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Engineering

Computational Modeling of Transcritical Shock-Droplet Interactions

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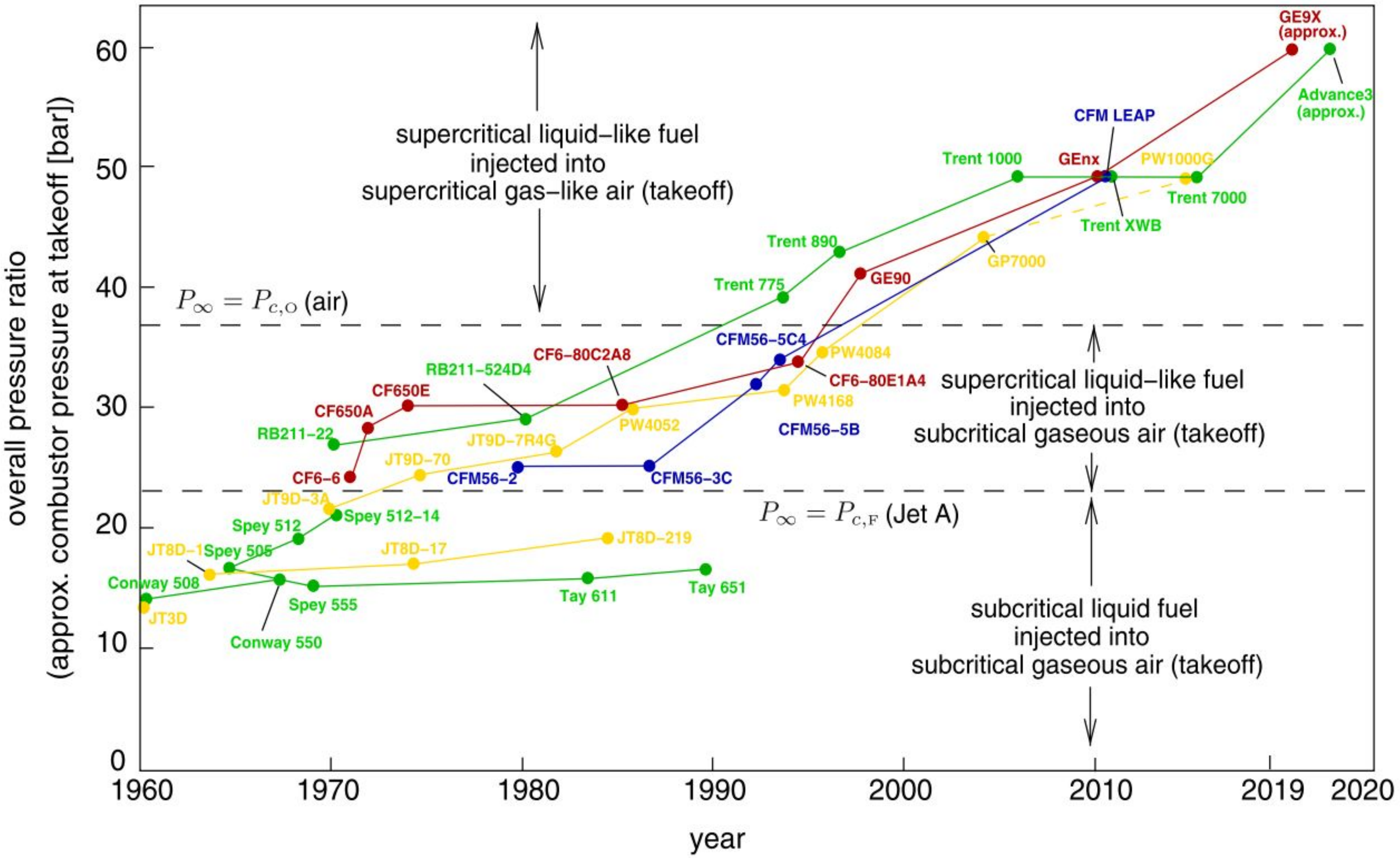
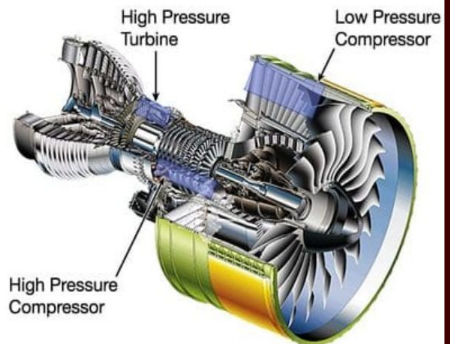
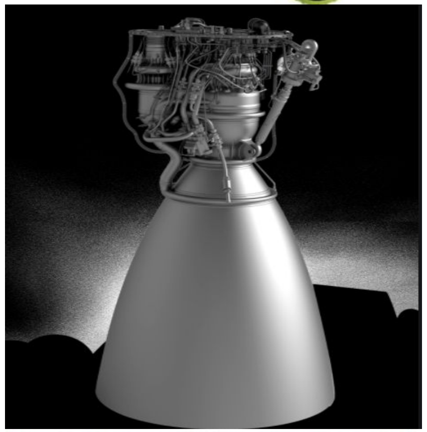
Supercritical Propulsion



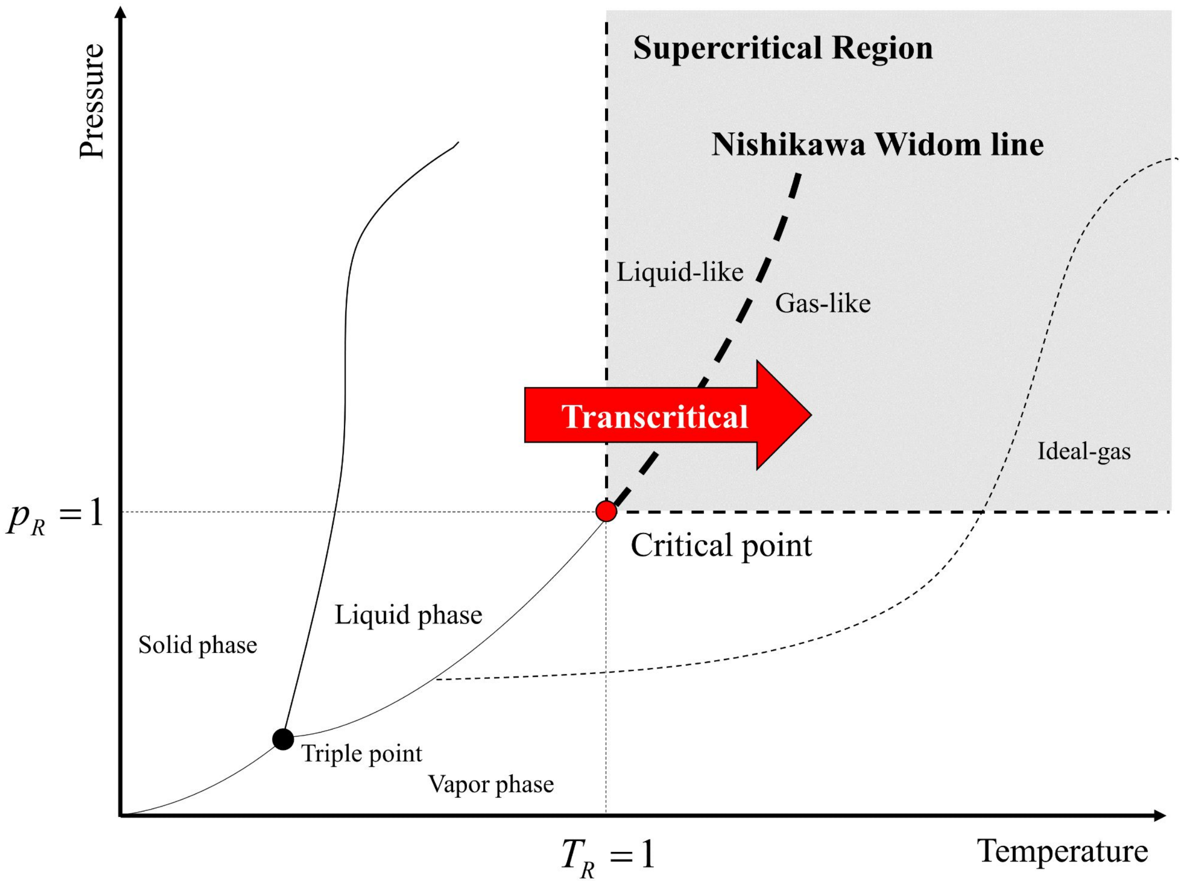
Jofre & Urzay, Progress in Energy & Combustion Science, 2021





Transcritical Behavior

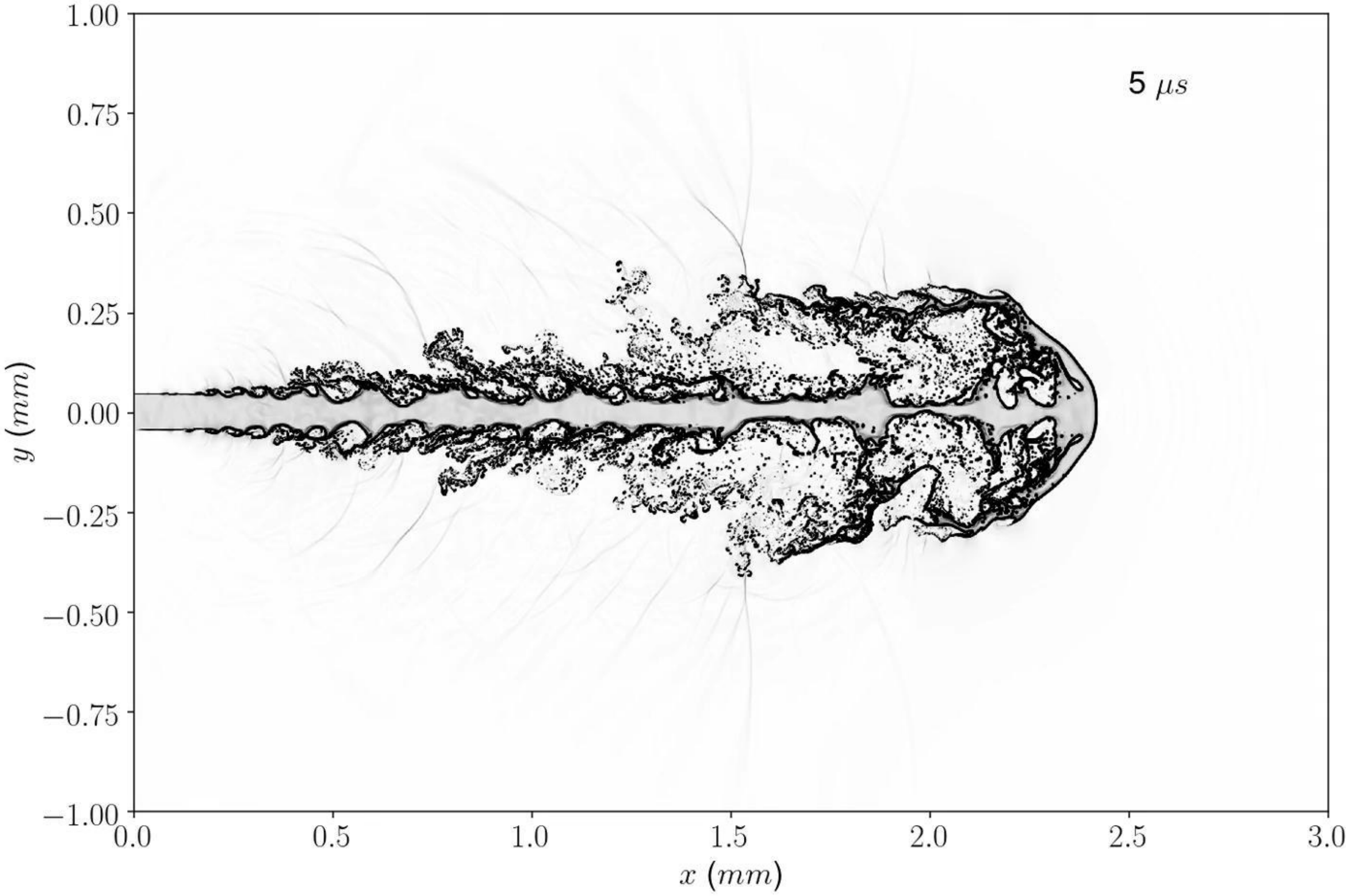
- Transcritical problems involve the injection of fuel at a supercritical pressure into a high-temperature environment.



- Transcritical problems involve the injection of fuel at a supercritical pressure into a high-temperature environment.
- As the fuel is heated it transitions from a **liquid-like** to **gas-like** supercritical fluid.
- This is termed **pseudo-boiling** and occurs across the Widom line.

Application - Spray A Diesel Injection

- 600 m/s jet
- 6 MPa
- 363 K (fuel)
- 900 K (air)



Numerical Method

- Diffuse-interface, fully-compressible, inviscid, multiphase model, with multiple fluid species
  - Conservation of mass, momentum, energy, and fluids species
- Peng-Robinson Equation of State (PR-EoS)
- WENO reconstruction
- Positivity-preserving and maximum-principle-satisfying limiter
- RK3-TVD time-stepping
- HLLC Riemann Flux
- In-house C++ code that is parallelized with MPI and domain decomposition.

$$\frac{\partial(\rho)}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0$$

$$\frac{\partial(\rho Y_1)}{\partial t}+\nabla\cdot(\rho\mathbf{u}Y_1)=0$$

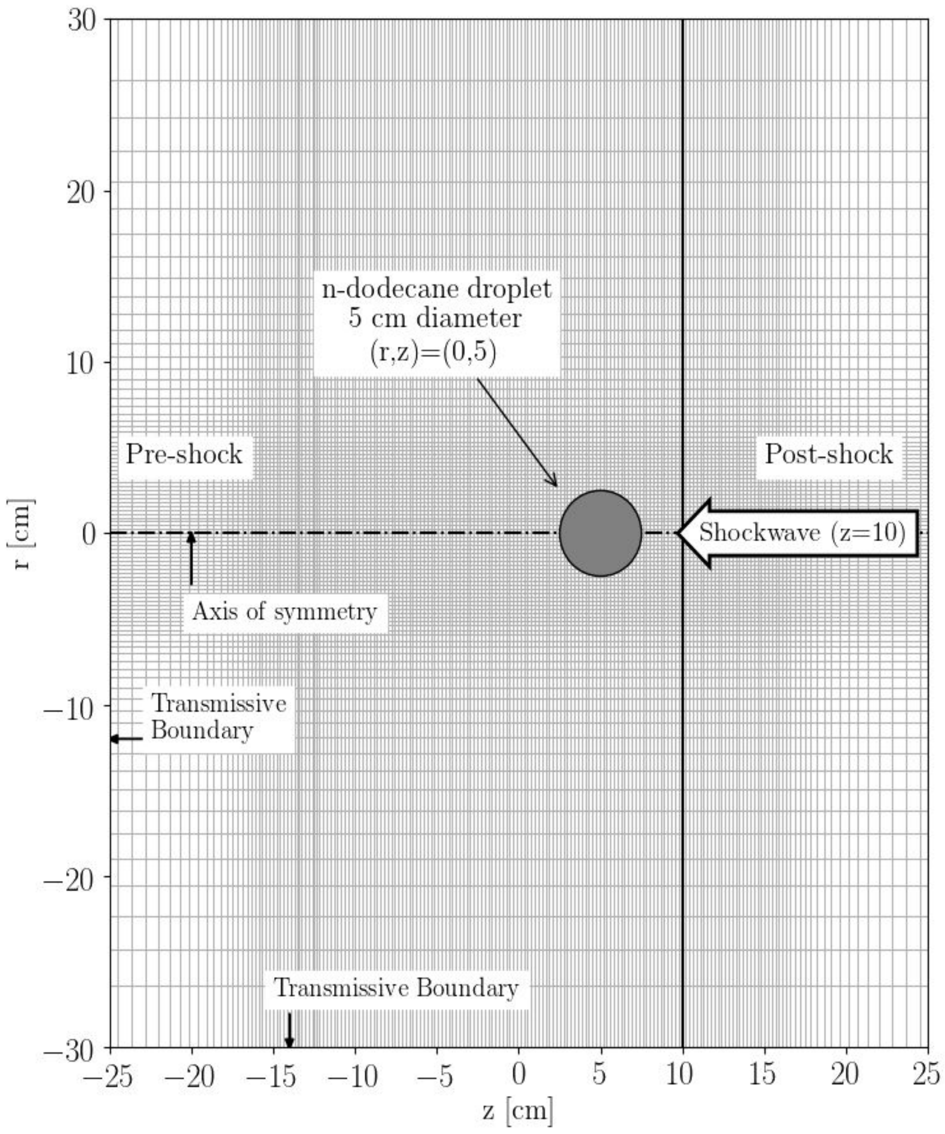
$$\frac{\partial(\rho\mathbf{u})}{\partial t}+\nabla\cdot(\rho\mathbf{u}\otimes\mathbf{u}+p\mathbf{I})=\mathbf{0}$$

$$\frac{\partial E}{\partial t}+\nabla\cdot(\mathbf{u}(E+p))=0$$

Droplet-Shock Interaction

- We consider the interaction of a ***shock wave*** with a ***fuel droplet*** at a supercritical pressure (6 MPa).
- The fuel droplet is ***n-dodecane*** and the surrounding fluid is ***nitrogen*** and the shock wave is ***Mach 1.2.***

	nitrogen	**n-dodecane**
$T_C\,[K]$	126.2	658.1
$p_C\,[MPa]$	3.396	1.82



Transcritical shock-droplet interaction

Computational Schlieren Images

- Visualization of density gradients
- Black corresponds to the largest density gradient

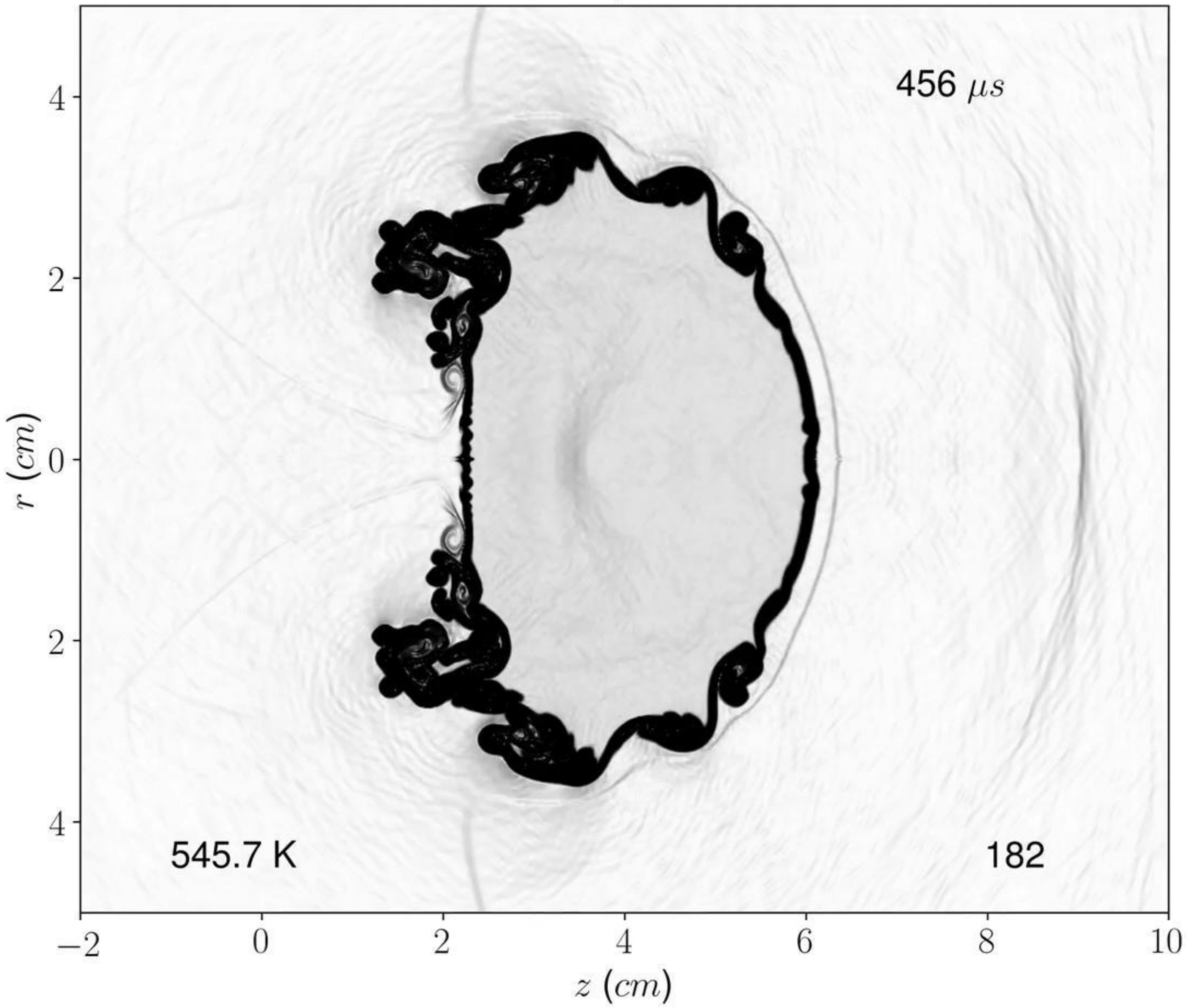
Fuel droplet (n-dodecane)

Surrounding fluid (nitrogen)

Pressure - 6 MPa

Mach 1.2 shock

$n = c_S/c_D = 1$



Speed of sound ratio (n)

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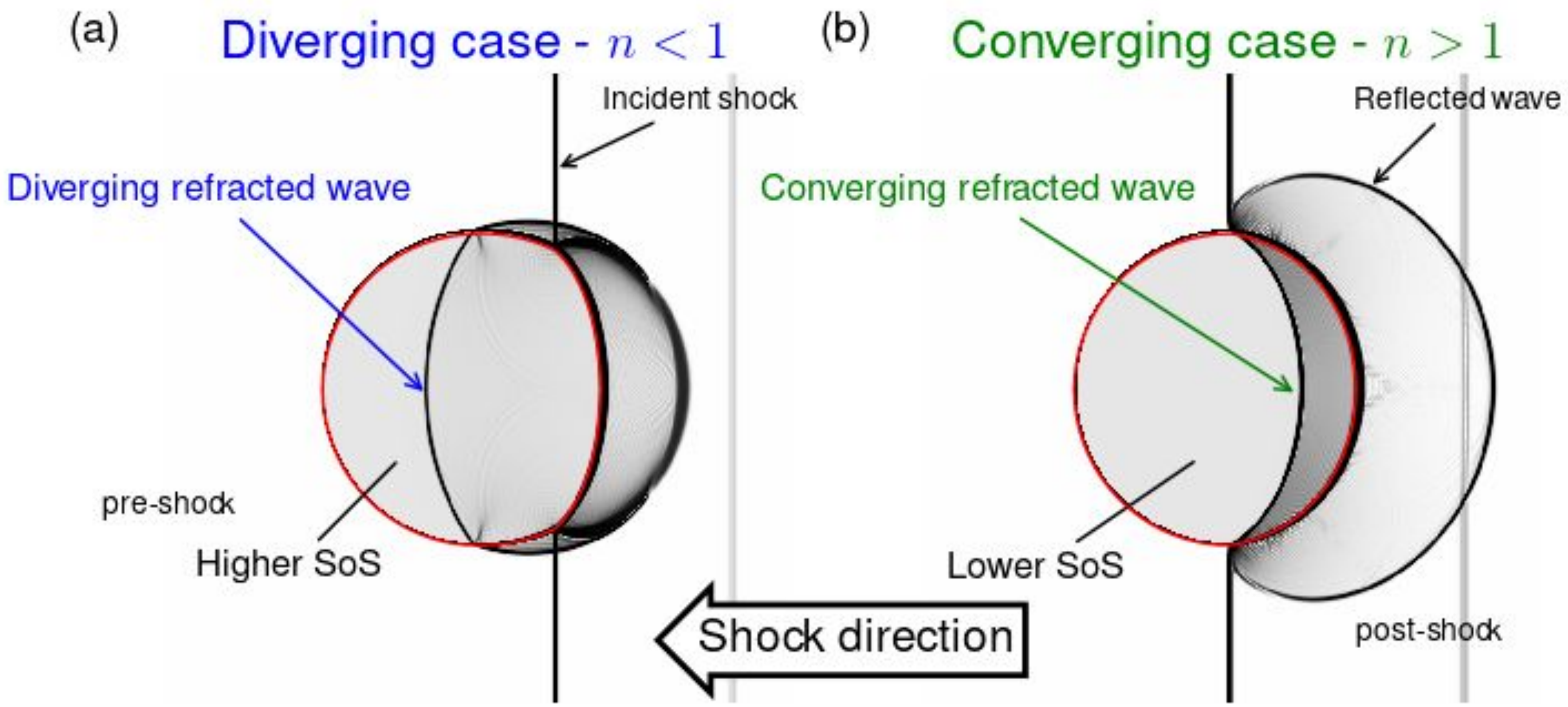
$$n = c_S / c_D$$



Speed of sound ratio (n)

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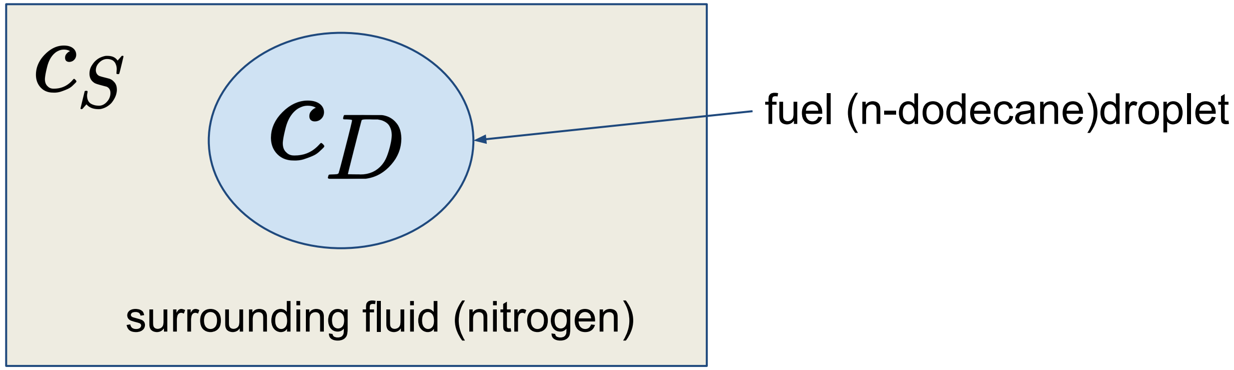
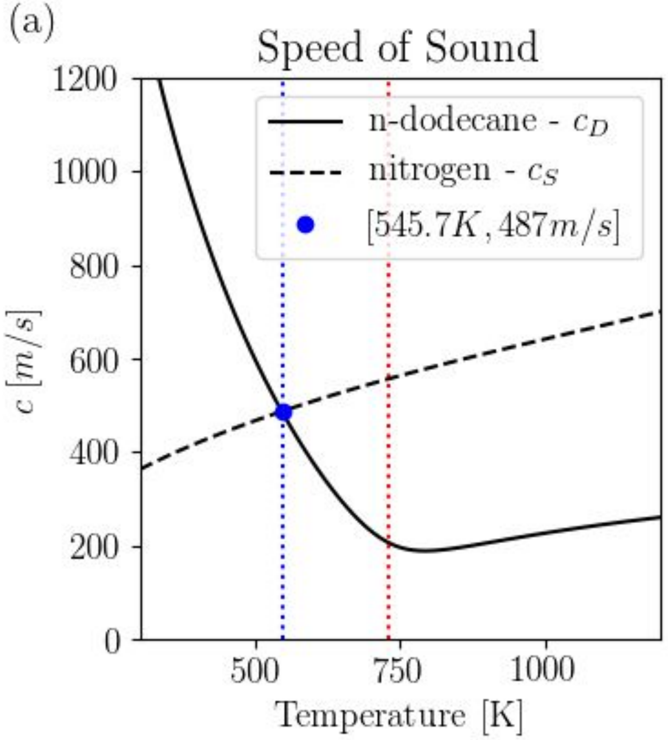
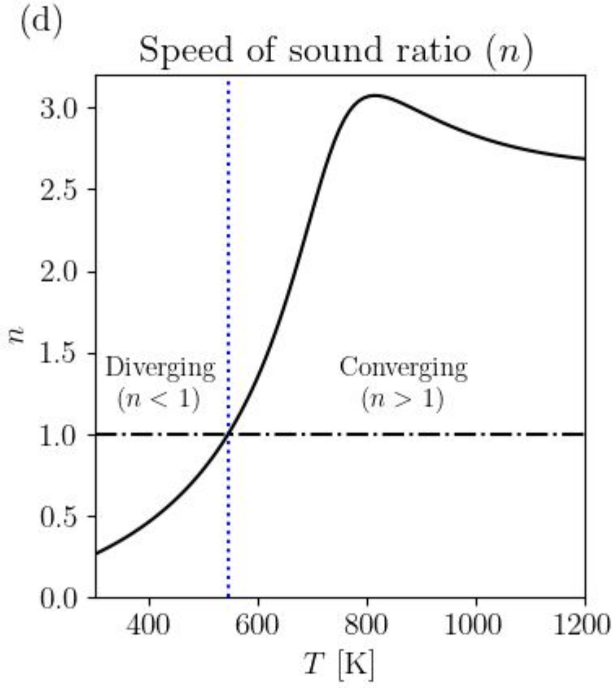


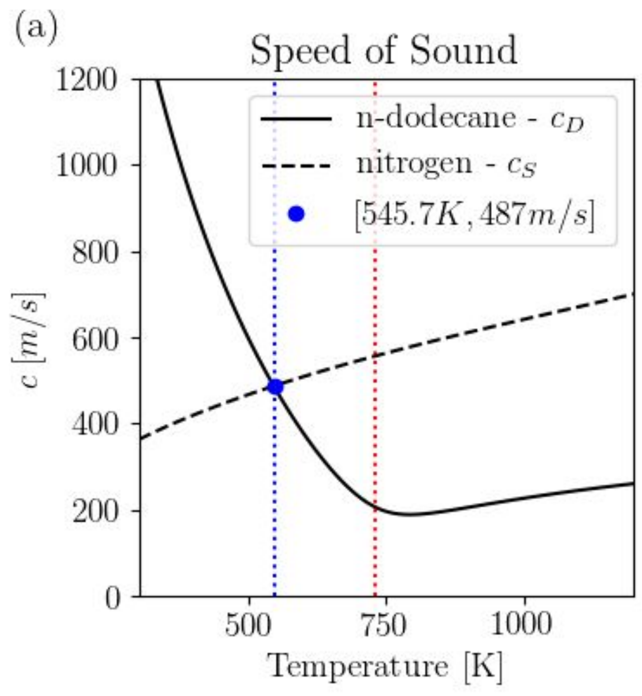
n=1 @ 545.7 K

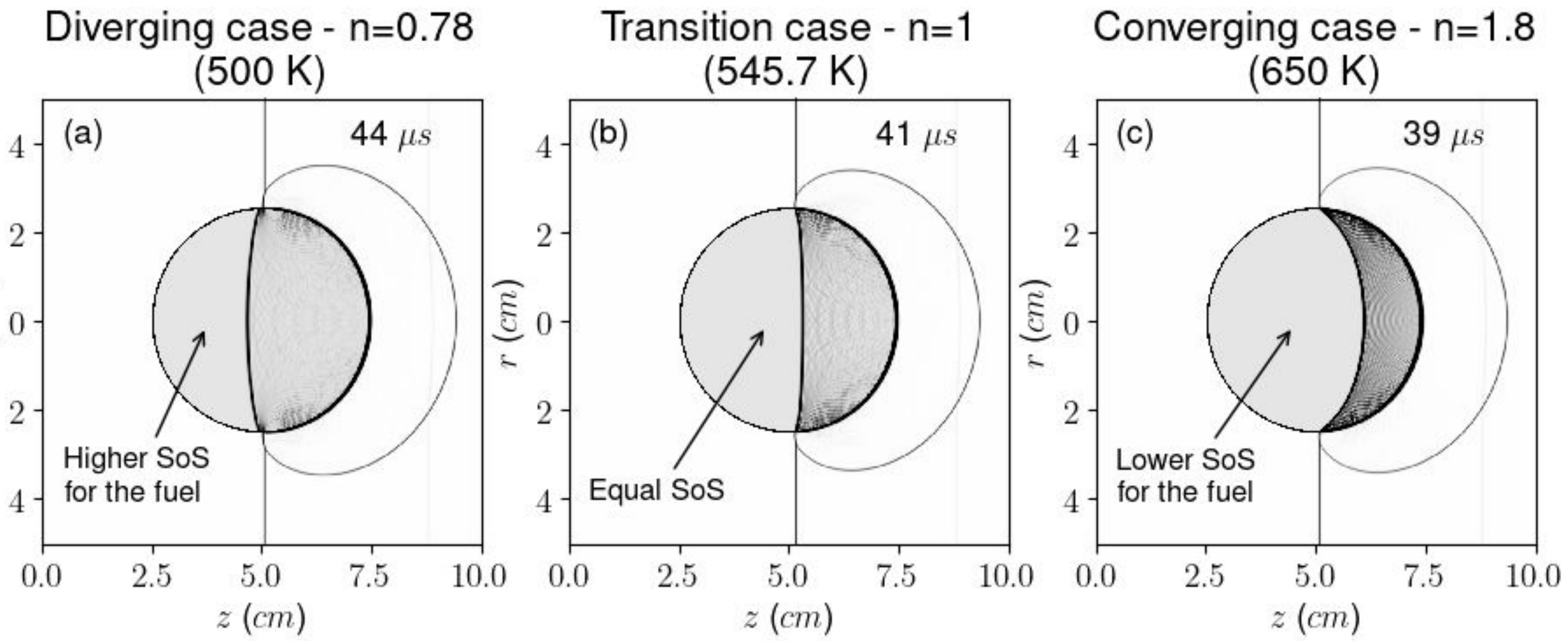
- n<1 - Diverging
- n>1 - Convering



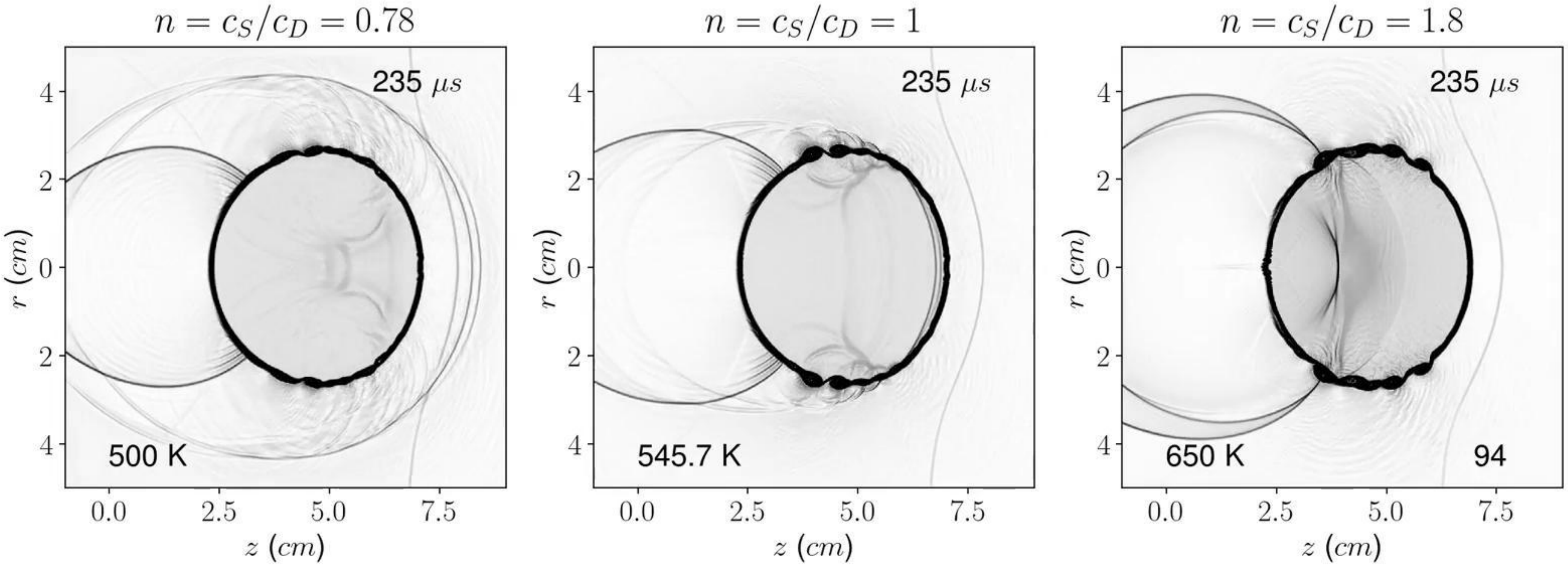


Transitional Behavior at 545.7 K





- The speed of sound of n-dodecane drops below nitrogen at 545.7 K.
- The shock-droplet interaction transitions from a *diverging* case (500K) to converging case (650K).



$n = c_S/c_D = 0.78$
$n = c_S/c_D = 1$
$n = c_S/c_D = 1.8$
235 μs
235 μs
235 μs
500 K
545.7 K
650 K
94
r (cm)
z (cm)
4
2
0
2
4
0.0
2.5
5.0
7.5

Diverging Case

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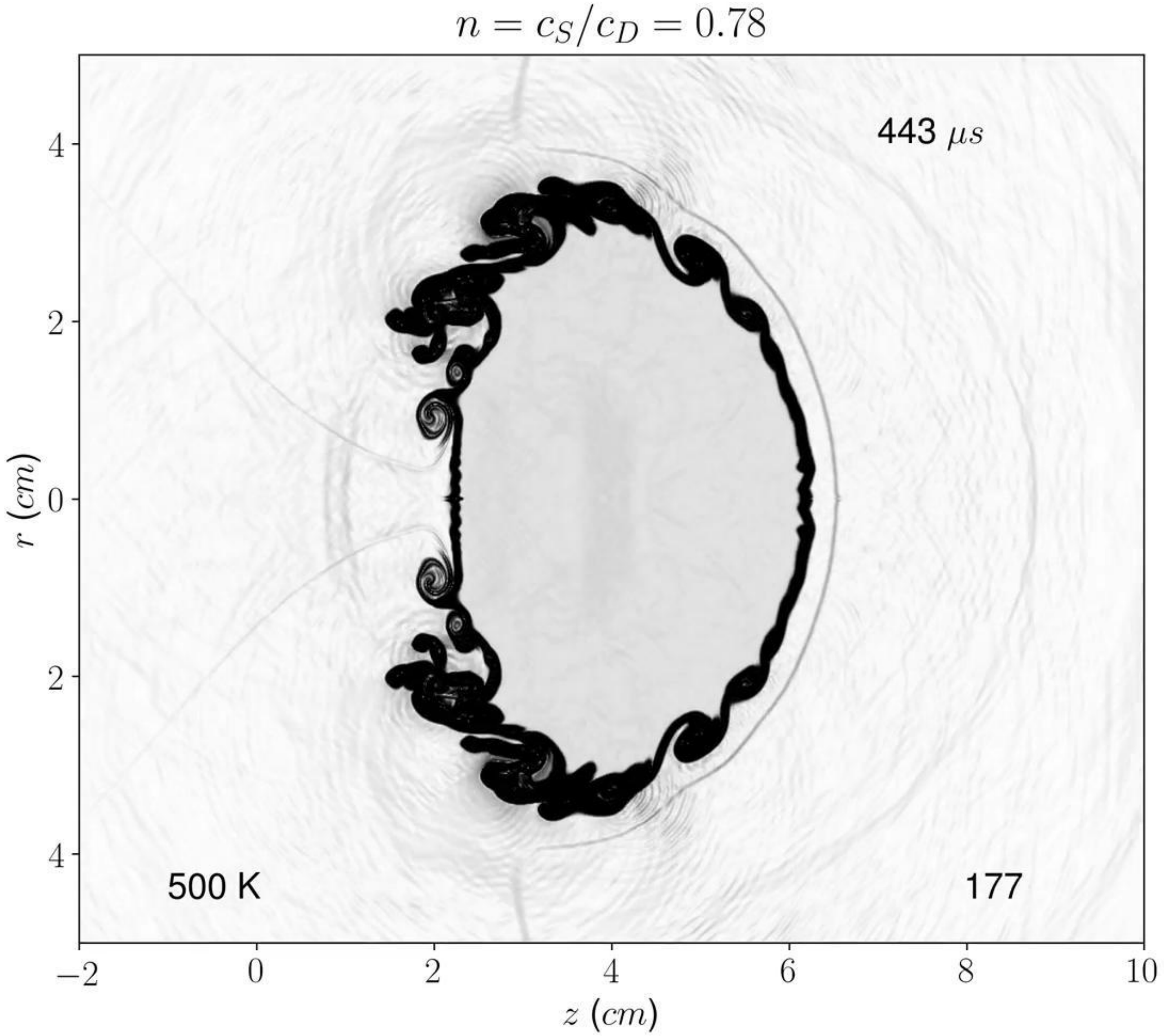
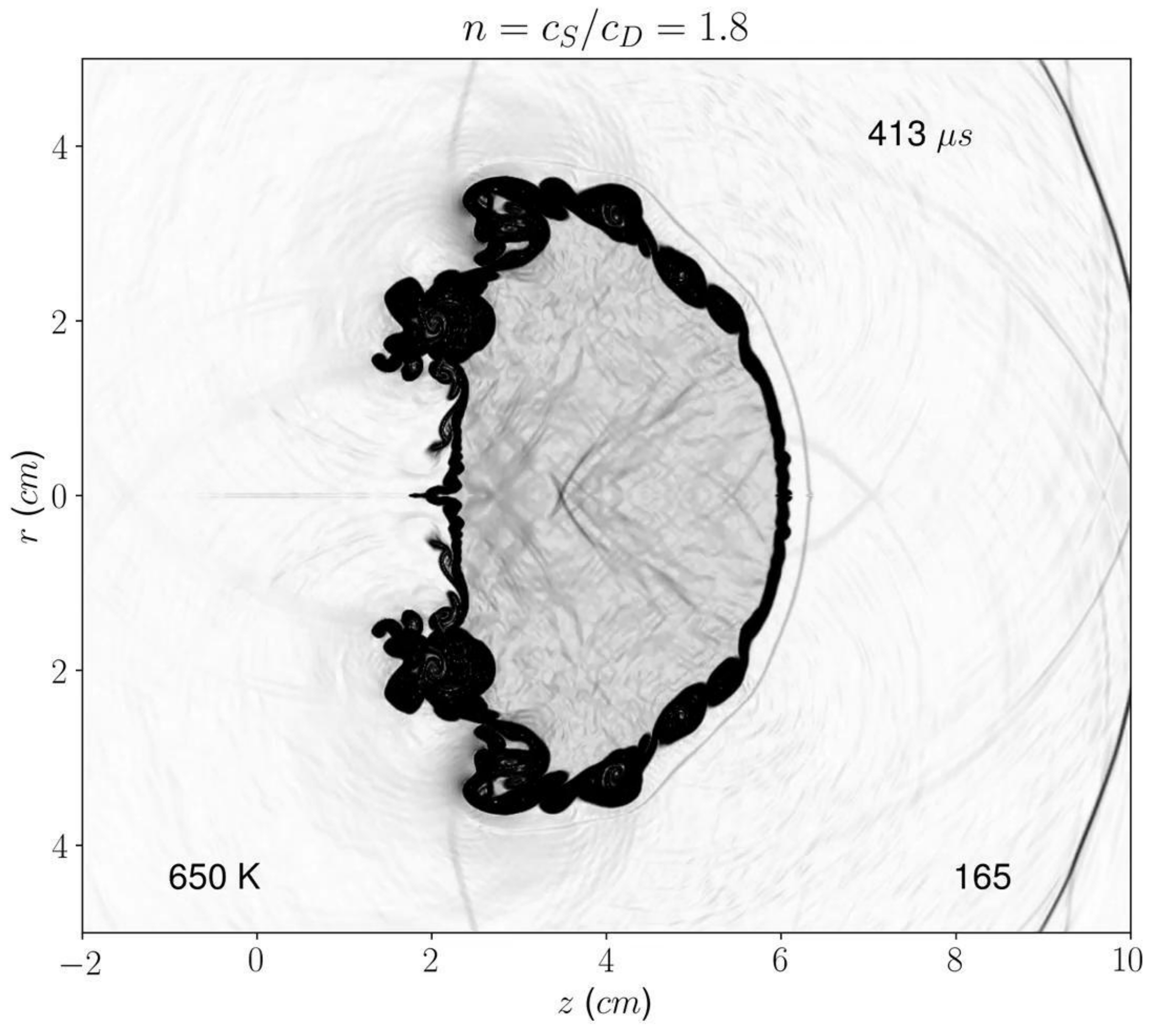
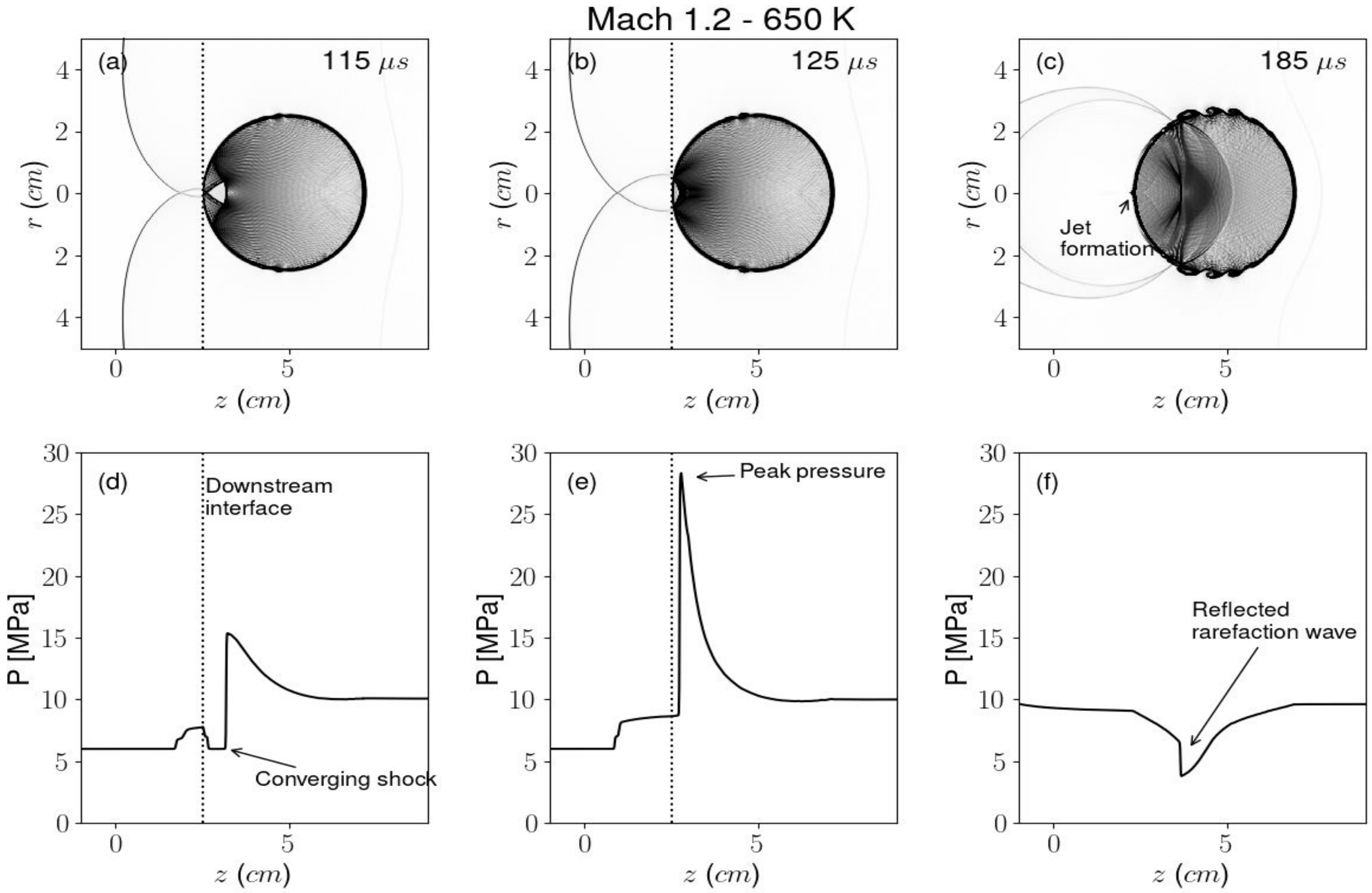


Converging Case



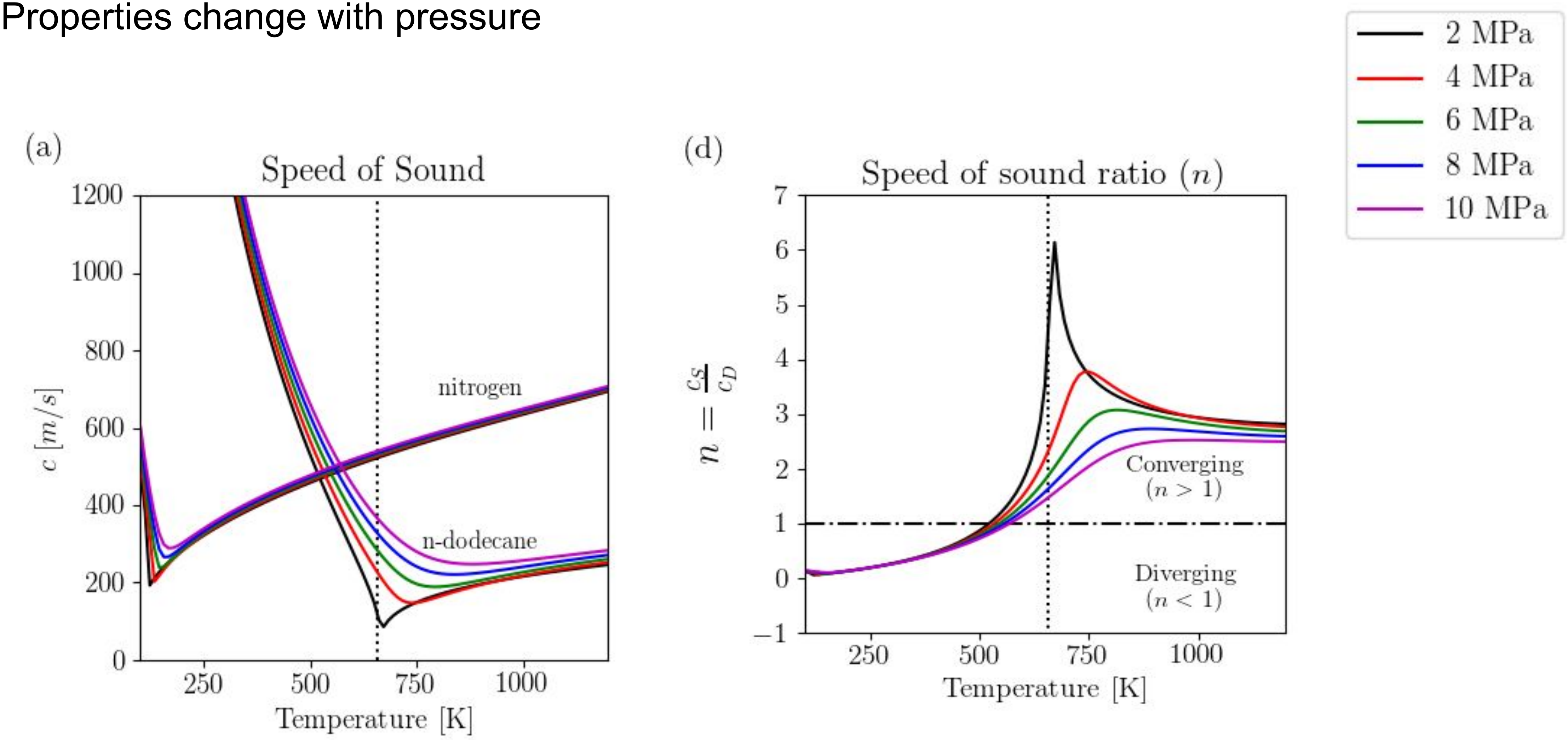
Convergent Case



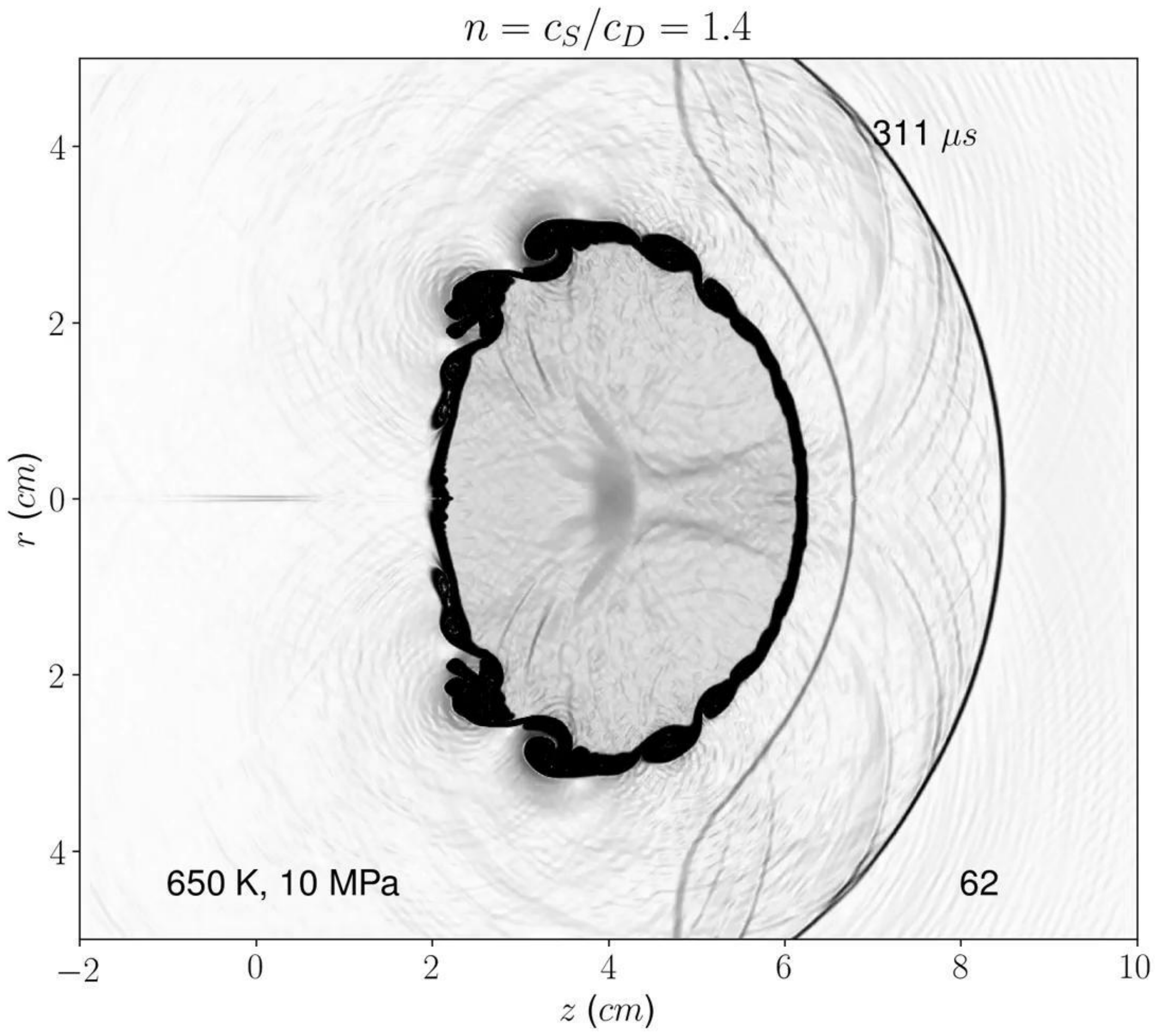
- The focusing of the refracted shock wave results in a high-pressure region in the droplet near the downstream interface.

Pressure Effect at Transcritical Temperature

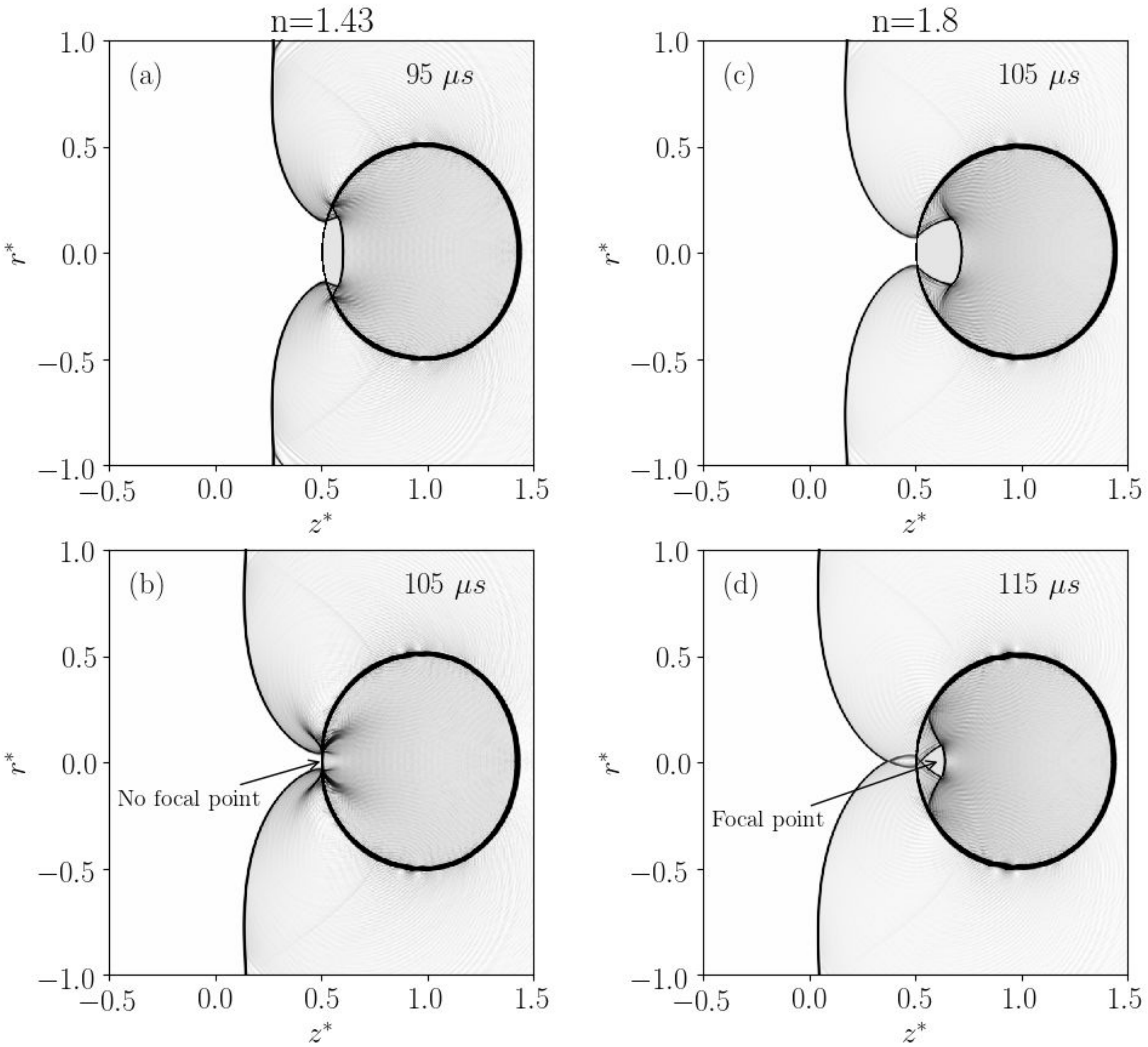
- Until now, pressure has been fixed - **6 MPa**
- Properties change with pressure



Weakly convergent - inward jet



Weak vs Strong Convergence



Weak convergence

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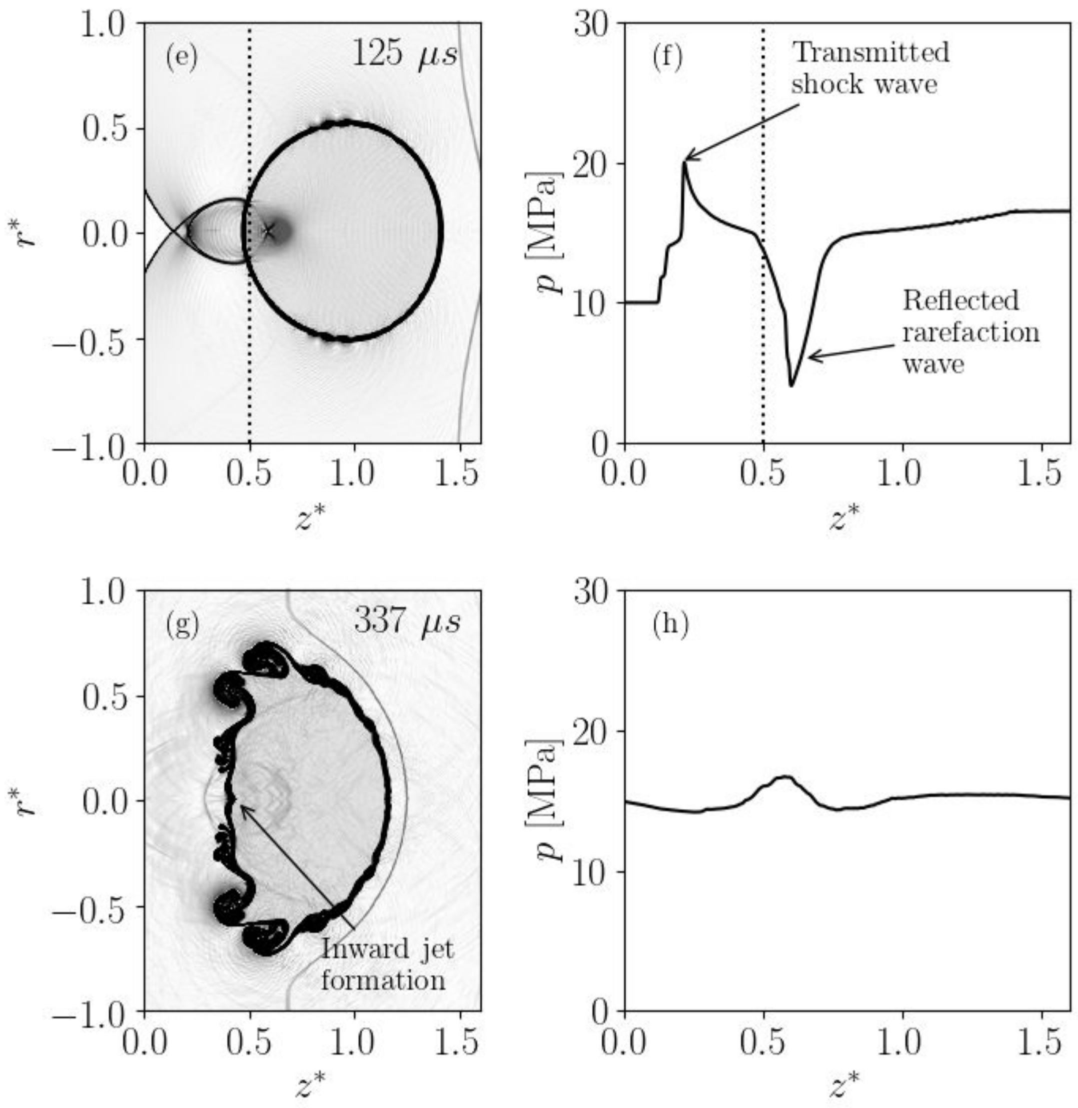
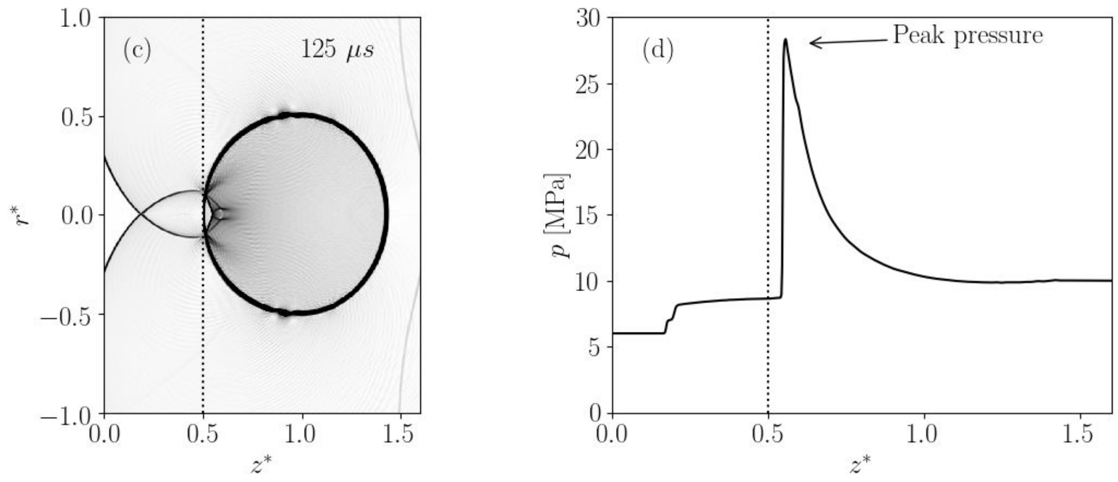
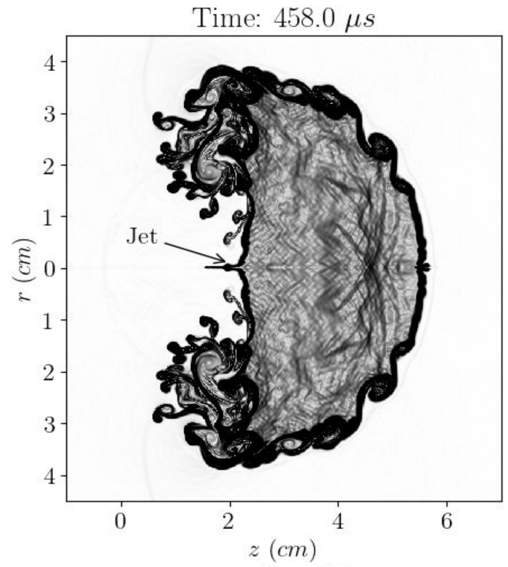
- The transmitted shock results in the pressure gradient at the downstream interface
- Drives the interface inward
- An inward jet begins to form

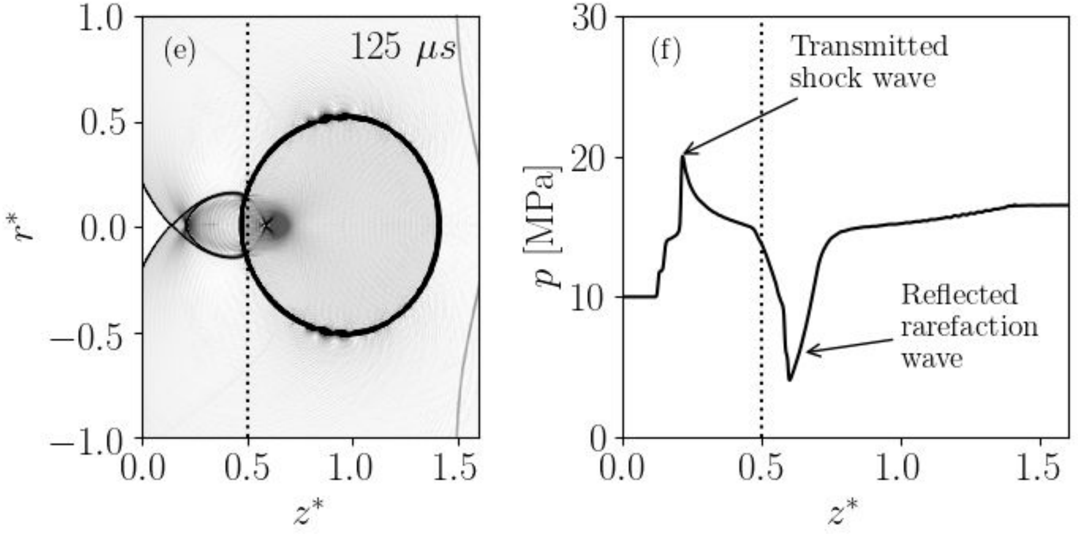


Inward vs. Outward Axial Jet

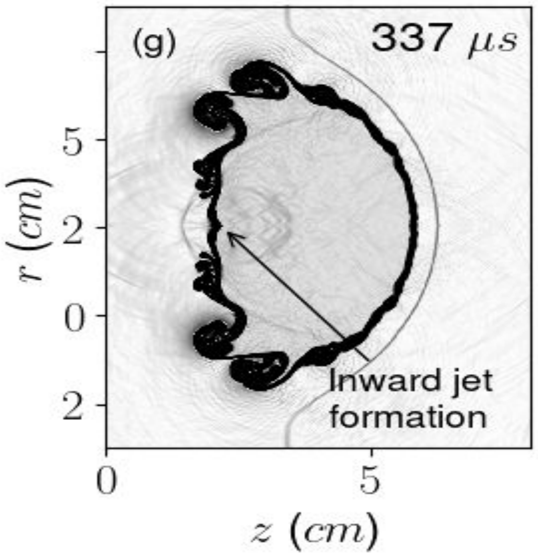


Shock Convergent - n>1.5

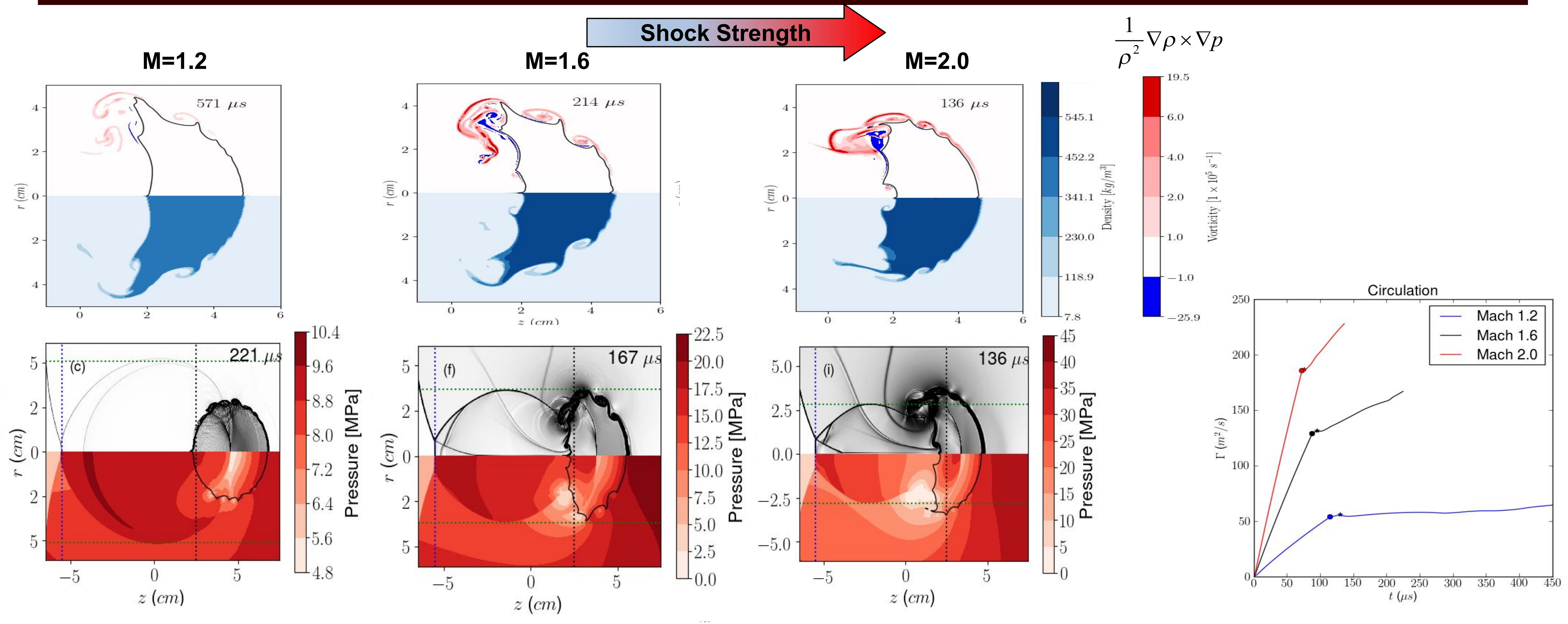




Weakly convergent- 1<n<1.5



Stronger Shock: Convergent



- By increasing the shock strength, the transmitted shock wave and crossover shock wave shapes change significantly, stretching the droplet less radially (consistent with SDI)

Summary & Conclusions

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- The ratio of the SoS indicates if the refracted shock diverge or converge.
- The transitional point from **diverging** to **converging** occurs when **n = 1** at approximately 545.7 K at 6 MPa.
- The convergence and localized maximum pressure results in the formation of an axial jet. If the convergence occurs within the bubble, this jet is directed outwards.
- Depending on the speed of sound ratio (**n**), the converged cases develop either **inward** axial jet **(weakly convergent)** or **outward** axial jet **(strong convergence)**. **(n~1.5)**

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Thank You!

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