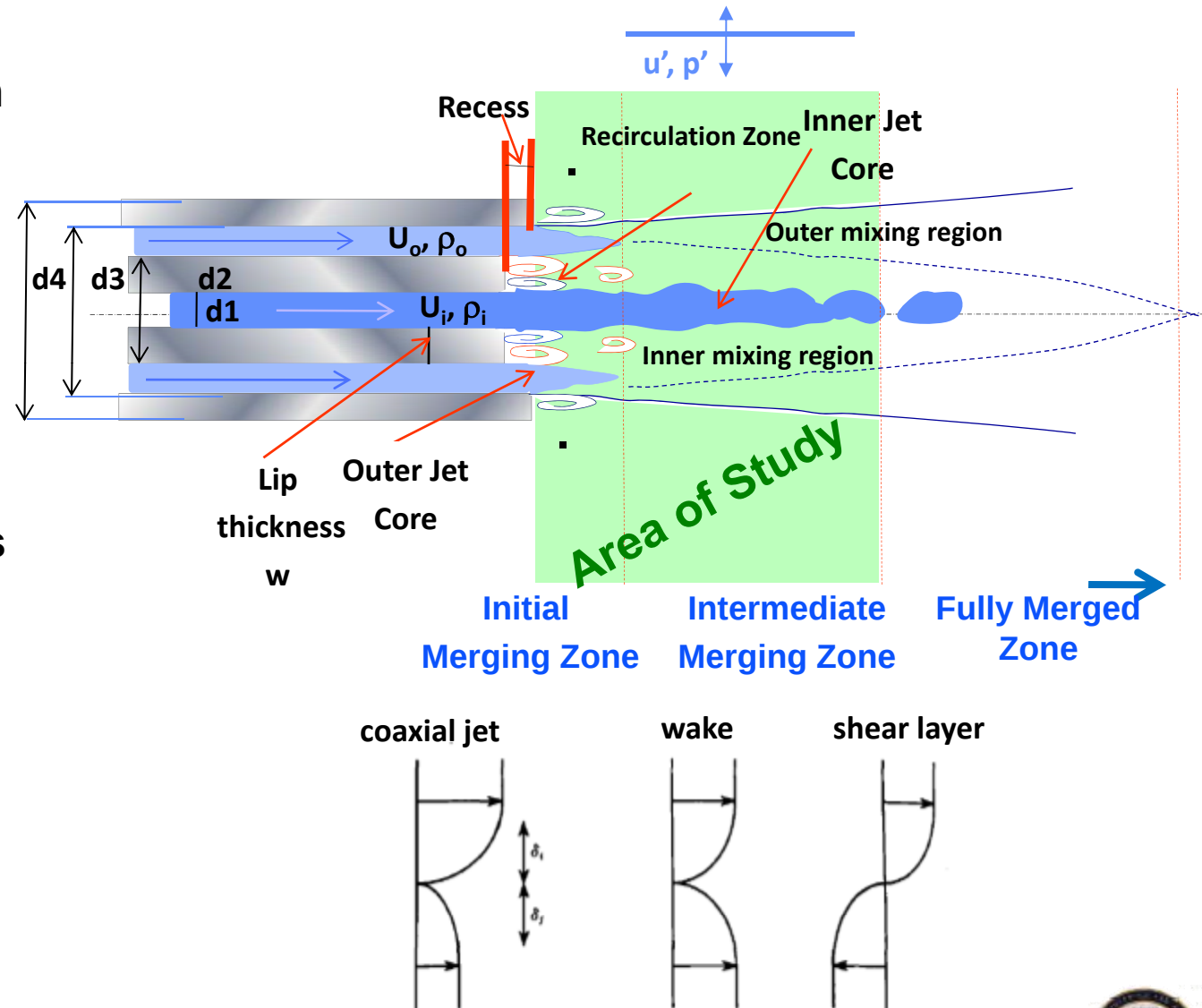
— $St=fw/U_{ch}$

4. Shear layer instabilities

— $St_\theta=f\theta/U_{ch}$

5. Jet preferred modes

— $St=fD_{ij}/U_{ij}$



Dahm et al, JFM, Vol 241, 1992

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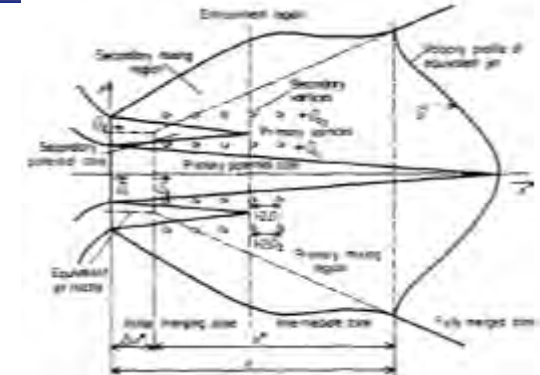


Highlights from literature review (1 of 2)

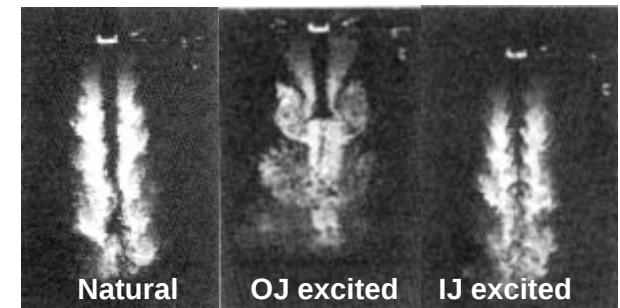


4

- Michalke, 1964
 - Linear stability theory for inviscid instability of a hyperbolic tangent velocity profile
- Crow and Champagne, 1971
 - Single jet preferred mode, $St_d = fd/U \sim 0.3$
- Ko et al, 1976-1989
 - Some of earliest detailed description of near field mixing for coaxial jets
- Boldman et al, 1975
 - Experimental and theoretical analysis for mixing of two air streams with different velocities – points out different vortex interactions, $St_1 \sim 0.2 (U_{ave})$
- Gutmark and Ho, 1983
 - Collects previous results on jet preferred mode, St_d has a range from $\sim 0.24-0.64$
- Wicker and Eaton, 1994
 - Forces air inner and outer jets independently – observes vortex growth
- Dahm et al, 1992
 - Seminal pictures of different instabilities plus effect of absolute velocity and R



Kwan and Ko, J. Sound and Vibration, 48 (2), 1976



Wicker and Eaton, AIAA J, (32) No.3, 1994



Dahm et al, JFM (241) 1992



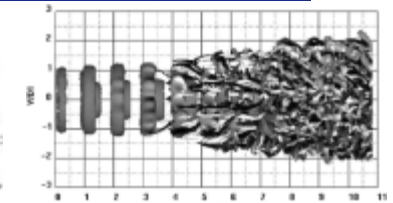
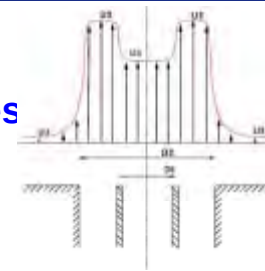


Highlights from literature review (2 of 2)



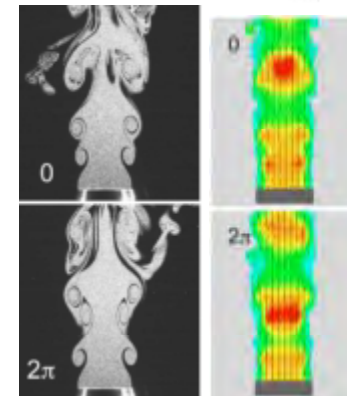
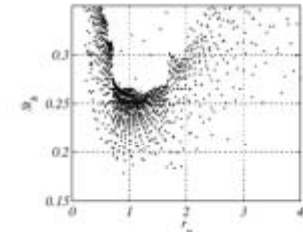
5

- Balarac, da Silva, Metais et al (2003, 2007)
 - DNS analysis of coaxial jets - same density, top-hat profiles
 - Consider two shear layers, study effect of R
 - Consider axisymmetric and azimuthal excitation
- Buresti, Talamelli, Petagna (1994, 1998)
 - Air jets, same density, top-hat profile, $St_{do}=fd_o/U_{oj} \sim 0.3$ to 1, function of x/D_i
- Segalini, Talamelli, et al (2006, 2011)
 - Air jets, same density, top-hat profile, $St_{b(lip)}=fb(lip)/U_{average}$
- Birbaud, Ducruix, Durox, Candel (2006-2007)
 - Single air jets, low Re , laminar, top-hat profile, subjected to acoustic modulation
 - Systematic study of effect of modulation in terms of St_d , St_θ
- Tshohas, Canino, Heister (2004, 2009)
 - 2D unsteady CFD for LOX/H₂ elements but non-reacting
 - Unforced behavior, found $St_{lip}=fd_{lox}/U_{lox} \sim 0.10-0.25$
- Richecoeur, Scoufflaire, Ducruix, Candel (2006)
 - Forced transverse acoustic excitation of flames

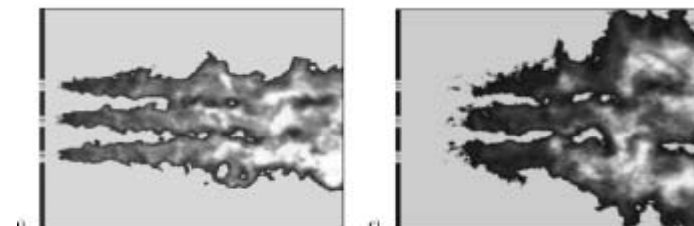


Balarac et al, Phys of Fluids (19), 2007

Segalini et al, Phys of Fluids (23), 2011



Birbaud et al, Phys of Fluids (19), 2007



Richecoeur et al, JPP (22) No 4, 2006





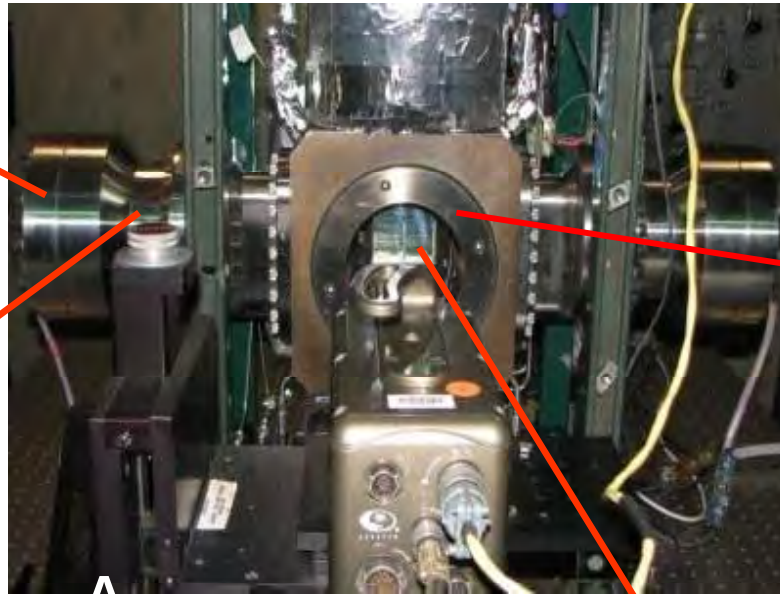
Experimental setup – EC-4



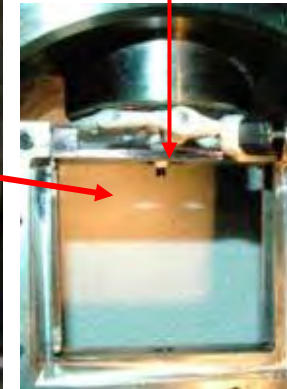
Piezo-Siren



Waveguide

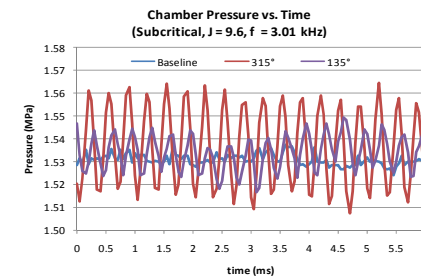
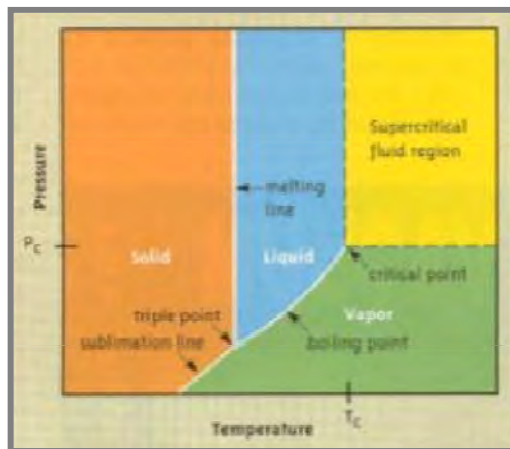


Coaxial Injector



Inner Chamber

$f \sim 3\text{kHz}$



Thermocouple and P transducer





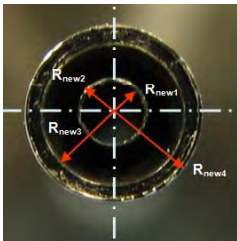
Geometric Rationale



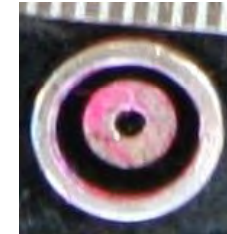
LAR_ThinLip



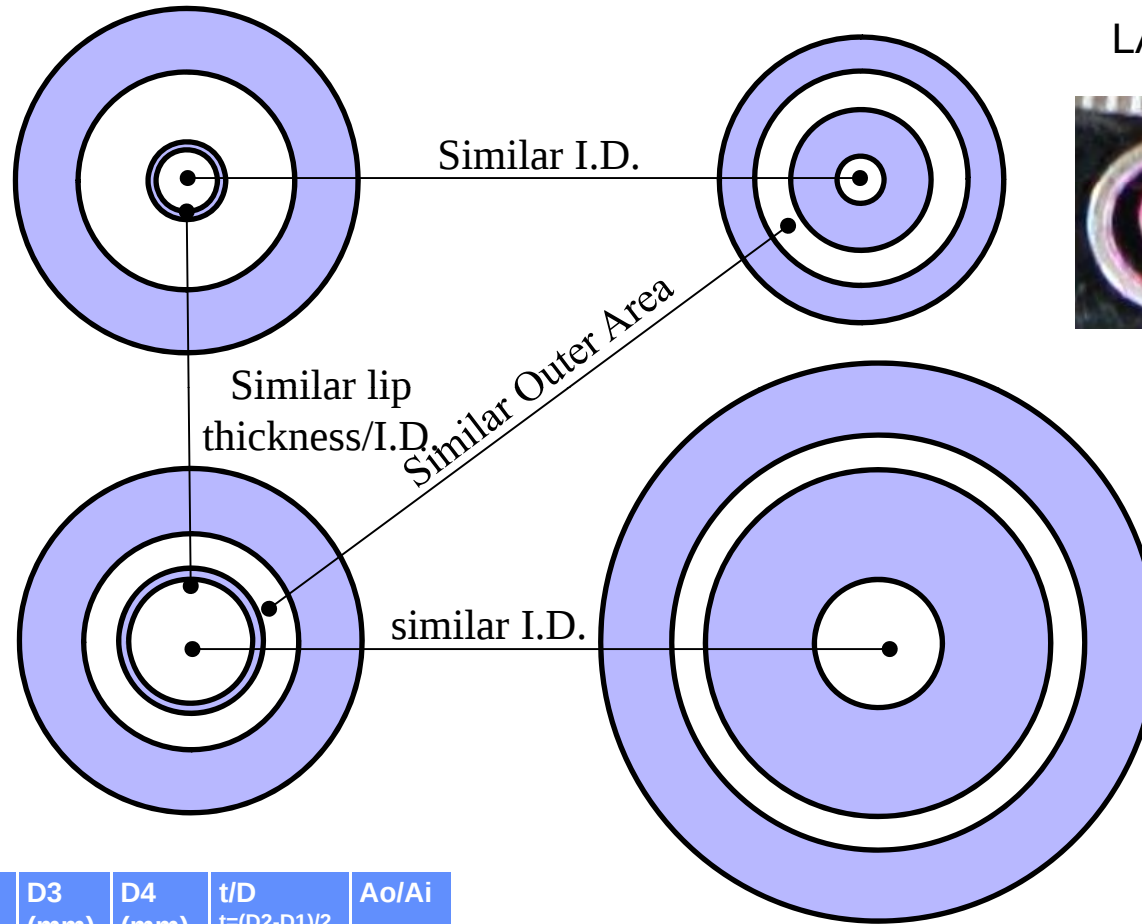
SAR_ThinLip



LAR_ThickLip



SAR_ThickLip



Two recesses

	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	t/D $t=(D2-D1)/2$	Ao/Ai
LAR_thickLip	0.51	1.59	2.42	3.18	1.05	12.9
SAR_thinLip	1.40	1.65	2.44	3.94	0.09	1.6
SAR_thickLip	1.47	3.96	4.70	6.35	0.84	2.9
LAR_thinLip	0.70	0.89	2.44	3.94	0.13	10.6

SAR, LAR -> Small, Large Area Ratio

ThickLip, ThinLip -> Post lip thickness

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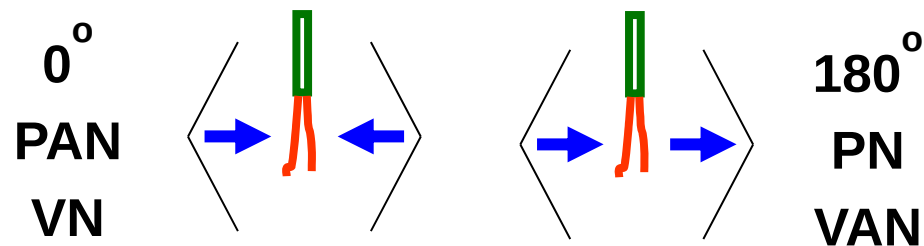


Other parameters varied



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- Momentum flux ratio $J = \rho_o u_o^2 / \rho_i u_i^2$
- Velocity ratio $R = u_o / u_i$
- Thermodynamic state
 - Subcritical to supercritical
- Acoustics
 - Acoustics off
 - Acoustics on (with and without mode matching)
 - Phase of the acoustics:
 - 0 degrees: Pressure Anti Node (PAN) (velocity node (VN))
 - 180 degrees: Pressure node (PN) (velocity antinode (VAN))





Chronological progression (only coaxial results are summarized in what follows)



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- **Single jets, no coaxial flow**
 - Davis et. al. (Ph.D. thesis) – single jets, no coaxial flow
 - Not briefed today
- **Coaxial jets**
 - Leyva et.al. – LAR_thick
 - Rodriguez et. al. (Ph.D. thesis) – LAR_thick, SAR_thin
 - Graham et. al. – SAR_thin, two recesses
 - Teshome et. al. (Ph.D. thesis, expected Mar 2012) – complete all four geometries
 - Also complete modal analysis of earlier geometries
- **Future: Combusting coaxial jets**
 - Wegener et. al. (Ph.D. thesis) (in process)
 - Article 219 facility funds



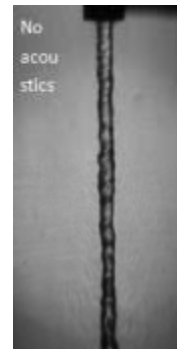


Image interpretation key



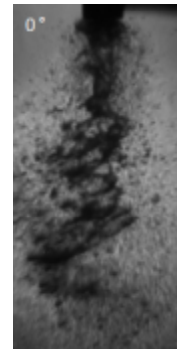
10

Baseline:
Acoustics
off



0°

Acoustics on
PAN, VN



"Pressure coupled"

180°

PN, VAN



Largest difference
expected from 0°
"Velocity coupled"

pressure = fixed

$$J(\rho_o u_o^2 / \rho_i u_i^2) = \text{fixed}$$

PN – pressure node - Min

PAN – pressure antinode - Max

VN – velocity node

VAN – velocity antinode





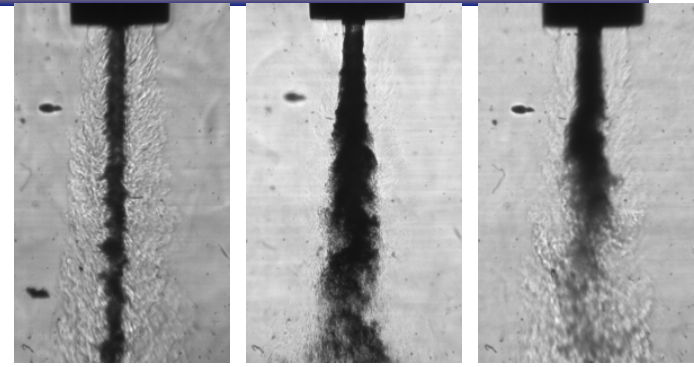
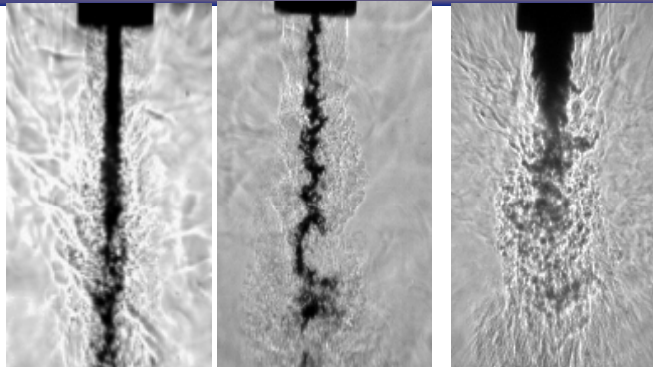
Sub-Critical Pressure: Two Geometries



LAR_thickLip

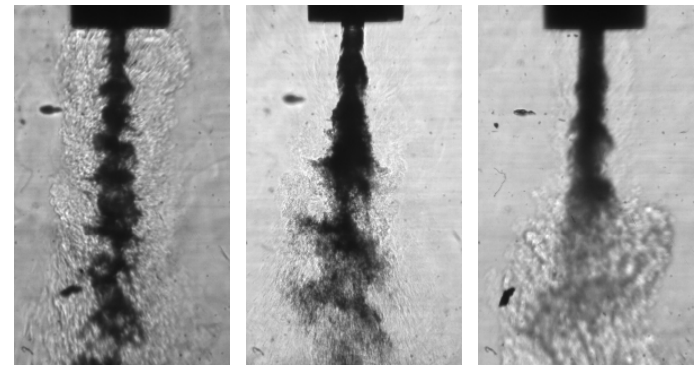
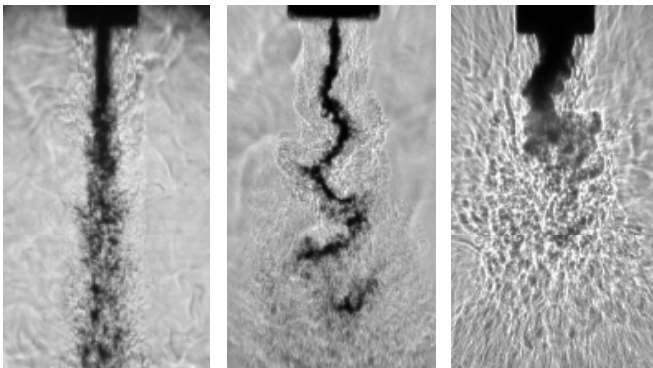
LAR_thinLip

Baseline



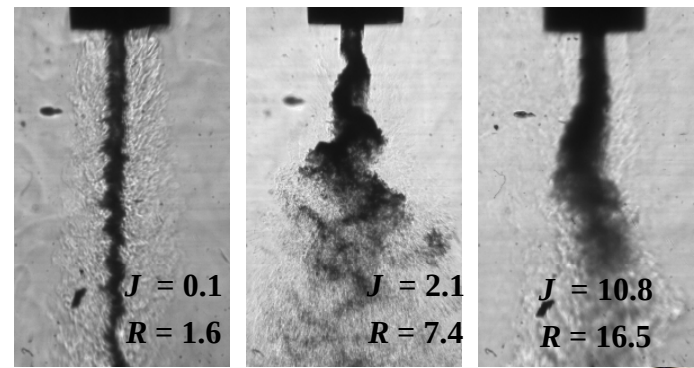
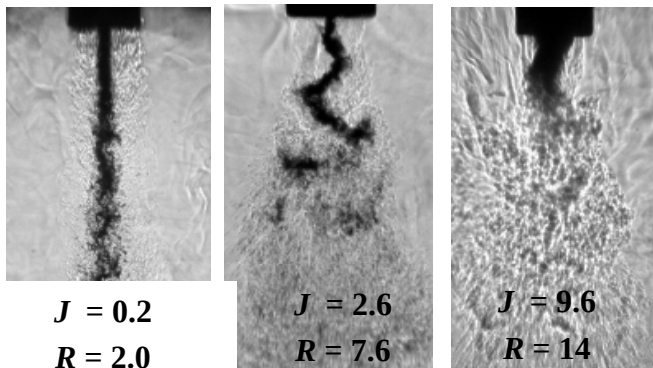
PAN

P
antinode



PN

P node



$$J = \rho_o u_o^2 / \rho_i u_i^2$$

$$R = u_o / u_i$$

$J = 0.2$
 $R = 2.0$

$J = 2.6$
 $R = 7.6$

$J = 9.6$
 $R = 14$

$J = 0.1$
 $R = 1.6$

$J = 2.1$
 $R = 7.4$

$J = 10.8$
 $R = 16.5$





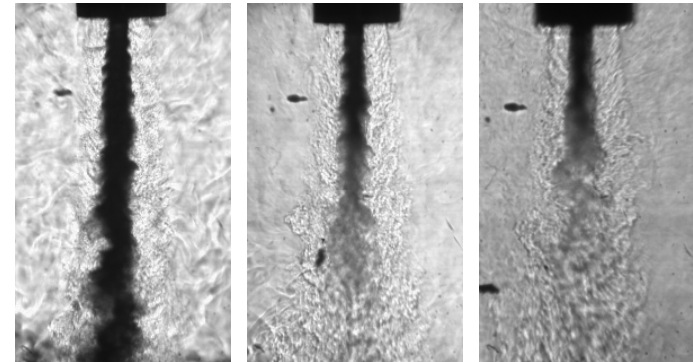
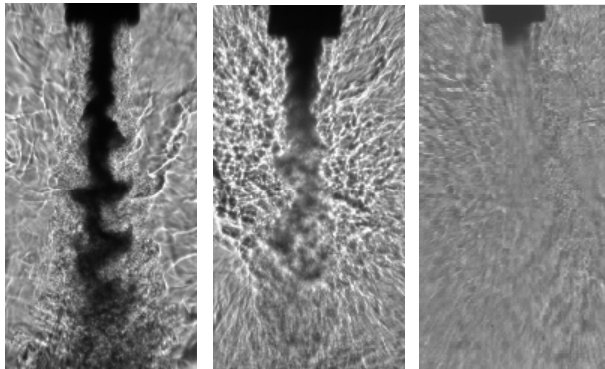
Near-Critical Pressure: Two geometries



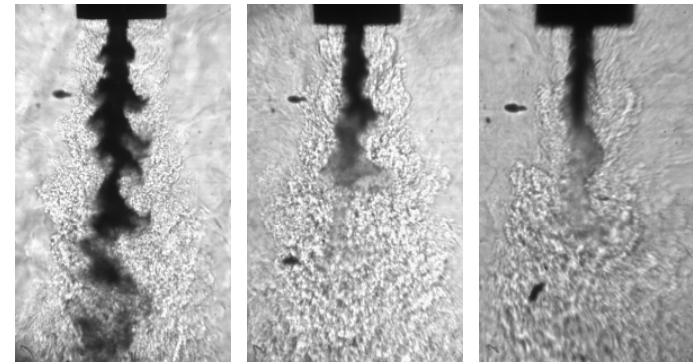
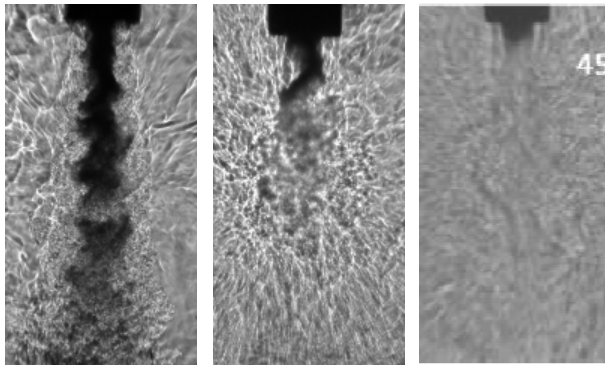
LAR_thickLip

LAR_thinLip

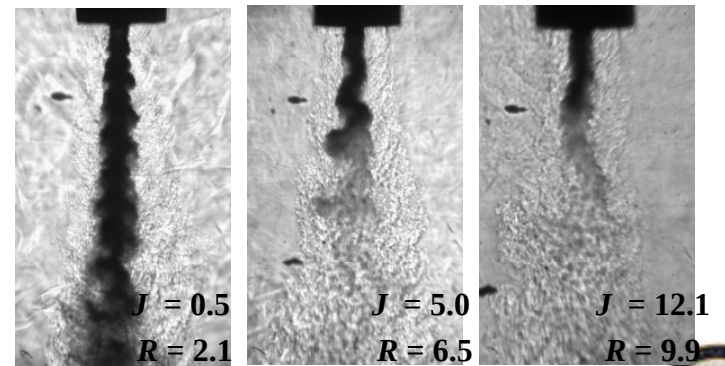
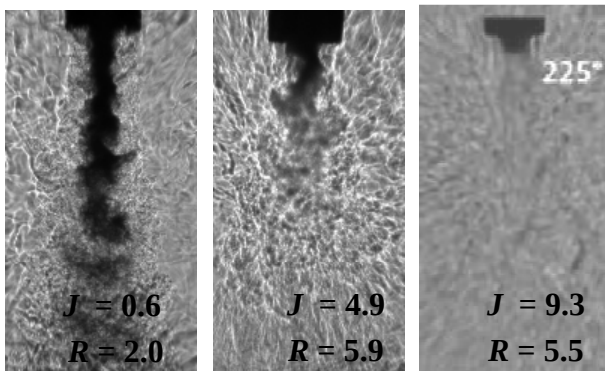
Baseline



PAN



PN

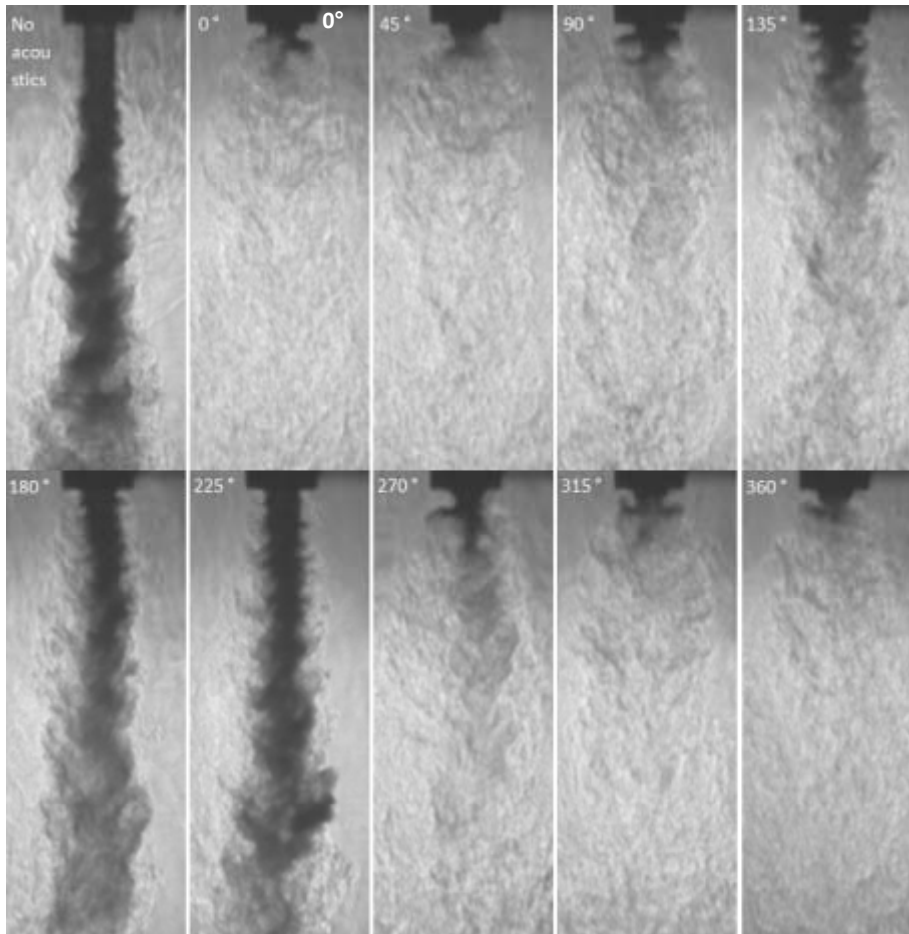




SAR_thinLip



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$Pr=1.05$, $J=1.7$, $p'/p=0.32\%$
Coupled to Outer Jet Acoustic Mode

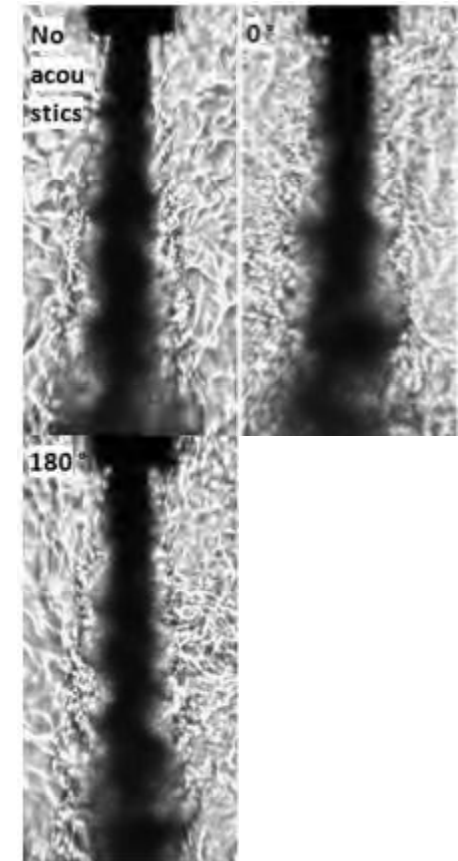
- Nearcritical conditions
 - **No jet bending observed**
 - large vortical structures generated when coupled to injector mode
 - Reduction of dark core can be as large as 90%
 - More clear response of jet to pressure antinode
- Subcritical conditions
 - Same mode – vortical structures
 - Not as dramatic reduction as with nearcritical cases



$Pr=1.05$, $J=0.5$, $R=2$



$Pr=1.05$, $J=0.5$, $R=1.3$



$Pr=1.05$, $J=2.2$,
 $p'/p=0.25\%$

Non Coupled

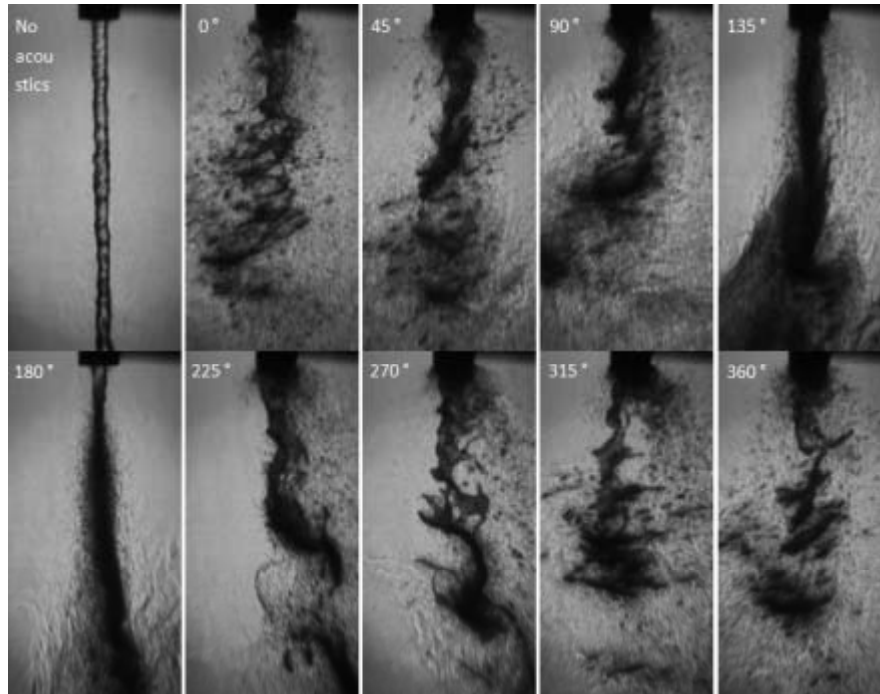




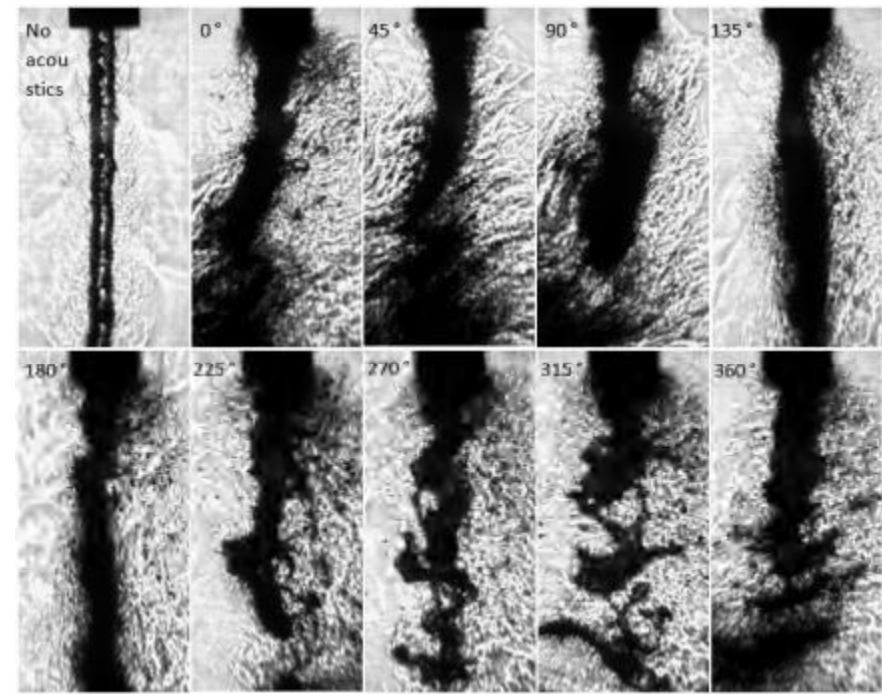
Effect of Recess: SAR_ThinLip; $Pr=0.45$, $J \sim 0.09$



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Flush inner post, $J=0.09$, $p'/p=0.45\%$



Recessed inner post, $J=0.089$, $p'/p=0.60\%$

Qualitatively similar at very low J values



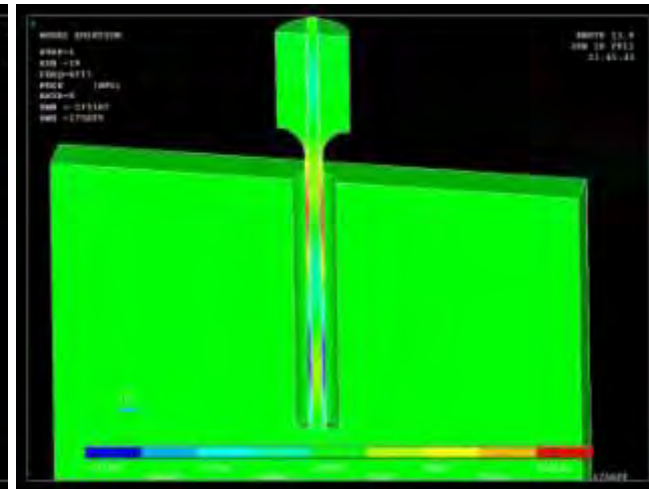
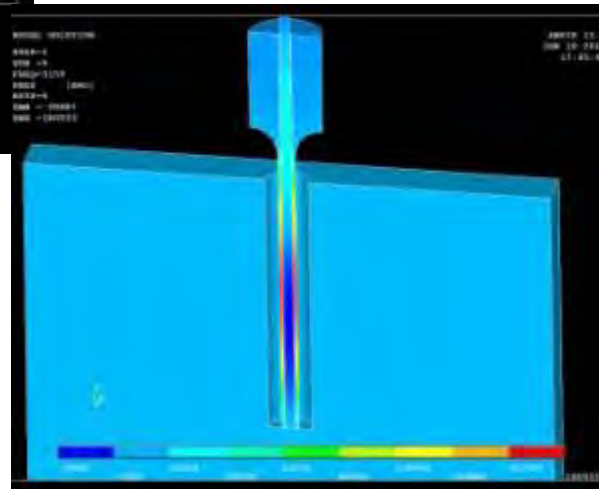
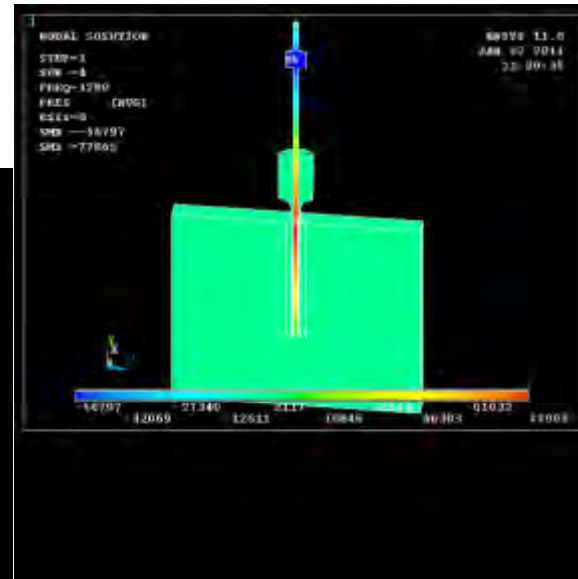
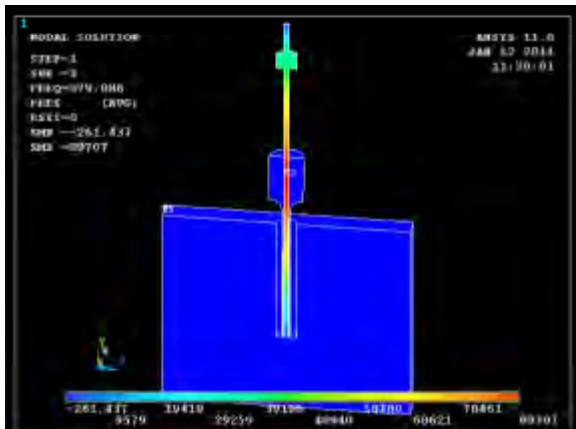


Acoustic Analysis for Injectors



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In collaboration
with Jeff Muss and
Rory Davis, Sierra
Engineering



Have more accurately
computed the acoustic
modes for the inner and
outer jets for constant and
linearly varying
temperatures for
subcritical and
supercritical pressures

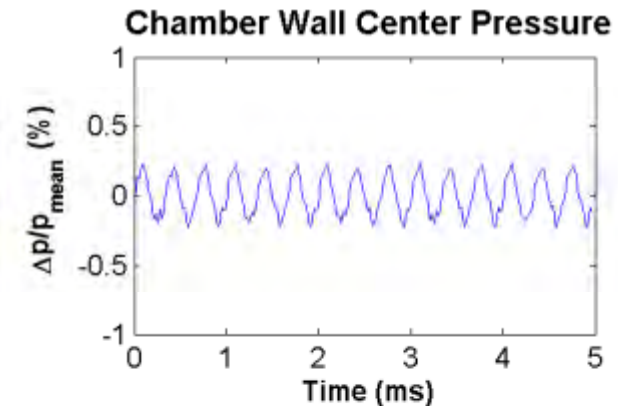
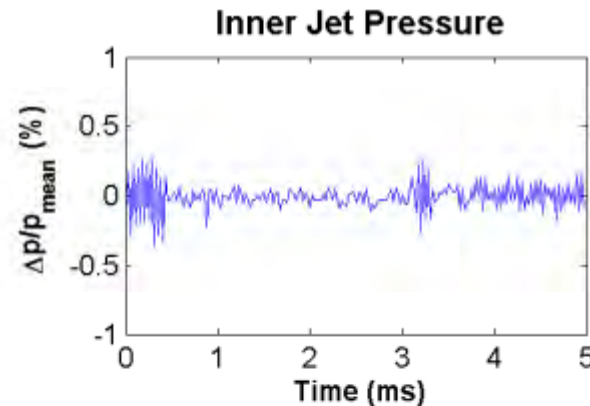
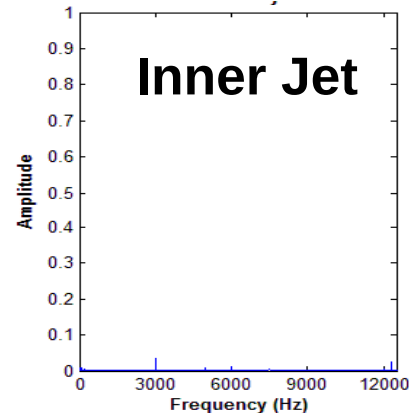
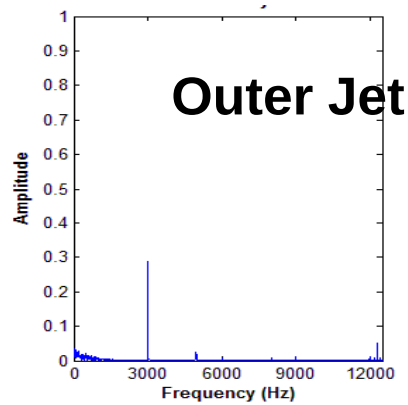
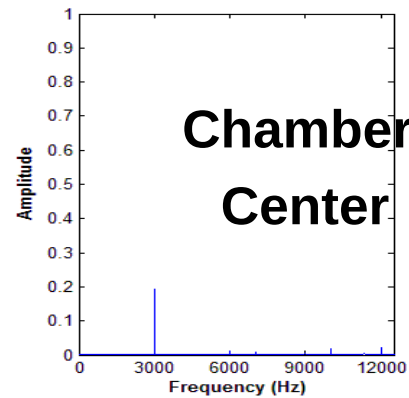




New analysis: synchronized p' and images taken with microscopic lens



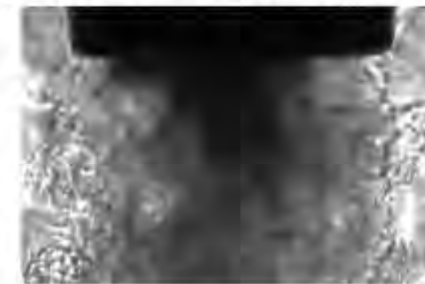
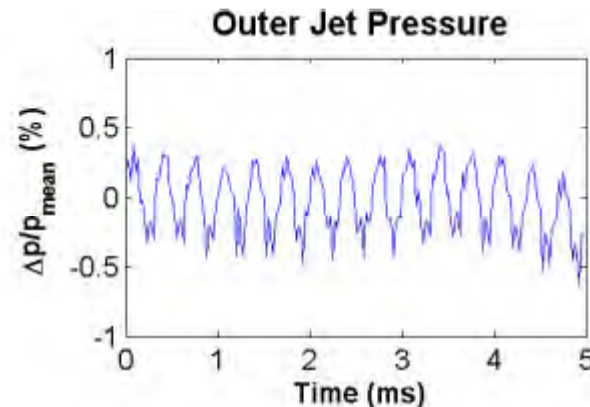
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Inner Injector Recessed $0.5 D_i$

$Pr = 1.03, J = 5.1, VR = 5.9$

Forcing Condition: 3000 Hz, Maximum Δp



$U_o = 6.25 \text{ m/s}, U_i = 1.06 \text{ m/s}, T_o = 165\text{K}, T_i = 118\text{K}$

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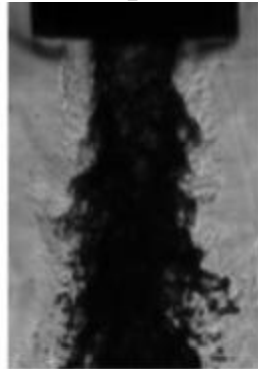


Case I: Baseline Flow



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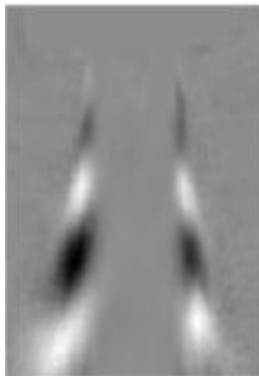
Snapshot



Average



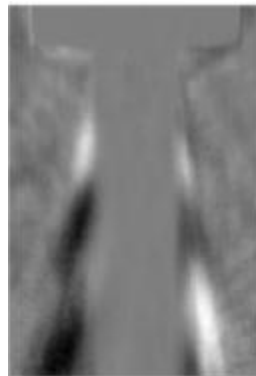
Mode 1



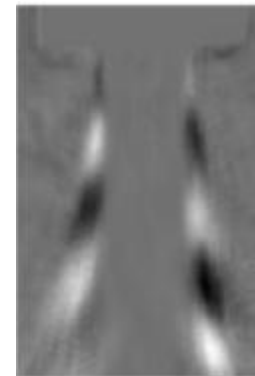
Mode 2



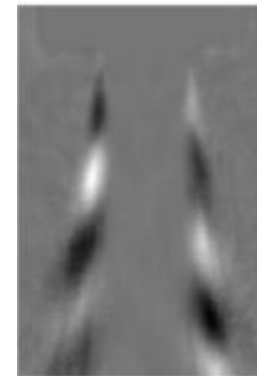
Mode 3



Mode 4



Mode 5



Mode 6



Case	P_R	$T_{R,OJ}$	$T_{R,IJ}$	R	J
I	0.44	1.19	0.84	5.8	2.0

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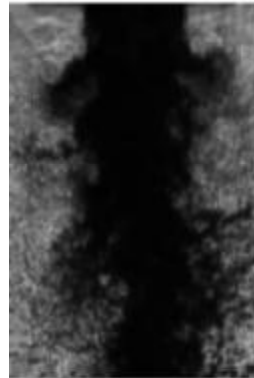


Case I: Acoustically Forced Flow



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Snapshot



Average



Mode 1



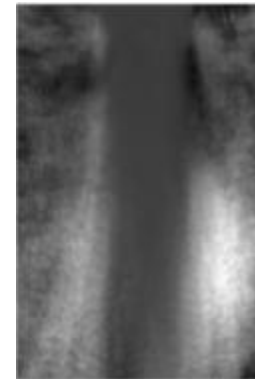
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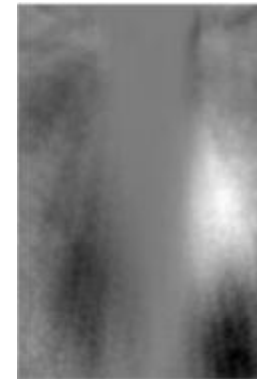
Mode 3



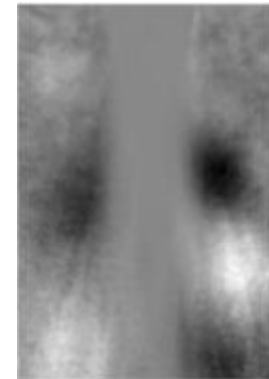
Mode 4



Mode 5



Mode 6



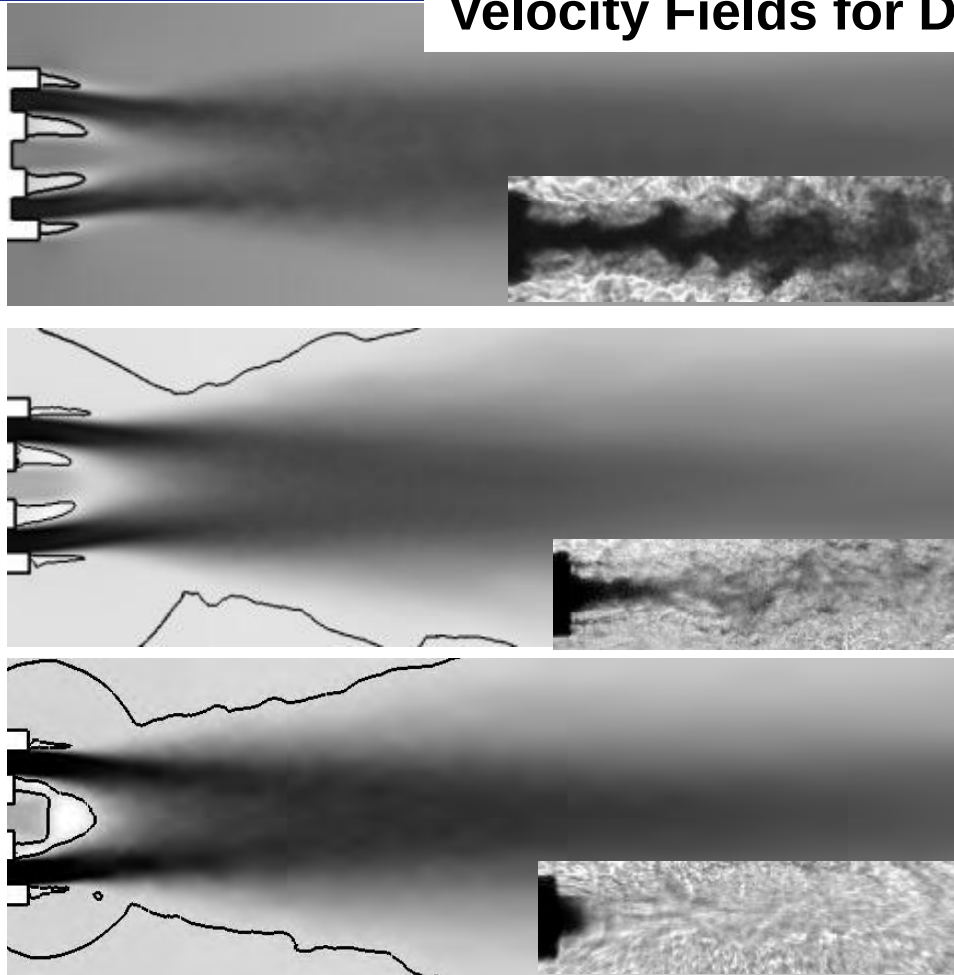
Case	P_R	$T_{R,OJ}$	$T_{R,IJ}$	R	J	f (kHz)
I	0.44	1.19	0.84	5.8	2.0	2.96

Distribution A: Approved for public release; distribution unlimited

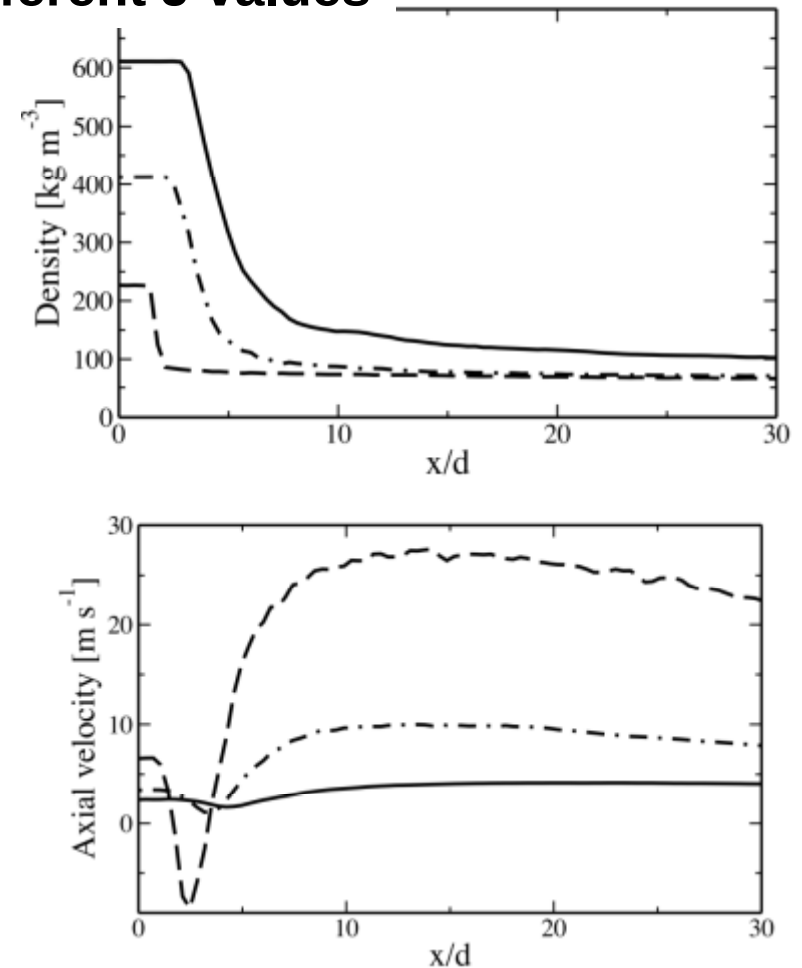




Velocity Fields for Different J values



Longitudinal slice of axial velocity. White: minimum; black: maximum. Dark line indicates iso-contour of zero axial velocity. Top: $J = 1.1$; middle: $J = 3.0$; bottom: $J = 9.3$.



Top: centerline profile of density; bottom: centerline profile of velocity. Dark line: $J = 1.1$; dash point line: $J = 3.0$; dashed line: $J = 9.3$.





Fundamental frequencies for baseline conditions



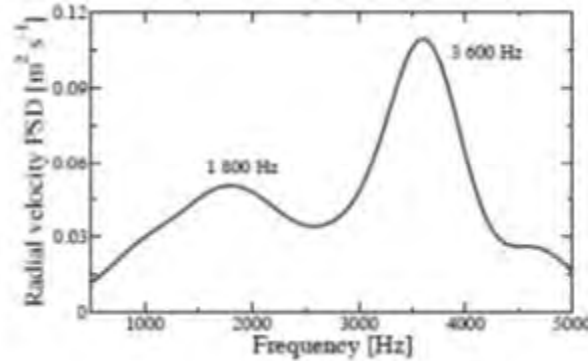
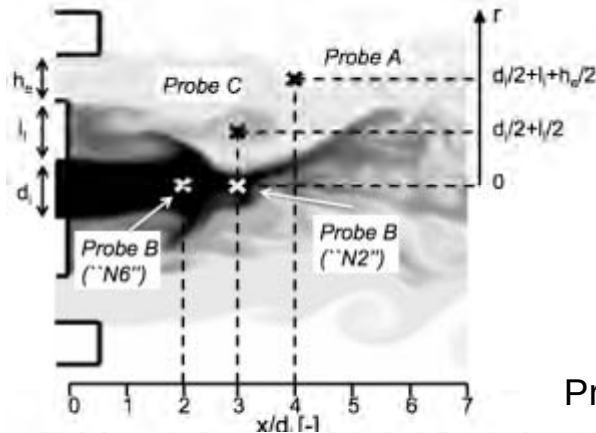
20

Case "N6"
($J=3.05$)
Density
distribution
(white: 60
 kg/m^3 ;
black: 410
 kg/m^3 ;
logarithmic
scale).

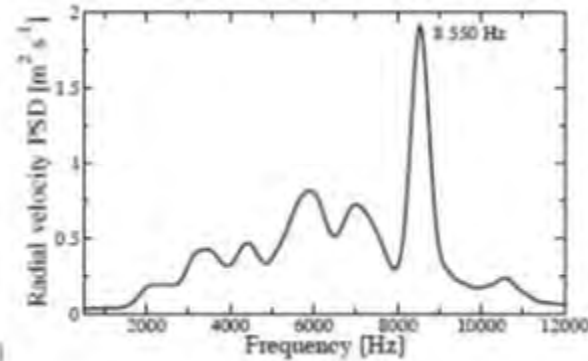
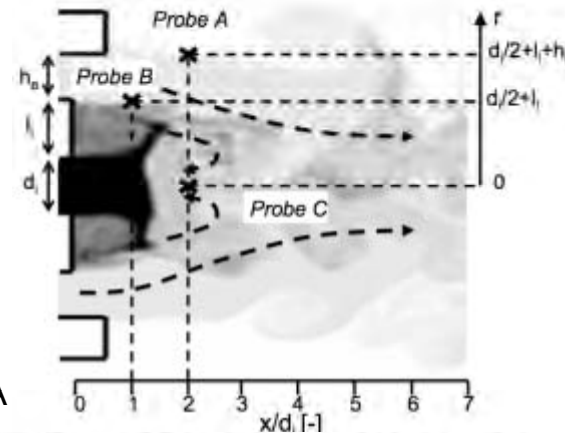
**OUTER
JET**

$J=1.05$

$R=2.48$



Probe A



Case "N8"
($J=9.3$)
Density
distribution
(white: 60 kg/m^3 ;
black:
maximum ;
logarithmic
scale).

**OUTER
JET**

$J=3.05$

$R=4.18$

Case	$St^e = h_e f / U_{oj}$ (probe A)	$St^i = d_i f / U_{ij}$ (probe B)	$St^l = l_i f / U_{oj}$ (probe C)
N2	0.25	0.34	0.15
N6	0.25	0.26	0.14

Found relevant St numbers for our configurations

Distribution A: Approved for public release; distribution unlimited





Conclusions



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- **For LARthickLip**
 - Found bending mode with largest effect at velocity antinodes
 - The reduction on the dark core length was greatest for a medium J range
 - For near critical pressures, the collaboration with ECP determined relevant St for our injector configuration and was able to capture qualitative behavior of natural and excited jets
- **For SARthinLip**
 - Did not see bending mode for conditions studied
 - Saw vortex roll-up and puffing occurring over entire J range (0.09-21) tested – most predominantly at pressure nodes and most likely associated with acoustic mode of outer jet
 - Vortex roll up and puffing is independent of injector recess configuration
- **For LARthinLip**
 - Sees both bending and vortex roll-up modes depending on the acoustic frequency
- **Synchronized measurements for p' and jet images - correlate structures observed to p' amplitudes**
- **Initial POD analysis recovers features seen in movies – next will be to compute convective velocities of structures observed**





AFOSR/NASA Combustion Stability Workshop



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- The single largest unknown in combustion instability is the “combustion response” (how combustion responds to acoustic waves)
- Within the combustion response, flame holding in the near injector field is a key mechanism
- AFRL – Edwards was tasked to develop an experiment and to lead a joint experimental / modeling team to study coupled flame holding mechanisms.
 - *LEVERAGE EXPERIENCE GAINED WITH COLD FLOW EXPERIMENTS*
- GA Tech was selected to lead an effort on a closed-loop study.



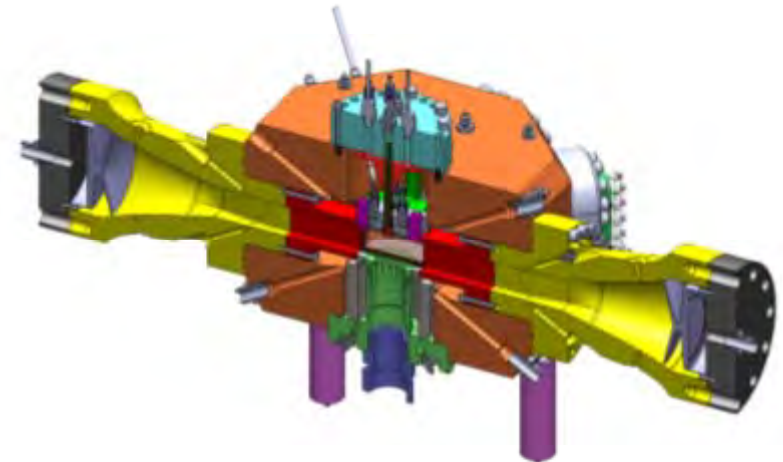
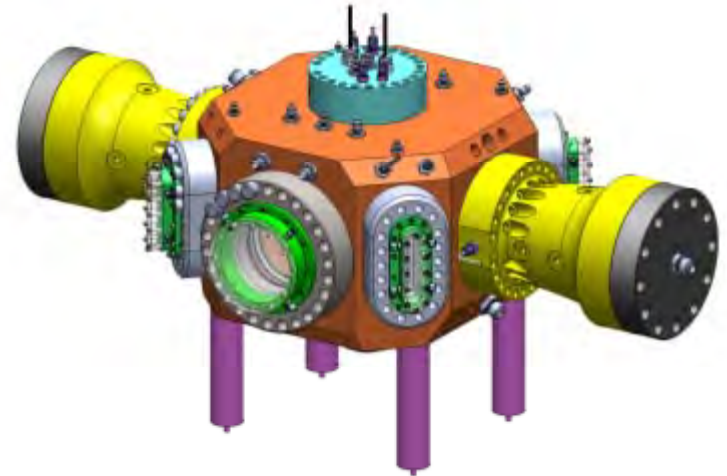


EC-4H – Combustion Instability Lab



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- Concentrate on near injector field
- Measure p' and q' simultaneously to evaluate the Rayleigh criteria for combustion instability
- Start with shear coaxial jets – cold flow heritage
- Lab designed for 2000 psi – about double the pressure from other labs in the world
- Start with current design for acoustic drivers pressure nodes and antinodes





BACKUP



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Distribution A: Approved for public release; distribution unlimited





Image interpretation key



pressure = fixed

$$J(\rho_o u_o^2 / \rho_i u_i^2) = \text{fixed}$$

Acoustics on
 0°

PAN, VN

"Pressure coupled"

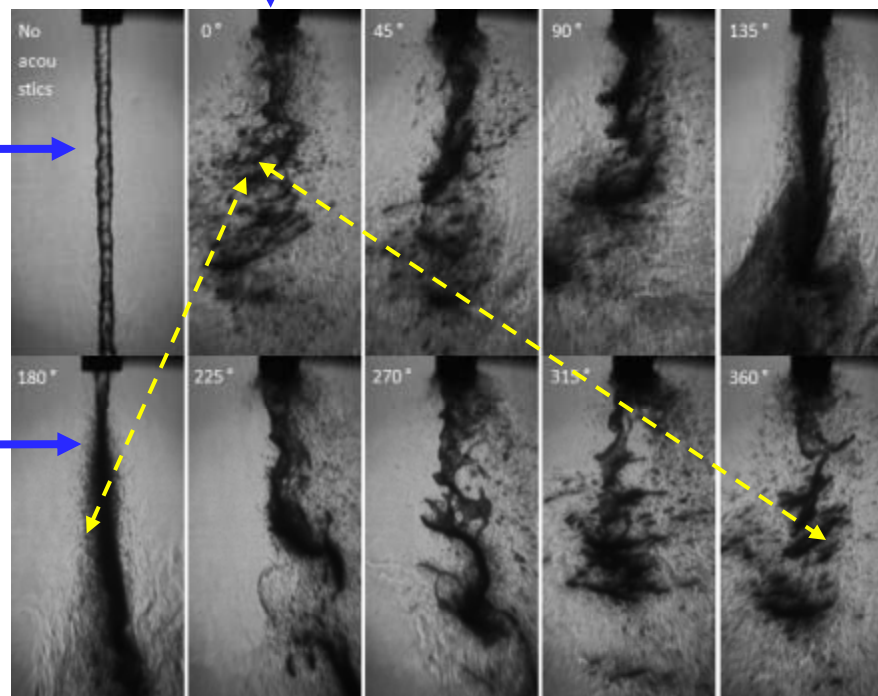
Subsequent images:
acoustics on;
Phase increases by 45°

Baseline:
Acoustics
off

180°

PN, VAN

Largest difference
expected from 0°
"Velocity coupled"



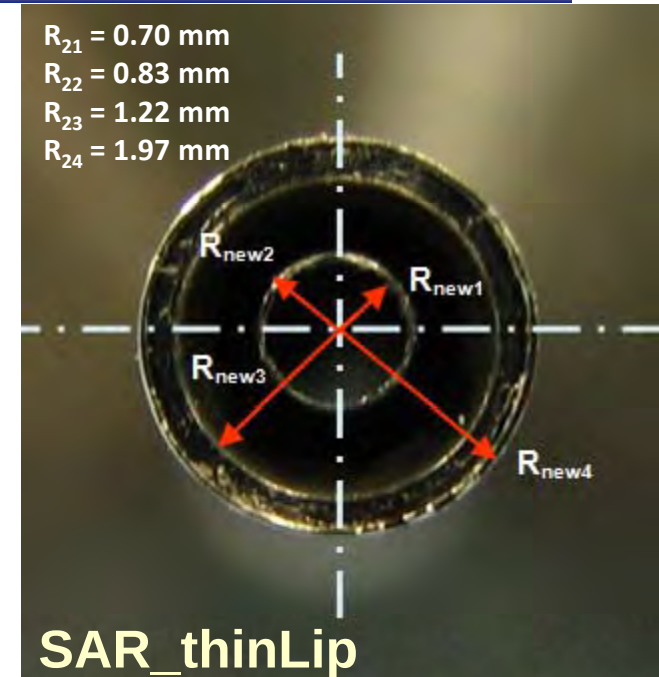
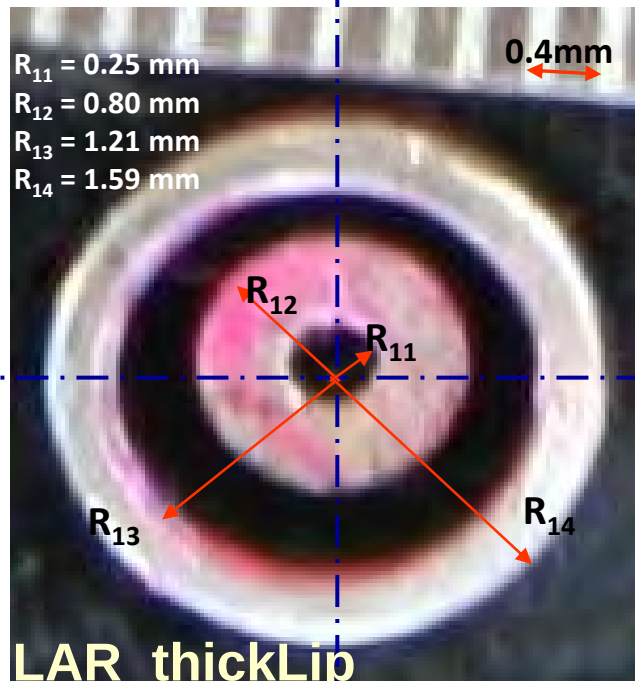
PN – pressure node - Min
PAN – pressure antinode - Max
VN – velocity node
VAN – velocity antinode

360°
should look
similar to 0°





Geometries for present study



LAR=LargeAreaRatio
 SAR=SmallAreaRatio

	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	t/D $t=(D2-D1)/2$	Ao/Ai
LAR_thickLip	0.51	1.59	2.42	3.18	1.05	12.9
SAR_thinLip	1.40	1.65	2.44	3.94	0.09	1.6
SAR_thickLip	1.47	3.96	4.70	6.35	0.84	2.9
LAR_thinLip	0.69	0.89	2.44	3.94	0.15	11.0





Relevant variables for cold-flow studies



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Geometry	Acoustics	Recess	Phase	VR	J	Coupling
Single Jet	On/Off	N/A	v' max	N/A		No
LAR_thickLip (injector 1)	Off P' max U' max	1/2D1	2-phase $P < P_c$ $P > P_c$ $T > T_c$ $T < T_c$	0.1-20 0.1-20		No
SAR_thinLip (injector 2)		1/2D1 D1 0				Yes& No
SAR_thickLip (injector 3)		0				
LAR_thinLip (injector 4)		0				

