An experimental and theoretical study of engine sprays

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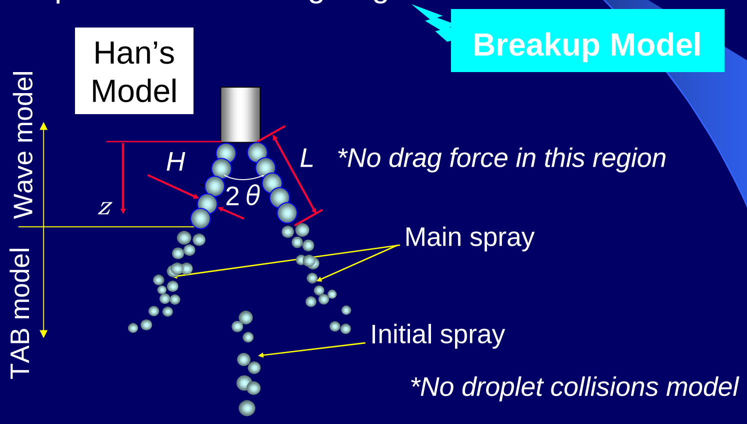
CONTENTS

- Analysis of different type injectors
  + Swirl-type injector (importance of I.C.)
  + Slit-type injector (meshing, evaluation by ILIDS, wall impinge, cross flow, cavitation)
  + Hole-type injector (ILIDS measurement)

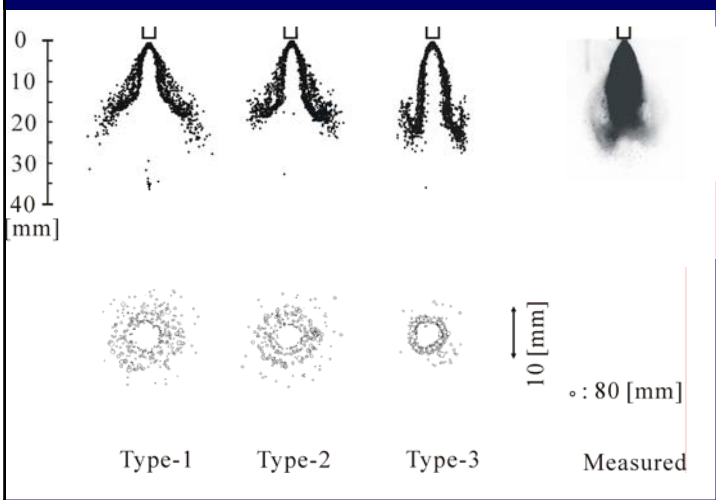
Initial/Boundary conditions for swirl-type injector

Gas: Solved in Eulerian

Liquid: Solved in Lagrangian



Results under pressurized field

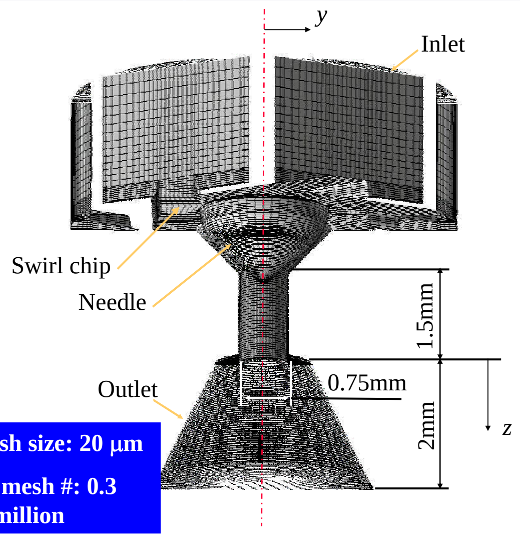


Ambient pressure P_a=0.5[MPa]

Time after injection t_{inj}=1.5[ms]

Now, this model is implemented into

VECTIS code



Min. mesh size: 20 μm

Total mesh #: 0.3 million

Calculation mesh geometry in swirl nozzle

Calculation conditions

- **Fluids**: **n-heptane, air**
- **B.C.**

	Pressure (MPa)	Turbulence length scale (mm)	Turbulence intensity	Volume faction of n-heptane
Inlet	0.5, 3	0.8	3.7%×U	1
Outlet	0.1	1	5.0%×U	0

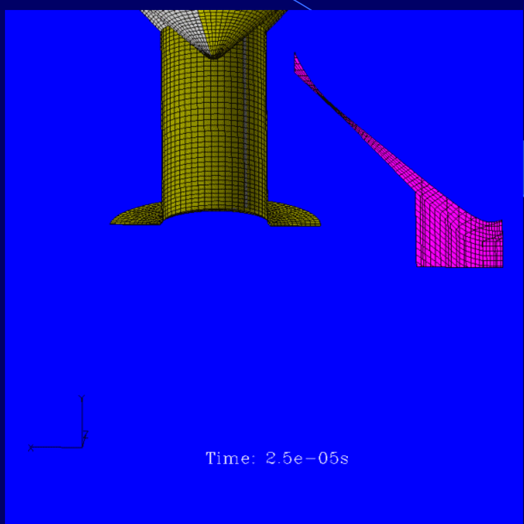
- **I.C.** **Upstream of Needle Sheet: Fuel Only**
  Downstream of Needle Sheet: Air Only
- **Temporal change of needle lift was assumed**

Comparison of conditions

Injection pressure	0.5MPa		3MPa	
VOF or Empirical Eq.	VOF	Empirical Eqs.	VOF	Empirical Eqs.
Injection velocity	19m/s	30m/s	61m/s	59.9m/s
Injection rate	5.1cm^3/s	5.02cm^3/s	12.0cm^3/s	12.2cm^3/s
Cone angle	54~62deg	55deg	53~59deg	55deg
Length of liquid sheet	1.8mm	9.2mm	1.5mm	5.1mm
Thickness of liquid sheet	0.120mm	0.087mm	0.106mm	0.10mm

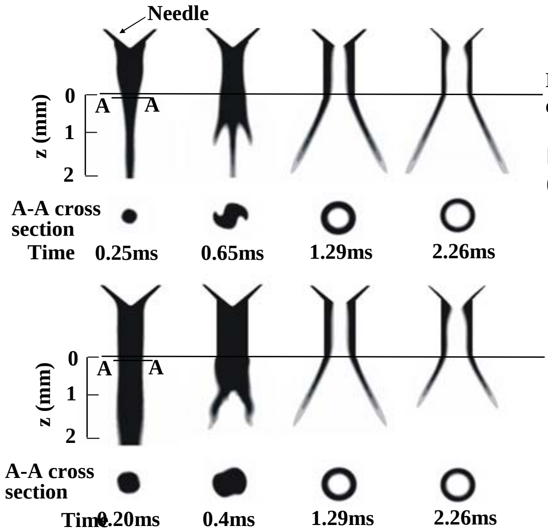
7

Animation (Inj. 0.5 MPa)



8

Results on vertical section



Injection pressure: 0.5MPa

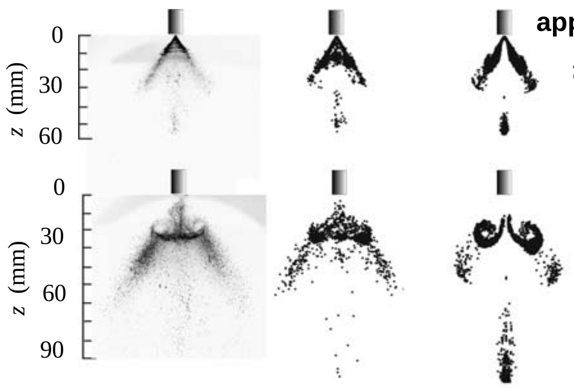
Injection pressure: 3MPa

9

Comparison on vertical section

(P_{inj}: 0.5MPa)

Time after spray appeared

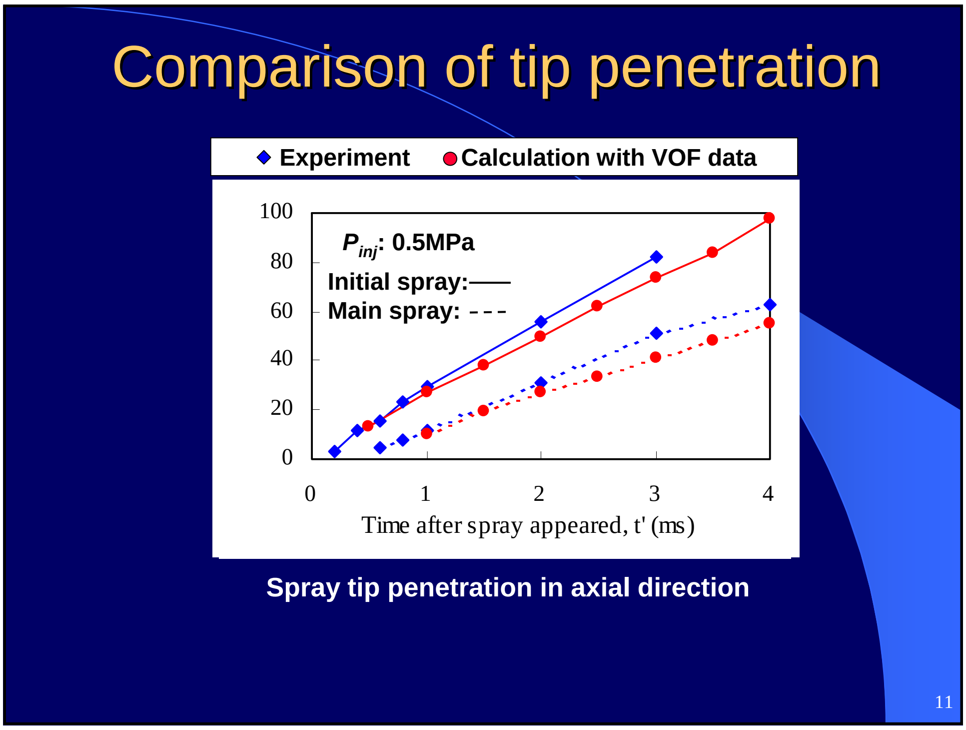


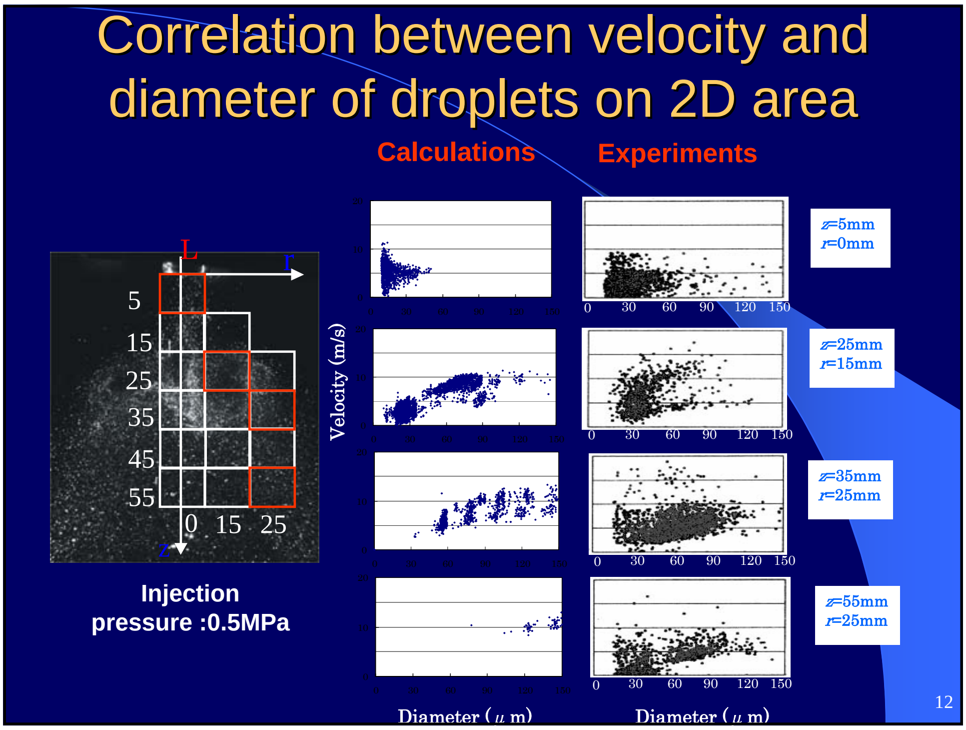
Measured tomogram

Calculation using VOF data

Calculation using empirical Eq.

10


Comparison of tip penetration
Experiment
Calculation with VOF data
P_{inj}: 0.5MPa
Initial spray:——
Main spray: - - -
100
80
60
40
20
0
0
1
2
3
4
Time after spray appeared, t' (ms)
Spray tip penetration in axial direction
11


Correlation between velocity and diameter of droplets on 2D area
Calculations
Experiments
L
r
5
15
25
35
45
55
0 15 25
z
Injection pressure :0.5MPa
Velocity (m/s)
z=5mm r=0mm
z=25mm r=15mm
z=35mm r=25mm
z=55mm r=25mm
0 30 60 90 120 150
Diameter (μ m)
Diameter (μ m)
12

Selection of turbulence model

Reasons why calculation cannot predict :

i) Strong anisotropy like a strong swirl field
ii) Overestimation of eddy viscosity like a stepping flow
iii) Strong nonequilibrium like engine in-cylinder flow

We have to know the reason at first !

13

RANS turbulence model

・$k-\varepsilon$ or its modified models

Modifications :

When you know the main reason of poor prediction :

Algebraic Reynolds stress model
Usage of RNG (Re-Normalized Group) theory
Usage of RDT (Rapid Distortion Theory)
Introduction of multi-scale model
Introduction of Low-Reynolds effect

Issues :

To find the best selection of turbulence model

In-cylinder engine flow, we have a problem of how to define turbulence (how to make accurate comparison between calculation and experiment)

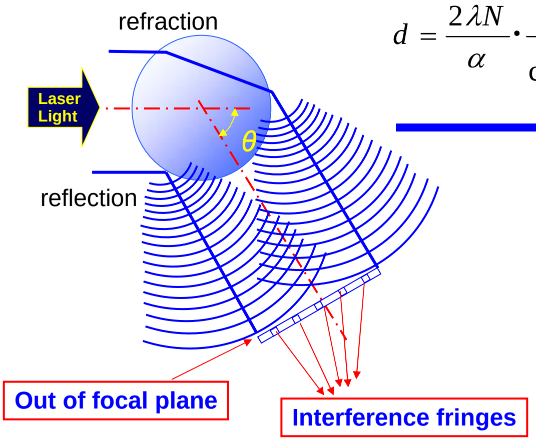
14

Analysis of slit-type spray

1. 2D simultaneous measurement of droplet size and velocity (ILIDS)
2. Effect of cross flow
3. In-nozzle flow calculations
4. Cavitation modeling

15

Principles of ILIDS



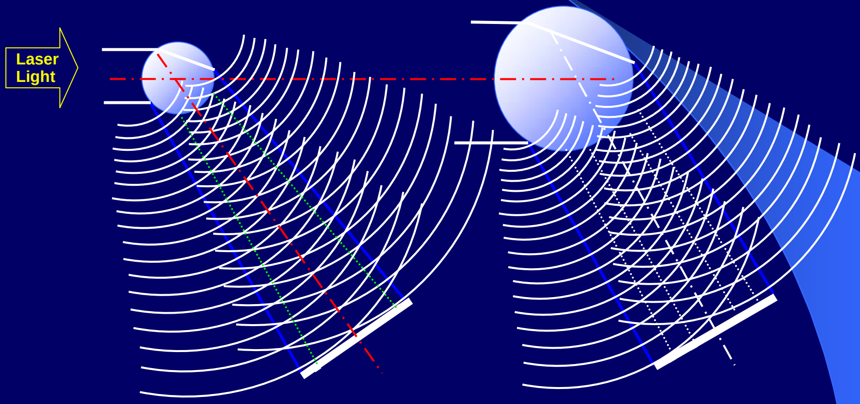
$$d = \frac{2\lambda N}{\alpha} \cdot \frac{1}{\cos\frac{\theta}{2} + \frac{m\sin(\theta/2)}{\sqrt{m^2 + 1 - 2m\cos(\theta/2)}}}$$

by Hesselbacher et al(1991)

d : the droplet diameter
N : the number of fringes
λ : the laser wavelength
α : the collecting angles
θ : the scattering angles
m : the relative refractive index

16

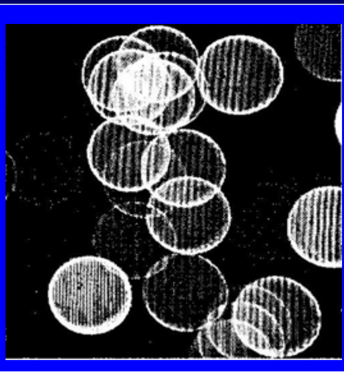
Principle of ILIDS



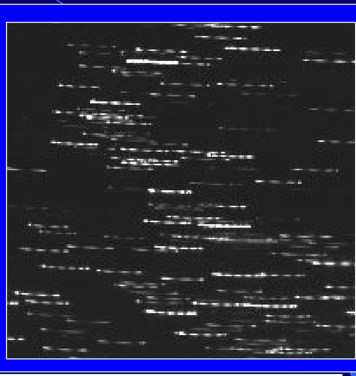
Small size droplet

Large size droplet

Interferometric image



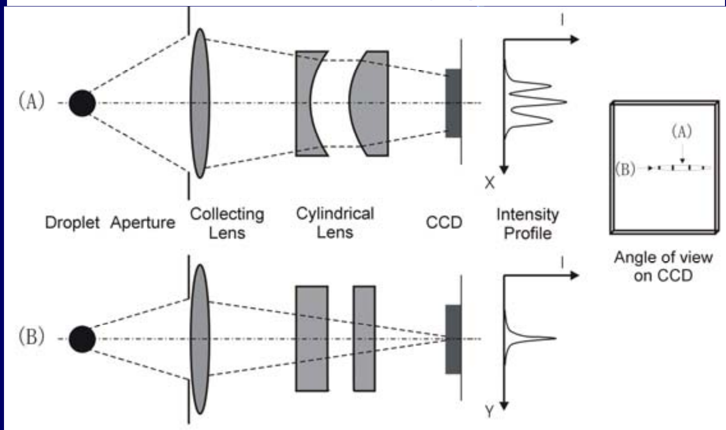
Conventional ILIDS(4x4 mm)
by Hesselbacher et al (1991)



Improved ILIDS (4x4 mm)
by Prof. Maeda et al (2001)

Improvement of ILIDS

- Schematics of the receiving optics

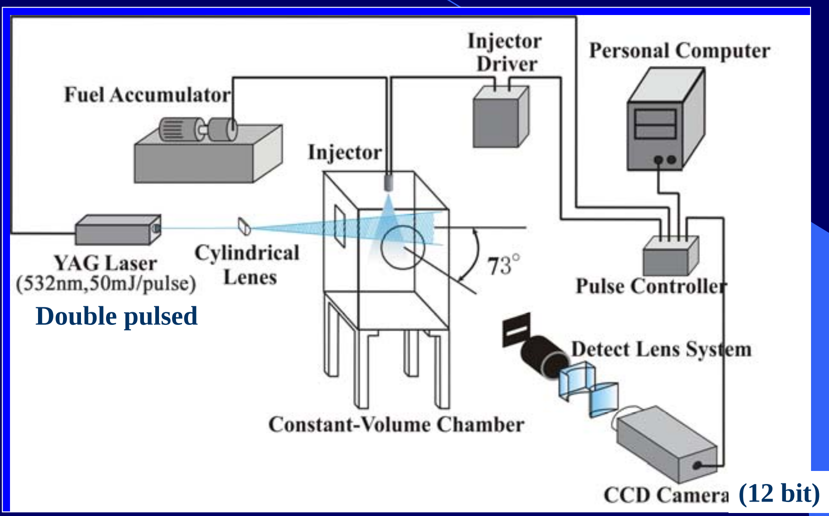


(A) is to adjust the collecting angle, alpha

(B) is to enhance the depth of focus

19

Experimental Apparatus



20

Analysis of Diesel hole-type spray

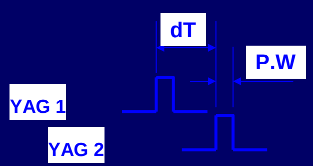
An example of measurement by ILIDS

46

Experimental Conditions

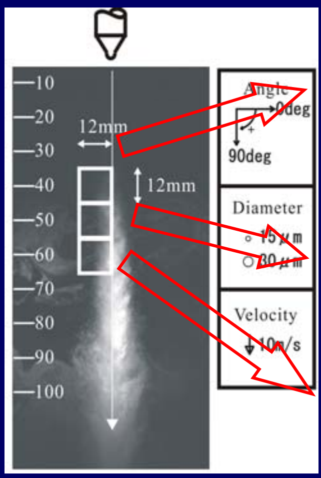
Injection system	Accumulator-type unit injector
Nozzle	Single hole
Fuel	JIS #2 diesel oil
Orifice diameter (mm)	ϕ 0.244
Injection pressure (MPa)	30, 40, 50
Ambient pressure	Atmospheric pressure
Ambient temperature	Room temperature

◇ **Timing Set up**

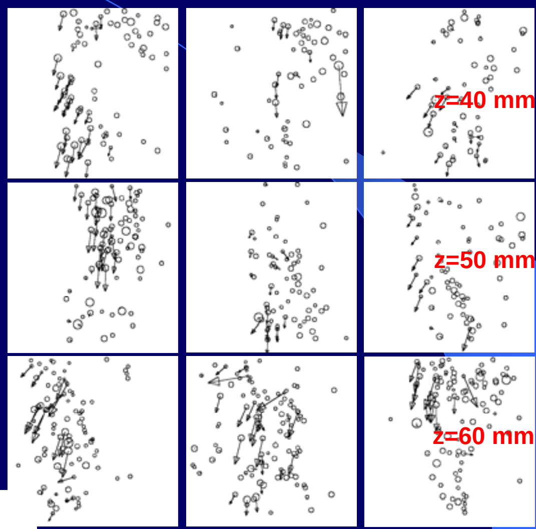


- **Q Switch interval (dT) : 3 μ s**
- **Pulse width : 5 ns**
- **Injection duration : 3ms**

Measurements Regions



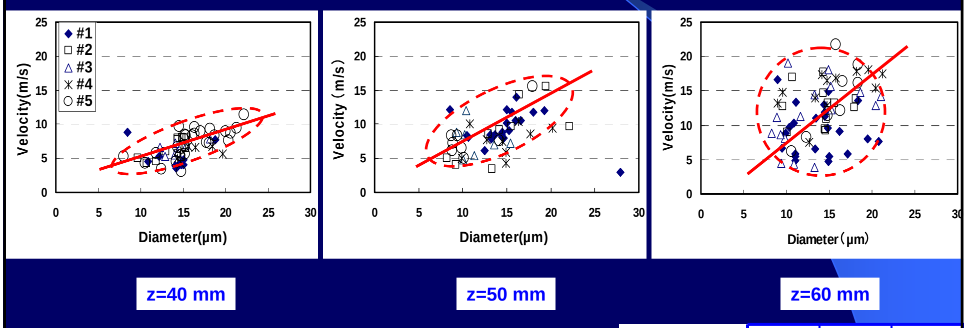
1.5 ms after end of injection (P_{inj}=50 MPa)



Examples of typical results

Results and Discussion(I)

- Correlation between velocity and diameter

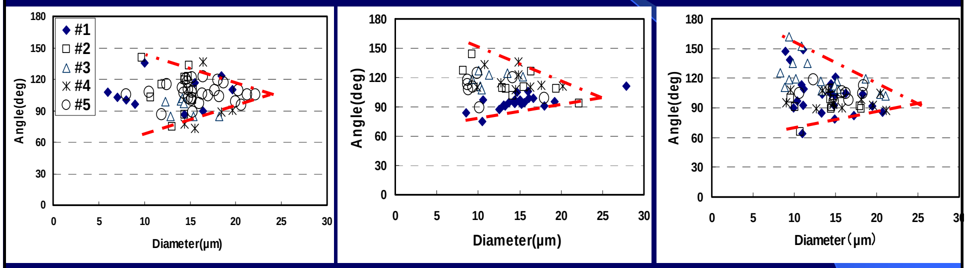


- The gradient becomes steep in downstream
- The scattering of data in downstream is larger than in upstream

	z=40	z=50	z=60
SMD (μm)	16.2	16.0	15.7
RMS (m/s)	6.9	9.1	12.7

Results and Discussion(II)

- Correlation between velocity angle and diameter

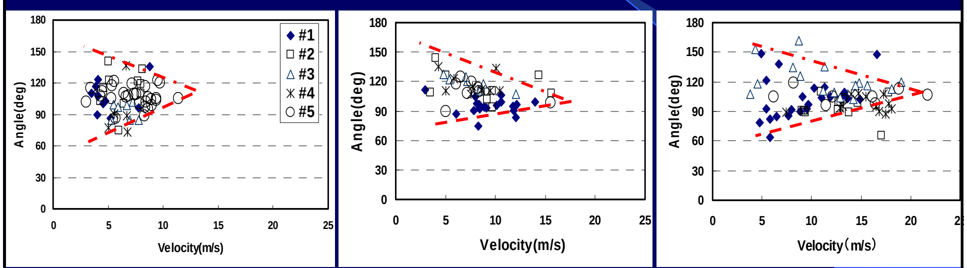


Z=40 mm Z=50 mm Z=60 mm

- Small droplets shows large scatter of angle in each position
- Small droplets are subject to be affected by the motion of vortices

Results and Discussion(III)

- Correlation between angle and velocity

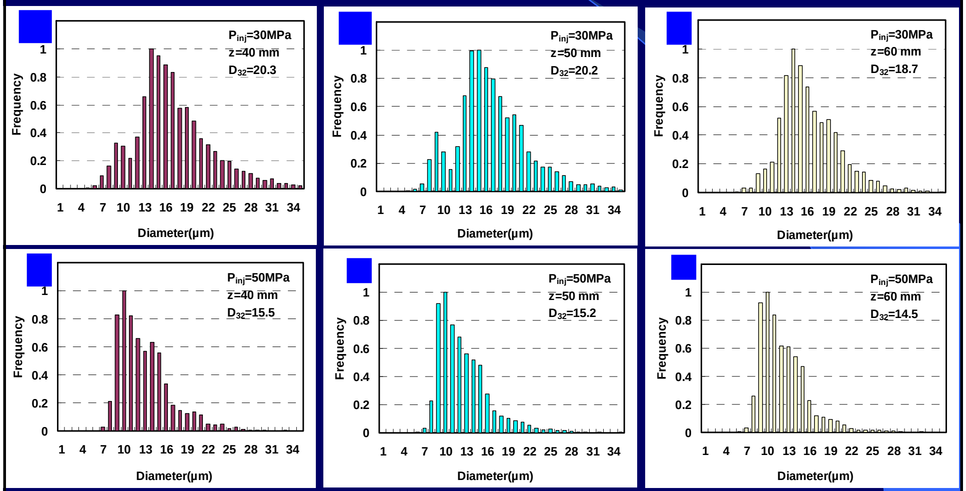


Z=40 mm Z=50 mm Z=60 mm

- The droplets with small velocity indicate a large scatter of angle as they have small diameter and tend to move in the motion of vortices

Results and Discussion(IV)

- Normalized distribution of droplets size



Summary

- Spray analysis is very important to control in-cylinder mixture spatially and temporally.
- An improved ILIDS method is useful to obtain spray characteristics in 2D area.
- Under quiescent condition, prediction of spray is possible, but effect of turbulence, cross flow, wall and evaporation cannot be predicted well.
- Cycle-to-cycle variation must be estimated numerically.