NTNU
Norwegian University of
Science and Technology

An experimental investigation of liquid droplets impinging vertically on a deep liquid pool

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Department of Energy and Process Engineering, NTNU.

03 December, 2009

Outline

Introduction and Background

Outline

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Theory

Outline

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Droplet phenomena in life

Numerous phenomena.

Droplet phenomena in life

Still droplets phenomena.

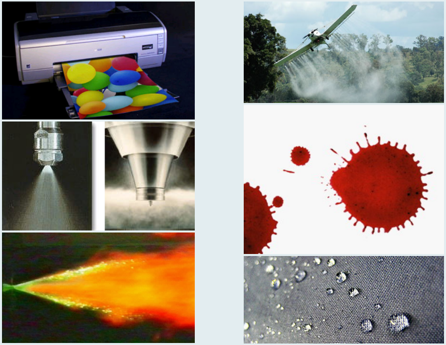
Droplet phenomena in life

Fast-evolving phenomena.

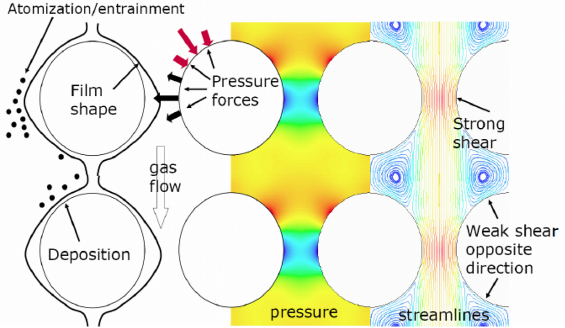
Application fields of droplet impacts

A few examples

- Ink-jet printing.
- Spray cooling and coating.
- Combustion process.
- Biology and agriculture.
- Forensic investigation.
- Material.
- . . .



Motivation



Phenomena in SWHE on shell side (StatoilHydro).

SWHE (Linde).

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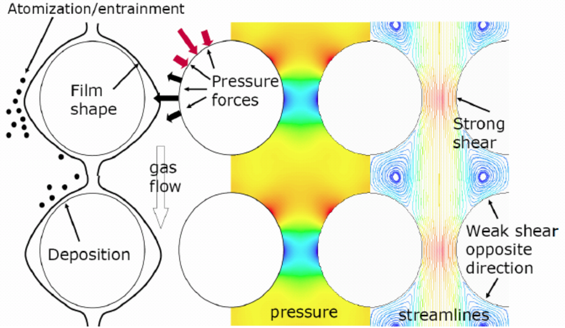

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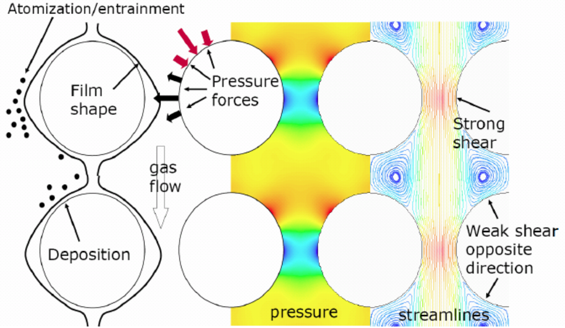

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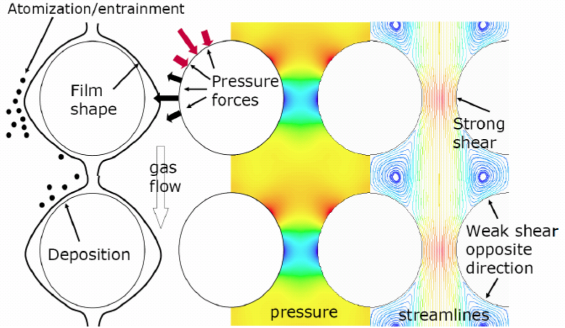

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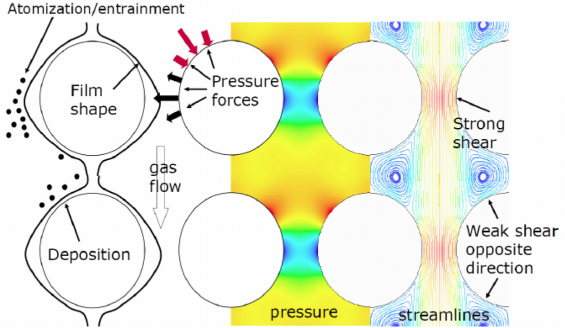

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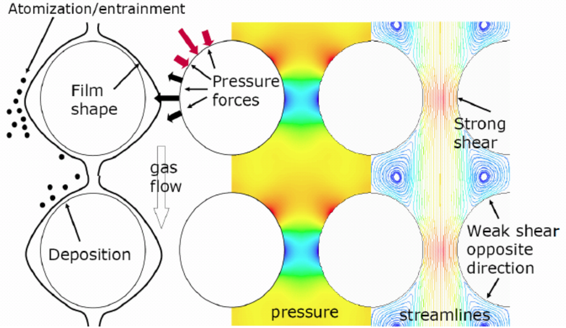

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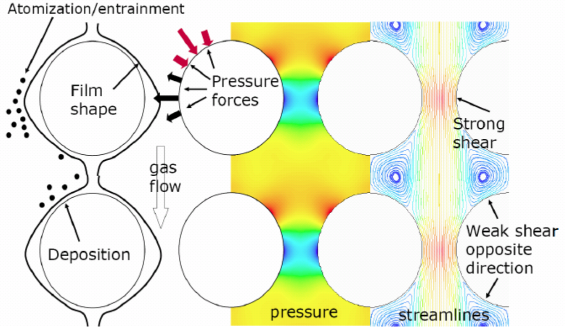

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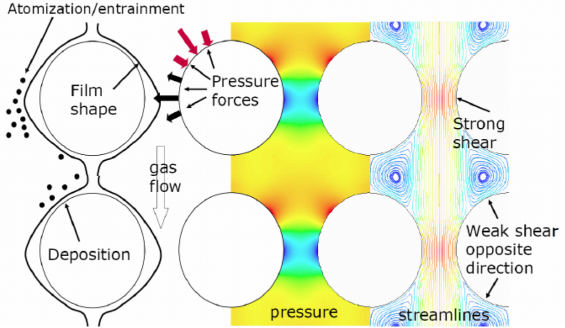

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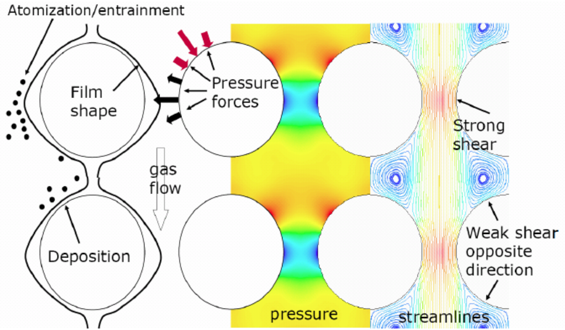

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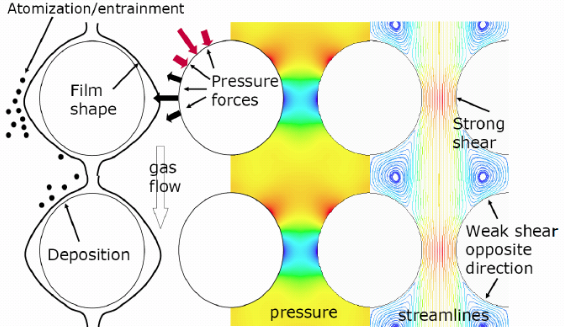

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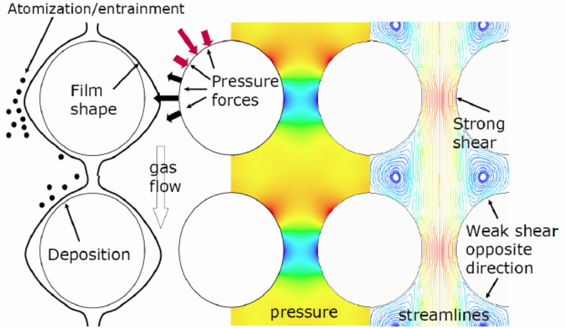

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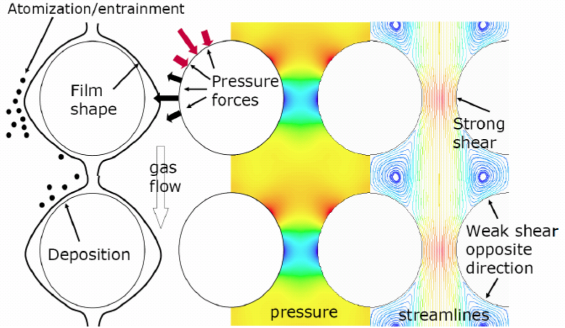

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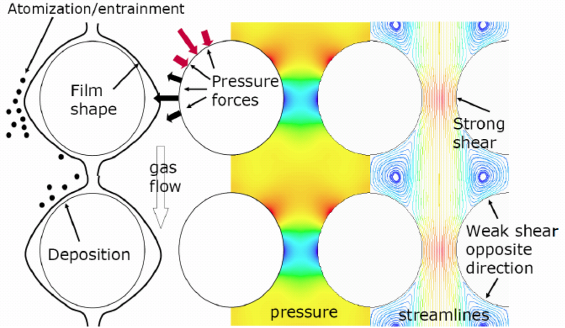

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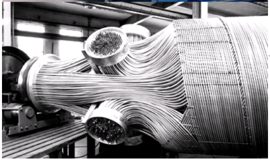

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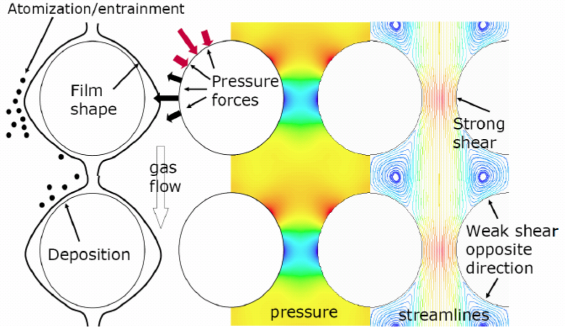

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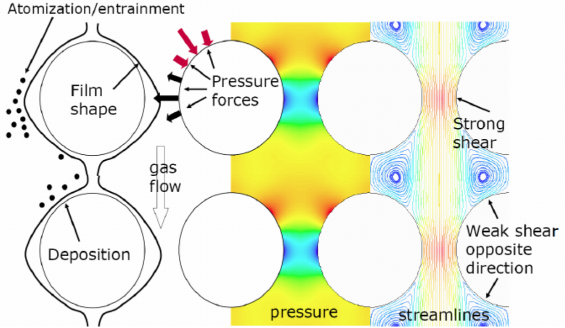

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Motivation (cont.)

Purpose

To gain insight into fundamental phenomena occurring in heat exchangers in liquefaction plants.

Basic hypothesis

A thorough understanding of the processes and phenomena occurring at a small-scale level in the heat exchanger is necessary to obtain an improved understanding of the heat exchanger, its design and operation.

Focus of the work

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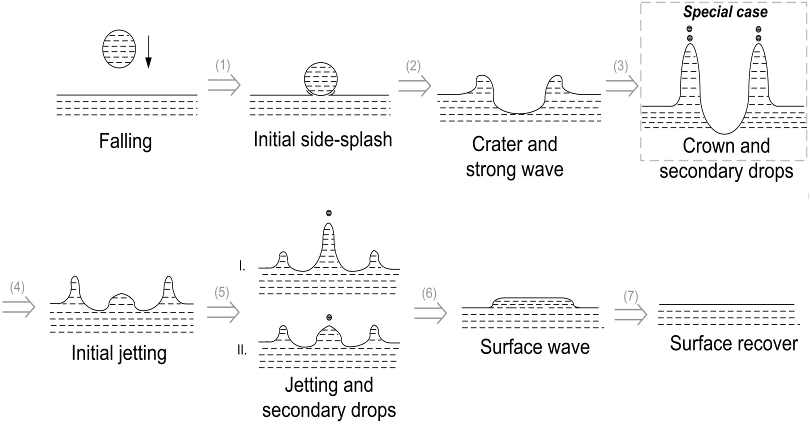
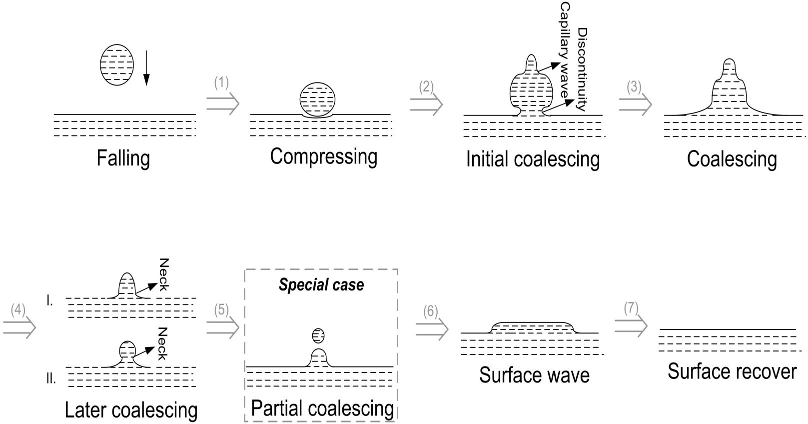
Outline

Definitions of regimes



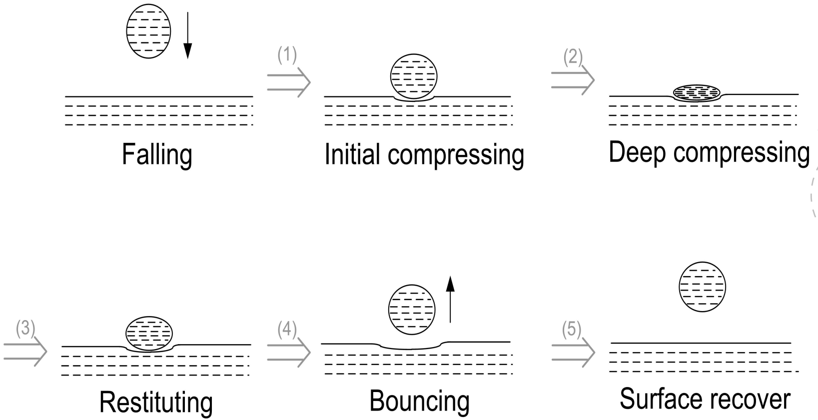
Jetting of a droplet on a deep pool.

Definitions of regimes



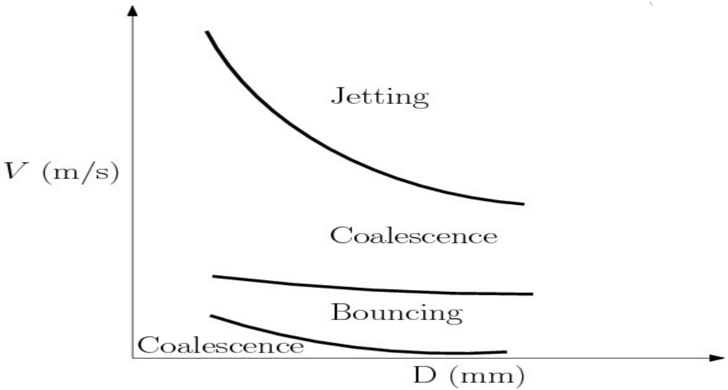
Coalescence of a droplet into a deep pool.

Definitions of regimes



Bouncing of a droplet on a deep pool.

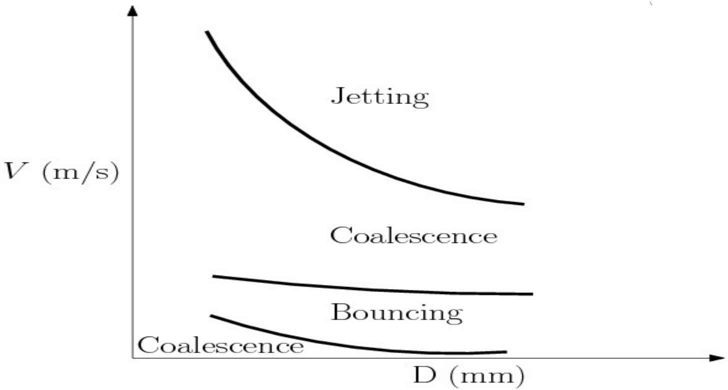
Regime-threshold characterization



- **Quantitative characterization = finding mathematical relation.**
- Complexity: many parameters involved in the impact process.

Jump to *Main regimes*

Regime-threshold characterization



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Parameters and simplifications

Involved parameters

- Physical properties.
  - Liquid phase.
  - Vapor phase.
- Surface condition.
  - Smooth and homogeneous.
  - Rough and inhomogeneous.
- Kinematic parameters.
  - Velocity.
  - Diameter.
  - Impinging angle.
  - Film movement and effects from neighboring impacts.
- Gravitational acceleration.

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Dimensional analysis

Dominant variables and fundamental dimensions

- Physical properties.
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According to the Buckingham Π-theorem, a combination of 3 dimensionless parameters can form a complete set to describe the threshold.

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Dimensional analysis (cont.)

Splashing/jetting

Weber number

$$We = \frac{\rho V^2 D}{\sigma}$$

Inertia-surface

Ohnesorge number

$$Oh = \frac{\mu}{\sqrt{\rho D \sigma}}$$

Viscosity-surface

Reynolds number

$$Re = \frac{\rho D V}{\mu}$$

Inertia-viscosity

Note: A combination of any two of We, Oh and Re is equivalent.

Bouncing

Weber number

Restitution coefficient

$$\epsilon = \left| \frac{V'}{V} \right|$$

Bouncing-impinging velocity

Literature model for splashing/jetting

Formulation of the model

$$We \cdot Oh^a = b$$

Ref.	Fluid	Impacted obj.	Focused Regime	a	b
Hsiao et al. [4]	mercury	Pool[1]	jetting	0	64
Mundo et al. [8]	water, ethanol	Dry surface	Splashing	-0.4	654
Cossali et al. [2]	water-glycerol	Film	Splashing	-0.4	2100[2]
Vander Wal et al. [13]	heptane etc.	Film	Splashing	-0.3	1191
Huang and Zhang [5]	water and oil	Pool	jetting	-0.5	784

[1] Vander Wal et al. [12] defined pool as the thickness of the liquid film much larger than 10 times the droplet diameter, and the liquid pool in this work agrees with this definition.

[2] Cossali et al. [2] included a function of dimensionless film thickness ($H_f^* = \frac{H_f}{D}$) to evaluate the effect from film.

Outline

Experiment constitution

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mena generation

Test cell

Droplet generation system

Droplet descretization system

Temperature, pressure sensors

Experiment constitution

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Test cell

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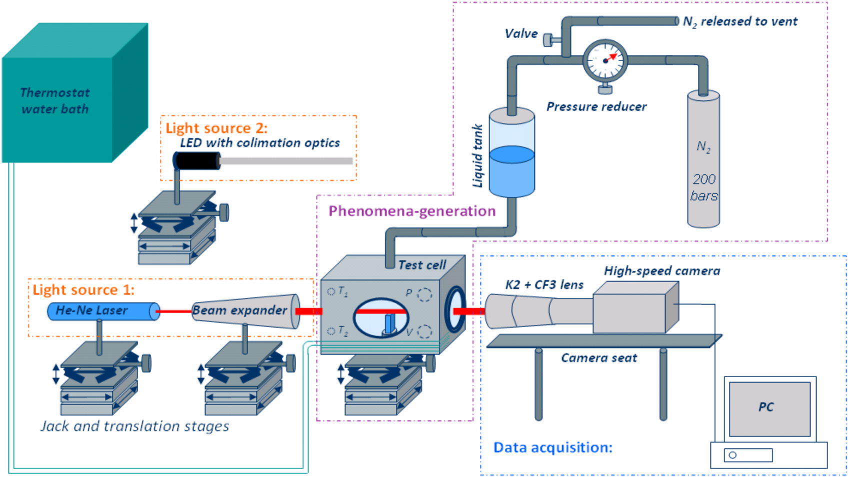
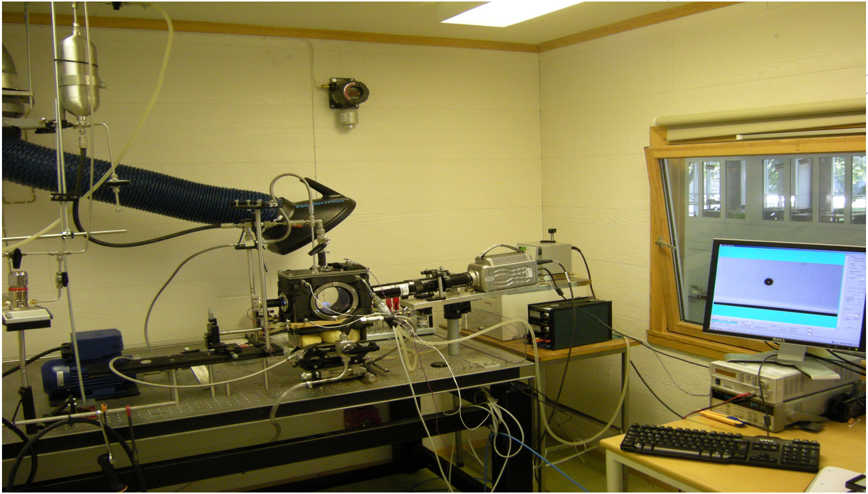
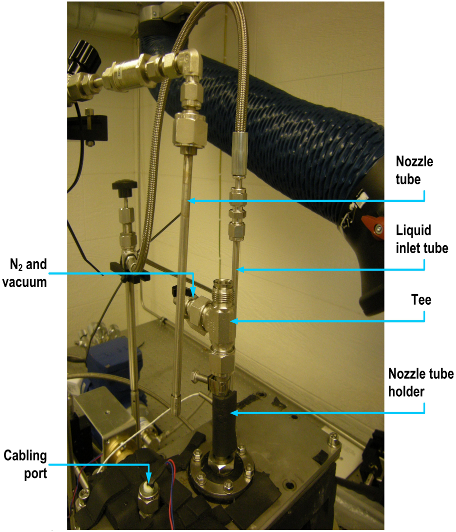
Overview of experimental setup



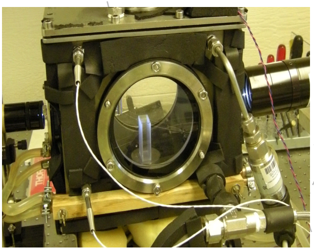
Overview of experimental setup (cont.)



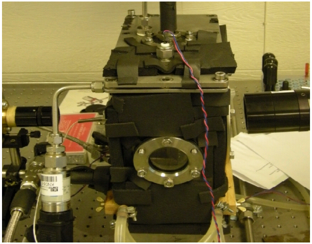
Test cell



Cell lid.

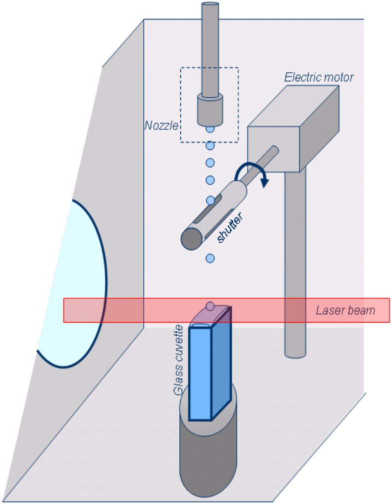


Cell front.



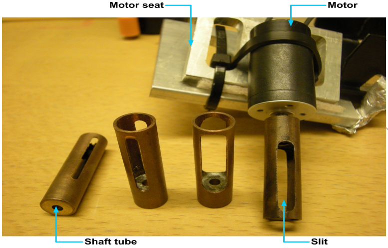
Cell side.

Droplet generation system

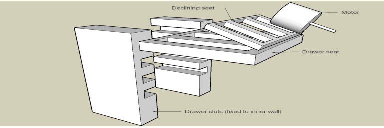


Droplet generation and descretization.

Nozzle.

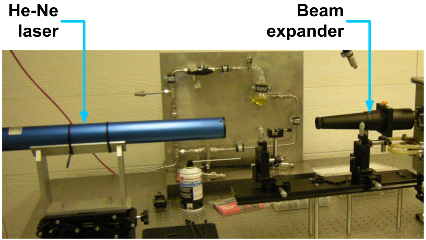


Electrical shutter.

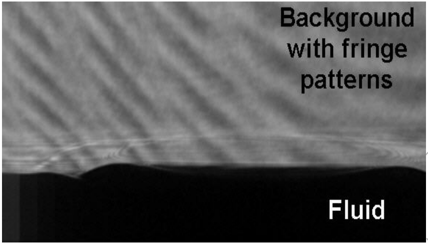


Shutter mount inside cell.

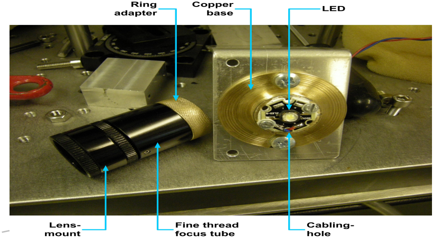
Light source



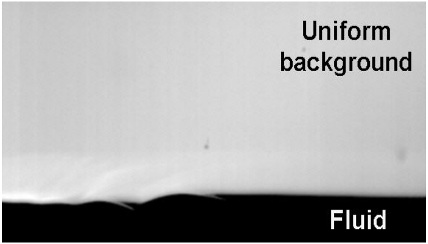
He-Ne laser + beam expander.



Background (He-Ne laser).

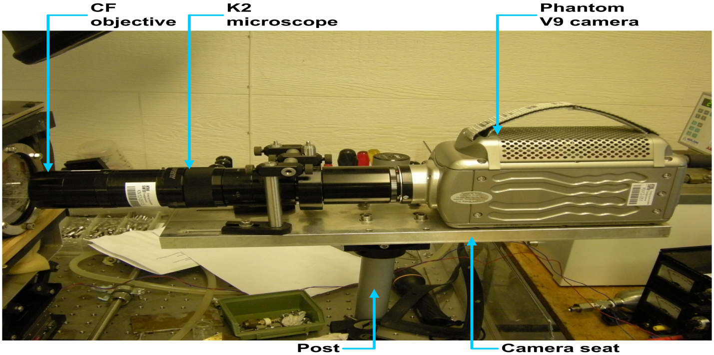


White LED + collimation optics.



Background (LED).

High-speed camera (Phantom V9)



Objective	Primary magnification	System magnification	Field of view	Working distance
CF-1	2.1-0.8×	86.7-33×	3-8 mm	286-715 mm
CF-2	4.1-2.4×	169-99×	1.56-2.7 mm	144-222 mm
CF-3	5.6-3.8×	231-157×	1.1-1.7 mm	96-132 mm
CF-4	9.8-7.7×	405-318×	0.65-0.8 mm	54-63 mm

Safety measures

Safety measures

"Perfect" rig: high strength, 0 leakage and spark

· · ·

Active measures-idealized

ressure failure

nd explosion

Passive measures-practical

Accident, failure may happen · · ·

Safety measures

“Perfect” rig: high strength, 0 leakage and spark

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pressure failure

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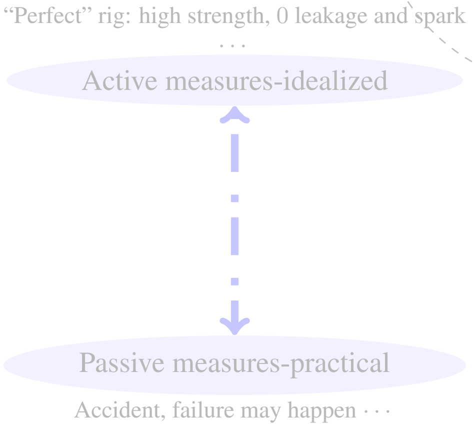

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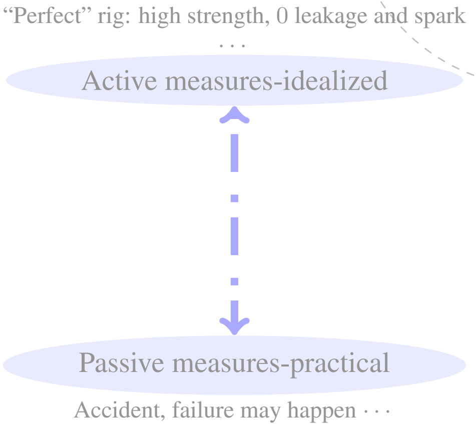

Safety measures

Overpressure failure

Fire and explosion

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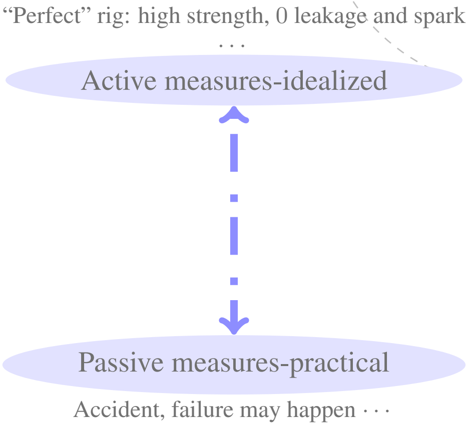

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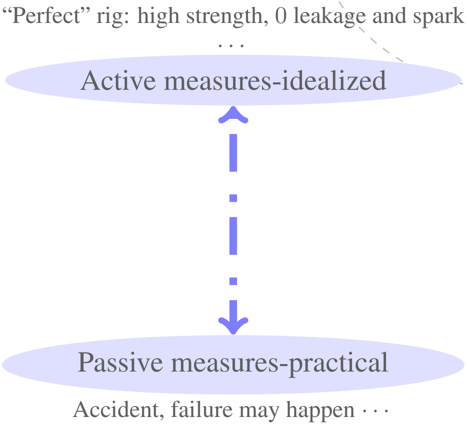

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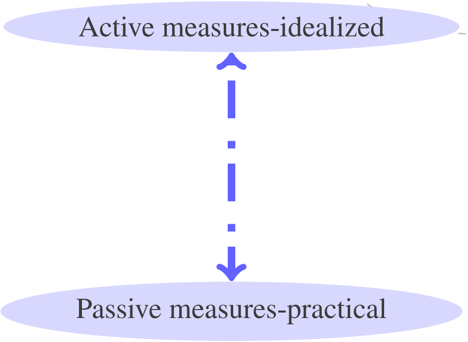

Accident, failure may happen · · ·

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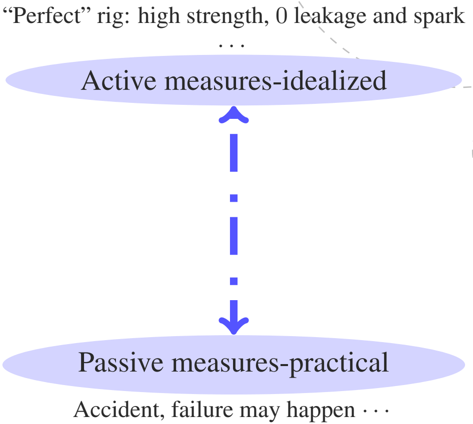

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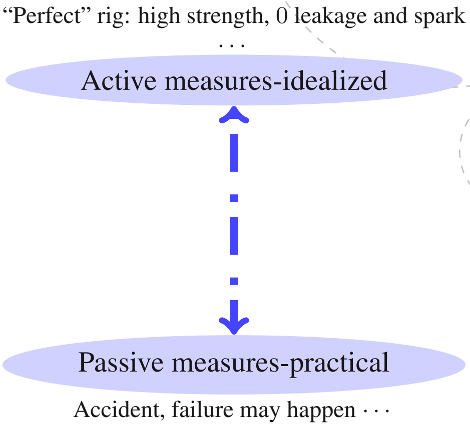

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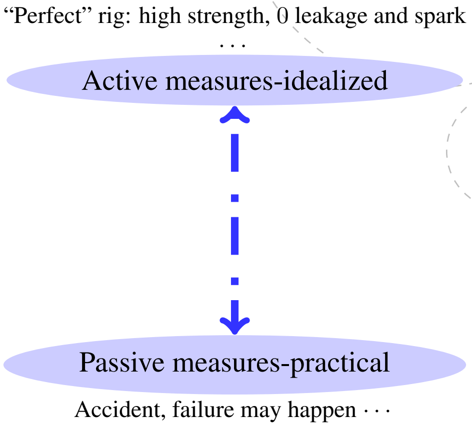
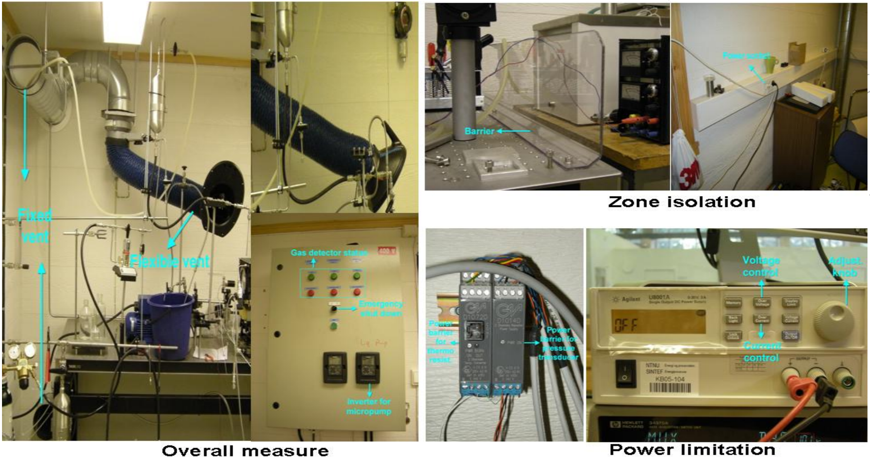


Safety measures (cont.)



Fire and explosion measures.

Material

Experimental fluids and liquid phase properties

Fluids	ρ (kg/m^3)	μ (mPa $\cdot$ s)	σ (mN/m)
Distilled water [7]	996.93	0.890	71.99
Technical ethanol[1]	805.8	1.367	22.406
n-pentane [3]	605.69	0.1969	13.66
Methanol	786.65 [7]	0.544 [7]	22.07 [10]
1-propanol	799.55 [7]	1.968 [11]	23.28 [14]

[1] measured in lab. Measuring accuracy: density-below 1%, surface tension-below 3%, viscosity-below 5%

Outline

Image processing procedures

Image processing procedures

l processing

ocess raw video → Parameters

auto processing

ideo conversion → ImageJ → Script → Parameters

More steps = Much higher efficiency and accuracy!

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Semi-auto processing

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Uncertainty sources

Frame rate. (T)

Gauge. (L)

Gauge measurement. (L)

Measurement of tilted angle of camera. (L)

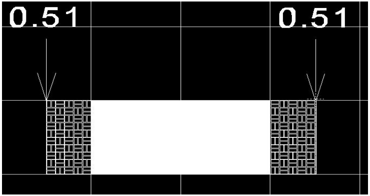
Image segmentation. (L)

Threshold judgment. (L)

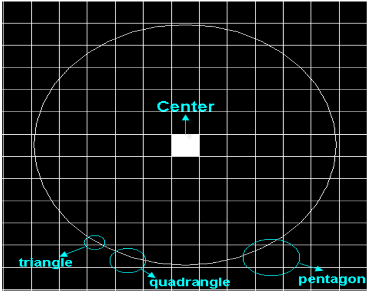
Droplet oscillation. (L)

Physical properties. (Dimensionless parameters)

Uncertainty sources - image segmentation

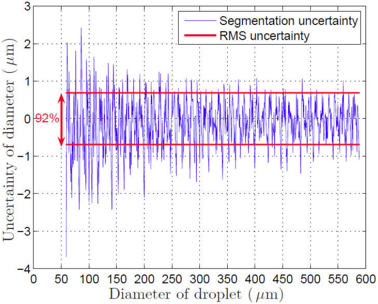


Length measurement (1D)



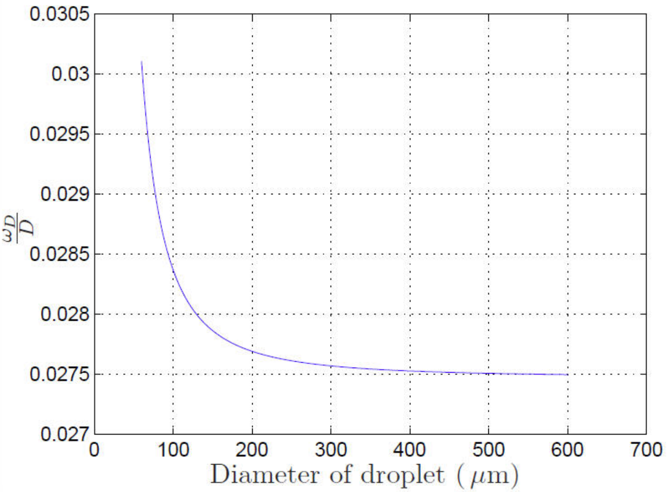
Diameter measurement (2D)

Uncertainty by 1D way: maximum $\approx 1\,\text{pixel} \approx 6\,\mu\text{m}$

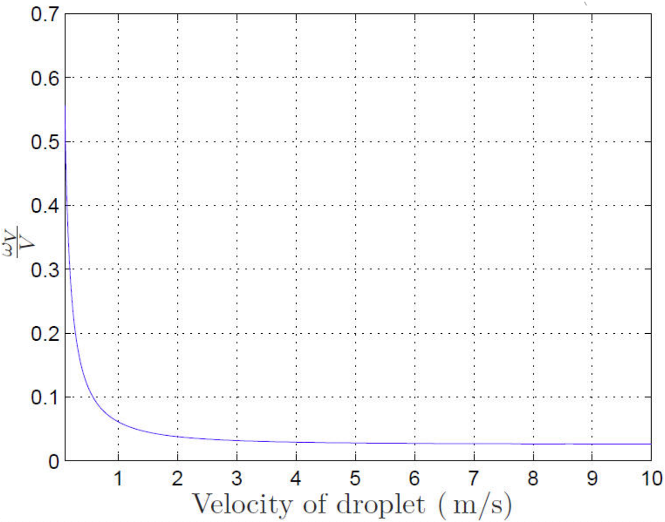


Diameter uncertainty from 2D way: RMS$= 0.69\,\mu$m

Diameter uncertainty



Velocity uncertainty



Dimensionless parameters uncertainties

Maximum uncertainties

We ($\pm\%$)	Oh ($\pm\%$)	Fr ($\pm\%$)	Ca ($\pm\%$)
7	8	3.5	9

Outline

Main regimes

▸ Jump to *Typical regime-distribution*

Main regimes

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Jetting

- Jetting type 1
- Jetting type 2
- Jetting type 3
- Jetting type 4

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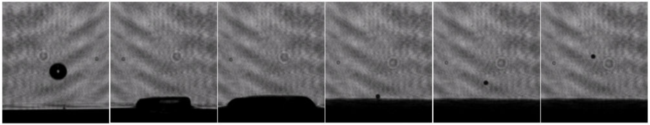
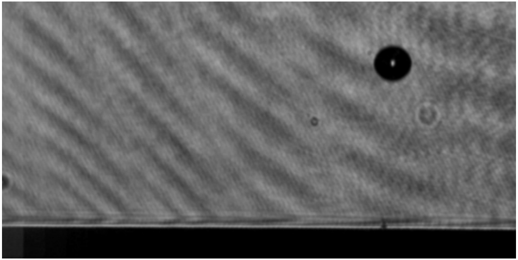
Bouncing

Jetting type 1

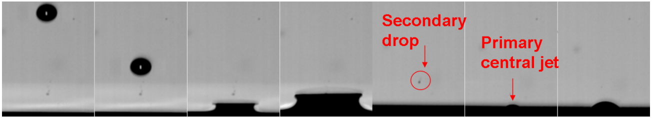


Characteristic steps of jetting type 1.

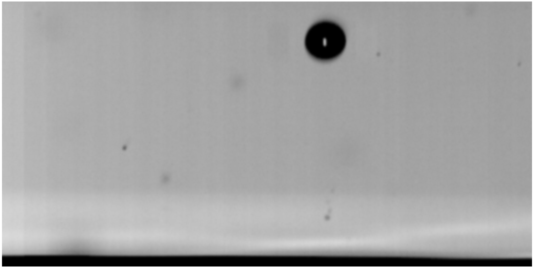


Technical ethanol: $D = 0.25(\,\mathrm{mm})\quad V = 5.3(\,\mathrm{m/s})$.

Jetting type 2

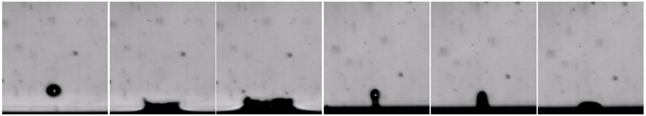


Characteristic steps of jetting type 2.

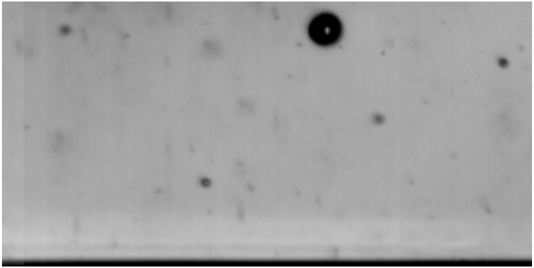


1-propanol: $D = 0.28(\text{mm}) \quad V = 7.3(\text{m/s})$.

Jetting type 3

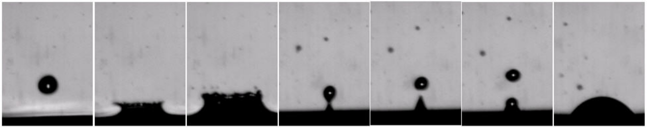


Characteristic steps of jetting type 3.

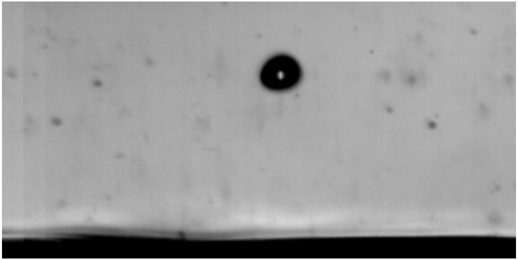


n-pentane: $D = 0.22(\,\mathrm{mm})\quad V = 5.2(\,\mathrm{m/s})$.

Jetting type 4

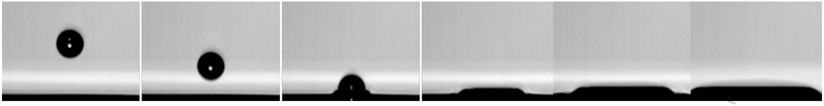


Characteristic steps of jetting type 4.

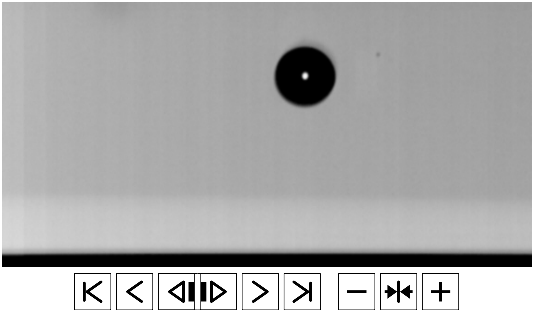


n-pentane: $D = 0.26(\text{ mm})$ $V = 5.9(\text{ m/s})$.

Coalescence (high-energy-collision)

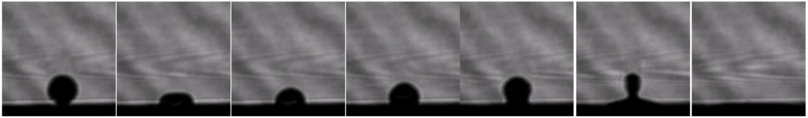


Characteristic steps of coalescence.

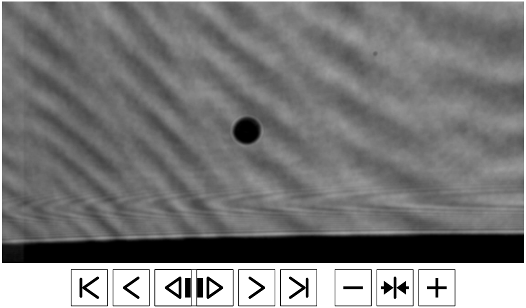


1-propanol: $D = 0.41(\,\mathrm{mm})\quad V = 2.3(\,\mathrm{m/s})$.

Coalescence (low-energy-collision)



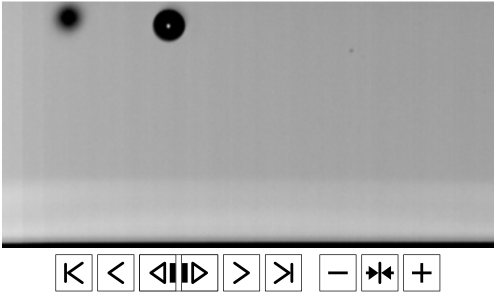
Characteristic steps of coalescence.



Distilled water: $D = 0.17(\text{ mm})$ $V = 0.9(\text{ m/s})$.

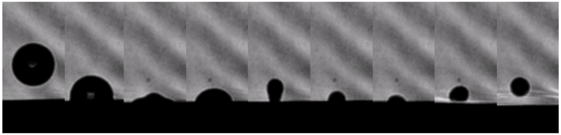
Bouncing

Characteristic steps of bouncing.

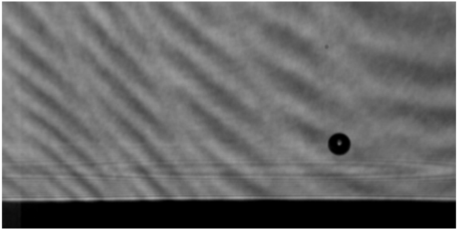


1-propanol: $D = 0.24(\,\text{mm})\quad V = 1.14(\,\text{m/s})$.
Bouncing: $D = 0.24(\,\text{mm})\quad V = -0.29(\,\text{m/s})$.

Partial coalescence (transitional regime)



Characteristic steps of partial coalescence.



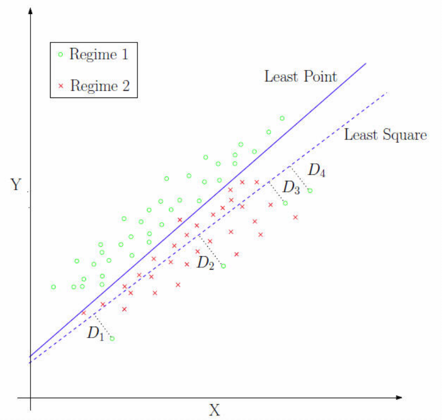
Distilled water: $D = 0.17(\text{ mm}) \quad V = 0.34(\text{ m/s})$.
Bouncing: $D = 0.08(\text{ mm}) \quad V = -0.47(\text{ m/s})$.

Outline

Data range

Fluid	Diameter range (mm)	Velocity range (m/s)
Distilled water	0.06 - 0.7	0.1 - 12
Technical ethanol	0.07 - 0.7	0.1 - 10
n-pentane	0.1 - 0.6	0.3 - 6.5
Methanol	0.17 - 0.42	1.8 - 8
1-propanol	0.1 - 0.5	1.3 - 10

Data regression methods and definitions



Threshold characterization between regime 1 and 2.

Definition of points

- Uncertain points: different from the majority of a regime.
- Certain points: same as the majority of a regime.

Two regression methods

- Least points: gives the least uncertain points.
- Least square: gives the least square to the uncertain points.

Threshold models for coalescence-jetting

Jump to *Dimensionless parameters*

Threshold models for coalescence-jetting

Exponential model

$$1705 = We \cdot Oh^{-0.57+\frac{\hat{\gamma}}{D}};$$

- Weighing the effects from inertia, viscosity and surface tension.
- Revised form of the classic formulation $We \cdot Oh^{a} = b$.

Linear model

$$Fr = \alpha\, Ca + \beta;$$

- Weighing the effects from inertia, gravity, viscosity and surface tension.

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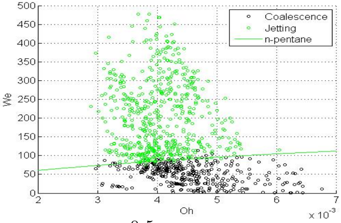
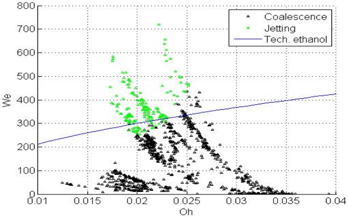
Jump to *Dimensionless parameters*

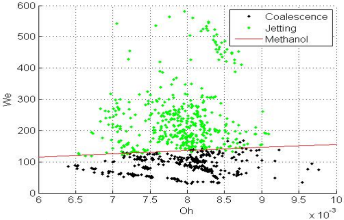
Exponential model - without $\hat{\gamma}$



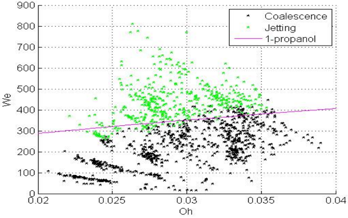
$We \cdot Oh^{-0.5} = 1349$ for n-pentane.



$We \cdot Oh^{-0.5} = 2125$ for technical ethanol.

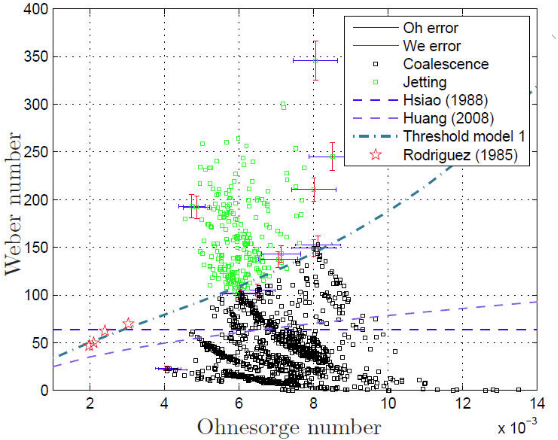


$We \cdot Oh^{-0.6} = 2446$ for methanol.



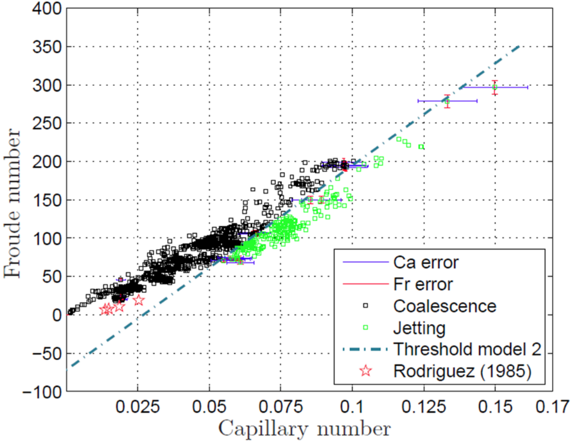
$We \cdot Oh^{-0.5} = 2028$ for 1-propanol.

Exponential model - with $\hat{\gamma}$



$We \cdot Oh^{-0.57+\frac{\hat{\gamma}}{D}} = 1705$ for distilled water. Literature data from [9].

Linear model



$Fr = \alpha Ca + \beta$ for distilled water. Literature data from [9].

C-J threshold characterization results of models

Exponential model

Fluid	$\hat{\gamma}(10^{-6})$	Uncertain points	$\frac{\text{Uncertain}}{\text{Total}}$
Distilled water	10	14	1.12%
Technical ethanol	25	35	3.25%
n-pentane	8	30	3.35%
Methanol	14	27	3.36%
1-propanol	29	62	4.83%

Linear model

Fluid	α	β	Uncertain points	$\frac{\text{Uncertain}}{\text{Total}}$
Distilled water	2668	−72	1	0.08%
Technical ethanol	544	−71	21	1.95%
n-pentane	2594	−48	30	3.35%
Methanol	1301	−47	25	3.11%
1-propanol	395	−80	71	5.53%

Generalizations of models

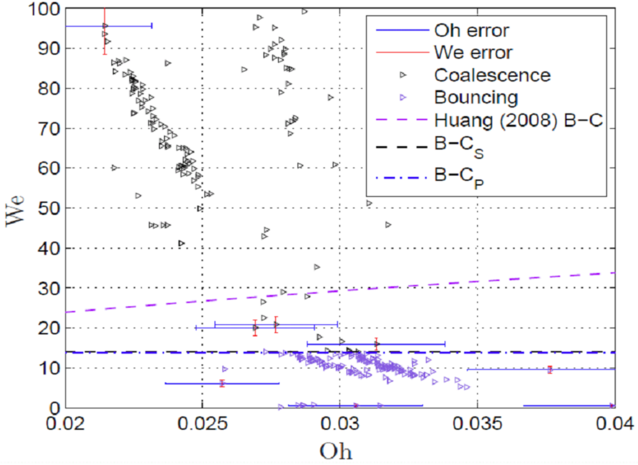
Exponential model

$$\frac{\hat{\gamma}_x}{\hat{\gamma}} = (\frac{\rho_x}{\rho})^{1.82} \cdot (\frac{\mu_x}{\mu})^{0.6} \cdot (\frac{\sigma_x}{\sigma})^{-0.96}$$

Linear model

$$\begin{aligned} \frac{\alpha_x}{\alpha} &= (\frac{\rho_x}{\rho})^{-1.02} \cdot (\frac{\mu_x}{\mu})^{-0.99} \cdot (\frac{\sigma_x}{\sigma})^{1.20} \\ \frac{\beta_x}{\beta} &= (\frac{\rho_x}{\rho})^{-2.91} \cdot (\frac{\mu_x}{\mu})^{0.36} \cdot (\frac{\sigma_x}{\sigma})^{0.74} \end{aligned}$$

Threshold of bouncing-coalescence



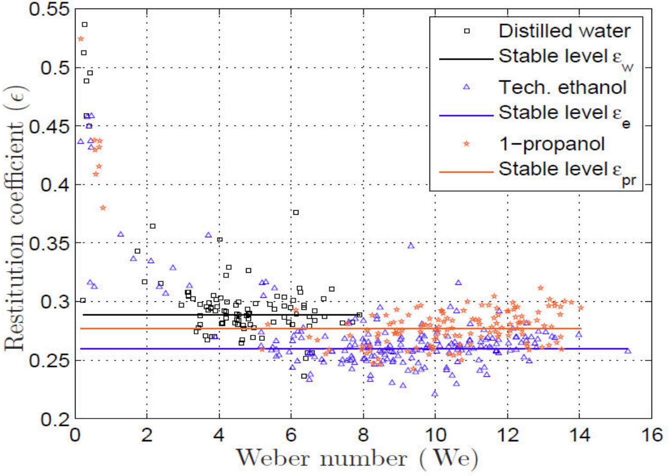
$We = C$ for 1-propanol. Literature threshold models from [5]

B-C and C-B characterization results using Weber number

Exponential model

Fluid	B-C Threshold (We_{critical})	C-B Threshold (We_{critical})
Distilled water	6.7	2.8
Technical ethanol	12.4	5.9
1-propanol	14.0	

Restitution coefficient



Agree with literature value 0.2-0.3 [6, 1].

Effects of parameters and properties

Kinetic parameters

(a) Swell.wav.-1. (b) Swell.wav.-2. (c) Swell.wav.-3. (d) C.j. drop-1. (e) C.j. drop-2.

Jetting of a methanol droplet: $D = 0.25$ mm and $V = 4.0$ m/s

(a) Crown-1. (b) Crown-2. (c) Crown-3. (d) Cen. jet-1. (e) Cen. jet-2.

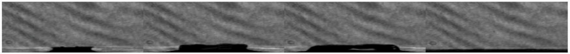
Jetting of a methanol droplet: $D = 0.26$ mm and $V = 7.3$ m/s

Viscosity

(a) Crown-1. (b) Crown-2. (c) Crown-3. (d) C.j. drop. (e) Cen. jet.

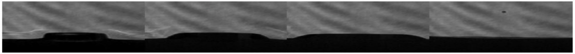
Jetting of a 1-propanol droplet: $D = 0.28$ mm and $V = 8.8$ m/s

Surface tension



(a) Crown-1. (b) Crown-2. (c) Crown-3. (d) C.j. drop.

Jetting of a technical ethanol droplet: $D = 0.17$ mm and $V = 8.9$ m/s



(a) Swell.wav.-1. (b) Swell.wav.-2. (c) Swell.wav.-3. (d) C.j. drop.

Jetting of a water droplet: $D = 0.21$ mm and $V = 8.9$ m/s

Outline

Conclusions

- Experiments:
  - Careful considerations on safety.
  - Test cell with good integration and gas-tight.
  - Mono-dispersed droplet stream isolation.
  - A suitable light source.
  - Observations of different regimes were carried out with five different fluids.
- Data analysis:
  - An accurate and efficient routine for image-processing.
  - Thorough uncertainty analysis.
- Phenomena and results:
  - Improved understanding of the phenomena.
  - Coalescence-jetting thresholds for five fluids with two models, for which generalization methods were suggested.
  - Bouncing-coalescence thresholds for three fluids, and coalescence-bouncing threshold for two fluids.
  - Restitution coefficient for three fluids, and good agreement with literature data.
  - Effects of parameters and properties.

Recommendations

- Verification of generalization methods by more fluids.
- Bouncing condition generalization.
- Characterization of 4 types distinguishable observations in jetting.
- More realistic geometries and flow conditions for simulating the flow in LNG heat exchanger.
- Numerical simulations for improving the understanding.

Thank you for your attention!

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