Internal Combustion Engines
I: Fundamentals and Performance Metrics

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2018 Princeton-Combustion Institute
Summer School on Combustion
Course Length: 9 hrs

(Mon.- Wed., June 25-27)

Short course outline:

Internal Combustion (IC) engine fundamentals and performance metrics, computer modeling supported by in-depth understanding of fundamental engine processes and detailed experiments in engine design optimization.

Day 1 (Engine fundamentals)

Hour 1: IC Engine Review, Thermodynamics and 0-D modeling
Hour 2: 1-D modeling, Charge Preparation
Hour 3: Engine Performance Metrics, 3-D flow modeling

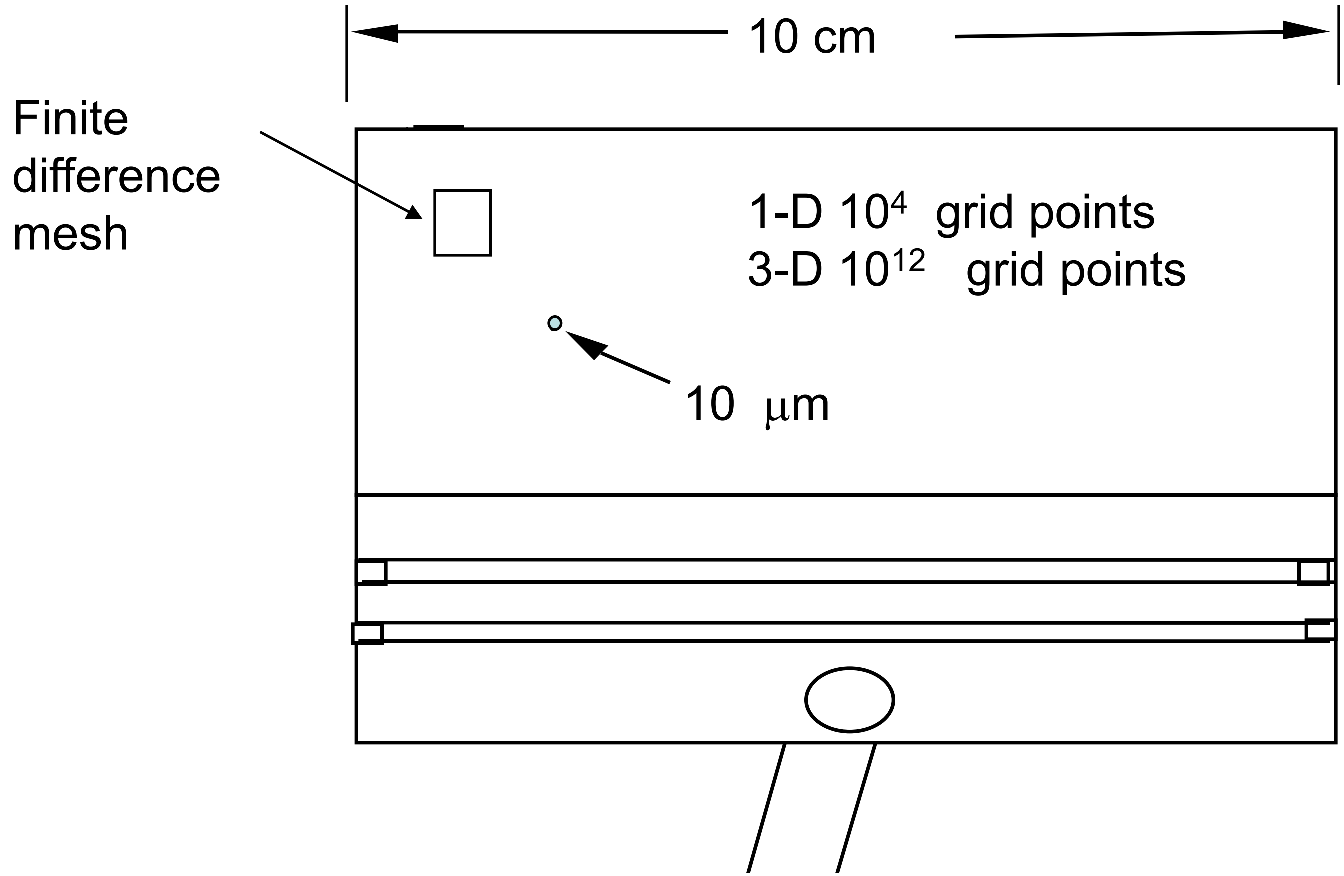
Day 2 (Computer modeling/engine processes)

Hour 4: Engine combustion physics and chemistry
Hour 5: Premixed Charge Spark-ignited engines
Hour 6: Spray modeling

Day 3 (Engine Applications and Optimization)

Hour 7: Heat transfer and Spray Combustion Research
Hour 8: Diesel Combustion modeling
Hour 9: Optimization and Low Temperature Combustion

Resolution – predictive spray models?



Engineering models will not be entirely predictive for decades
Accurate submodels will be needed for detailed spray processes
(e.g., drop drag, drop turbulence interaction, vaporization, atomization, drop breakup, collision and coalescence, and spray/wall interaction)

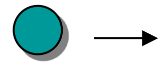
Governing Equations

Amsden, 1997

Gas phase

Liquid phase

Turbulence



$$f = f(\mathbf{x}, \mathbf{v}, r, T_d; t)$$

$\mathbf{x}, \mathbf{v}, r, Td$

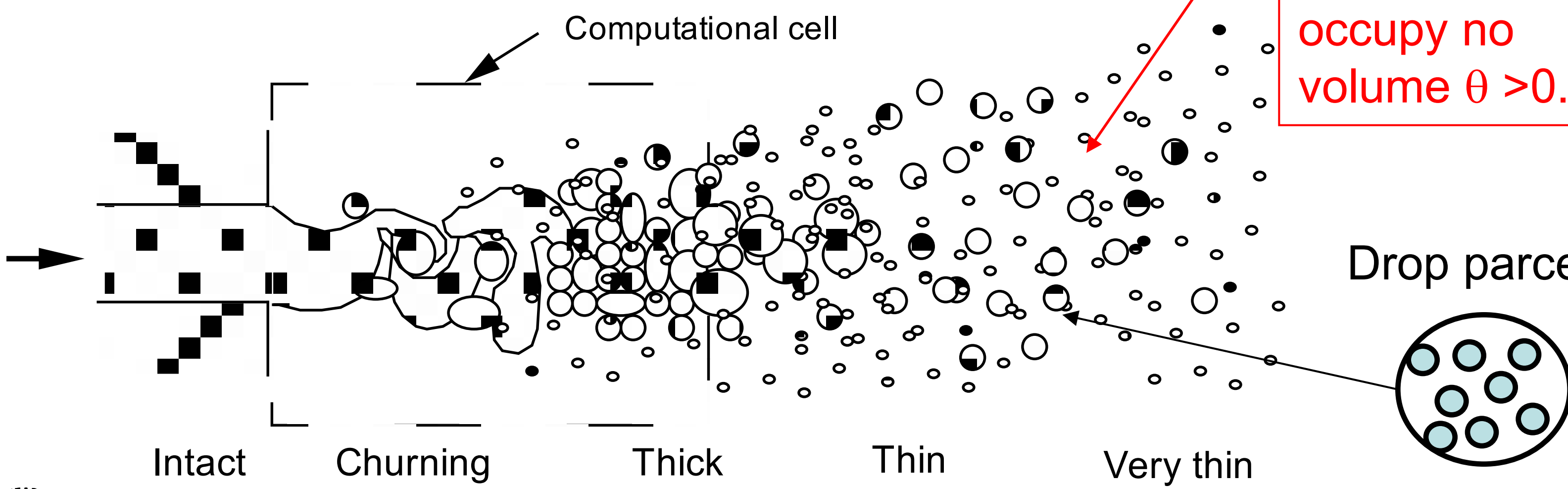
Gas void fraction and drop number density

Lagrangian Drop,
Eulerian Fluid (LDEF) models

$$\theta = 1 - \int_{Vol} \left(\iiint \frac{4}{3} \pi r^3 f \, dr \, d\mathbf{v} \, dT_d \right) dVol \, / \, Vol$$

Two-Phase Flow Regimes

Current LDEF spray models:
– drops occupy no volume $\theta > 0.9$



Dukowicz, 1980

LDEF Spray Modeling

- Concept of using “drop parcels”

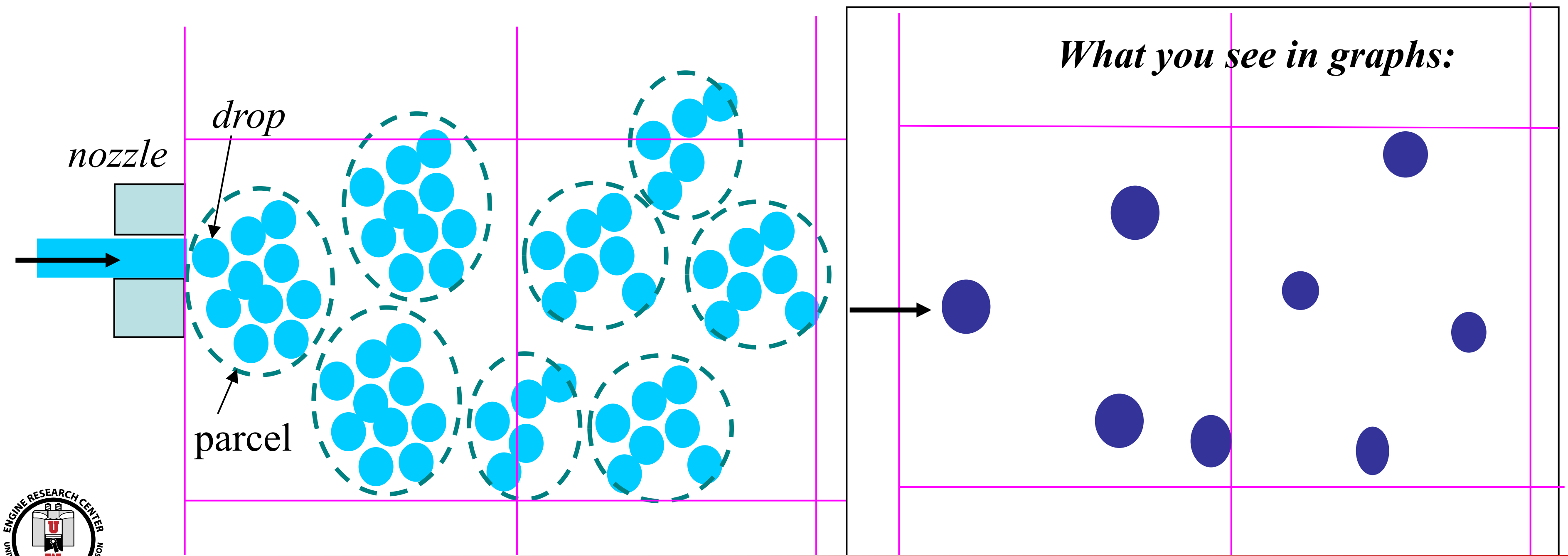
  For typical heavy-duty diesel, injected fuel per cycle (75% load): 0.160 g

  One spray plume: m_{fuel}=0.160/6=0.0267 g

  If average SMD=10 μm → m_{drop} =3.8×10^{-10} g

  # of drops in the domain=0.0267g/m_{drop}=7.1×10^{7}

  Impractical to track individual fuel drops – group identical drops into ‘parcels’



Liquid Phase

Amsden, 1997

Spray drop number conservation $f = f(\mathbf{x}, \mathbf{v}, \mathrm{r}, \mathrm{T_d}, \mathrm{y}, \dot{\mathrm{y}}; \mathrm{t})$

$$\frac{\partial f}{\partial t} + \nabla_{\mathbf{x}} \cdot (f\mathbf{v}) + \underbrace{\nabla_{\mathbf{v}} \cdot (f\mathbf{F})}_{} + \underbrace{\frac{\partial}{\partial r}(fR) + \frac{\partial}{\partial T_d}(f\dot{T}_d)}_{} + \underbrace{\frac{\partial}{\partial y}(fy) + \frac{\partial}{\partial y}(f\dot{y})}_{} = \underbrace{\dot{f}_{coll} + \dot{f}_{bu}}_{}$$

F = d**v**/*dt*
drop drag

R = d*r*/dt
Vaporization and heating

Drop distortion

Drop breakup, coalescence

Spray exchange functions

$$\mathbf{F}^s = -\int f\rho_d \left(4/3\ \pi r^3 \mathbf{F}' + 4\pi r^2 R\mathbf{v}\right) d\mathbf{v}\ dr\ dT_d\ dy\ dy$$

$$\mathbf{Q}^s = -\int f\rho_d \left\{4\pi r^2 R\left[I_l + \tfrac{1}{2}(\mathbf{v}-\mathbf{u})^2\right] + 4/3\ \pi r^3\left[c_l T_d + \mathbf{F}'\cdot(\mathbf{v}-\mathbf{u}-\mathbf{u}')\right]\right\} d\mathbf{v}\ dr\ dT_d\ dy\ dy$$

Work done by drop drag forces $W^s = -\int f\rho_d\ 4/3\ \pi r^3 \mathbf{F}'\cdot\mathbf{u}'\ d\mathbf{v}\ dr\ dT_d\ dy\ dy$

Amsden, 1997

Lagrangian drop - liquid phase

Discrete Drop Model

drop position

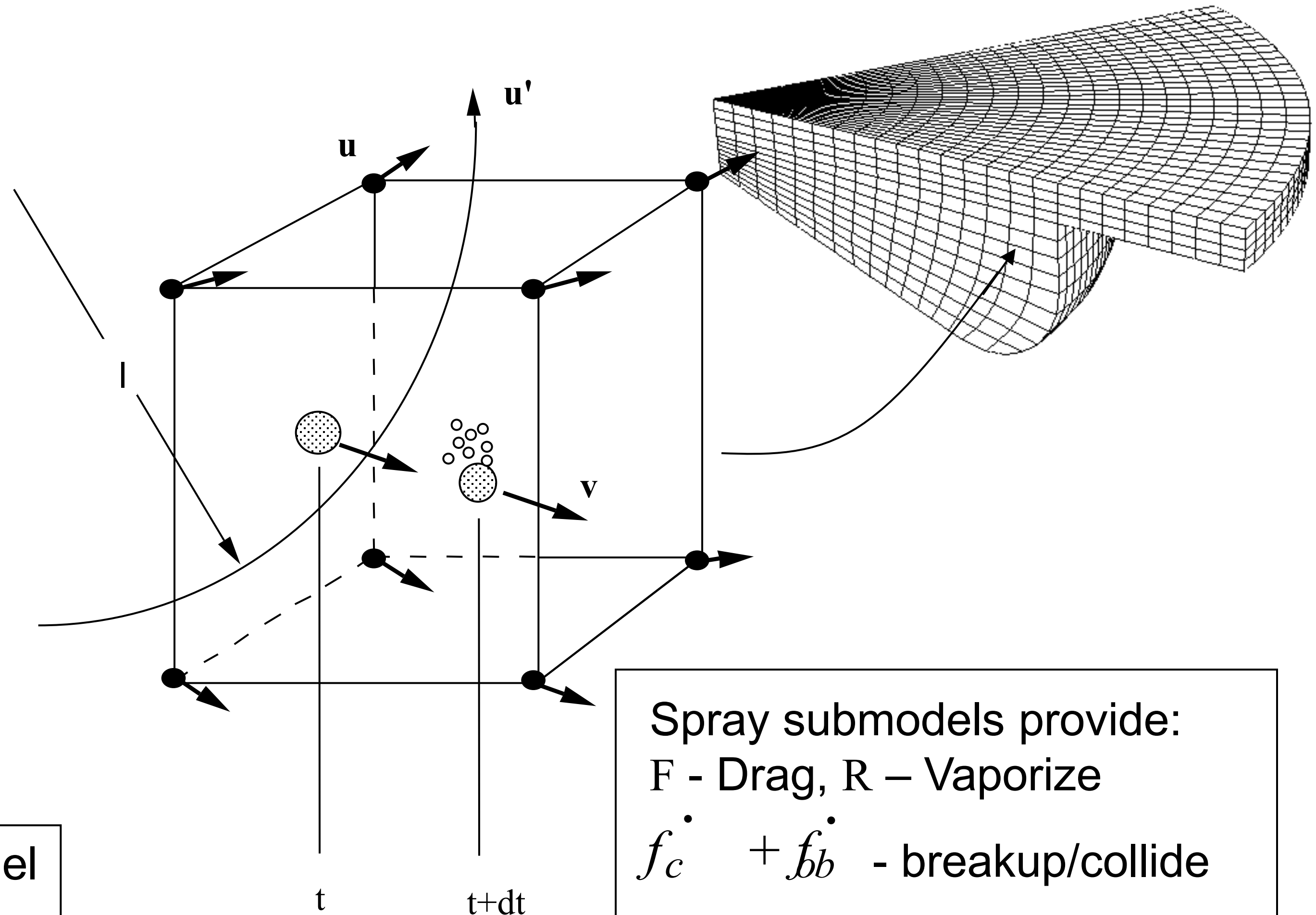
$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

drop velocity

$$\frac{d\mathbf{v}}{dt} = \mathbf{F}$$

drop size

$$\frac{dr}{dt} = \mathbf{R}$$



Turbulence model provides: l, $\boldsymbol{u}'$

Spray submodels provide:
F - Drag, R – Vaporize
$\dot{f}_c + \dot{f}_b$ - breakup/collide

Initial data:
v, r, T_d – Atomization model

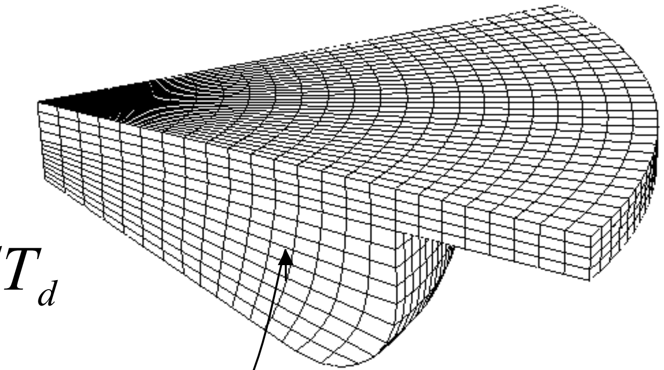
Eulerian Gas Phase

Amsden,1997

Mass conservation (species)

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = -\iiint \rho_l\, \underbrace{4\pi r^2 R}\, f\, dr\, d\mathbf{v}\, dT_d$$

R = *dr/dt* - Vapor source



Momentum conservation

$$\frac{\partial \rho\mathbf{u}}{\partial t} + \nabla\cdot(\rho\mathbf{u}\mathbf{u}) = -\nabla p - \underbrace{\nabla(\tfrac{2}{3}\rho k) + \nabla\boldsymbol{\tau}} + \underbrace{F^s} + \rho\mathbf{g}$$

Turbulent and viscous stress

Rate of momentum gain due to spray – drop drag

Amsden,1989

Gas Phase energy conservation

Internal energy conservation

$$\frac{\partial \rho I}{\partial t} + \nabla \cdot (\rho \mathbf{u} I) = -P\nabla \cdot \mathbf{u} - \nabla \cdot \mathbf{J} + \underbrace{\rho\varepsilon}_{\text{Turbulence dissipation}} + \overbrace{Q^c}^{\text{Combustion heat release}} + \underbrace{Q^s}_{\text{Energy due to Spray - vaporization}}$$

Heat flux

$$\mathbf{J} = -\lambda \nabla T - \rho D \sum_m h_m \nabla(\rho_m / \rho)$$

Equations of state

$$p = RT \sum_m \rho_m / W_m$$

Specific heat, enthalpy from JANAF data

Turbulence Model (RANS)

Amsden, 1989, 1997

Kinetic energy

$$\frac{\partial \rho k}{\partial t} + \nabla\cdot(\rho \mathbf{u} k) = -\tfrac{2}{3}\rho k \nabla\cdot\mathbf{u} + \underbrace{\boldsymbol{\tau}:\mathbf{u}}_{\text{Production due to mean flow}} + \nabla\cdot\left[\left(\frac{\mu}{\mathrm{Pr}_k}\right)\nabla k\right] \overbrace{-\rho\varepsilon}^{\text{Dissipation}} + \underbrace{\dot{W}}_{\text{Rate of work to disperse drops}}$$

Dissipation rate

$$\frac{\partial \rho\varepsilon}{\partial t} + \nabla\cdot(\rho\mathbf{u}\varepsilon) = -\left(\frac{2}{3}C_{\varepsilon 1} - C_{\varepsilon 3}\right)\rho\varepsilon\nabla\cdot\mathbf{u} + \nabla\cdot\left[\left(\frac{\mu}{\mathrm{Pr}_\varepsilon}\right)\nabla\varepsilon\right] + \frac{\varepsilon}{k}\left[C_{\varepsilon 1}\boldsymbol{\tau}:\nabla\mathbf{u} - C_{\varepsilon 2}\rho\varepsilon + C_s W^s\right]$$

Turbulence diffusivity

$$D = C_\mu k^2 / \varepsilon$$

Eddy size

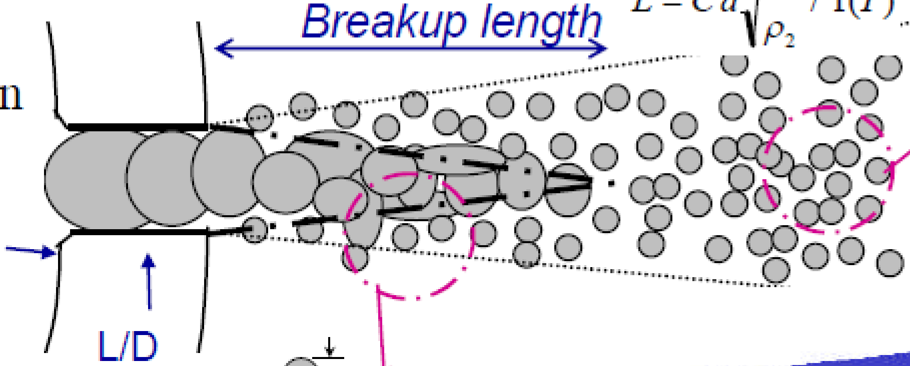
$$l = C k^{3/2}/\varepsilon$$

Turbulence intensity

$$u'^2 = (2k/3)$$

ERC Spray modeling

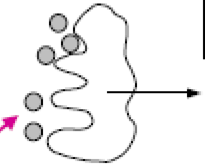
Blob injection model



$$L = C a \sqrt{\frac{\rho_1}{\rho_2}} / f(T)$$

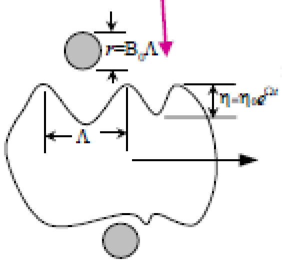
RT Model

Beale &Reitz, 1999



Kelvin-Helmoltz
Rayleigh Taylor
Linearized instability analysis

KH Model



Spray Models

Nozzle flow/cavitation

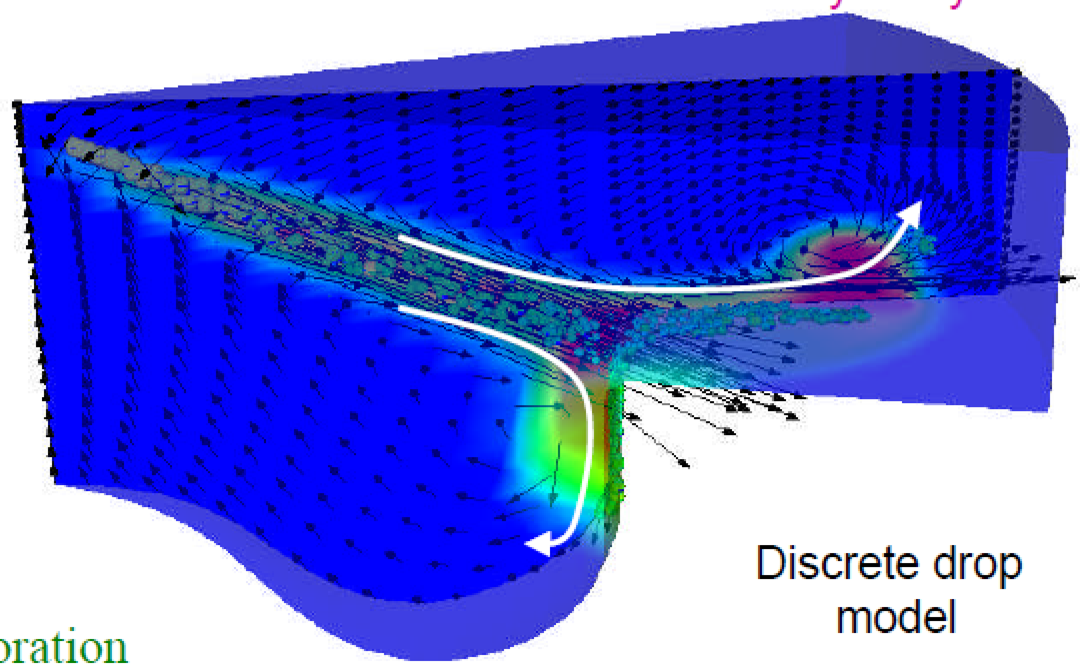
Jet atomization } KH-RT
Drop breakup

Drop collision/coalescence

Drop drag

Multi-component fuel evaporation

Spray-wall impingement

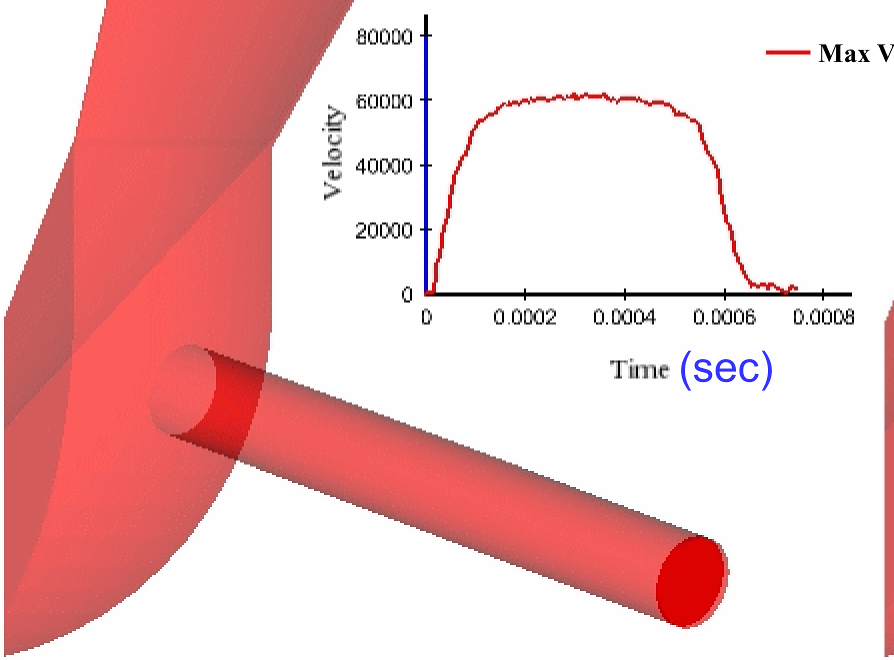


Discrete drop model

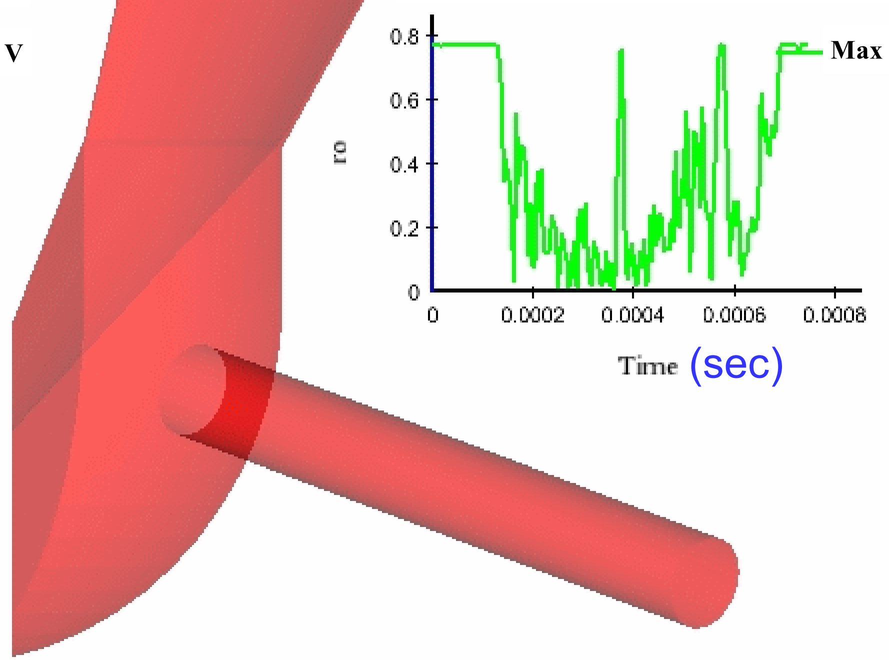
Lee & Reitz, 2010

Fuel Injection and Nozzle Cavitation

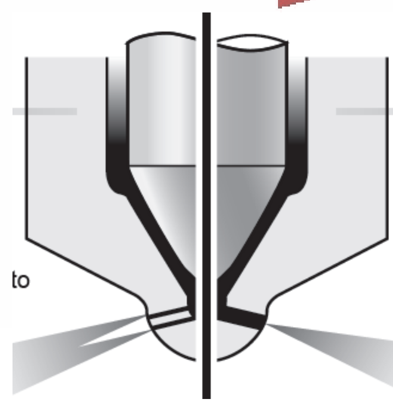
max velocity at exit, cm/s



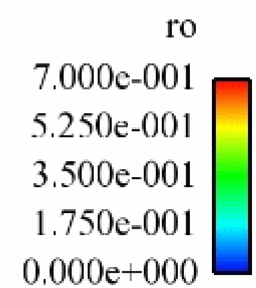
min. density at exit, g/cm^3



streamline and exit velocity



density and iso-surface (ρ=0.35g/cm^3)

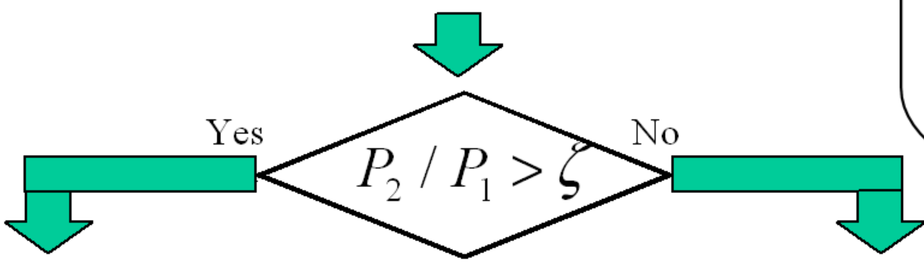


Sarre, 1999

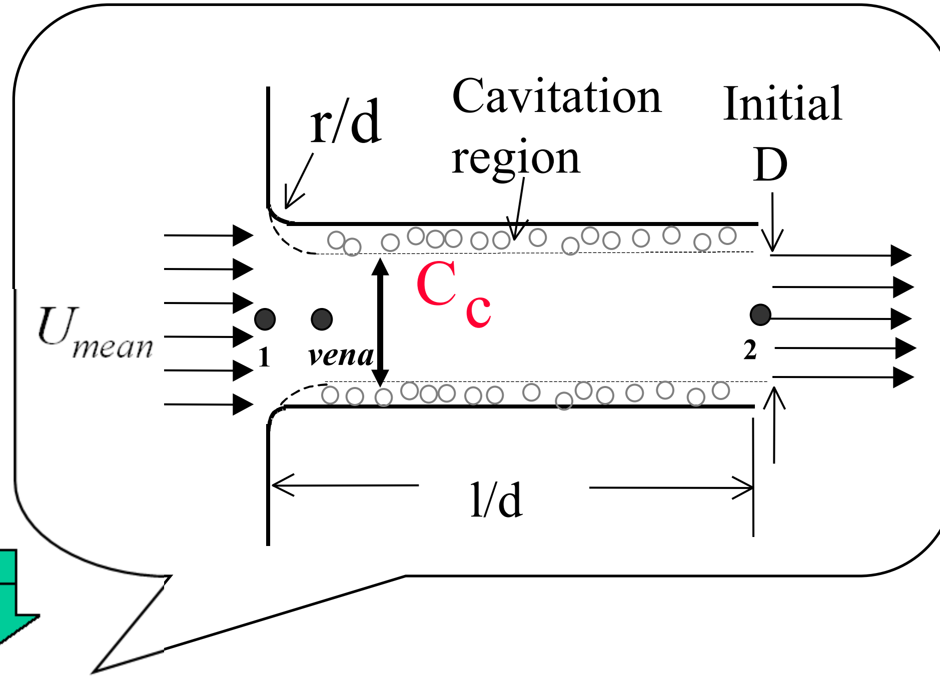
Cavitation inception

Account for effects of nozzle geometry

Cavitation if $P < P_V$

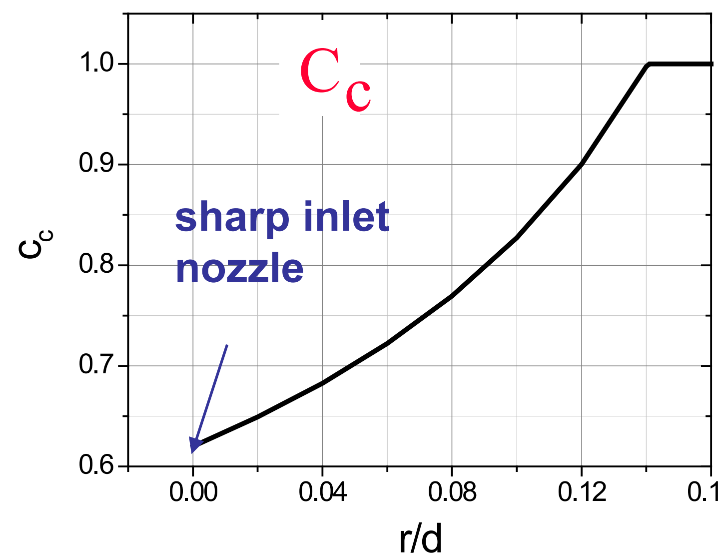


$$\zeta = \frac{1}{2(C_c - C_c^2)}$$



Contraction coefficient (Nurick (1976)

$$C_c = [(\frac{1}{0.62})^2 - 11.4r/d]^{-1/2}$$



Sarre, 1999

ERC Nozzle Flow Model

$$P_2 / P_1 > \zeta$$

Cavitating flow — Yes

Nozzle discharge coefficient

$$C_d = C_c \sqrt{\frac{p_1 - p_v}{p_1 - p_2}}$$

Effective injection velocity

$$u_{eff} = \frac{2C_c P_1 - P_2 + (1 - 2C_c) P_v}{C_c \sqrt{2\rho (P_1 - P_v)}}$$

Effective nozzle area

$$A_{eff} = \frac{2C_c^2 (P_1 - P_v)}{2C_c P_1 - P_2 + (1 - 2C_c) P_v} A$$

Non-cavitating flow — No

Nozzle discharge coefficient

Lichtarowicz (1965)

$$C_d = 0.827 - 0.0085\, {}^{l}\!/\!{}_{d}$$

Effective injection velocity

$$u_{eff} = C_d \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

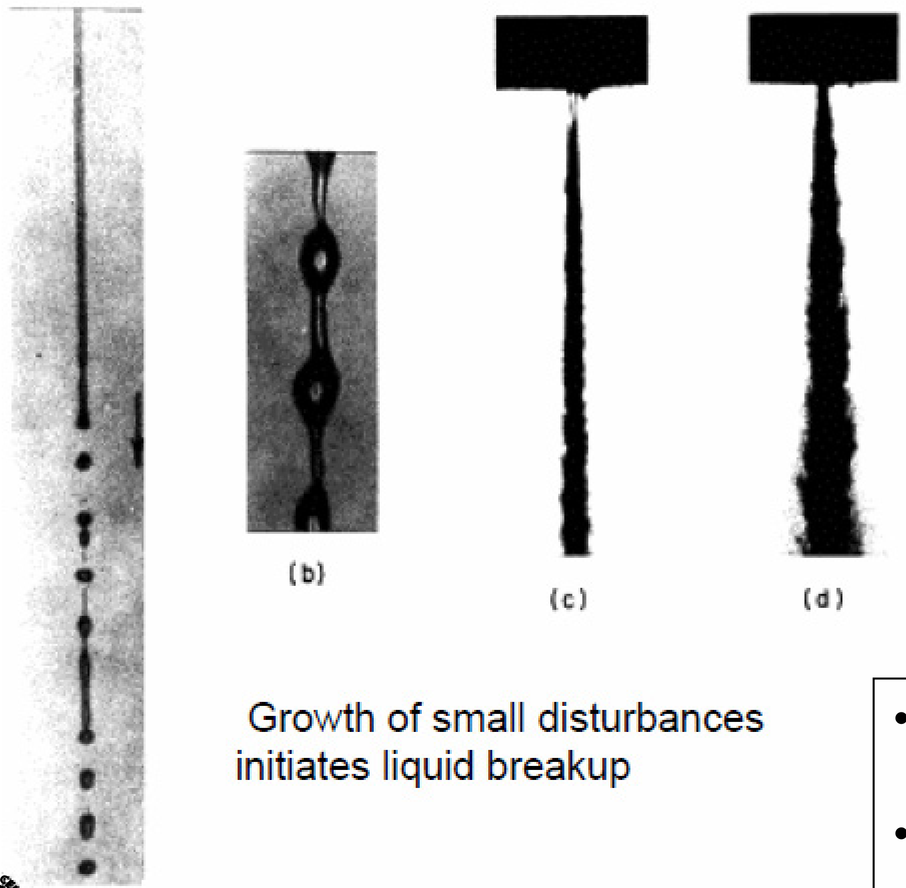
Effective nozzle area

$$A_{eff} = A$$

Atomization models (Single hole nozzle)

Reitz, 1982

Four main jet breakup regimes:
Rayleigh, first wind-induced, second wind-induced and atomization



(a) (b) (c) (d)

Growth of small disturbances initiates liquid breakup

a.) Rayleigh breakup
Drop diameters > jet diameter.
Breakup far downstream nozzle

b.) First wind-induced regime
Drop diameter ~ jet diameter.
Breakup far downstream of nozzle

c.) Second wind-induced regime
Drop sizes < jet diameter.
Breakup starts close to nozzle exit

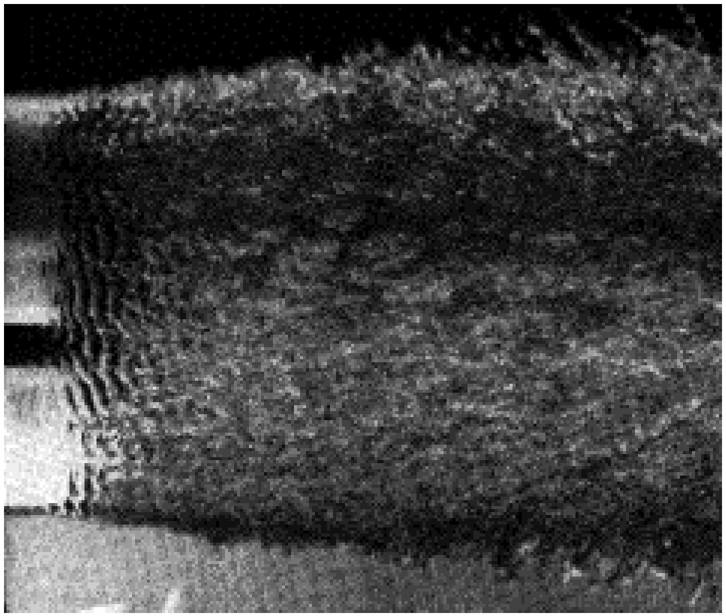
d.) Atomization regime
Drop sizes << jet diameter.
Breakup at nozzle exit.

- Jet breakup known to depend on nozzle design details.
- Need to start by considering flow in the injector nozzle passage

Atomization - "Wave" breakup model

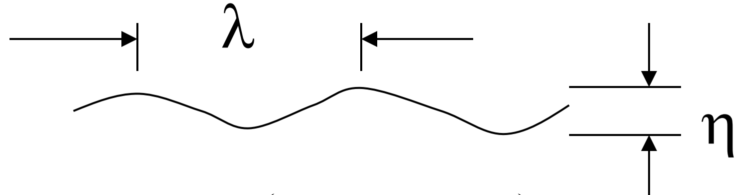
Reitz, 1982

Taylor & Hoyt, 1983



High speed photograph of water jet close to nozzle exit (at top) in the second wind-induced breakup regime showing surface wave instability growth and breakup

Kelvin-Helmholtz Jet Breakup Model



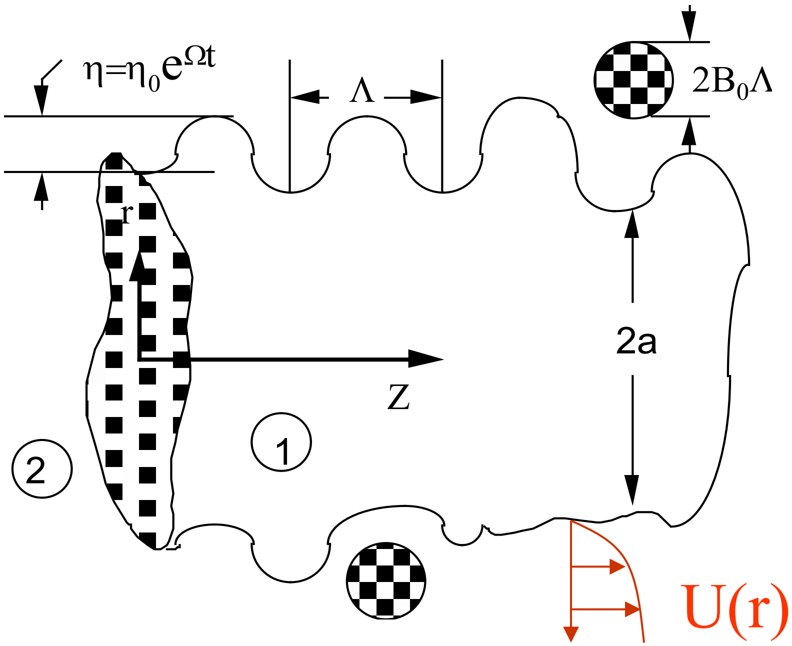
$$\eta = R\left(\eta_0 e^{ikz + \omega t}\right)$$

Linear Stability Theory:

Cylindrical liquid jet issuing from a circular orifice into a stationary, incompressible gas.

Relate growth rate, ω, of perturbation to wavelength $\lambda = 2\pi/k$

Reitz, 1982



Linearized analysis

U = Jet velocity

Surface waves breakup on jet or "blob"

$$\eta = R\left(\eta_0 e^{ikz+\omega t}\right)$$

Equation of liquid surface: $r = a + \eta$,

Axisymmetric fluctuating pressure, axial velocity, and radial velocity for both liquid and gas phases.

Fluctuations described by continuity equation $$\frac{\partial u_i}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(r v_i) = 0$$

plus linearized equations of motion for the liquid and the gas,

Axial: $$\frac{\partial u_i}{\partial t} + U_i(r)\frac{\partial u_i}{\partial z} + v_i\frac{dU_i}{dr} = -\frac{1}{\rho_i}\frac{\partial p_i}{\partial z} + \frac{\mu_i}{\rho_i}\left[\frac{\partial^2 u_i}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_i}{\partial r}\right)\right]$$

Analysis (Cont.)

Reitz, 1982

Radial: $$\frac{\partial v_i}{\partial t} + U_i(r)\frac{\partial v_i}{\partial z} = -\frac{1}{\rho_i}\frac{\partial p_i}{\partial r} + \frac{\mu_i}{\rho_i}\left[\frac{\partial^2 v_i}{\partial z^2} + \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial r v_i}{\partial r}\right)\right]$$

Gas is assumed to be inviscid $U(r) = U$ - slip

With $\eta \ll a$, the gas equations give the pressure at the interface $r = a$

$$p_2 = -\rho_2 (U - i\frac{\omega}{k})^2 k\eta \frac{K_0(ka)}{K_1(ka)}$$

Boundary conditions-

Kinematic, tangential and normal stress at the interface:

$$\mathrm{v}_1 = \mathbf{w} = \frac{\partial \eta}{\partial t}, \qquad \frac{\partial \mathrm{u}_1}{\partial r} = -\frac{\partial \mathrm{v}_1}{\partial z}$$

$$\boxed{-p_1 + 2\nu_1\rho_1\frac{\partial \mathrm{v}_1}{\partial r} - \frac{\sigma}{a^2}(\eta + a^2\frac{\partial^2 \eta}{\partial z^2}) + p_2 = 0}$$

Dispersion relationship

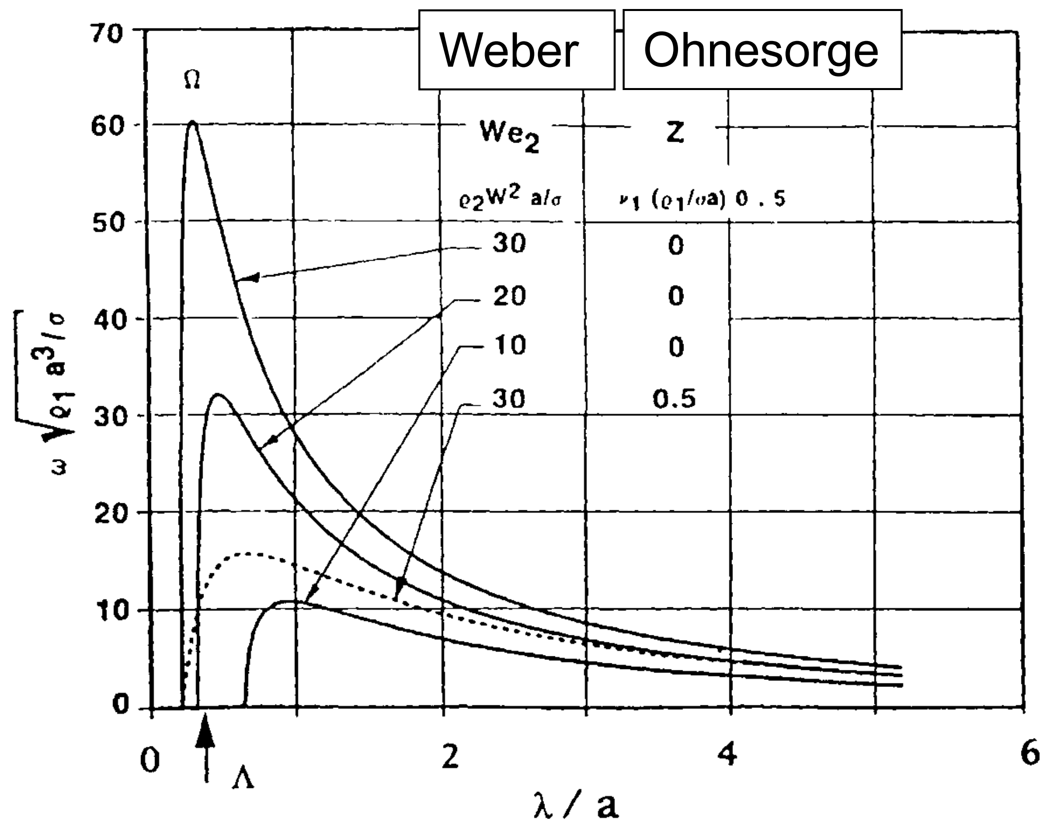
Reitz, 1988

$$\omega^2 + 2\nu_1 k^2 \omega \left[\frac{I_1'(ka)}{I_0(ka)} - \frac{2kl}{k^2+l^2} \frac{I_1(ka)}{I_0(ka)} \frac{I_1'(la)}{I_0(la)} \right] = \frac{\sigma k}{\rho_1 a^2}\left(1 - k^2 a^2\right)\left(\frac{l^2 - k^2}{l^2 + k^2}\right)\frac{I_1(ka)}{I_0(ka)}$$

$$+ \frac{\rho_2}{\rho_1}\left(U - i\omega/k\right)^2 k^2 \left(\frac{l^2 - k^2}{l^2 + k^2}\right)\frac{I_1(ka)K_0(ka)}{I_0(ka)K_1(ka)}$$

Maximum wave growth rate characterizes fastest growing waves which are responsible for breakup
(as a function of Weber and Ohnesorge numbers)

Maximum wave growth rate and length scale: Ω and Λ



Curvefits of dispersion equation

Reitz, 1988

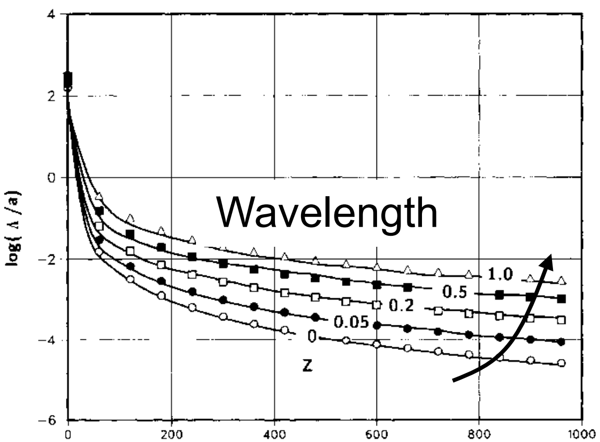
$$\frac{\Lambda}{a} = 9.02\frac{\left(1 + 0.45\,Z^{0.5}\right)\left(1 + 0.4T^{0.7}\right)}{\left(1 + 0.87\,We_2^{1.67}\right)^{0.6}}$$

$$\Omega\left(\frac{\rho_1 a^3}{\sigma}\right)^{0.5} = \frac{0.34 + 0.38\,We_2^{1.5}}{(1 + Z)\left(1 + 1.4T^{0.6}\right)}$$

where $Z=\frac{We_1^{0.5}}{Re_1}$; $T=ZWe_2^{0.5}$; $We_1=\frac{\rho_1 U^2 a}{\sigma}$; $We_2=\frac{\rho_2 U^2 a}{\sigma}$; $Re_1=\frac{Ua}{\nu_1}$

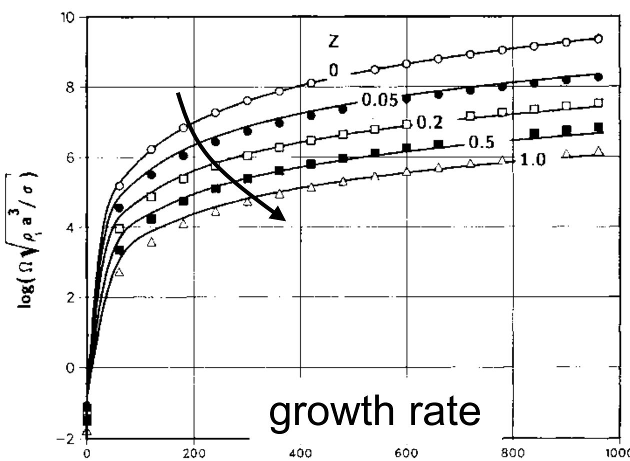
Maximum growth rate increases and wavelength decreases with We

Increased viscosity reduces growth rate and increases wave length



Ohnesorge number, Z

Weber number, We_2



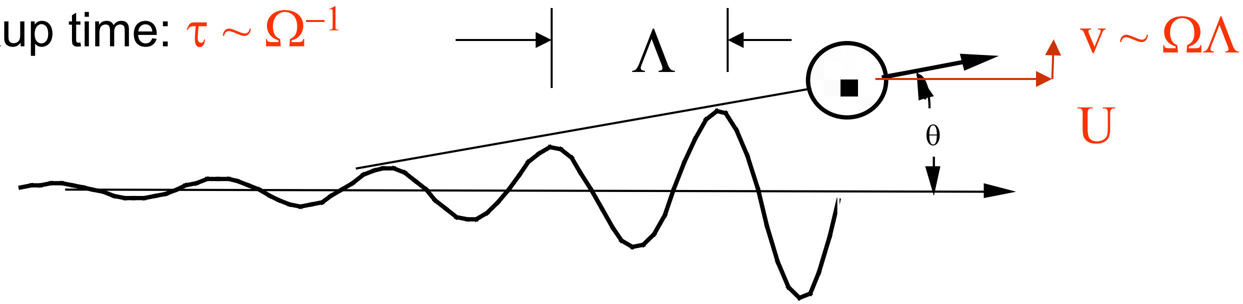
Weber number, We_2

"Wave" atomization model

Reitz, 1988

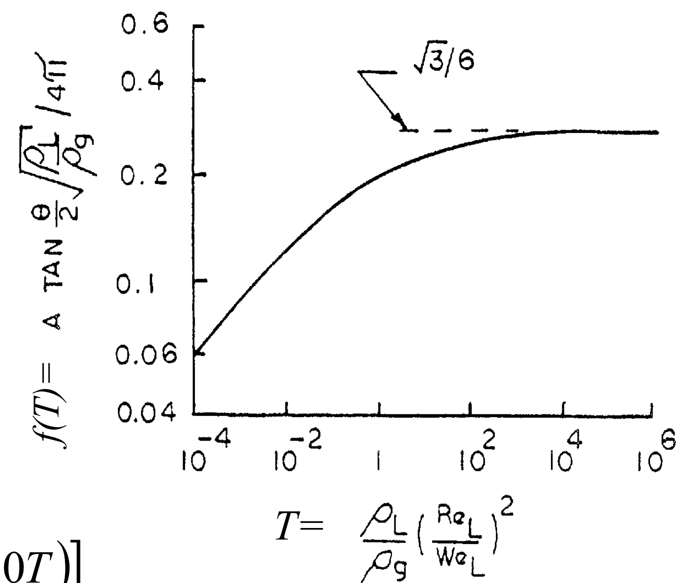
Drop size: $r = B\Lambda$

Breakup time: $\tau \sim \Omega^{-1}$



Spray angle prediction:

$$Tan\ \theta = \frac{v}{U} = \frac{1}{A} 4\pi \left(\frac{\rho_2}{\rho_1}\right)^{1/2} f(T)$$

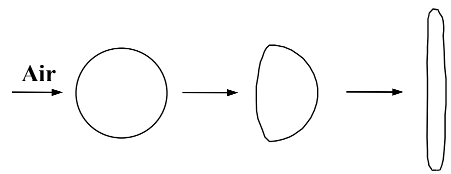
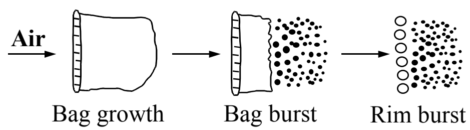
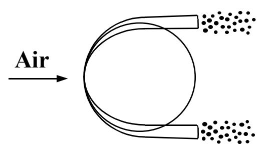
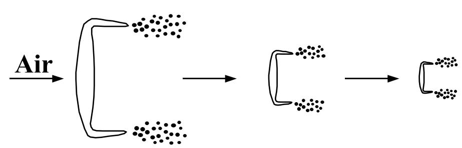
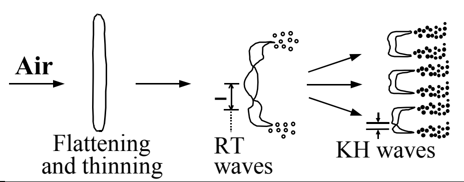


Breakup length of the core (Taylor, 1940):

$$L = C\,a\sqrt{\frac{\rho_1}{\rho_2}} \,/\, f(T) \quad \text{where} \quad f(T) = \frac{\sqrt{3}}{6}\left[1 - \exp(-10T)\right]$$

Drop breakup regimes

Lee, 2001

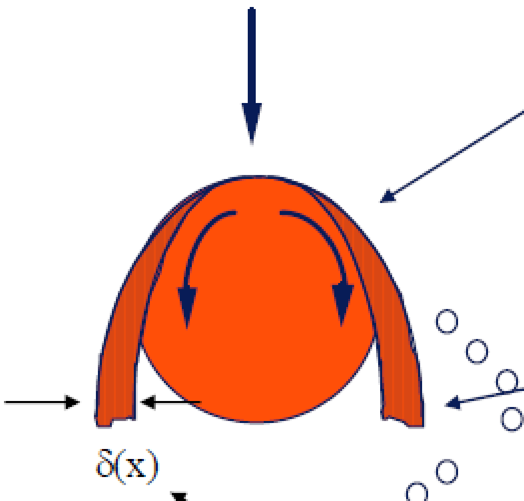
Breakup stages	Deformation or breakup regimes	Breakup process	Weber number	References
First breakup stage	(1) Deformation and flattening		We < 12	
Second breakup stage	(b) Bag breakup		12 ≤ We ≤ 100 (including the Bag-and-Stamen breakup)	Pilch and Erdman
	(c) Shear breakup		We < 80	Ranger and Nicolls 1969
	(d) Stretching and thinning breakup		100 ≤ We ≤ 350	Liu and Reitz 1997
	(e) Catastrophic breakup		350 ≤ We	Hwang et al. 1996

High Speed Drop breakup

Liu, 1997

Mechanisms of drop breakup at high velocities poorly understood - Conflicting theories

Bag, 'Shear' and 'Catastrophic' breakup regimes



Breakup due to capillary surface waves

Hinze Chem Eng (1955) and
Engel Nat. Bureau Stds (1958)

Boundary Layer Stripping due to Shear at the interface

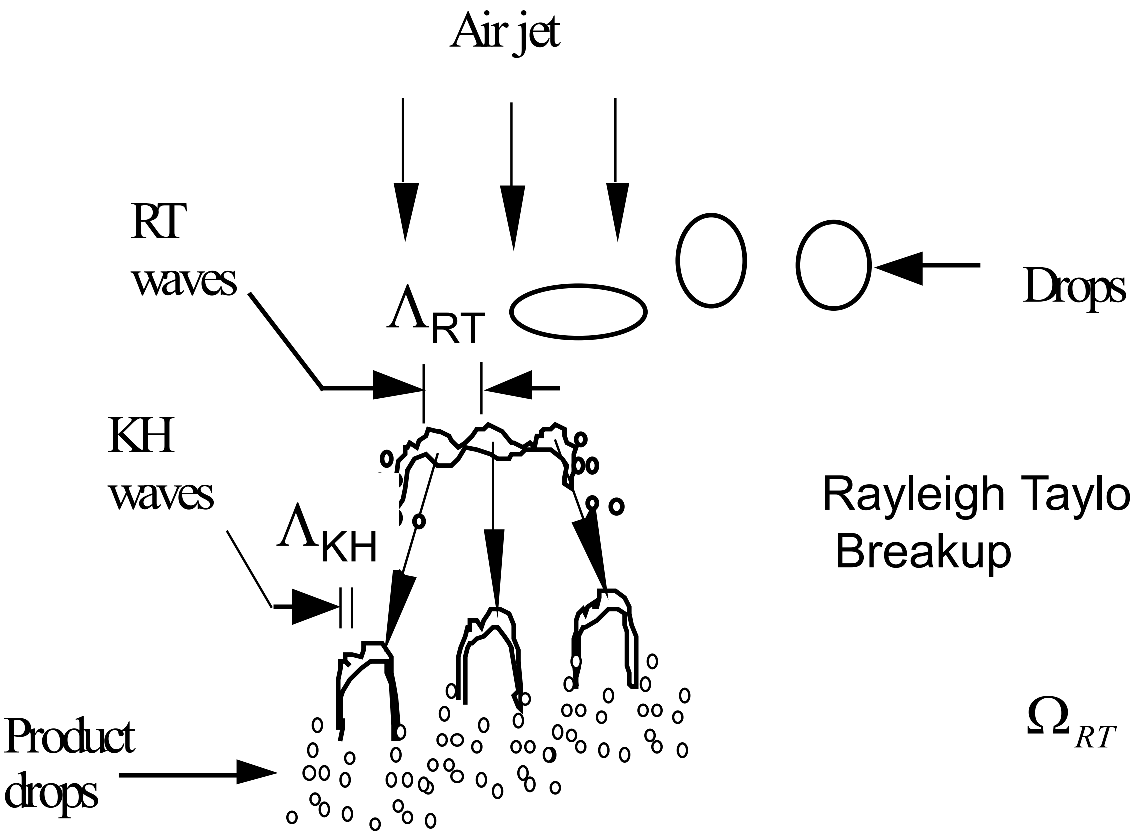
Ranger and Nicolls AIAA J. (1969)
Reinecke and Waldman AVCO Rep (1970)

Delplanque & Sirignano Atom Sprays (1994)

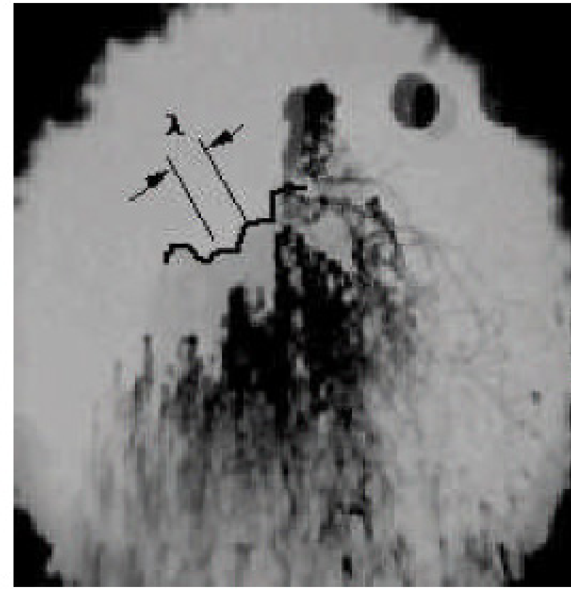
Stretching and thinning – drop distortion - Liu and Reitz IJMF (1997)

Hwang, 1996

High speed drop breakup mechanisms



Double pulse images



Rayleigh Taylor Breakup

$$\Omega_{RT} = \sqrt{\frac{2}{3\sqrt{\sigma}} \frac{\left[-g_t\left(\rho_l - \rho_g\right)\right]^{3/2}}{\rho_l + \rho_g}}$$

g_t = acceleration

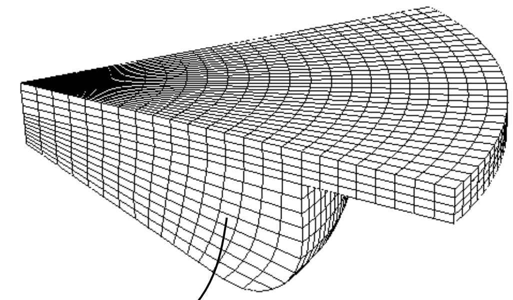
$$\Lambda_{RT} = \sqrt{\frac{-g_t\left(\rho_l - \rho_g\right)}{3\sigma}}$$

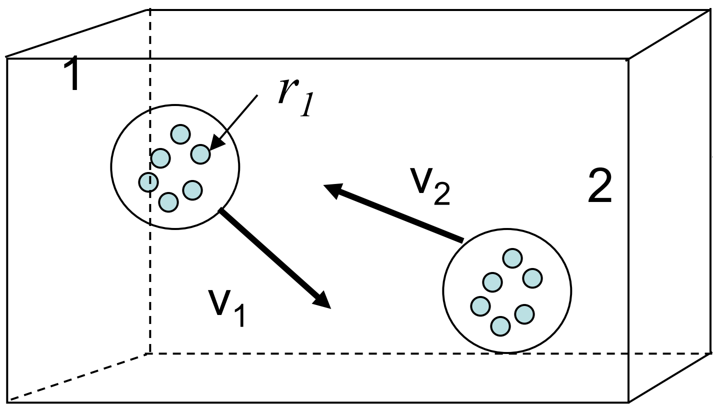
Drop collision modeling

O'Rourke, 1981

Collision frequency

$$\boxed{\nu_{12} = N_2 \pi (r_1 + r_2)^2 E_{12} |\mathbf{v}_1 - \mathbf{v}_2| / Vol}$$





Collision efficiency

$$E_{12} = \left(\frac{K}{K + 1/2} \right)^2 \sim 1$$

$$\boxed{K = \frac{2}{9} \frac{\rho_l |\mathbf{v}_1 - \mathbf{v}_2| r_2^2}{\mu_g r_1}}$$

Number of collisions from Poisson process

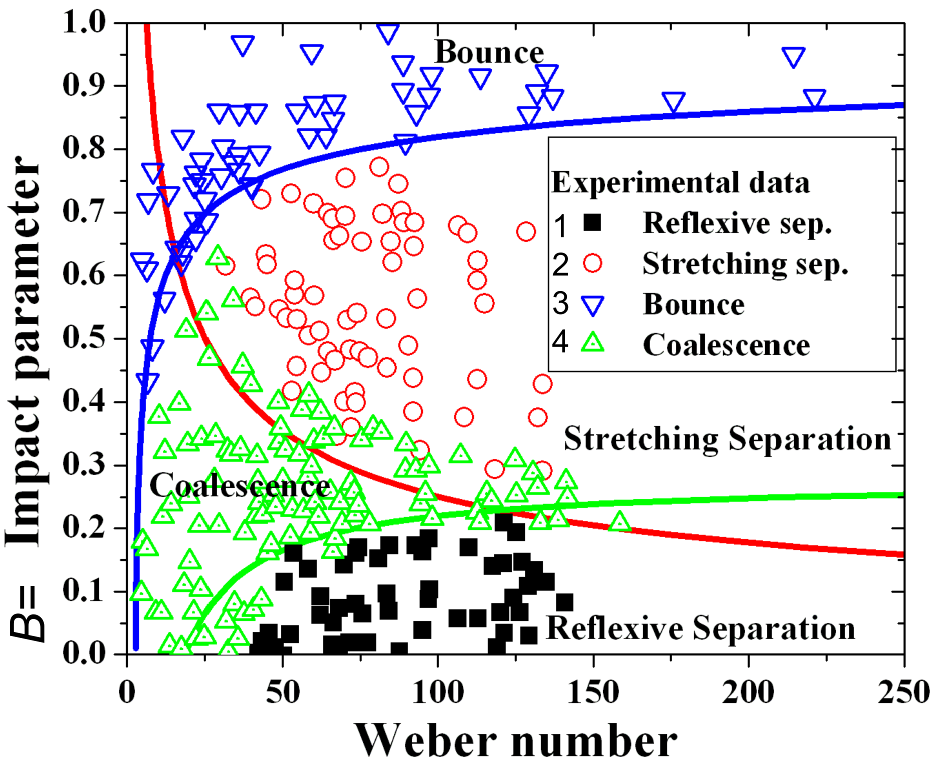
$$p(n) = e^{-\nu_{12}\Delta t} (\nu_{12} \Delta t)^n / n!$$

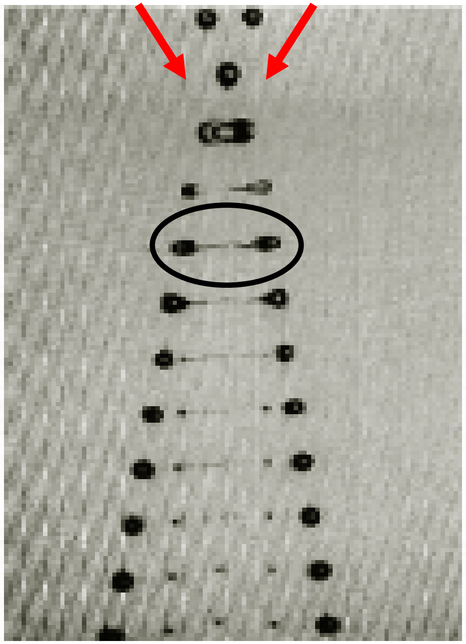
$$\boxed{0 < p < 1 \quad \text{random number}}$$

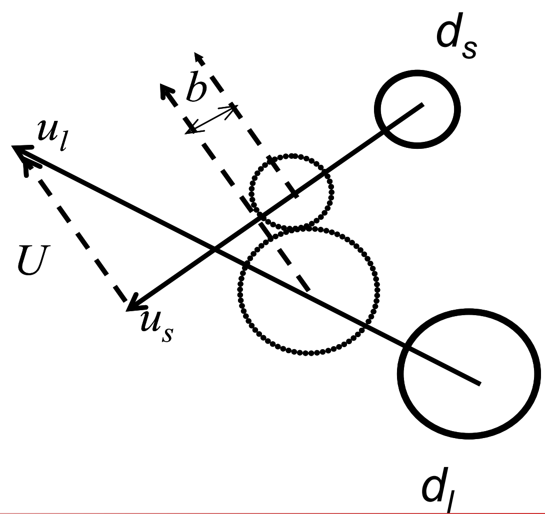
Drop collision and coalescence

Munnannur, 2007
Georjon, 1999

1. Reflexive vs. surface energy
2. Kinetic energy of unaffected part vs. surface energy
3. Drops cannot expel trapped gas film (bounce apart)
4. Drops form combined mass (coalesce)







$$We = \frac{\rho_L U^2 d_s}{\sigma}, \quad B = \frac{2b}{(d_s + d_l)}, \quad \Delta = \frac{d_s}{d_l}$$

Liu et al. SAE 930072

Drop drag modeling

Steady-state Stokes viscous drag, added-mass and Basset history integral

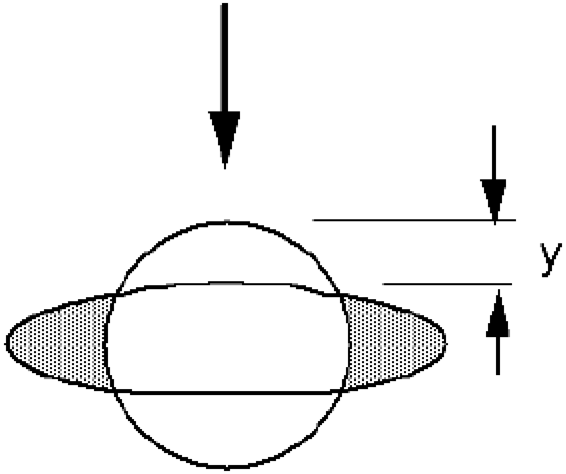
$$\mathrm{dv/dt} = \mathbf{F} = 6\pi r \mu_g \mathbf{v} + \tfrac{1}{2}\left(\tfrac{4}{3}\pi r^3 \rho_g\right)\frac{d\mathbf{v}}{dt} + 6r^2\sqrt{\pi\mu\rho_g}\int_0^t \frac{d\mathbf{v}/dt'}{\sqrt{t-t'}}\,dt'$$

General form

$$\boxed{\rho_L V_d\, d\mathbf{v}/dt = C_D A_f \frac{\rho_g U^2}{2}\{\mathbf{U}/|\mathbf{U}|\}}$$

$$C_d = \begin{cases} 24\,\mathrm{Re}_d^{-1}(1+\mathrm{Re}_d^{2/3}/6), & \mathrm{Re}_d < 1000 \\ 0.424, & \mathrm{Re}_d \ge 1000 \end{cases}$$

Drop distortion (TAB model)

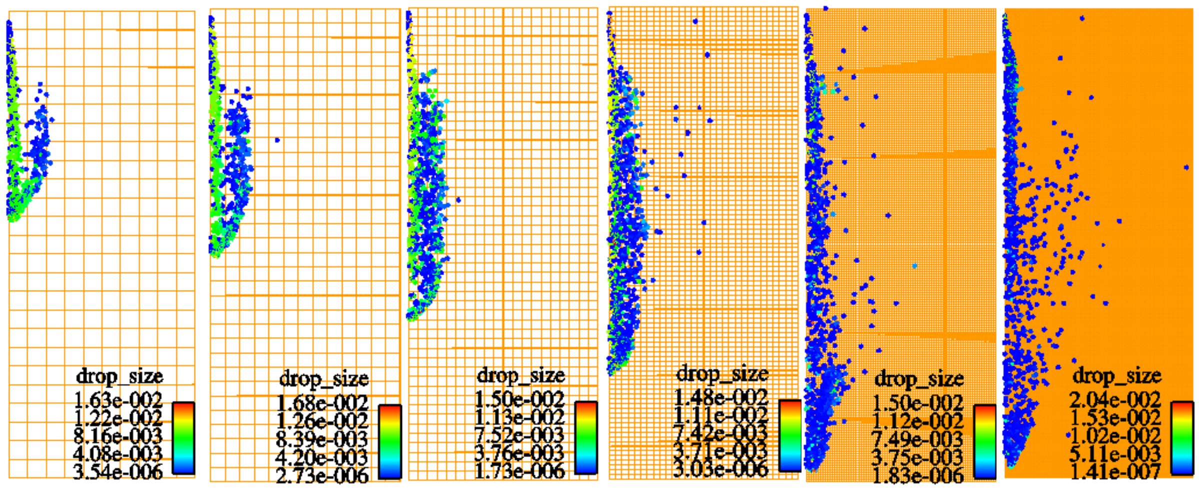


$$\ddot{y} = -5\frac{\mu_l}{\rho_l}\frac{\dot{y}}{r_d^2} - \frac{8\sigma y}{\rho_l r_d^3} + \frac{2}{3}\frac{\rho}{\rho_l}\frac{U_{rel}^2}{r_d^2}$$

$$C_d = C_{d,sphere}(1 + 2.632\,y)$$

Grid independent spray models

Abani, 2008, Wang, 2013

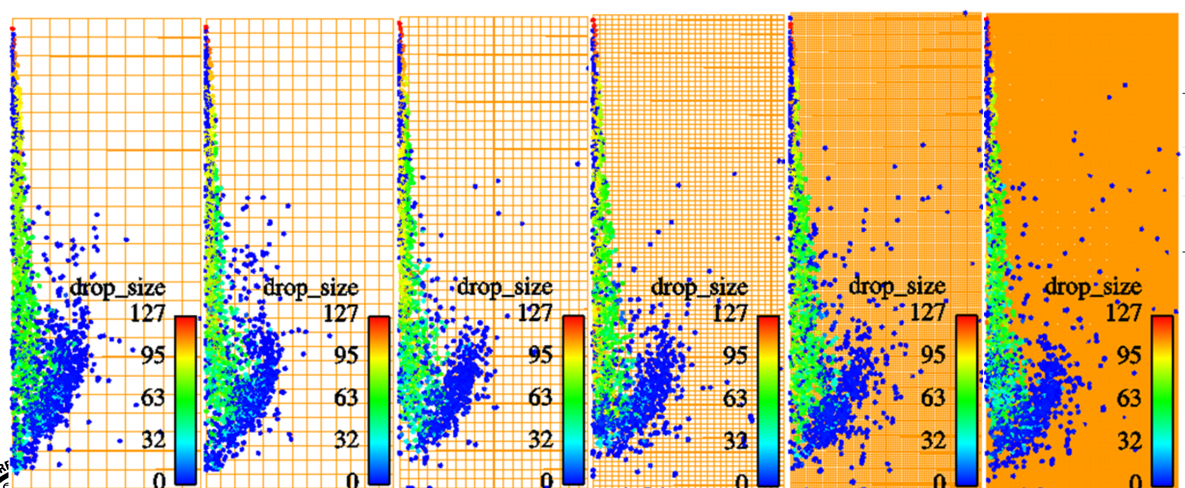


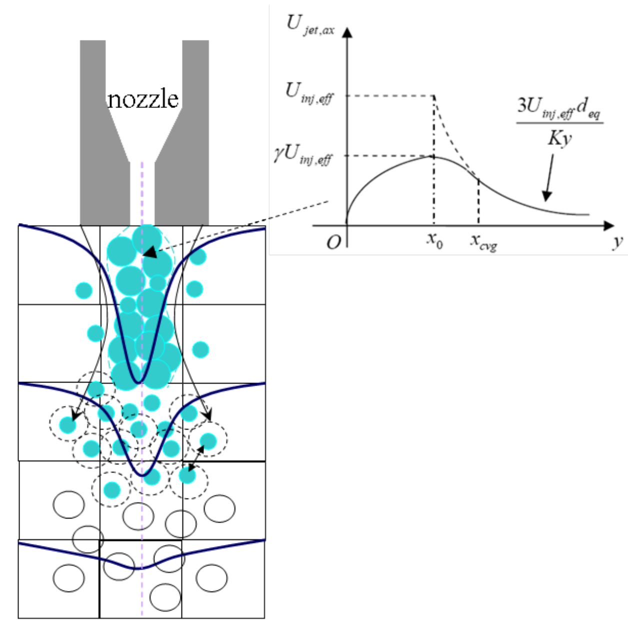
4 mm 3mm 2 mm 1 mm 0.5 mm 0.25n

Coarse mesh:
Drop drag over-predicted

Fine mesh:
Drop coalescence under-predicted

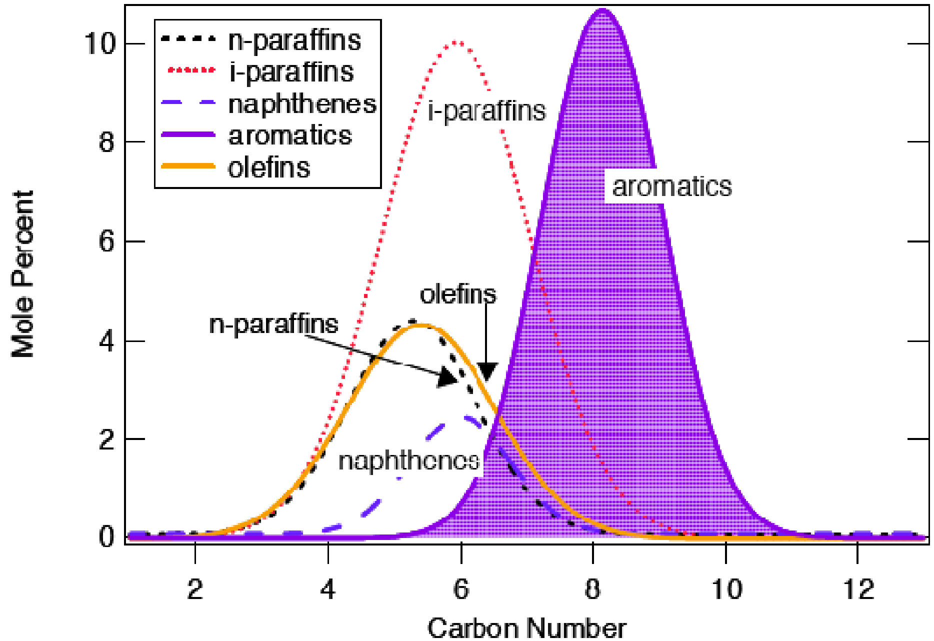
Gas-jet sub-grid momentum exchange near nozzle





Ra and Reitz, IJMF 2009

Drop vaporization



No.	Physical property	No.	Physical property
p1	**Liquid density**	p7	**Vapor heat capacity**
p2	**Vapor pressure**	p8	**Vapor diffusivity**
p3	**Surface tension**	p9	**Vapor viscosity**
p4	**Liquid viscosity**	p10	**Vapor thermal conductivity**
p5	**Liquid thermal conductivity**	p11	**Liquid Heat capacity**
p6	**Heat of vaporization**	p12	**Critical properties**

- Physical properties used in sub-models
- Mixture properties calculated from pure components using appropriate equations

Discrete Multi-Component

- Discrete system of liquid phase + discrete mixture system of vapor phase fuel and ambient gas:

$$G_p(I) = \sum_{F=1}^{N_F} x_F{}^p \delta(I - I_F) + \sum_{s=1}^{N_s} x_s{}^p \delta(I - I_s)$$

discrete phase of fuel

discrete phase of air/fuel mixture

- Vapor phase transport equation,

$$\frac{\partial}{\partial t}[\rho y_i] + \nabla \cdot [\rho y_i v] = \nabla \cdot (\rho D_i \nabla y_i) + s_{g,i}$$

$$\sum \;=>$$

$$\frac{\partial}{\partial t}[\rho y_F] + \nabla \cdot [\rho y_F v] = \nabla \cdot (\rho \overline{D} \nabla y_F) + S_g$$

Hour 6: Spray modeling

Ra, 2003

18 component DMC model

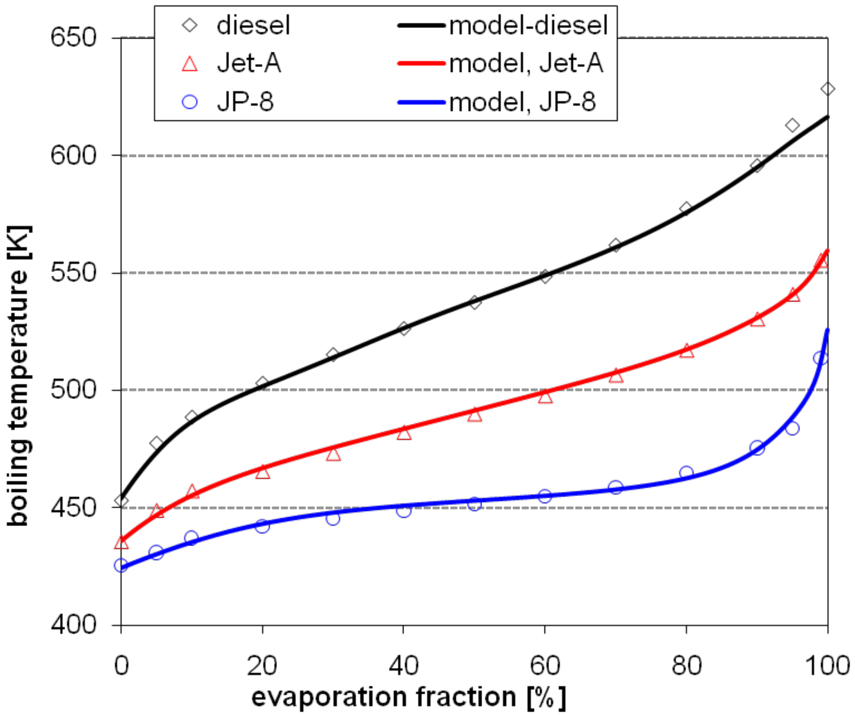
	diesel	Jet-A	JP-8
cyC6	0.010000	0.022529	0.012529
c7h8	0.037698	0.035873	0.025873
c10h8	0.020000	0.009607	0.0
c10h18	0.0	0.0	0.030000
c10h22	0.113977	0.253797	0.721022
c12h26	0.124544	0.298704	0.118311
c14h10	0.0	0.0	0.0
c14h30	0.210805	0.202265	0.022265
c16h34	0.172593	0.060627	0.0
c18h38	0.085615	0.0	0.0
c20h42	0.084268	0.0	0.0
mxylene	0.010000	0.079442	0.0
mcymene	0.050355	0.0	0.0
c11h16	0.0	0.019881	0.0
tetralin	0.017362	0.017275	0.0
c12h18	0.017362	0.0	0.0
c13h20	0.045421	0.0	0.0
nc7h16	0.0	0.0	0.070000

alkanes

aromatics

cycloalkanes

PAH

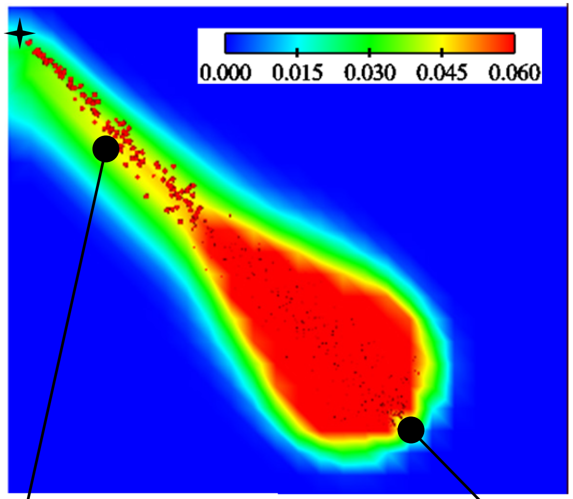


	Diesel	Model-Di	Jet-A	Model-JetA	JP-8	Model-JP8
Density [g/cm^3]	0.8478	0.7800	0.8101	0.7638	0.7547	0.7333
Viscosity [cSt]	2.71	2.05	1.55	1.36	1.15	1.01
Surface tension [dynes/cm]	30	26.91	29.1	25.53	25.2	23.64
LHV [kJ/kg]	42526	42527.7	43305	43306.6	44185	44199.4
Saturates [%]		81.4	84.4	83.7	94.7	94.1
Aromatics [%]		17.6	14.0	14.1	1.2	2.2
Olefins [%]			1.6		4.1	
Naphthenes [%]		1.0		2.2		3.7
C/H ratio	6.852	6.102	6.534	5.997	5.95	5.565
Molecular weight [g/mol]	190	177	160	152	150	139

← corrected

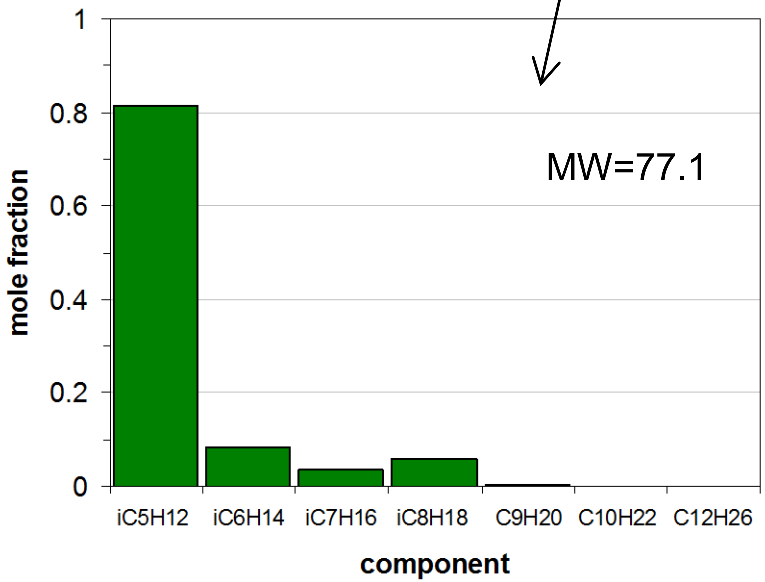
Multi-component spray vaporization

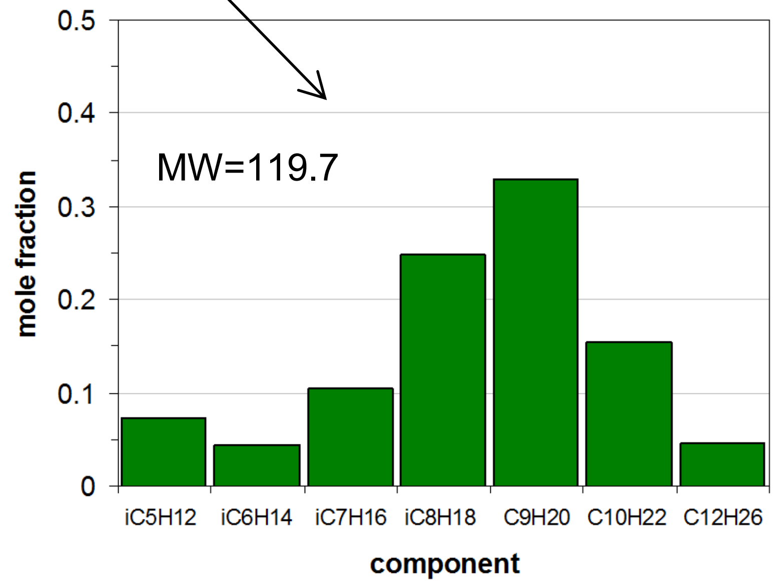
Ra and Reitz, IJMF 2009



Gasoline
Do=30 μm
Vinj=100 m/s

2.0 ms after SOI





Reitz, 2014

Summary

The Lagrangian Drop/Eulerian Fluid (LDEF) Discrete Drop model is the work-horse approach in commercial codes for simulating 2-phase flows.

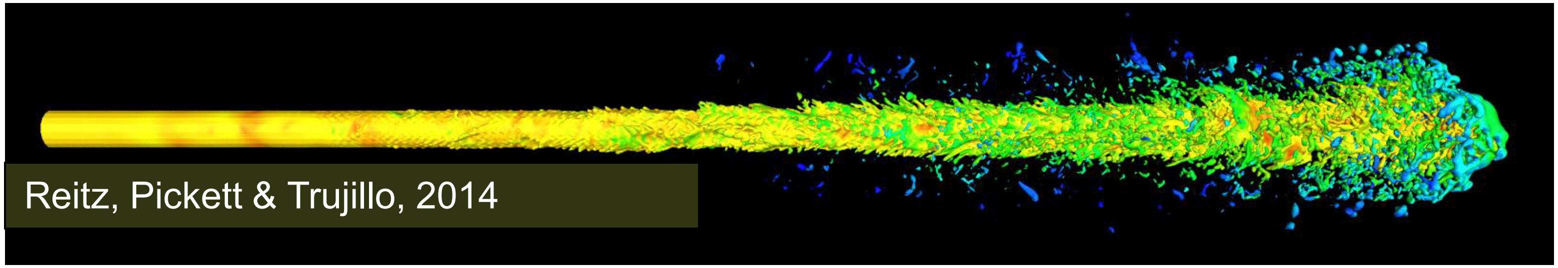
Detailed models are available for use in engine CFD models to describe the effects of injector nozzle flow, and liquid and gas properties on spray formation and drop breakup physics.

Significant progress is being made using LES/DNS spray modeling with high resolution experimental diagnostics to validate engine CFD spray models.

Ballistic imaging: Linne, 2009; **X-Ray imaging:** Liu SAE paper 2010-01-0877

LES: Villiers & Gosman, LES Primary Diesel Spray Atomization, SAE 2004-01-0100

DNS: Near field spray modeling (Trujillo - ERC)



Reitz, Pickett & Trujillo, 2014

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