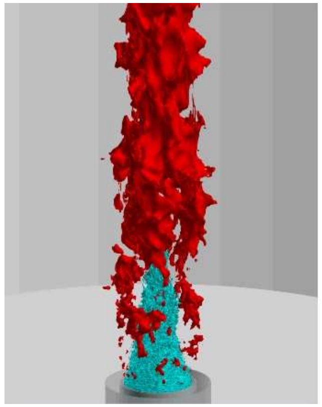
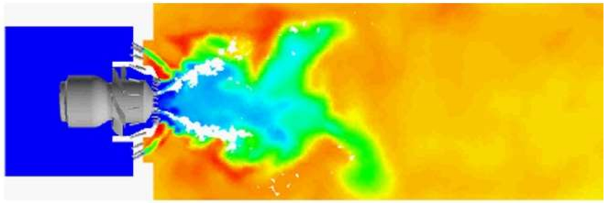
Aalto University
School of Engineering

Fundamentals of Sprays

AAE-E3030 Numerical Modeling of Multiphase Flows
25.2.2019

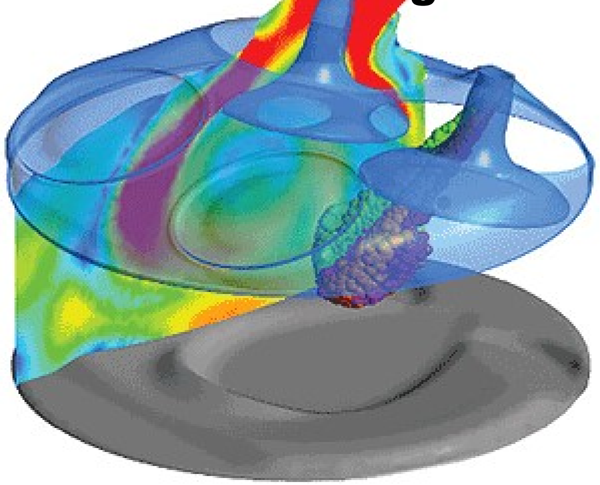
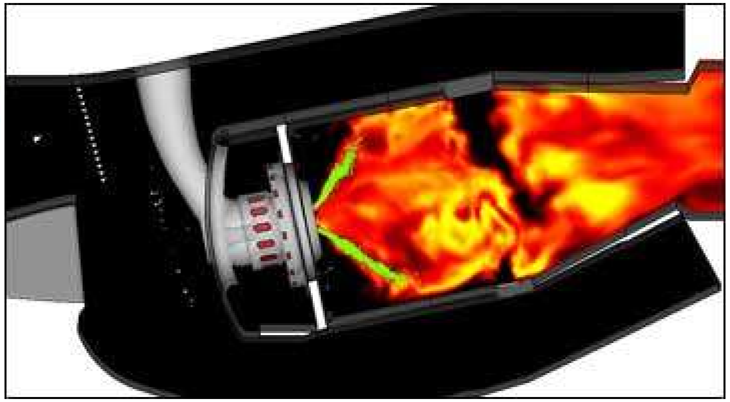
D.Sc. (Tech) Ossi Kaario


Motivation

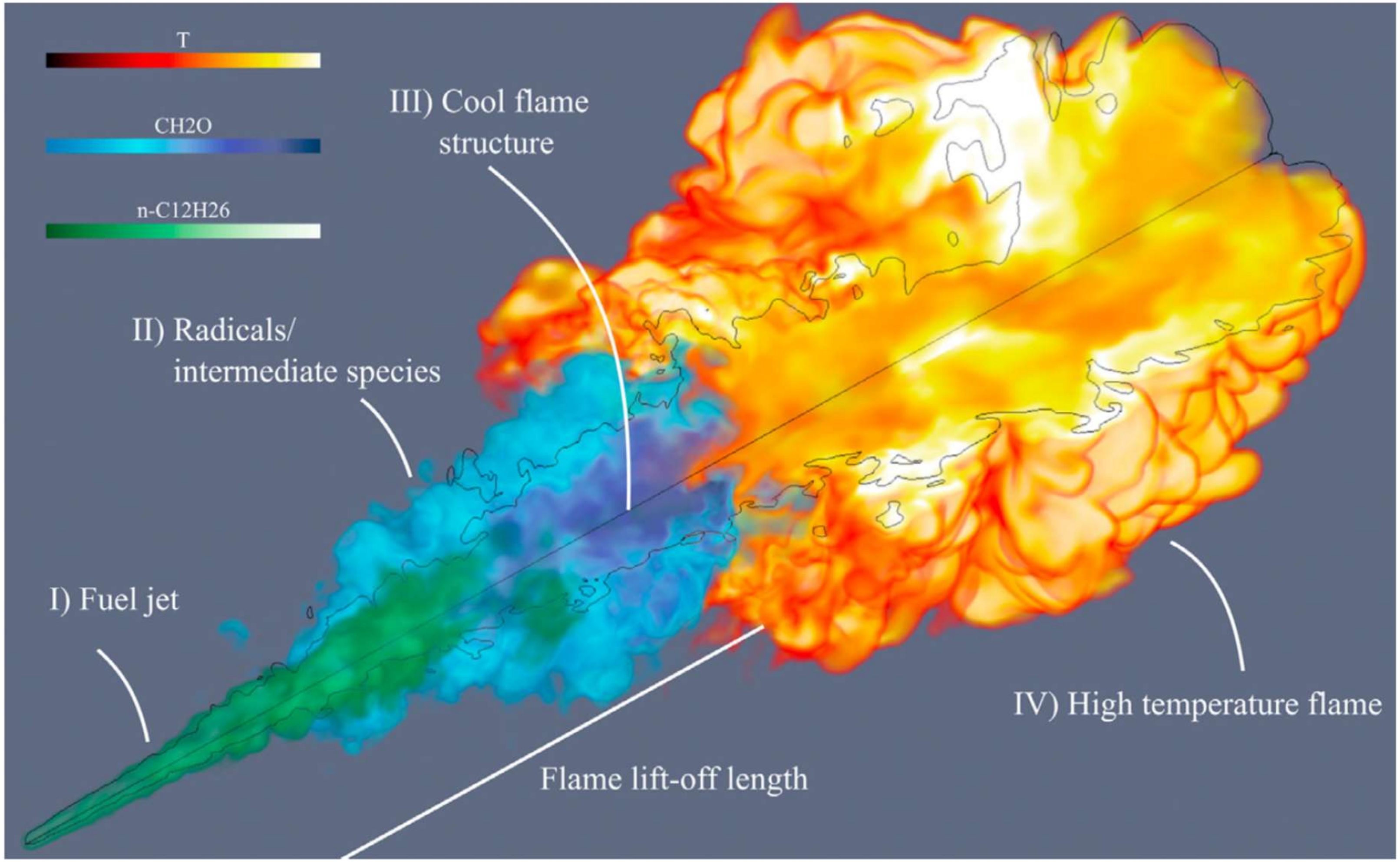
- **Why learn about sprays ?**

- **Sprays are used in many industrial applications: engines (diesel & gasoline), furnaces, gas turbines, rockets and in many other applications: aerosols, water taps…**
- **Therefore, understanding concepts related to sprays might be beneficial**
- **This lesson is about sprays: general topics of sprays in order to better understand what sprays are and how they form and interact with their surroundings**


Aalto University
School of Science
and Technology

Course related phenomena



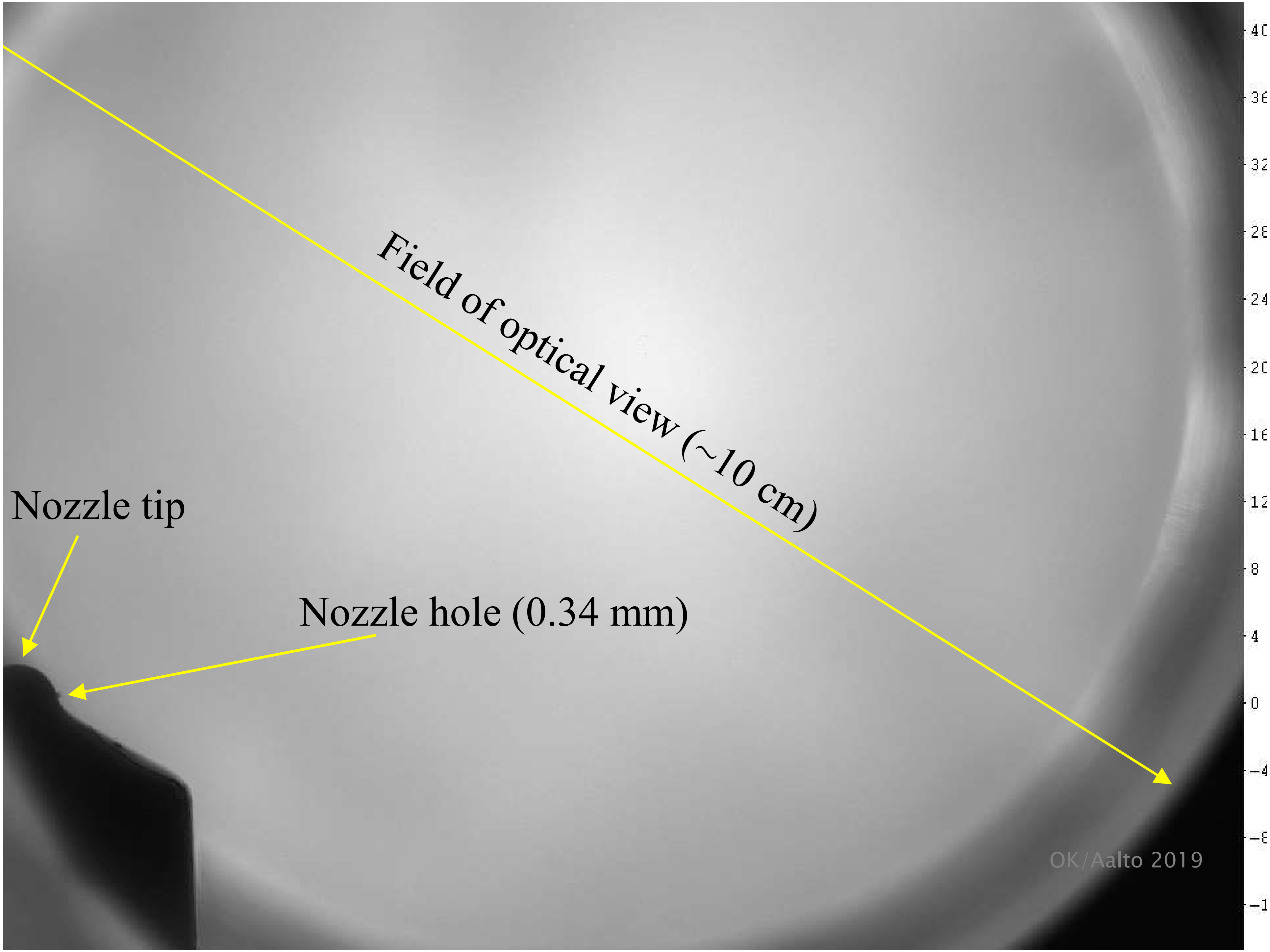
Wehrfritz et al., Comb. Flame 2016.

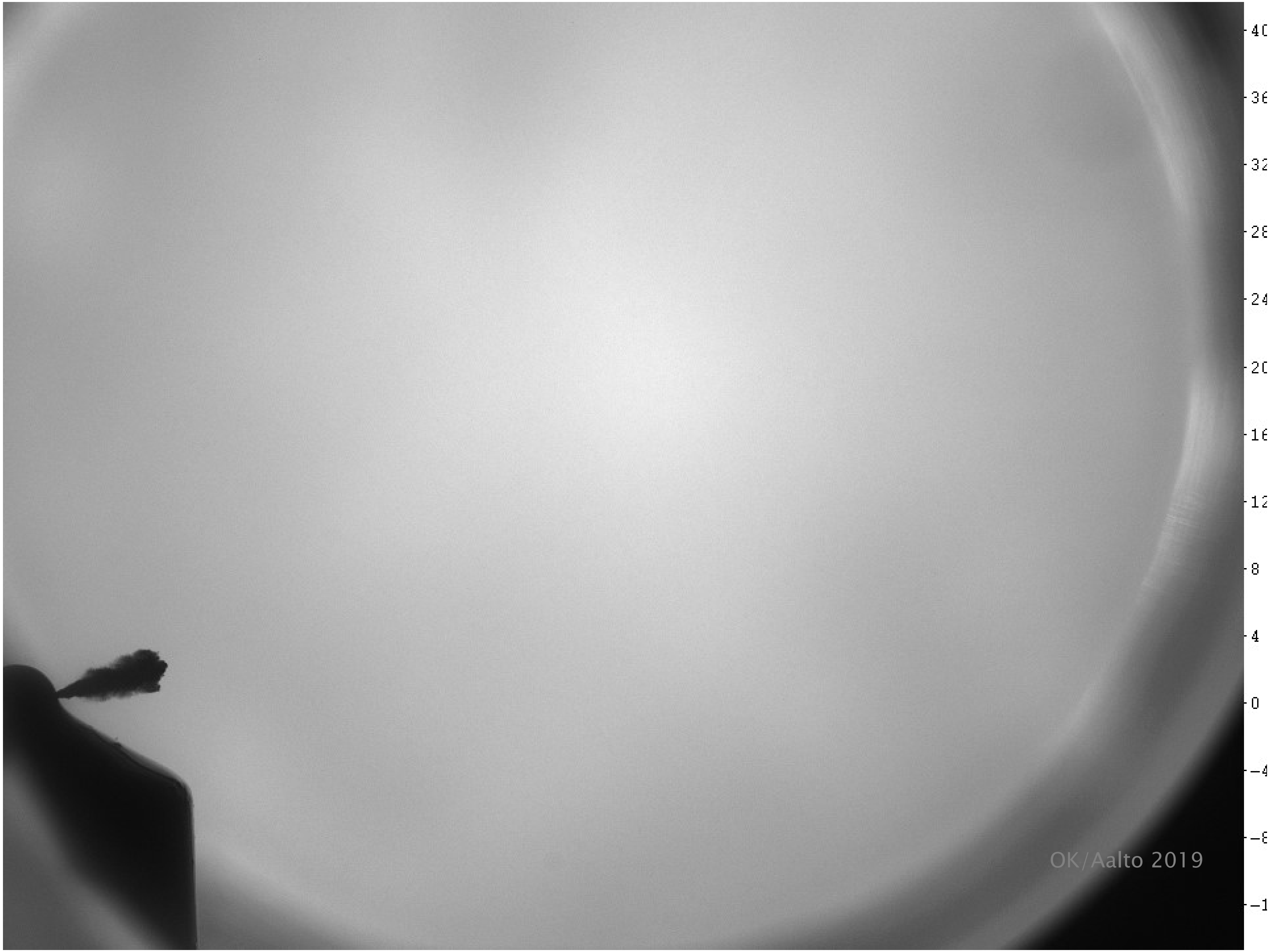
Aalto University
School of Engineering

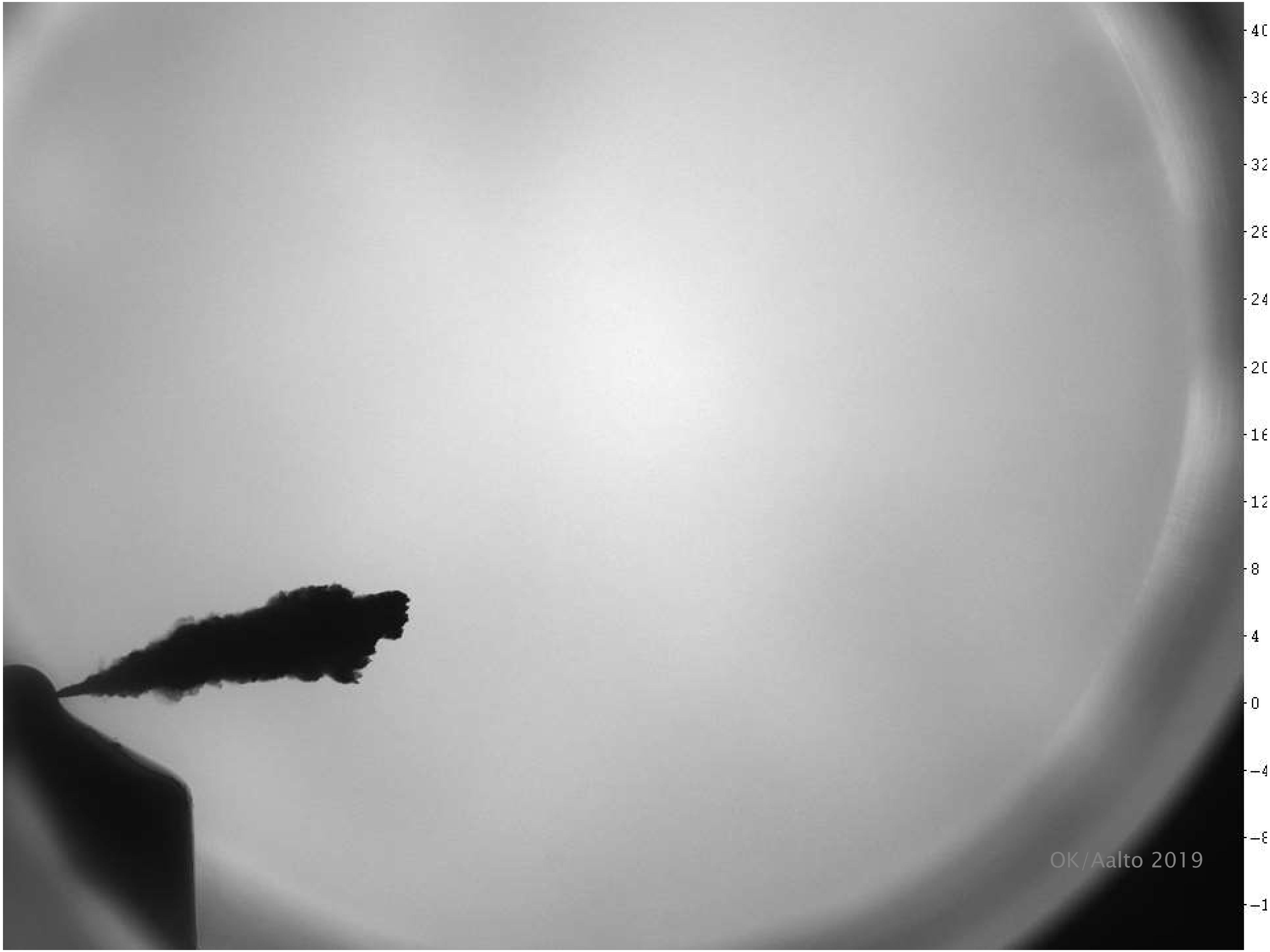
What does a fuel spray look like ?

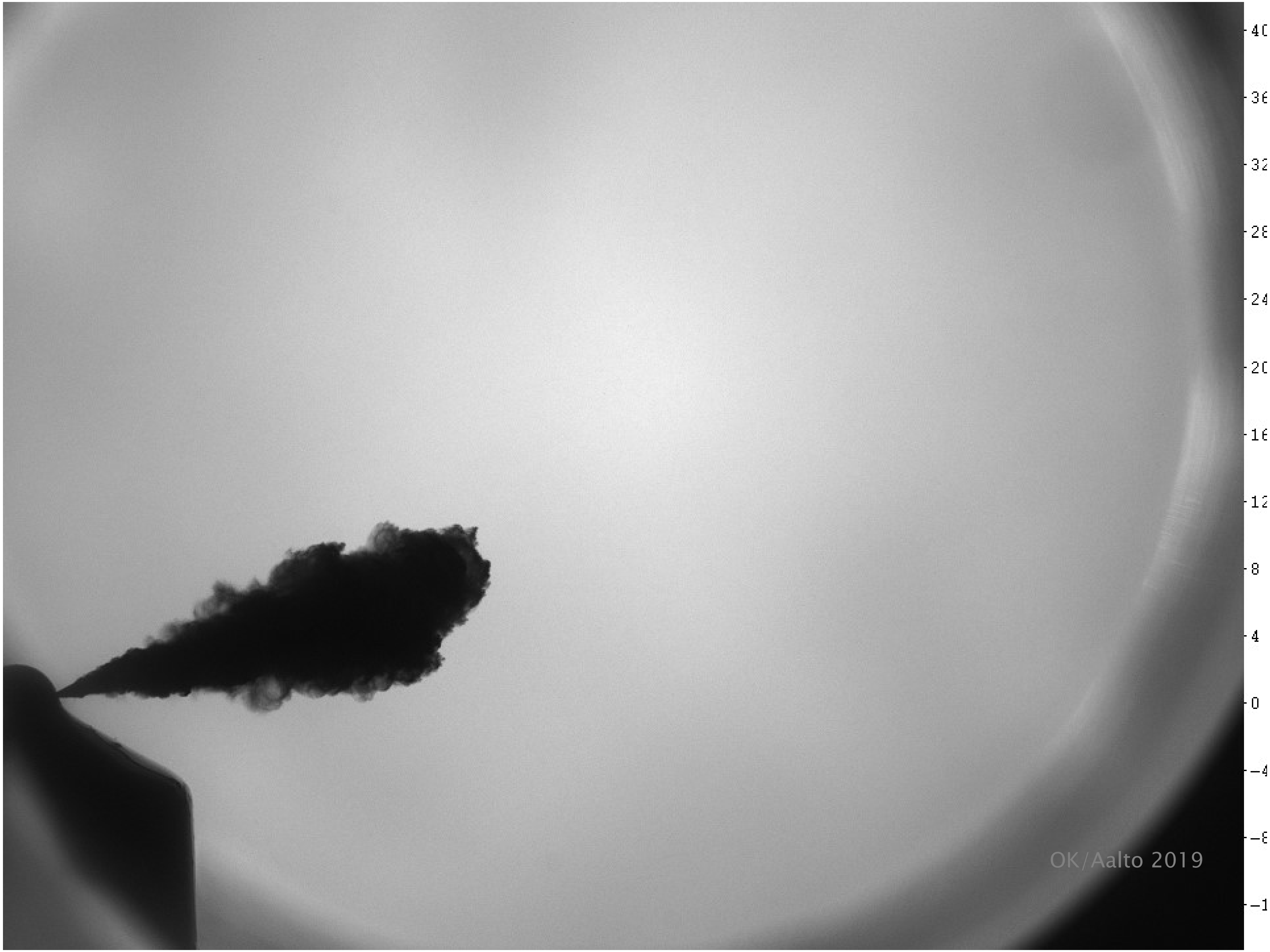
Optical Spray Investigations

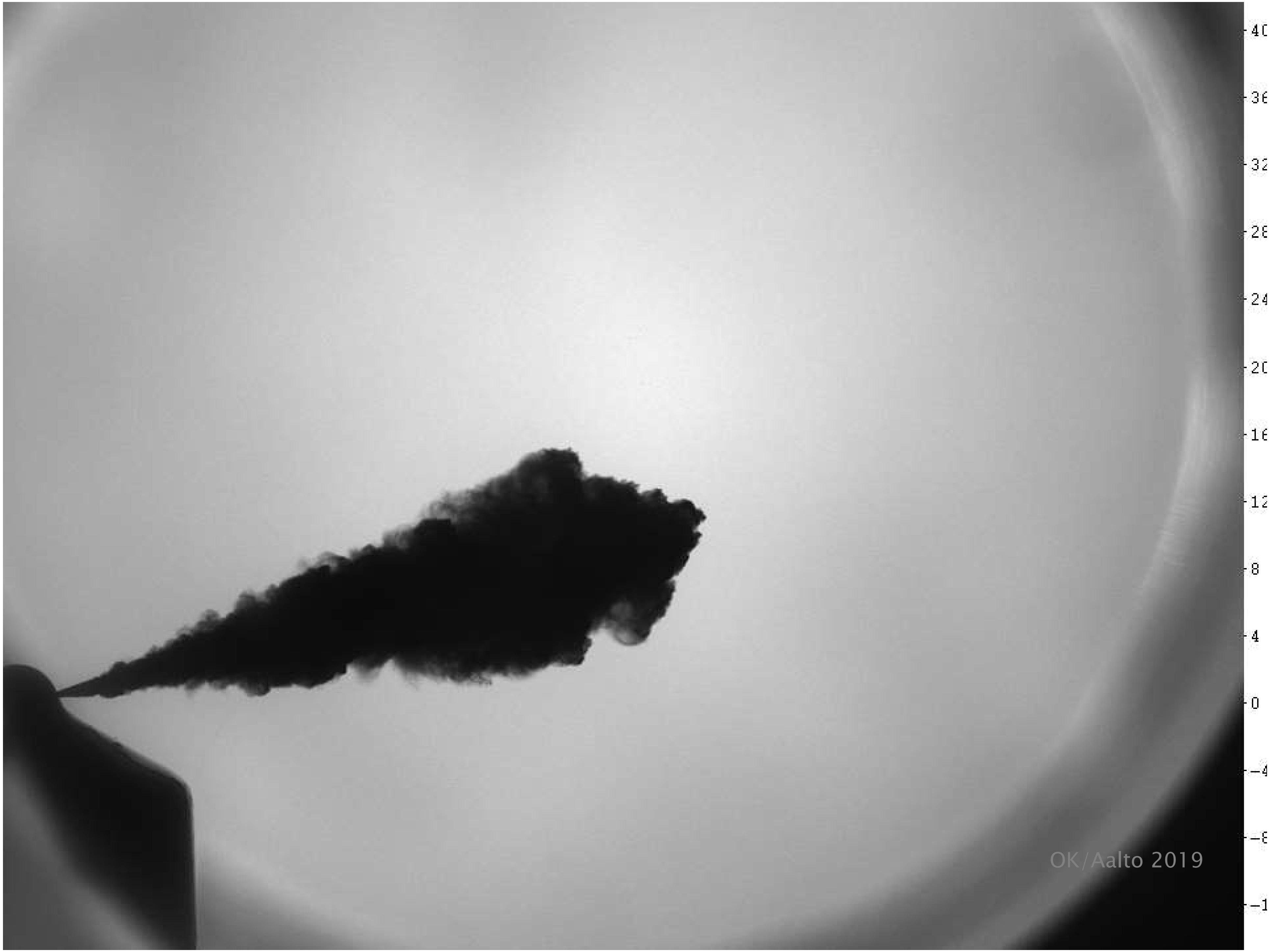
- Pictures by Harri Hillamo, 2010
- Fuel injection pressure is 1400bar
- Gas density is 35 kg/m3
- Nozzle diameter d=0.34mm


Field of optical view (~10 cm)
Nozzle tip
Nozzle hole (0.34 mm)
8
4
0
OK/Aalto 2019


4
3
3
2
2
2
1
1
8
4
0
−4
−8
−1
OK/Aalto 2019


8
4
0
OK/Aalto 2019


8
4
0
OK/Aalto 2019

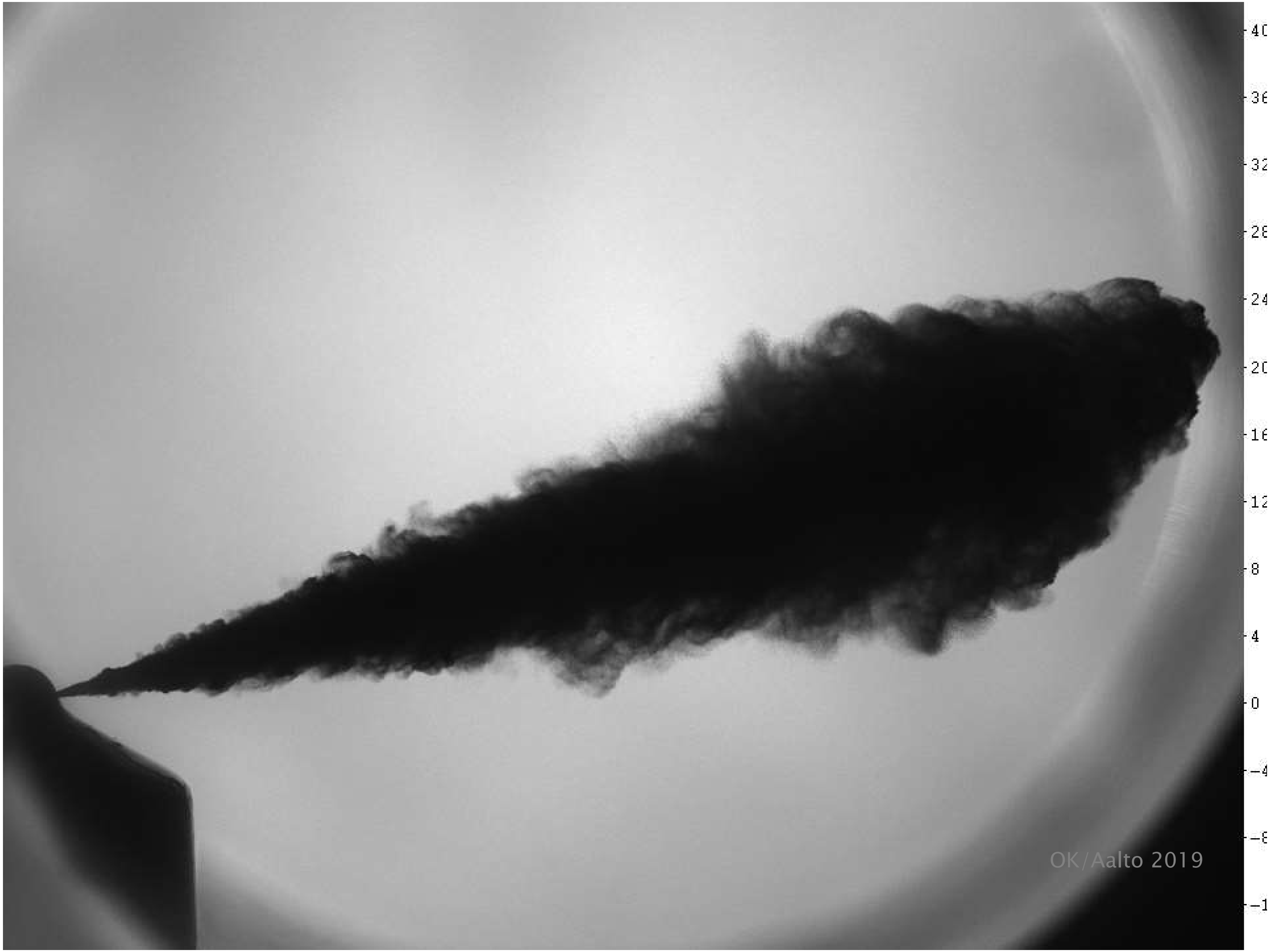


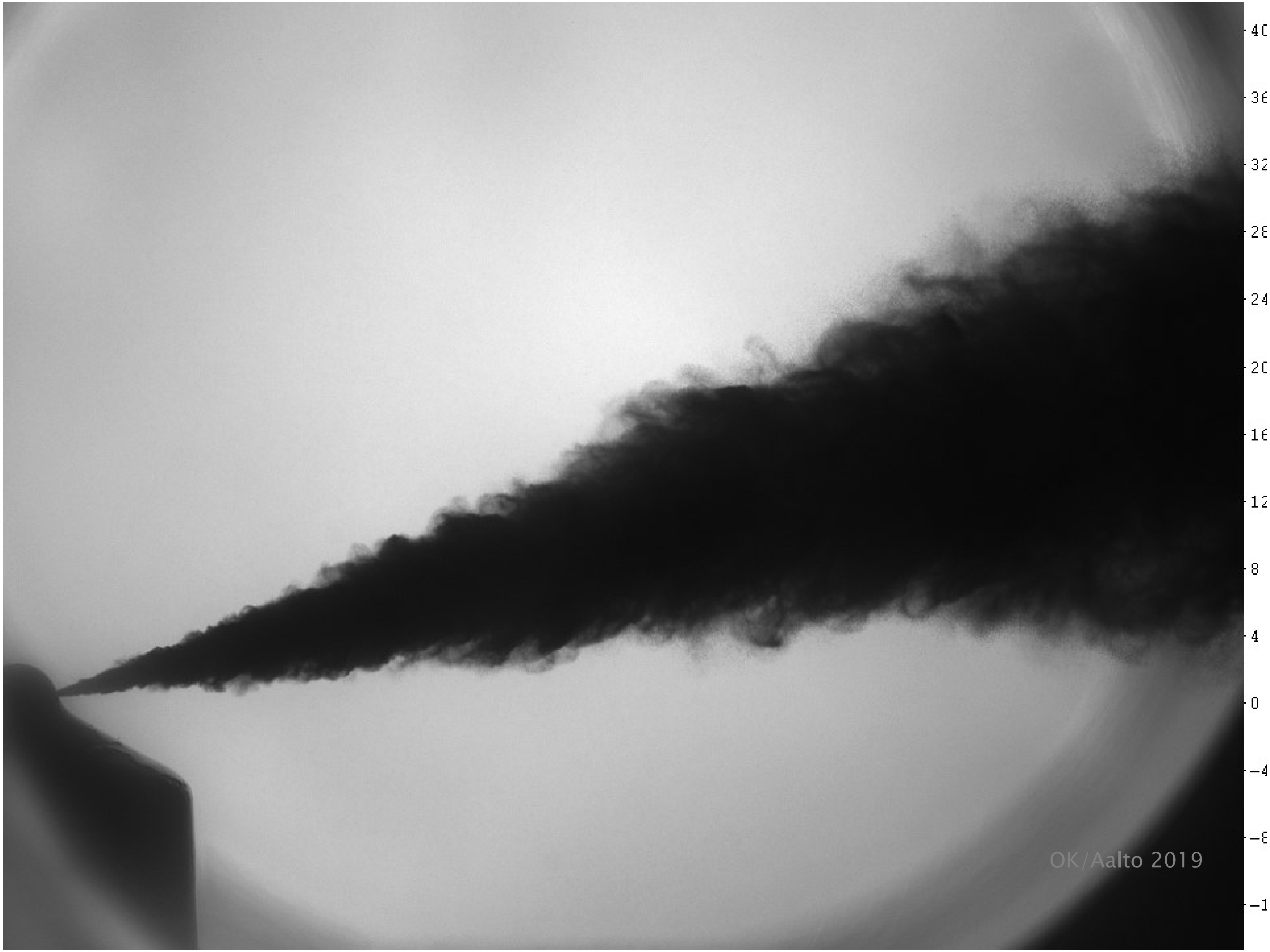
40
36
32
28
24
20
16
12
8
4
0
−4
−8
−1
OK/Aalto 2019

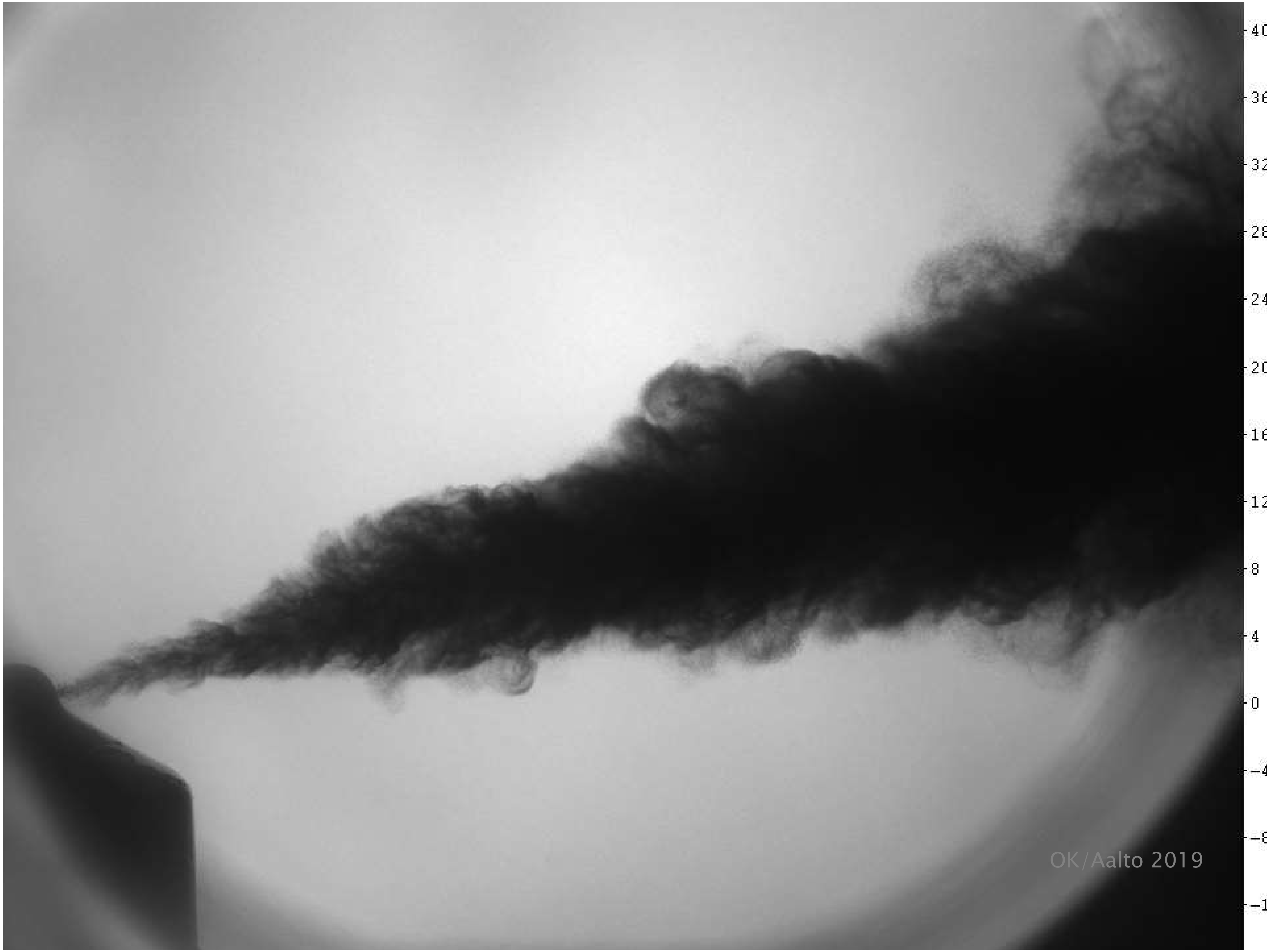

4
3
3
2
2
2
1
1
8
4
0
−4
−8
−1
OK/Aalto 2019

OK/Aalto 2019

OK/Aalto 2019

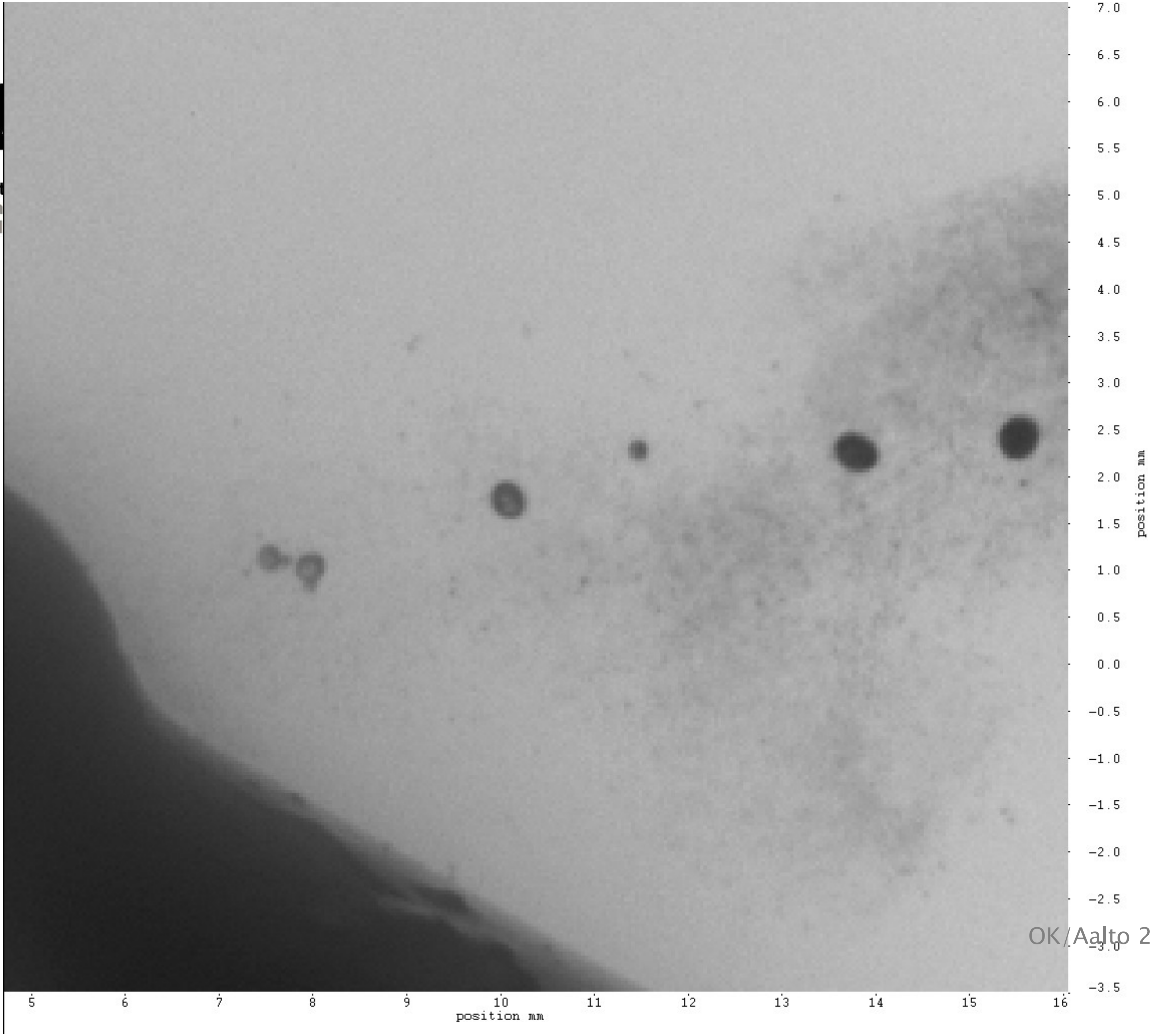

8
4
0
OK/Aalto 2019


4
3
3
2
2
2
1
1
8
4
0
−4
−8
−1
OK/Aalto 2019


40
36
32
28
24
20
16
12
8
4
0
−4
−8
−1
OK/Aalto 2019

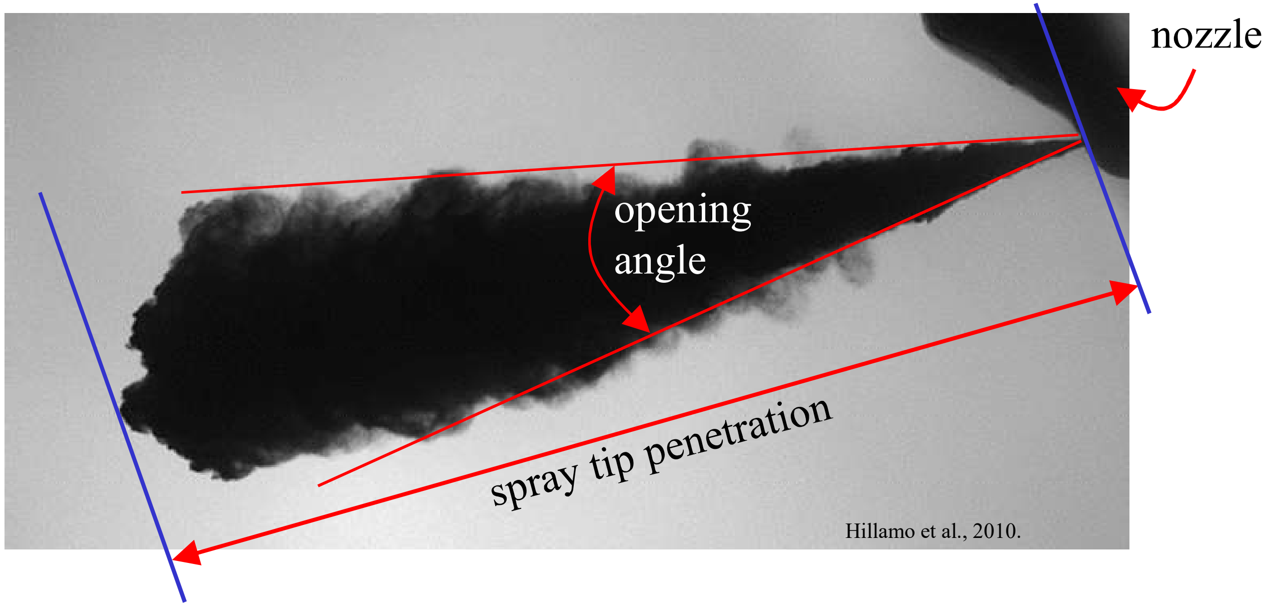

40
36
32
28
24
20
16
12
8
4
0
−4
−8
−1
OK/Aalto 2019


40
36
32
28
24
20
16
12
8
4
0
−4
−8
−1
OK/Aalto 2019


7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
position mm
5
6
7
8
9
10
11
12
13
14
15
16
position mm

OK/Aalto 2019

Spray penetration & opening angle



Hillamo et al., 2010.

Spray penetration correlations

Dent (1971)

$$S = 3.07\left(\frac{\Delta p}{\rho_g}\right)^{1/4}(tD)^{1/2}\left(\frac{294}{T_g}\right)^{1/4}$$

Hiroyasu & Kadota (1980)

$$t < t_{break}: \quad S = 0.39\left(\frac{2\Delta p}{\rho_l}\right)^{1/2} t$$

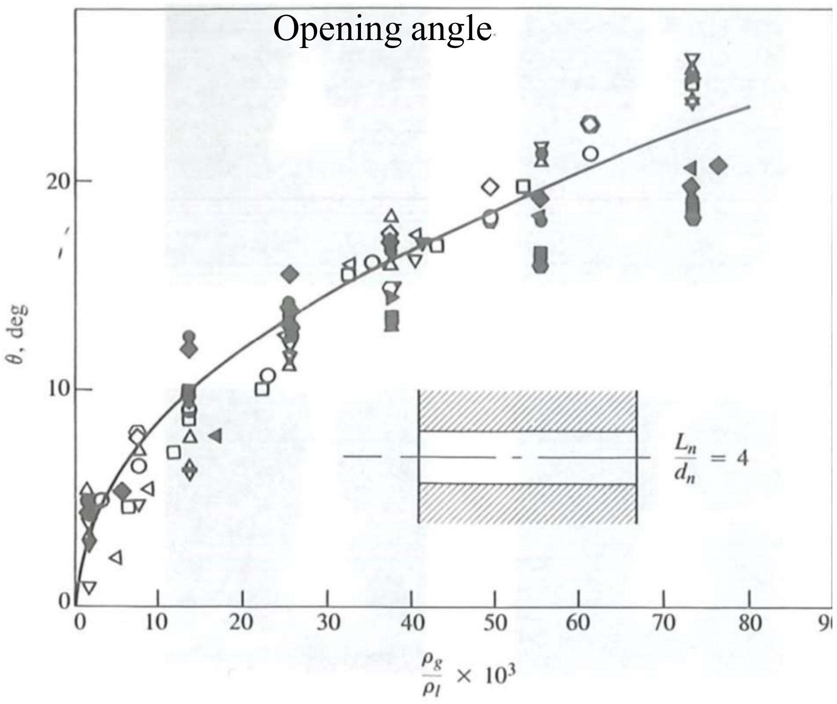
$$t > t_{break}: \quad S = 2.95\left(\frac{\Delta p}{\rho_g}\right)^{1/4}(tD)^{1/2}$$

$$t_{break} = \frac{29\rho_l D}{\left(\rho_g \Delta p\right)^{1/2}}$$

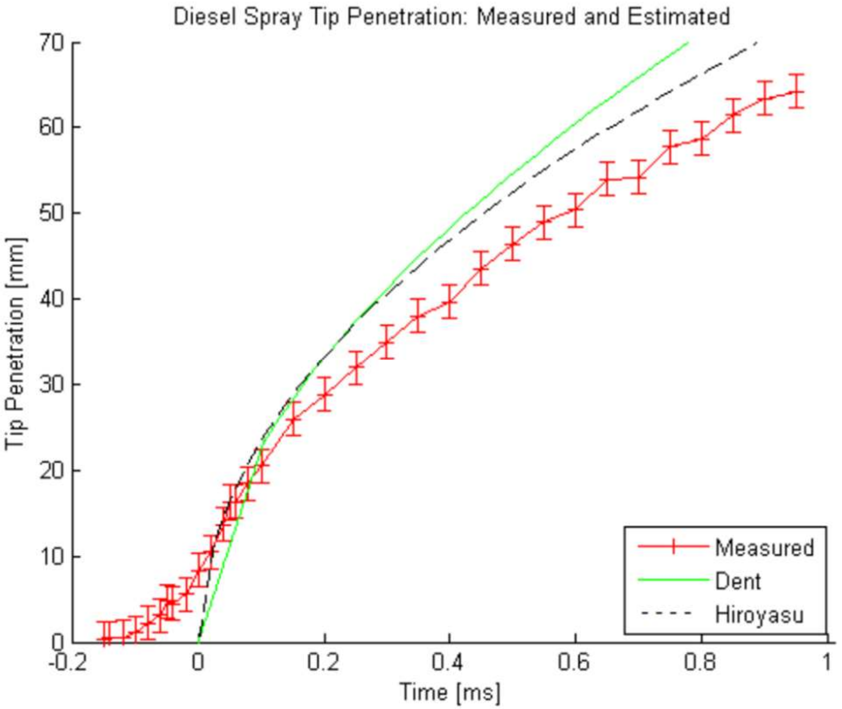
ρ_g	Gas density (kg/m3)
ρ_l	Liquid density (kg/m3)
Δp	Pressure difference (Pa)
t	Time (s)
D	Nozzle diameter (m)

Aalto University
School of Science
and Technology

Spray penetration & opening angle



Heywood, 1988



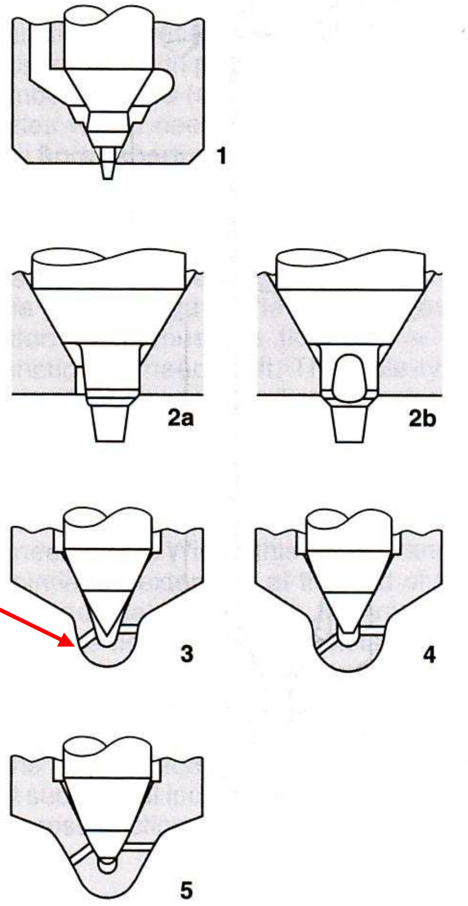
Hillamo et al., SAE 2008

Nozzle types

Furnaces:
diameter ~ 1m

Engines:
hole diameter
D ~ 0.1-0.5mm

Nozzle shapes
1 Throttling-pintle nozzle,
2 Throttling-pintle nozzle with flat-cut pintle,
2a Side view, 2b Front view,
3 Hole-type nozzle with conical blind hole,
4 Hole-type nozzle with cylindrical blind hole,
5 Sac-less (vco) nozzle.



Aalto University
School of Science
and Technology

Some liquid fuel properties

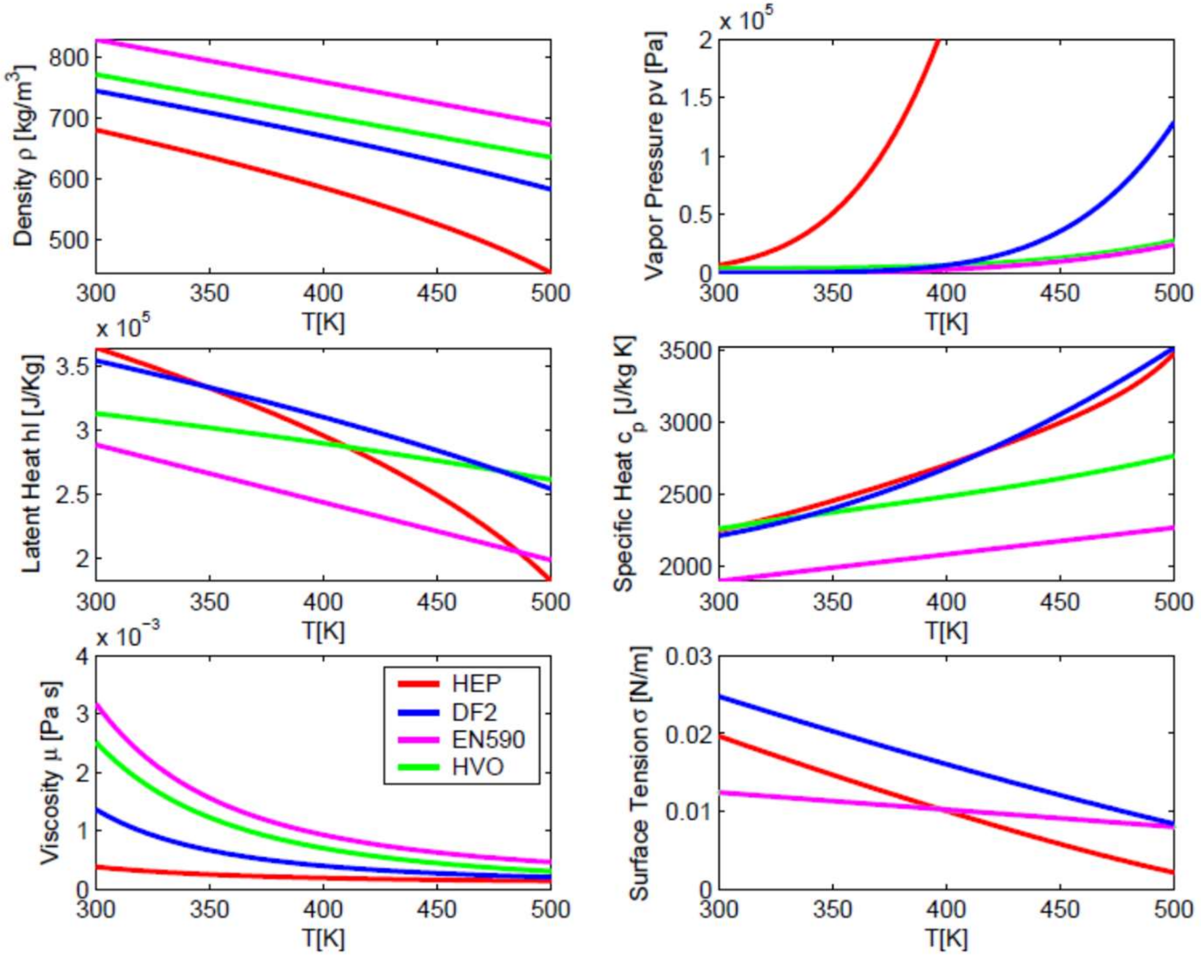
Fuel	HVO	Fischer-Tropsch diesel	FAME (RME)	EN 590
Density at +15C° (kg/m3)	775-785	770-785	885	835
Viscosity at +40C° (mm2/s)	3.0-3.5	3.2-4.5	4.5	3.5
Cetane number	80-99	73-81	51	53
Distillation range (C°)	180-320	180-360	350-370	180-360
Heating value (MJ/kg)	44	43	37.5	43

Aalto University
School of Science
and Technology

Some liquid fuel properties

Fuel	Methanol	DME
Density at +15C° (kg/m3)	722.1	612
Viscosity at +40C° (mm2/s)	0.45	0.22
Cetane number	~ 5	55
Heating value (MJ/kg)	22.7	29

Some liquid fuel properties



Y. Gong et al., SAE 2010.

HEP = Heptane ($C_7 H_{16}$)
DF2= U.S. Diesel fuel
EN590=Standard Diesel in EU
HVO=Hydrotreated vegetable oil

Aalto University
School of Engineering

Topics on Spray Velocity

Sprays are pressure driven

Cavitation

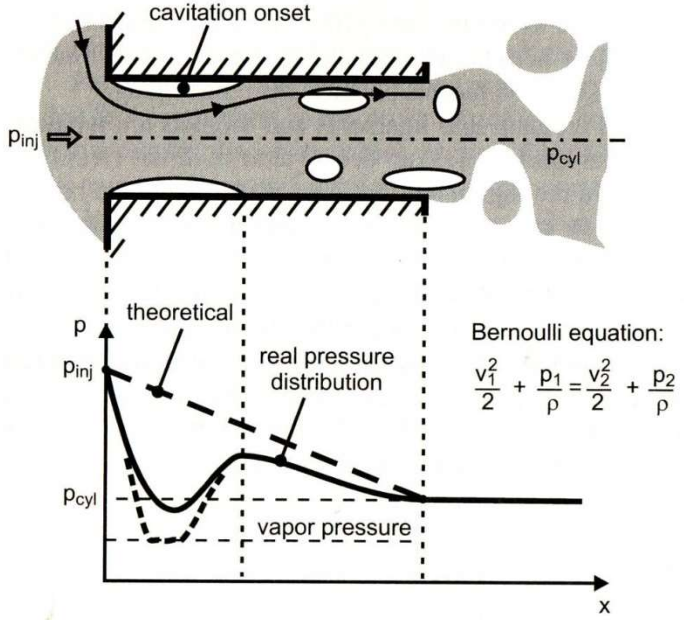


Fig. 5.6. Schematic illustration of cavitation formation inside the nozzle hole

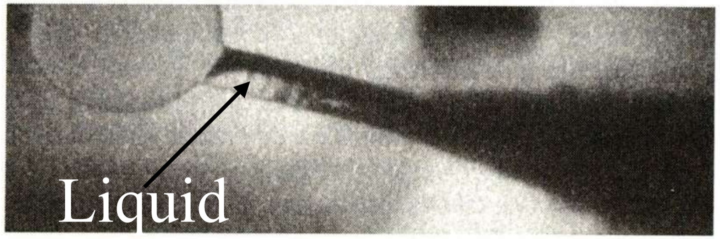
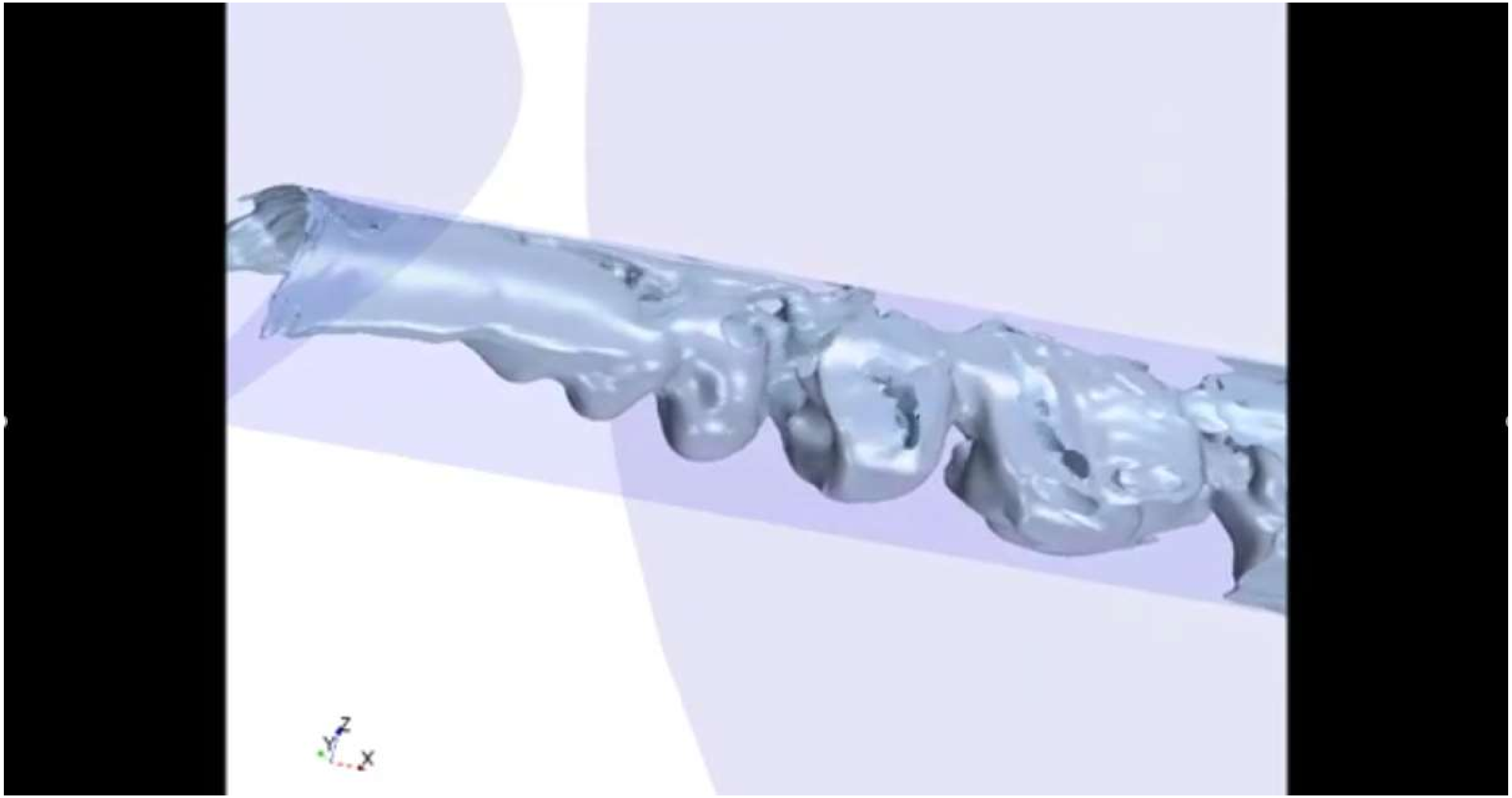


Fig. 5.7. Cavitation inside an acrylic glass diesel injection nozzle. The liquid phase is transparent, the gas phase is opaque. p_{inj} = MPa, p_{cyl} = MPa, d_{noz} = mm [15]

Cavitation



Sprays are pressure driven

Calculating the theoretical fuel exit velocity

- **Theoretical fuel exit velocity from nozzle**

$$p_1 + \frac{1}{2}\rho u_1^2 = p_2 + \frac{1}{2}\rho u_2^2 \quad \Rightarrow \quad U_{Exit} = \sqrt{\frac{2\Delta P}{\rho_f}}$$

- **Velocity in practice**

$$U_{Exit} = \underset{\nearrow}{C_v} \sqrt{\frac{2\Delta P}{\rho_f}}$$

Discharge coefficient Cd

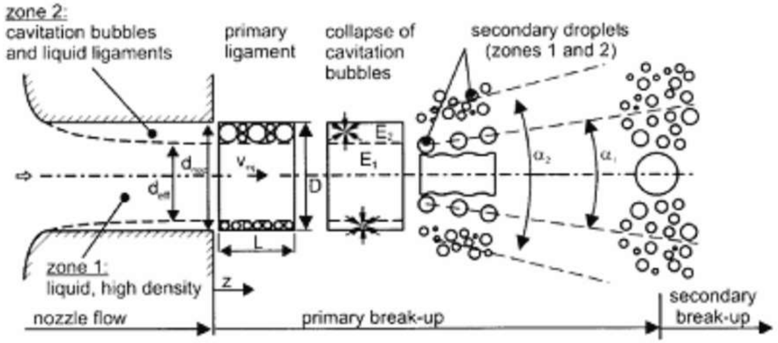
- **Discharge coefficient**

$$C_d = C_v \cdot C_a$$

C_d **used when calculating mass flow** $\dot{m} = C_d \, A \rho_f \sqrt{\dfrac{2\,\Delta P}{\rho_f}}$

C_v **'velocity coefficient', used when calculating real injection velocity**

C_a **'area contraction coefficient', used when calculating effective nozzle hole diameter**

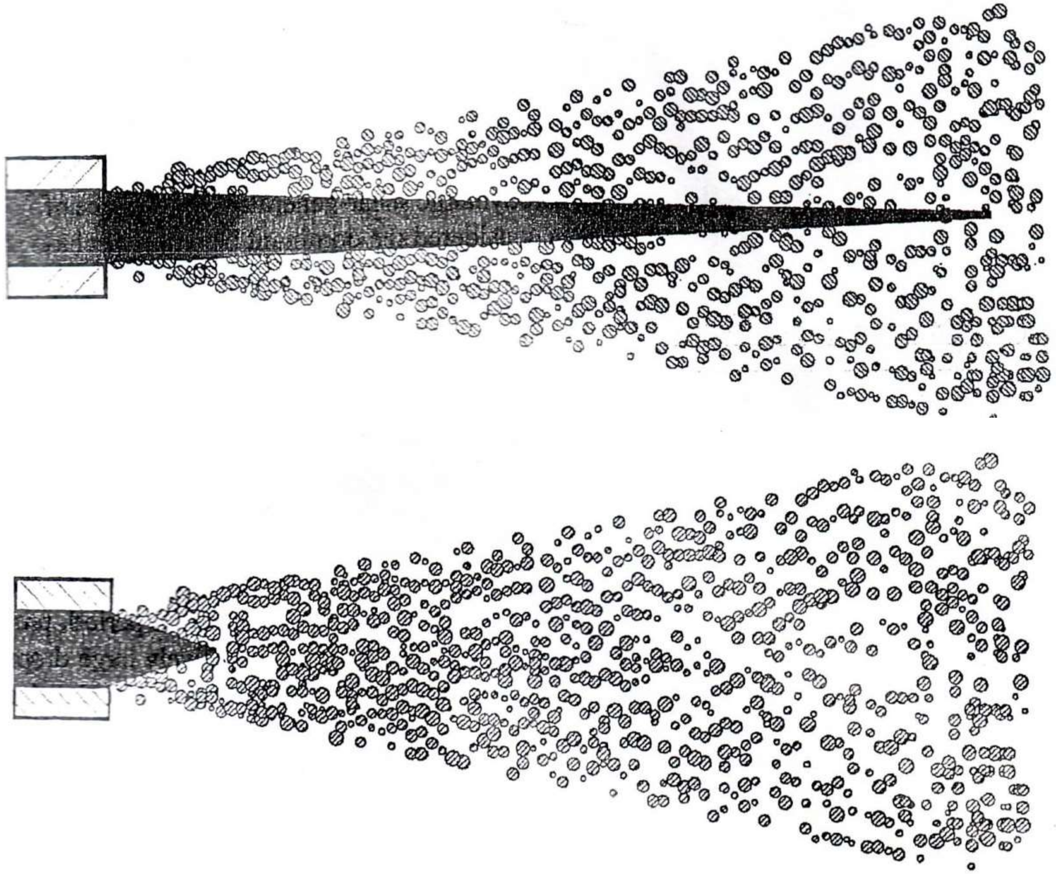


Additional material

Intact Liquid Core

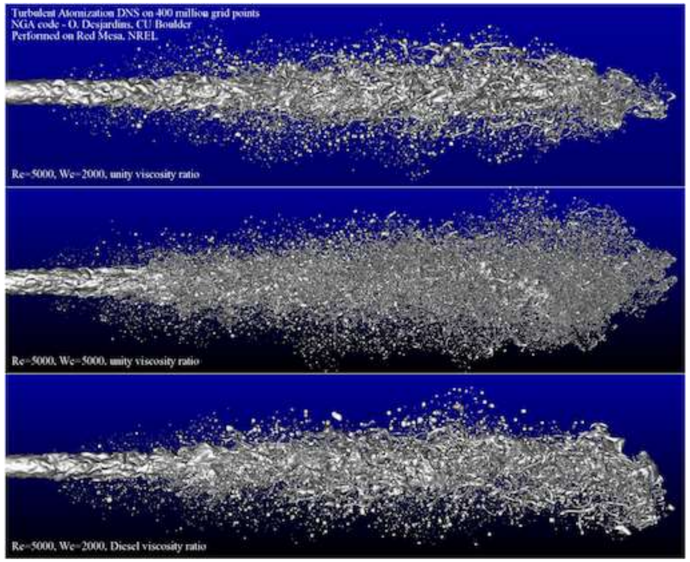
Aalto University
School of Engineering

Additional material
Intact liquid core ?



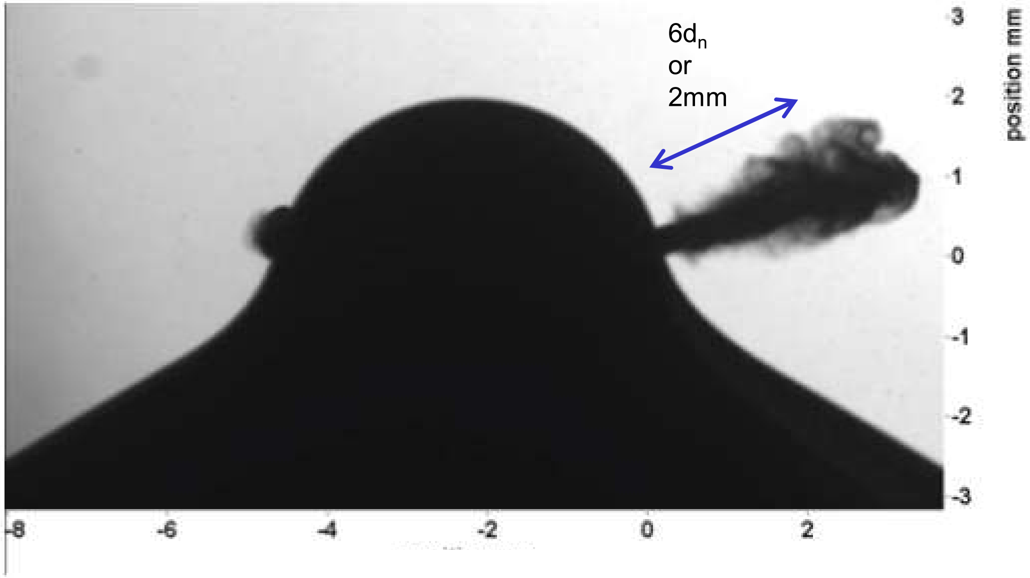
Smallwood, G., and Gulder, O., Atom & sprays, 2000.

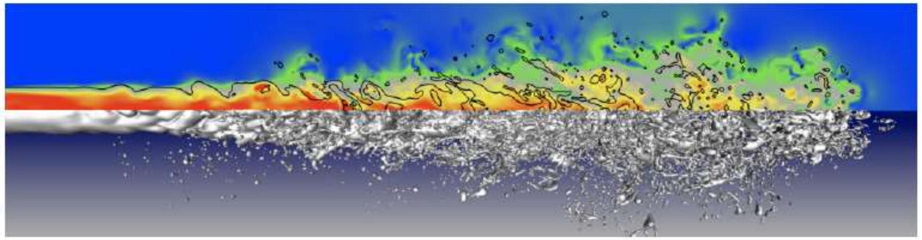
Additional material
Intact liquid core ?

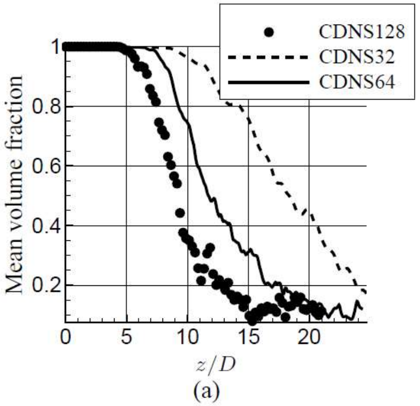


Desjardins et al, 2010

Hillamo et al. 2010, Atom. Sprays





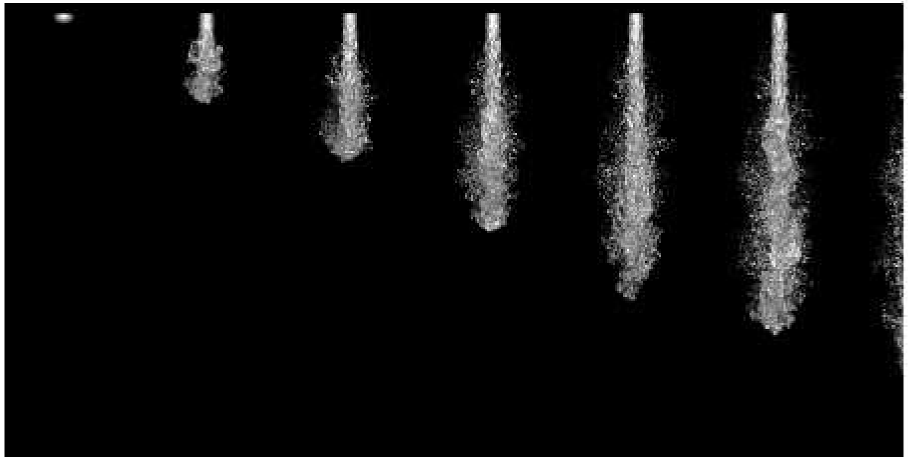


Chesnel et al. 2011

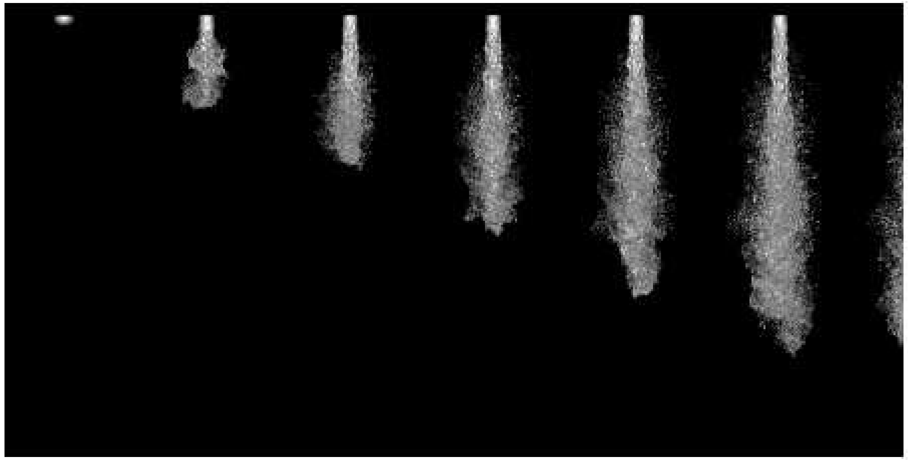
OK/Aalto 2019

Reynolds number compared to real high-pressure sprays.
DNS done with U_{exit}~100m/s

Additional material
Intact liquid core ?



(a) Re = 5000, We = 2000



(b) Re = 5000, We = 5000

Desjardins et al, 2013, Atom. Sprays

- **Turbulence inside the nozzle has bigger effect than previously thought of.**
- **Taken the experimental and numerical evidence, it seems very likely that in modern high-pressure injection systems, the intact liquid core is either very short or even non-existent.**

Aalto University
School of Engineering

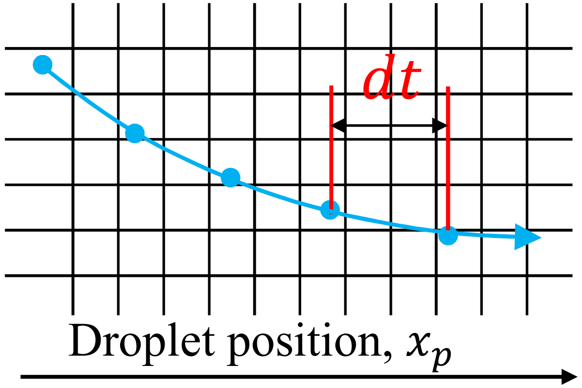
Spray Equations

Lagrangian spray modeling

- **Discrete computational points are tracked**

- **Spray equations (Ordinary differential equation (ODE)):**

$$\frac{dx_p}{dt} = u_p$$



  - **Parcel position**

$$\rightarrow \quad x_{p,2} = x_{p,1} + u_p\, dt \qquad (1)$$

  - **Eq. (1) can be used to calculate the particle position at each time instant.**

Lagrangian spray modeling

- **Parcel equation of motion** $F = ma$

$$ma = F_{drag} = \frac{1}{2}\rho_g C_d A U^2$$

$$\frac{1}{6}\rho_p \pi d^3 \frac{du_p}{dt} = \frac{1}{2}\left(u_g - u_p\right)\left|u_g - u_p\right|\rho_g C_d \frac{\pi d^2}{4}$$

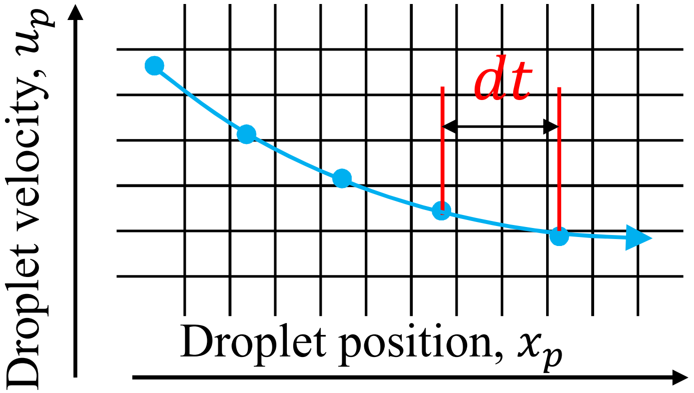
$$\rightarrow \qquad \frac{du_p}{dt} = \frac{C_d}{\tau_p}\frac{Re_p}{24}\left(u_g - u_p\right)$$

$$\tau_p = \frac{\rho_l d^2}{18\,\rho_g \nu_g}$$

Lagrangian spray modeling

or

$$\boxed{u_{p,2} = u_{p,1} + \frac{C_d}{\tau_p}\frac{Re_p}{24}\left(u_g - u_{p,1}\right)\mathrm{dt}} \qquad (2)$$



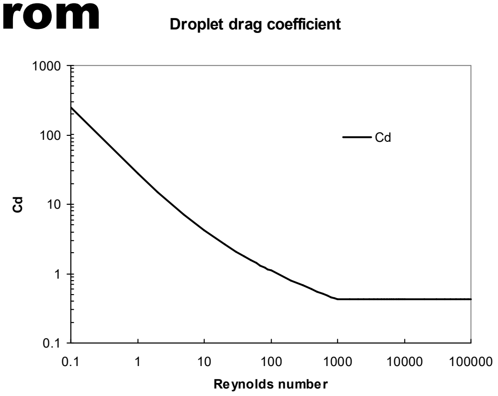
Eq. (2) can be used to update the particle velocity for each time instant, and then use Eq. (1) to update the position.

Aalto University
School of Engineering

Droplet Drag

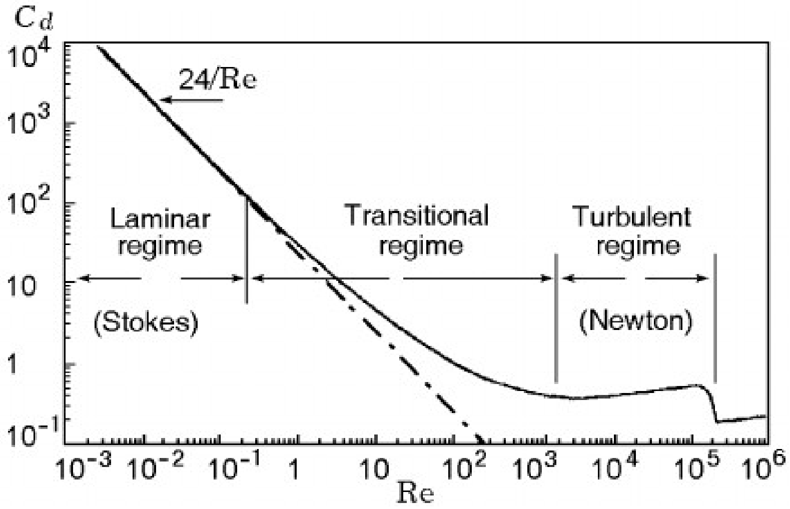
- **The resistance a droplet/particle encounters, is due to shear and form drag**
- **Droplet drag coefficient Cd is calculated from**

$$C_D = \begin{cases} \dfrac{24}{\mathrm{Re}_p}\left(1+\dfrac{1}{6}\mathrm{Re}_p^{\,2/3}\right) & \mathrm{Re}_p < \quad 1000 \\ 0.424 & \mathrm{Re}_p \geq \quad 1000 \end{cases}$$



- **Droplet Reynolds number is**

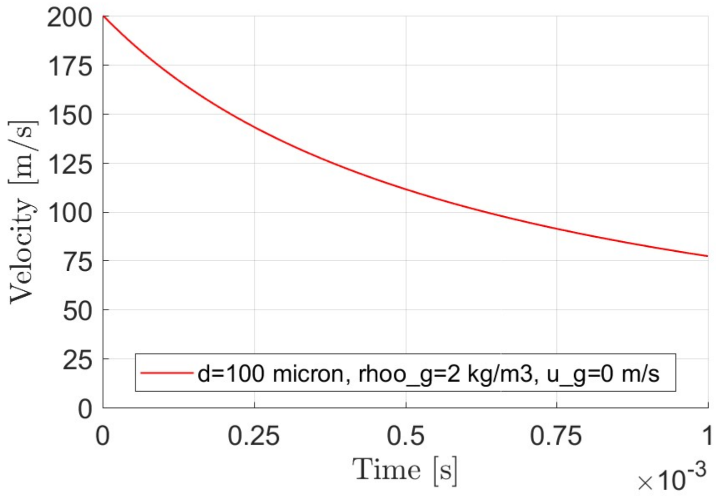
$$Re_p = \frac{\rho_g |u_g - u_p| d}{\mu_g} = \frac{|u_g - u_p| d}{\nu_g}$$

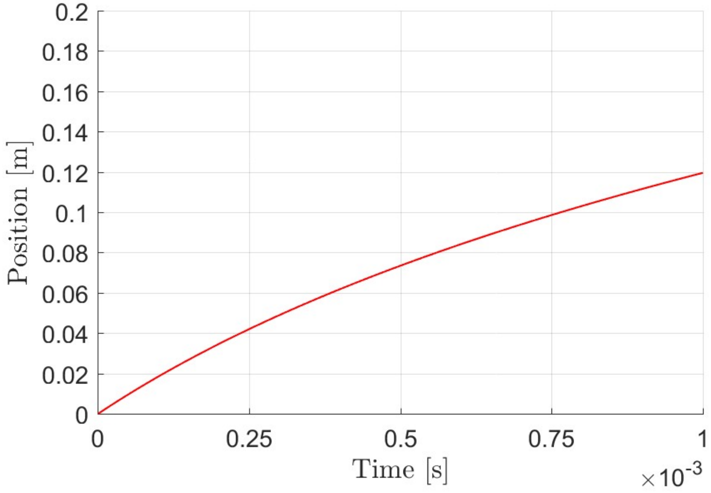


Boiko et al., 2013

Aalto University
School of Engineering

Lagrangian spray modeling (Matlab)





Constant Cd=0.424 and constant gas phase velocity (0 m/s)

Droplet size is constant d=100micro-m

Gas density is 2 kg/m3 and liquid density is 800kg/m3.

Constant gas phase velocity may be a strong assumption.

Aalto University
School of Engineering

Dispersed and continuous phase coupling

Aalto University
School of Engineering

Stokes number

- **Stokes number** $St = \dfrac{\tau_p}{\tau_f}$
- **Ratio of the characteristic particle time scale (or the momentum relaxation time scale)**

$$\tau_p = \frac{\rho_l d^2}{18\rho_g \nu_g}$$

- **To the characteristic flow time scale**

$$\tau_f = \frac{D}{U_0}$$

d droplet diameter
D nozzle diameter
U_0 flow velocity

Stokes number & Turbulent dispersion

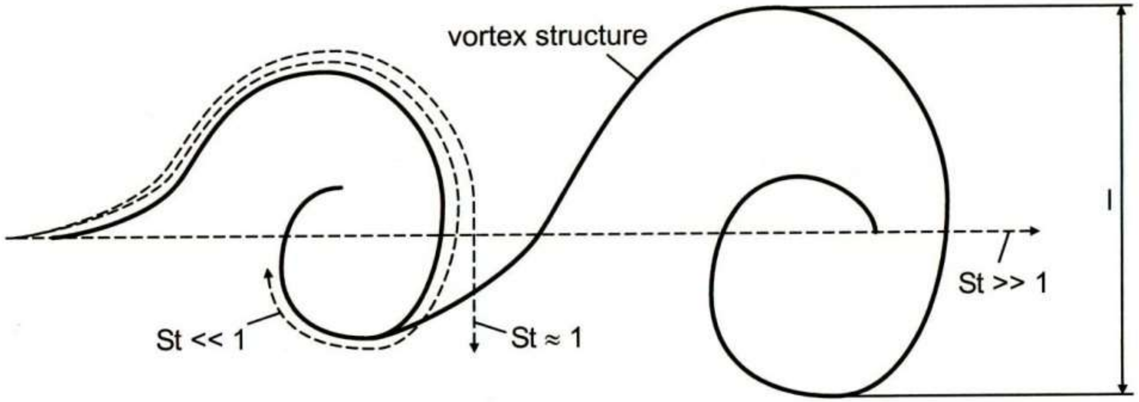


Figure by G. Stiesch

Coupling regimes

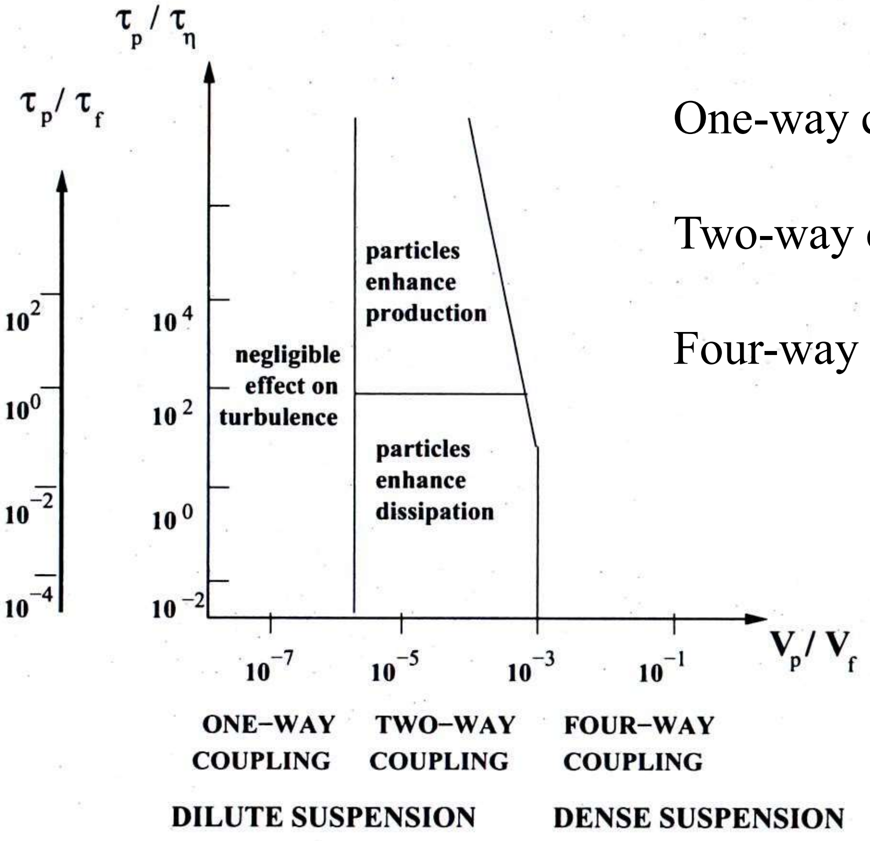


Figure by Elghobashi, 1994.

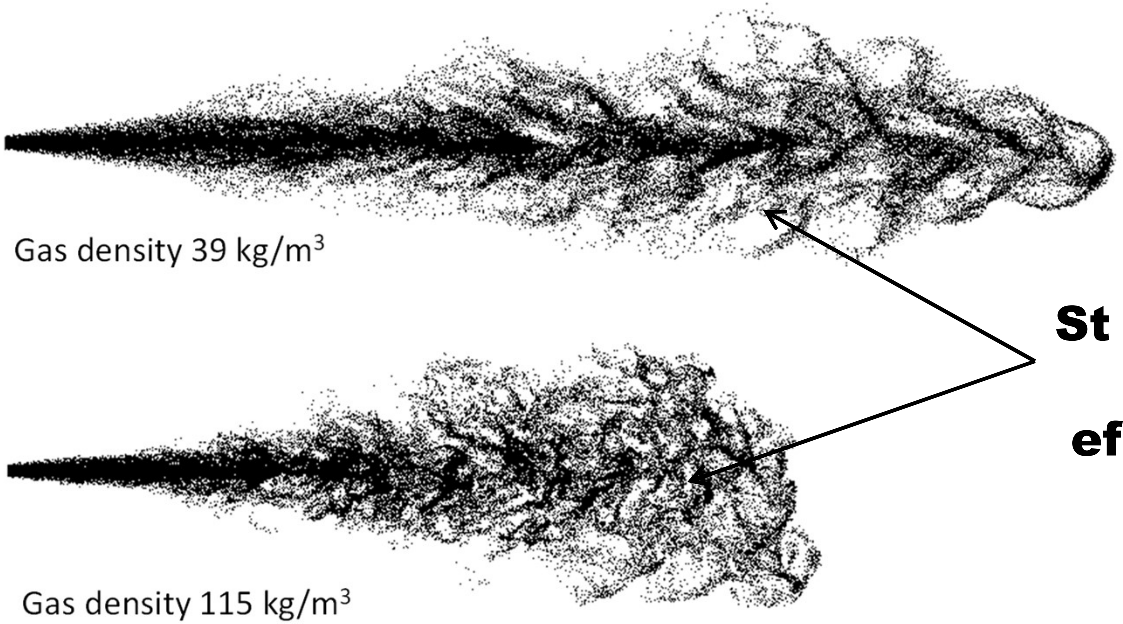
One-way coupling → Gas phase only interacts with particles

Two-way coupling → Gas phase and particles both interact with each other

Four-way coupling → Additionally, particles interact with each other

Stokes number

- **If $St \ll 1$ Particles will have plenty of time to adjust to changes in flow field velocity. Particle and fluid velocities nearly equal.**
- **If $\mathrm{St} \gg 1$ Particle velocity will be little affected by flow velocity.**



St number

effect $\mathrm{St} \sim \frac{1}{\rho_g}$

Kaario, 2012

Aalto University
School of Engineering

Source term in N-S Eqs.

- **The flow field ’sees’ the droplets via source terms in the N-S eqs. In the 2-way coupling regime, the source term *M***

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(p\delta_{ij} - \tau_{ij}\right) + \underline{M_d}$$

$$\underline{M_d} = \frac{1}{2}\rho_g C_d A \left|u_g - u_p\right|\left(u_g - u_p\right)$$

Aalto University
School of Engineering

Group Work

Discussion in pairs for about 10 min:

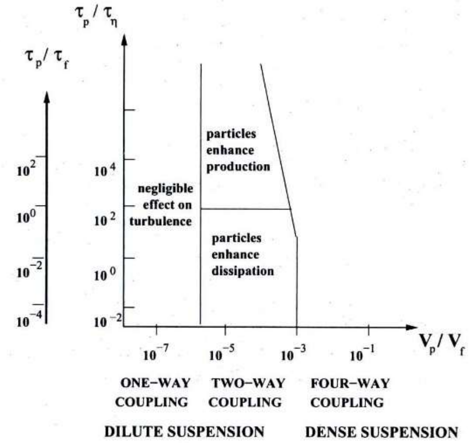
1. **What information is needed to calculate droplet/particle Stokes number ?**
2. **What information is not needed ?**
3. **What does a particle St number mean ?**
4. **If you would be given a task to design a spray configuration that would give a homogeneous mixture (of droplets and air / vapor and air), what kind of a St number would you aim for and why ?**

Aalto University
School of Engineering

What is dense ?

Aalto University
School of Engineering

What is dense ?



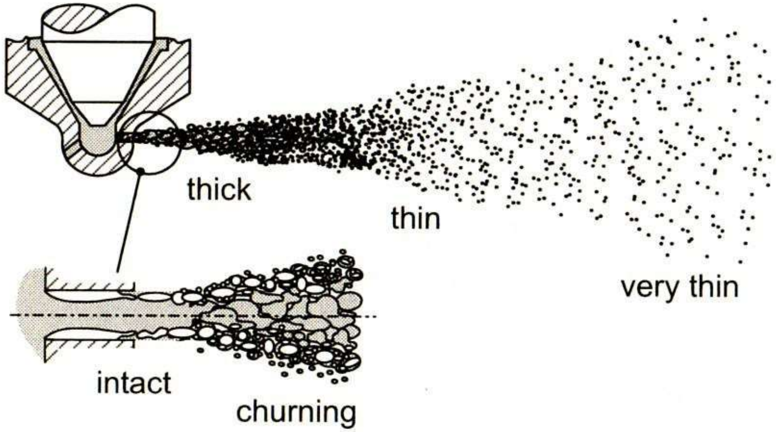
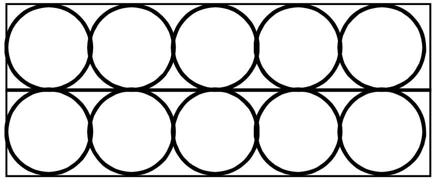
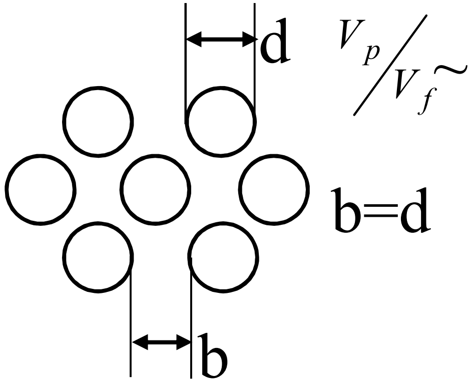


Fig. 5.2. Schematic illustration of different flow regimes

$V_p / V_f \sim 52\%$

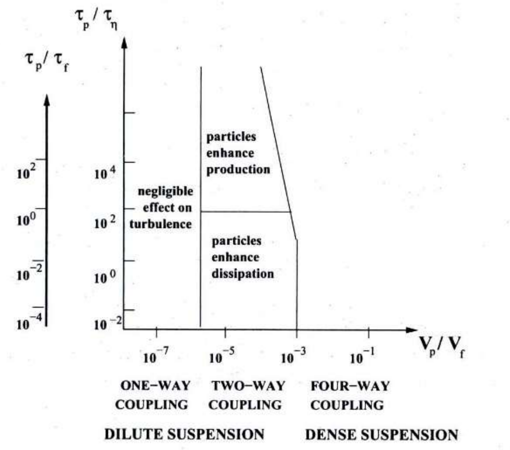


$V_p / V_f \sim 8\%$

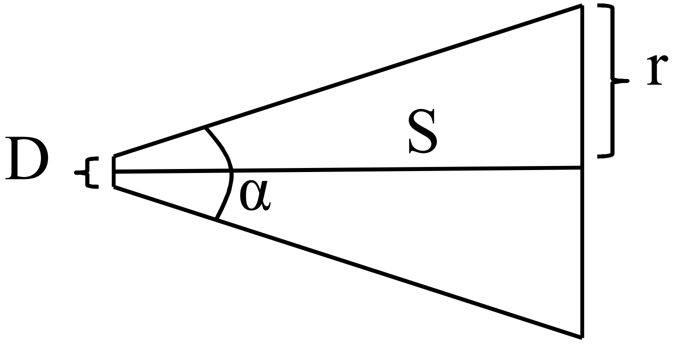


Aalto University
School of Engineering

What is dense ?



- **Typically assumed dense if $V_p/V_f > 10^{-3}$**
- **Assuming spray mass is divided homogenously in a cone –like volume**
- **From the schematic spray opening angle picture, the area ratio:**



$$\tan\frac{\alpha}{2} = \frac{r}{S}$$

$$r = \tan\frac{\alpha}{2} S$$

$$\left(\frac{D/2}{r}\right)^2 > \frac{1}{1000}$$

$$\left(\frac{D/2}{\tan(\alpha/2)S}\right)^2 > \frac{1}{1000}$$

$S < 90D$ assuming $\alpha = 20^\circ$

If D=90μm, S<8.1mm

D nozzle diameter
S spray penetration
α spray opening angle

Aalto University
School of Engineering

Additional material

Nozzle Hole Size vs Average Fuel Concentration

- **Average concentration** $c_{ave} = {}^{m_s}\!/\!_{V_s}$
- **Assumed constant injection rate** $m_s \sim t\,D^2$
- **The spray volume evolves as a cone** $V = \frac{1}{3} A\, S$
- **Bottom area of the cone** $A(t) \sim \left(\tan\left(\frac{\alpha}{2}\right) S \right)^2$
- **Spray penetration assumes well known correlation** $S(t) \sim (t\,D)^{1/2}$
- **We obtain**

$$c_{ave} \sim \frac{t\,D^2}{\frac{1}{3}\pi \left(\tan\left(\frac{\alpha}{2}\right) S \right)^2 S} \sim \left(\frac{D}{t} \right)^{\frac{1}{2}}$$

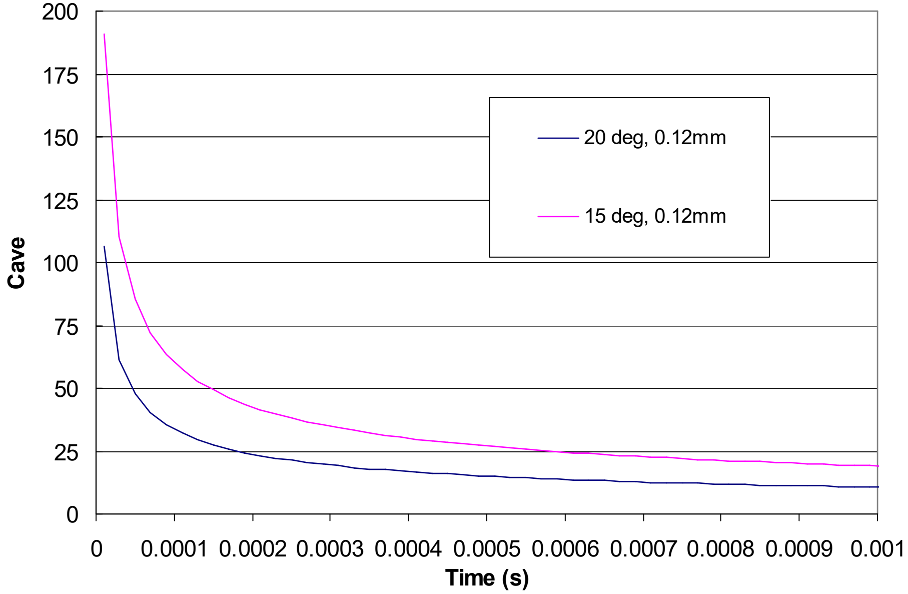
$$\uparrow$$

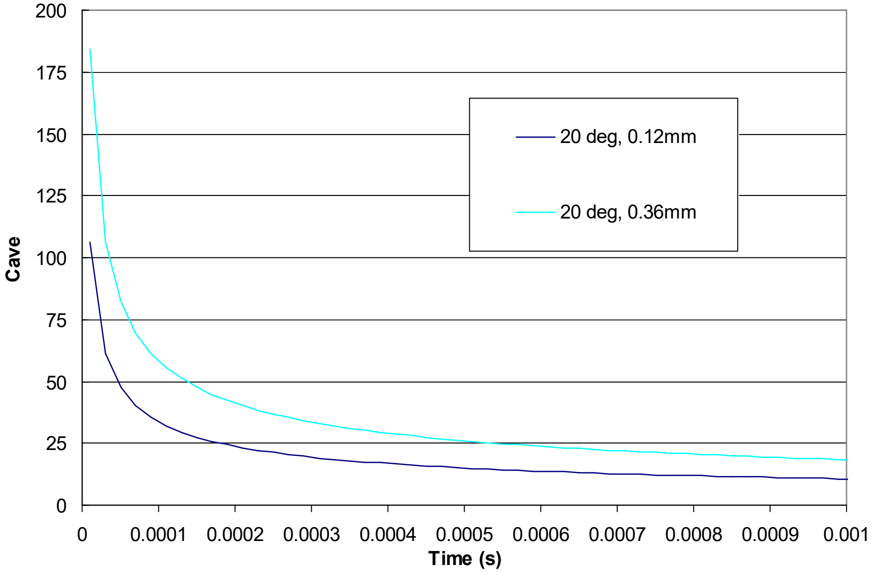
Vuorinen, V., thesis 2010

Additional material

Nozzle Hole Size vs Average Fuel Concentration

Calculated result from the previous slide final result





D=0.12mm, α=15° or 20°

D=0.12mm or 0.36mm, α=20°

Turbulence in flow

- Turbulent flow consists of vortices (eddies) of different size
- The biggest vortices are of the size of the flow geometry
- The eddies are breaking up into smaller eddies. At the same time kinetic energy is transported from the bigger eddies to smaller ones
- At the smallest turbulent scale (Kolmogorov scale) kinetic energy is dissipated into heat
- Fluctuations
- Convection

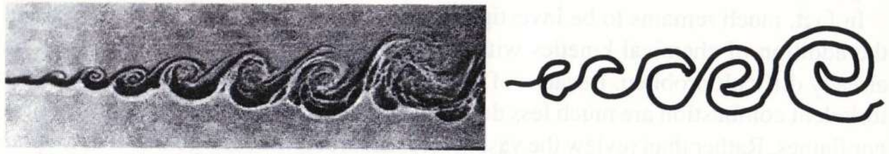
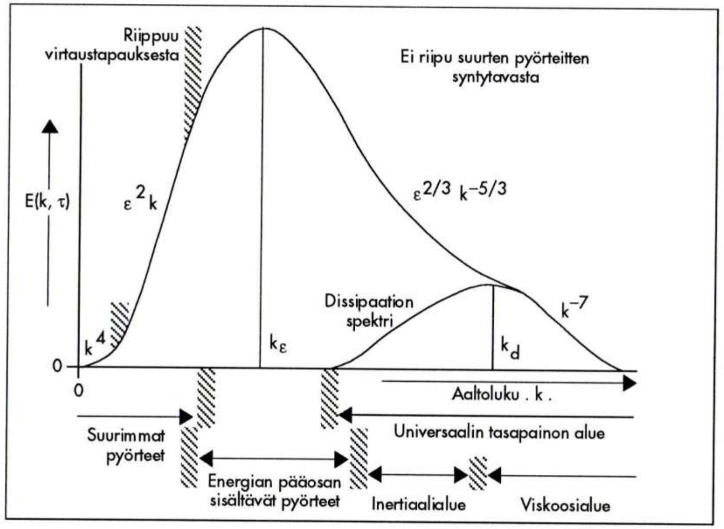


Fig. 12.1. Formation of a turbulent shear layer (Roshko 1975)

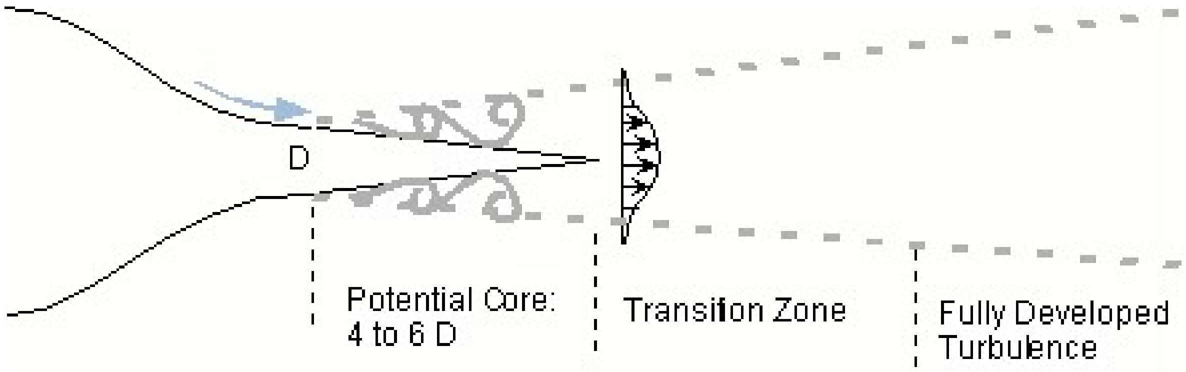


Kuva 12.4 Turbulenssin kineettisen energian jakauma aaltoluvun k funktiona. Aaltoluku on pyörteen halkaisijan käänteisluku.

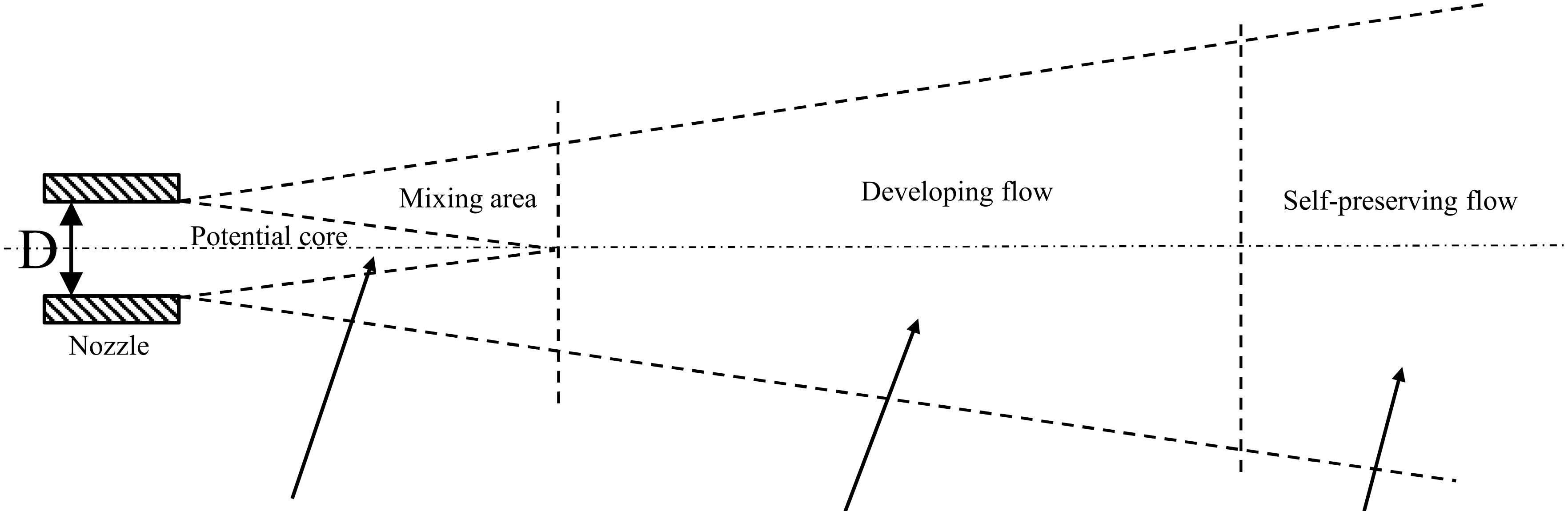
Turbulence in flow

- Turbulence ←→ Shear
- Turbulence is characterized by the following:
  - Three dimensional
  - Unsteady
  - Random
  - Strong vorticity
  - Dissipative
  - Strongly diffusive

Turbulence = increased mixing !



Jet development



Potential core

~ 4-6D

Developing flow

~15-20D

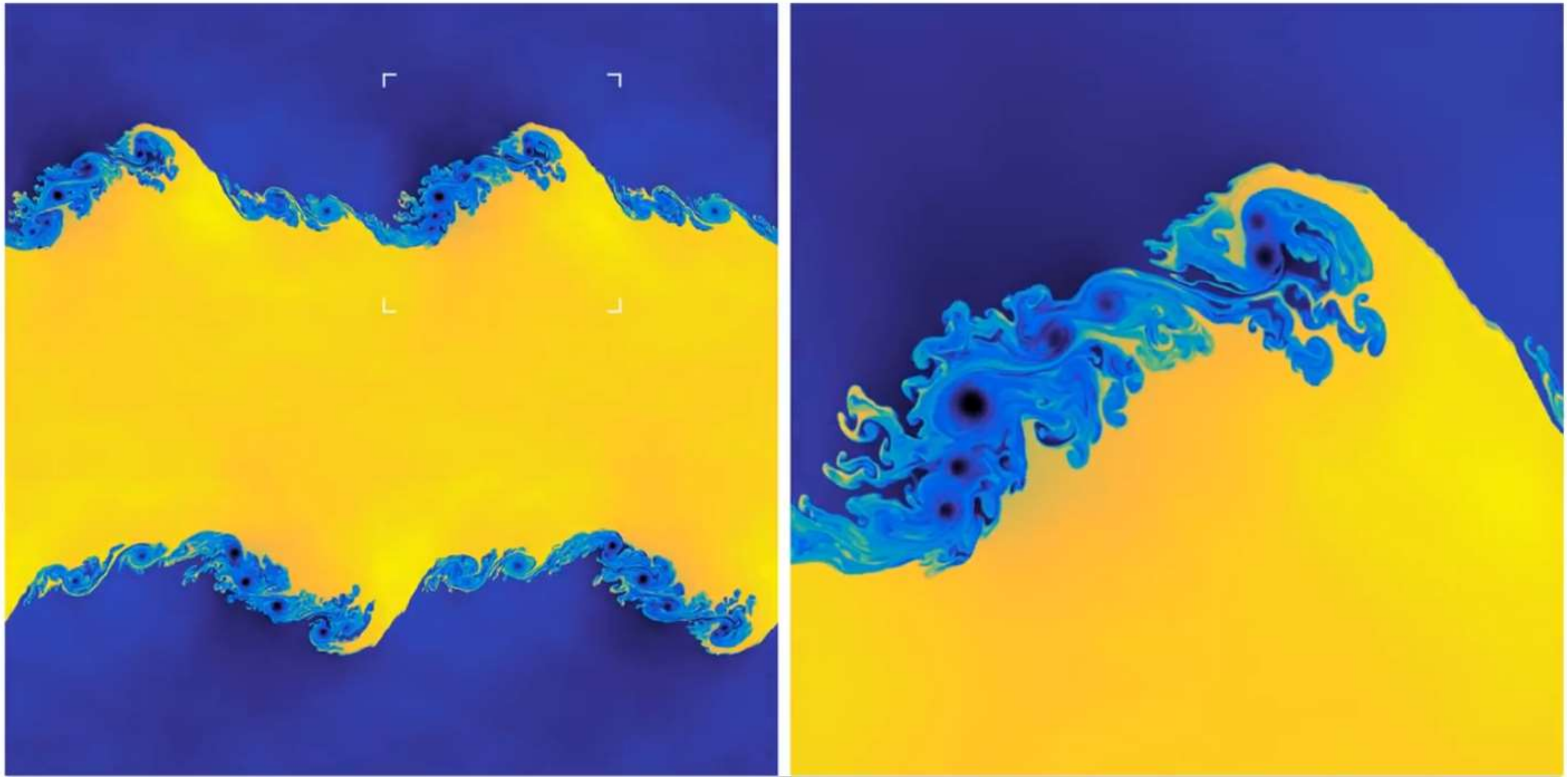
Self-preserving flow

Jet development: Kelvin Helmholtz Instability and Spray Mixing

- **Spray and jet turbulence is initiated by a Kelvin Helmholtz instability at the near nozzle region**
- **Growth rate of KH instability is related to the velocity difference of the fluids and to the wavelength.**

Aalto University
School of Engineering

KH Instability



KH Instability and Mixing

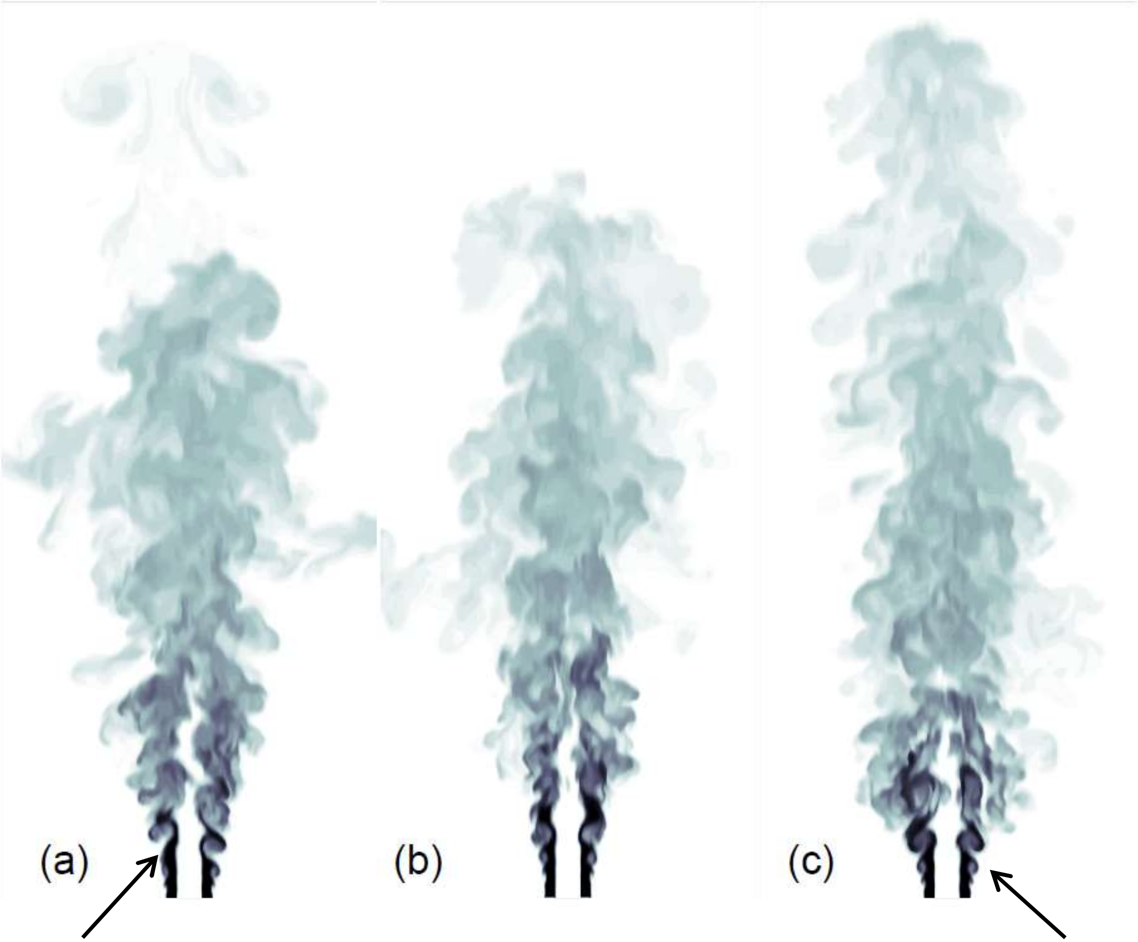


Figure V. Vuorinen

Aalto University
School of Engineering

Additional Reading

- Crowe, C.T., Schwarzkof, J.D., Sommerfeld, M., and Tsuji, Y., Multiphase Flows with Droplets and Particles, 2nd edition, CRC Press, ISBN 978-1-4398-4050-4, 2012.
- Wehrfritz Armin, Kaario Ossi, Vuorinen Ville, and Bart Somers, Large Eddy Simulation of n-dodecane spray flames using flamelet generated manifolds, Combustion and Flame, Vol. 167, pp. 113-131, 2016.
- Vuorinen, V., Hillamo, H., Kaario, O., Larmi, M., and Fuchs, L., Large Eddy Simulation of droplet stokes number effects on turbulent spray shape, Atomization and Sprays, vol. 20, no. 2, pp. 93–114, 2010.
- Kaario Ossi, Vuorinen Ville, Hulkkonen Tuomo, Keskinen Karri, Nuutinen Mika, Larmi Martti, and Tanner Franz, Large Eddy Simulation of High Gas Density Effects in Fuel Sprays, Atomization and Sprays, Vol. 23, Issue 4, pp. 297-325, 2013.
- Eaton, J. and Fessler, J., Preferential concentration of particles by turbulence, Int. J. Multiphase Flow, vol. 20, pp. 169–209, 1994.
- Elghobashi, S., Particle-laden turbulent flows: Direct simulation and closure models, Appl. Sci. Res., vol. 52, pp. 309–329, 1994.
- G. J. Smallwood and Ö. L. Gulder, Views on the structure of transient diesel sprays, Atomization and sprays, Vol. 10, pp.-355-386, 2000.
- J. Naber and D. L. Siebers, Effects of gas density and vaporization on penetration and dispersion of diesel sprays, SAE paper 960034, 1996.
- D.L. Siebers, Scaling liquid-phase fuel penetration in diesel sprays based on mixing-limited vaporization, SAE paper 1999-01-0528, 1999.
- Harri Hillamo, Teemu Sarjovaara, Ossi Kaario, Ville Vuorinen, and Martti Larmi, Diesel spray visualization and shockwaves, Atomization and Sprays, Vol. 20, Issue 3, pp. 177-189, 2010.