Development of Background Oriented Schlieren methods for multi-phase objects

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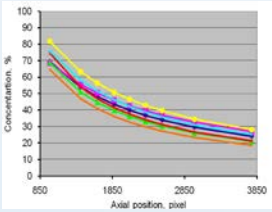
Motivation

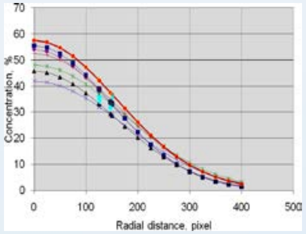
PRESLHY-project: Pre-normative research for liquid hydrogen safety

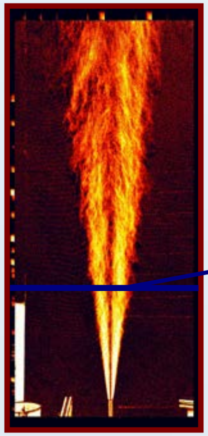
Optical methods for examination of gaseous / liquid system are widely used and demonstrated good capabilities for obtaining qualitative and quantitative results

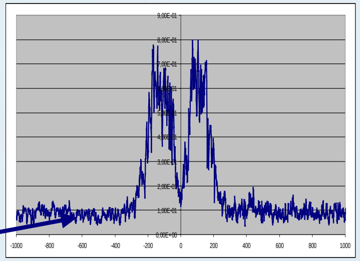
Since 2006, the experiments in KIT are supported by application of BOS (modification of schlieren method) technique for visualisation

Approach allowing to obtain data on e.g., concentration and turbulence was created on the base of the BOS-technique as well



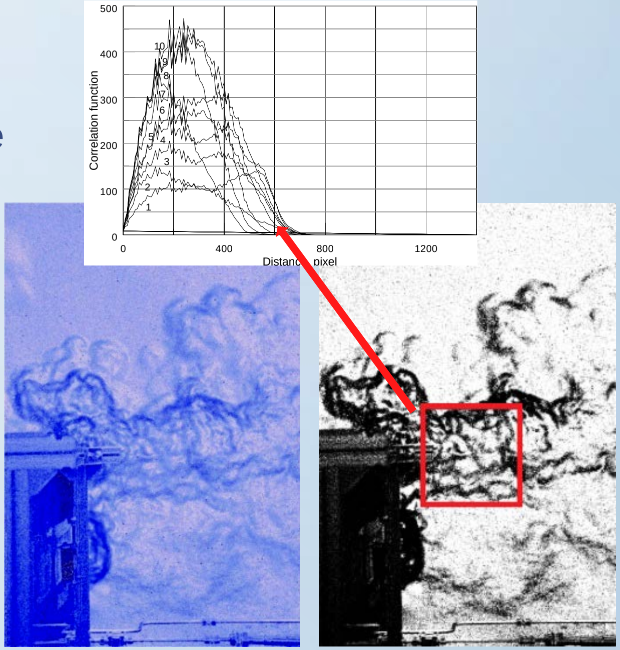






Concentration measurements in a round hydrogen jet

The correlation method to analyse the gas mixing process on the basis of BOS method



Method concept

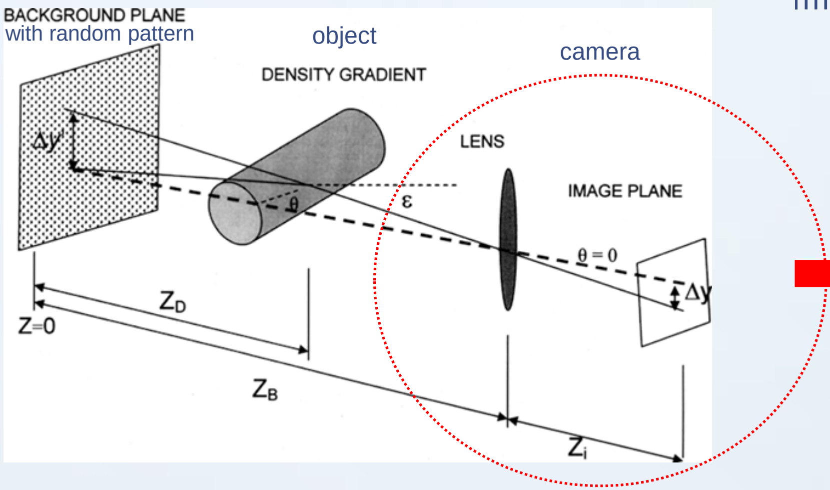
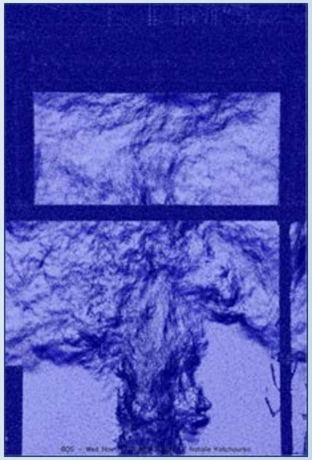


Image without object

Image with object

Processing of two images using cross-correlation algorithm

Data treatment using in-house code BOSIFY



Idea: instead of experiments create such two images using one of the numerical program capable to render a scene consisting of the studied objects (e.g., POV Ray, Mental Ray, Iray, V-Ray, Render Man are available)

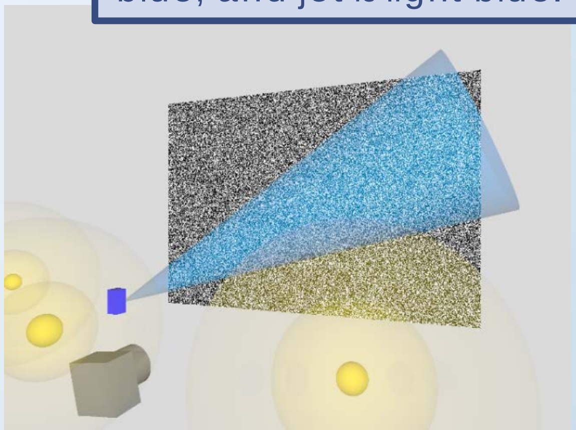
POV Ray is non-commercial, convenient in work, gives possibility to create object with definite optical properties, also transparent

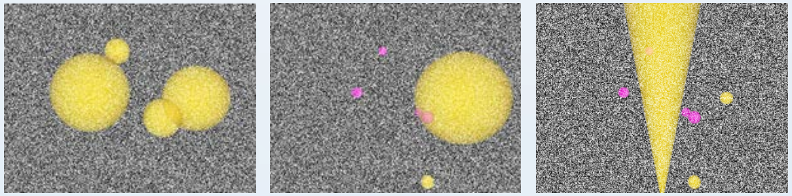
Test of POV RAY applicability for BOS

Simple POV Ray scenes were created:
- perspective camera focusing on BOS background,
- three point light source,
- plane covered by BOS-background (from own collection)
- objects with different locations and optical properties

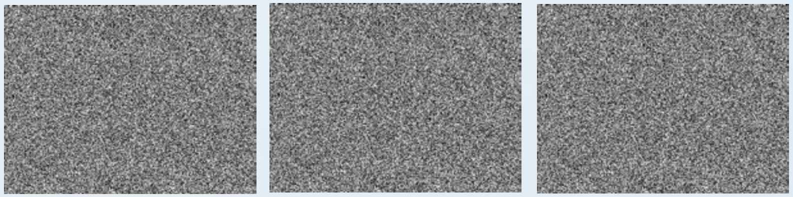
Two types of scene: coloured objects and transparent objects with different refractive index. Refractive index of the yellow spheres corresponds to gaseous hydrogen, pink colour corresponds to liquid water.

Light sources colored in yellow, camera is gray, jet source is blue, and jet is light blue.

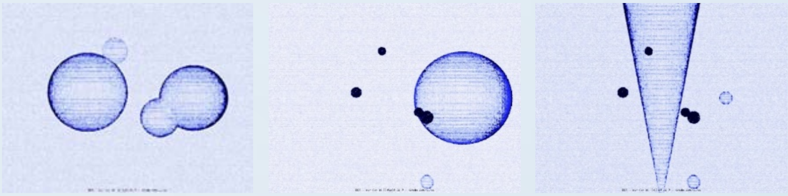




Result of POV Ray rendering with coloured spheres



How POV RAY scene looks when spheres are transparent



Result of the BOS application to the transparent object images

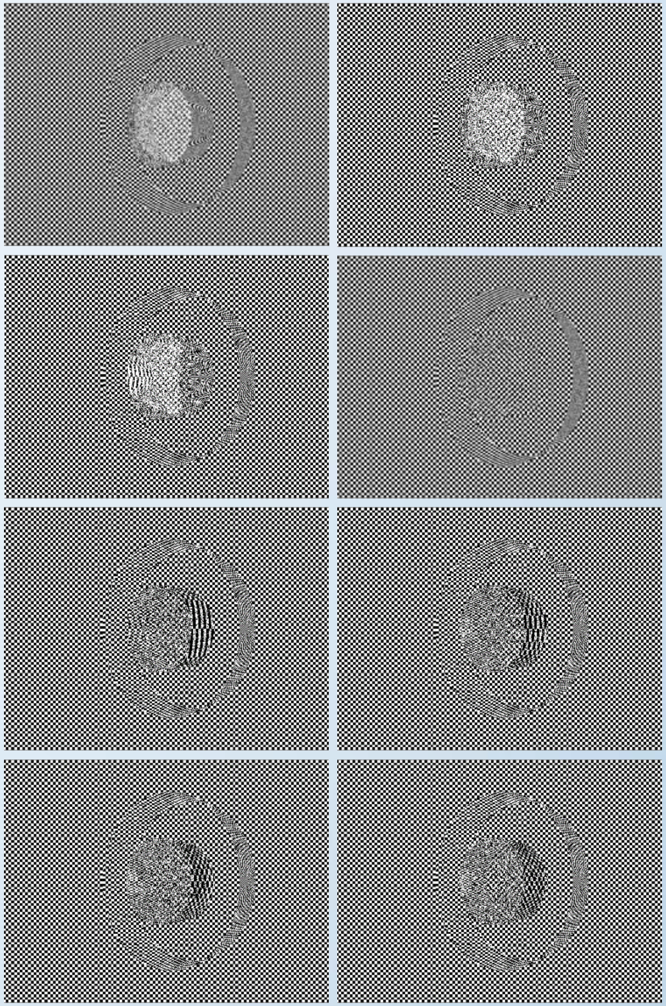
IMAGES CREATED BY POV RAY CAN BE PROCESSED APPLYING BOS

Objectives

- Test of concept (POVRAY + BOS)
- Test of possibility to create realistic POV Ray scene (gaseous jet surrounded by liquid particles) applicable for BOS
- Study of scene object characteristics on system properties identification:
  - Influence of the particle density (amount)
  - Influence of the particle size
  - Influence of the droplet material

Gaseous jet in POV Ray

- The only parameter that characterizes properties of a transparent object in POV Ray is refractive index
- Unfortunately, in the POV Ray program, the refractive index cannot be monotonically changed over space
- **Option**: create complex object (model) with stepwise variable refractive index
- A series of tests was conducted to obtain a complex object with correct physical characteristics

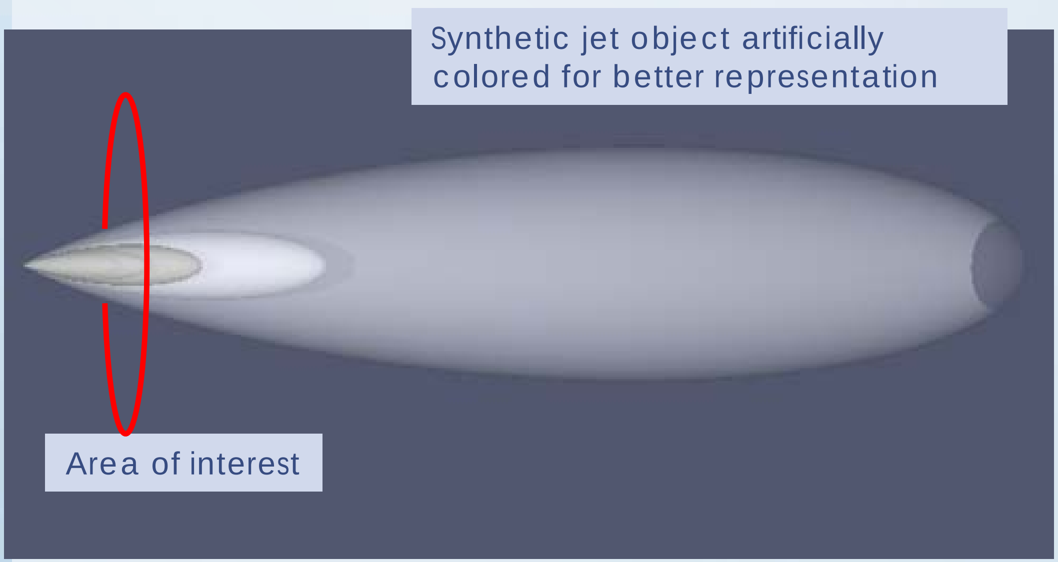


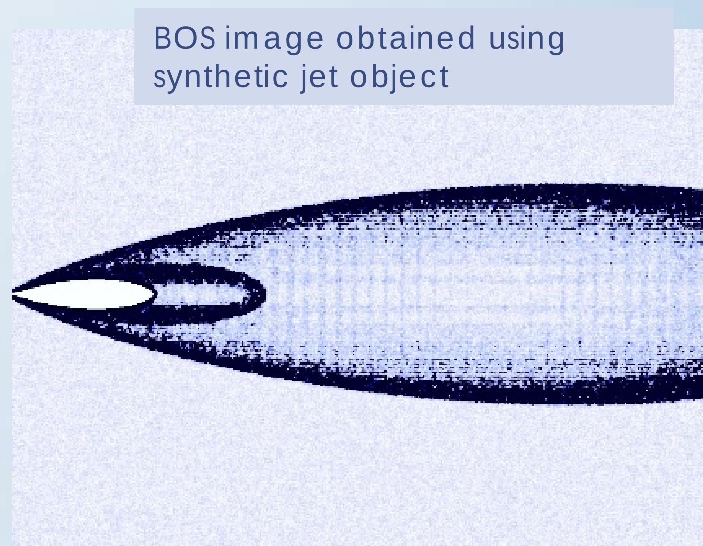
Resulting object after simple overlapping of two cylinders. Set of trials with variable refractive index of internal small cylinder from 0.2 to 1.8 with a step 0.2 was performed. Large cylinder had constant n equal to 0.9.

Gaseous jet in POV Ray

Python program:

- in accordance with the hydrogen distribution dependence in the jet, set of points with equal hydrogen concentration are created
- for each set of points, in accordance with concentration of the hydrogen-air mixture, the refractive index n was calculated
- data (coordinates and n) is translated into POV Ray scene description. This set of points builds curve and by rotation this curve around Y-axis builds a surface with constant n
- series of objects with surfaces corresponded to relative density from 0 to 1 prepared
- objects are placed one into another (overlapping)
- as a result, a 3D model of a hydrogen gas jet consisting of 10-20 rotating surfaces with stepwise variable hydrogen density (i.e., refractive index) was created





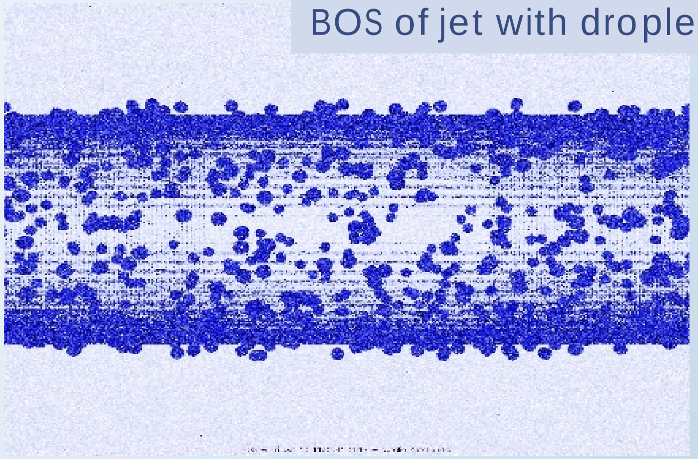
Liquid droplets surrounding gaseous jet

In cryogenic jet, droplets of original material or of condensed surrounding gases exist near the interface between low / high temperature regions

Model

- For the simplicity, a cylindrical section was taken as a slice of a jet
- It was assumed that the process is located relatively far downwards, where gradients of hydrogen concentration is not severely sharp
- The refractive index of the jet slice is equal to relative hydrogen concentration as small as 4% vol.; this value was taken with the idea to provide the highest possible sensitivity of the method. If it will work with low-density gradient, it will work with larger density gradients too
- Arrangement of POV Ray scene corresponds to the arrangement of „Ice Fuel“ experiments, including characteristics of camera and light source

BOS of jet with droplets



Specialized program was created to generate data for POV Ray scene:

- define number of droplets (N)
- with definite droplet radius (R)
- and refractive index (material) n
- which are irregularly located near by surface of gaseous object

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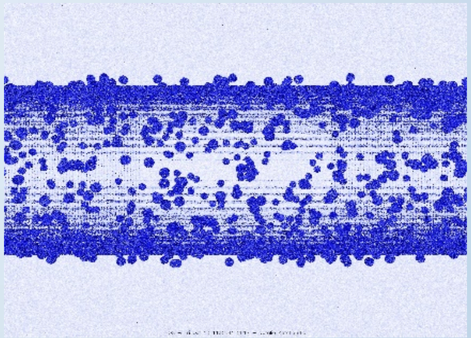
Influence of the particle density

Number of particles	Particle size R*	Droplet material
5	0.25;0.5;1;2;4;10	Liquid H_2 and liquid CH_4
10	0.25;0.5;1;2;4;10	Liquid H_2 and liquid CH_4
25	0.25;0.5;1;2;4	Liquid H_2 and liquid CH_4
50	0.25;0.5;1;2	Liquid H_2 and liquid CH_4
100	0.25;0.5;1;2	Liquid H_2 and liquid CH_4
150	0.25;0.5;1;2	Liquid H_2 and liquid CH_4
200	0.25;0.5;1;2	Liquid H_2 and liquid CH_4
500	0.25;0.5;1;2	Liquid H_2 and liquid CH_4
1000	0.25;0.5;1;2	Liquid H_2 and liquid CH_4
5000	0.25;0.5;1	Liquid H_2 and liquid CH_4
10000	0.25;0.5;1	Liquid H_2 and liquid CH_4

R* radius in POV Ray units. 10 POVRay units = 1Pix

In the used POV Ray scene, because of the selected camera's viewing angle, only a part of the cylinder is visible. Accordingly, the number of droplets is reduced!

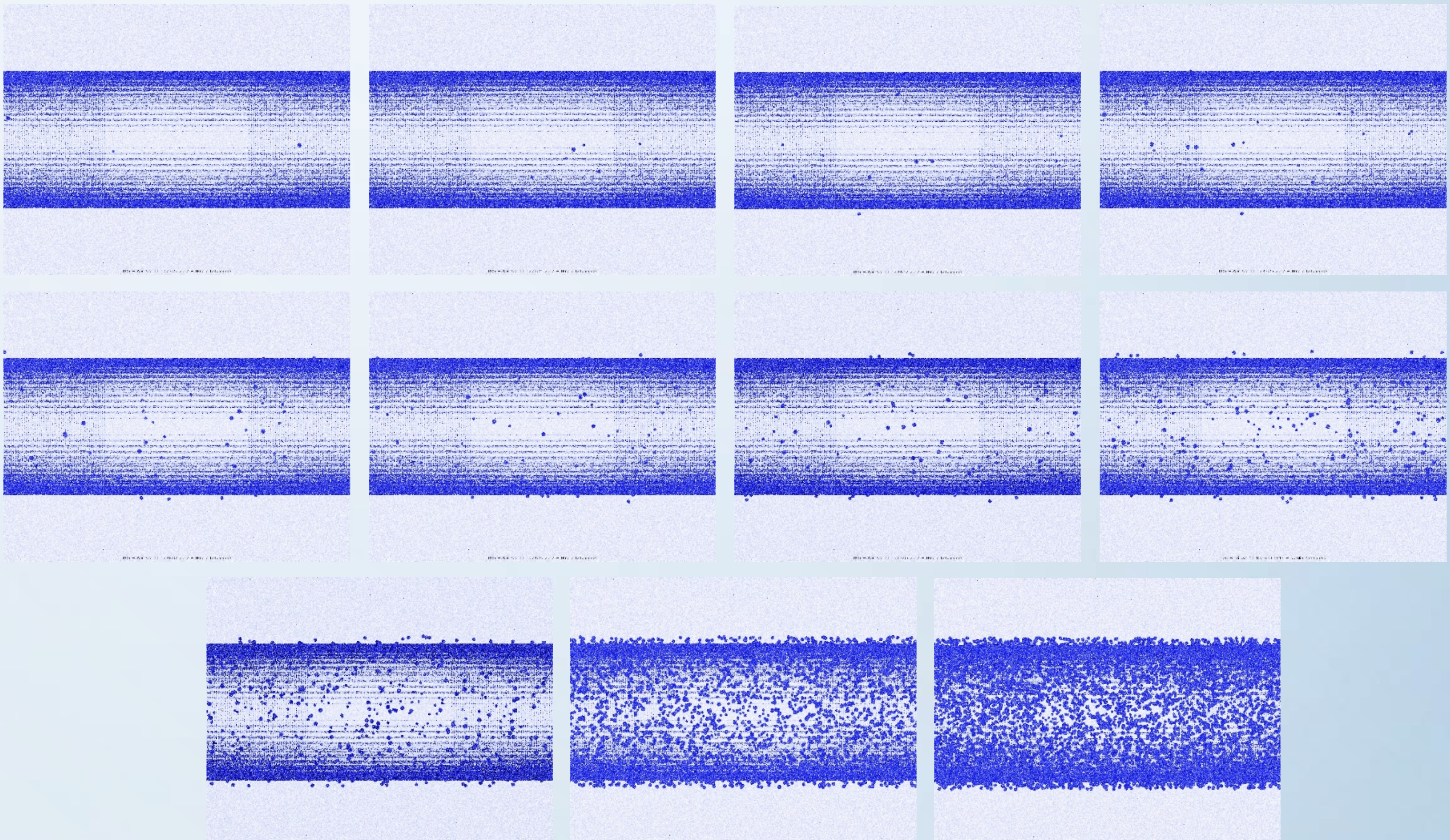


The particles are distributed over the whole length of a cylinder (partially not visible)

- Two liquid material, liquid hydrogen (refractive index n = 1.0974)and liquid methane (refractive index n = 1.286), were tested.
- During program application these data were replaced by the normalized ones, the required normalization is connected with the fact that POV Ray program uses refractive index for gaseous air equal to 1.0.

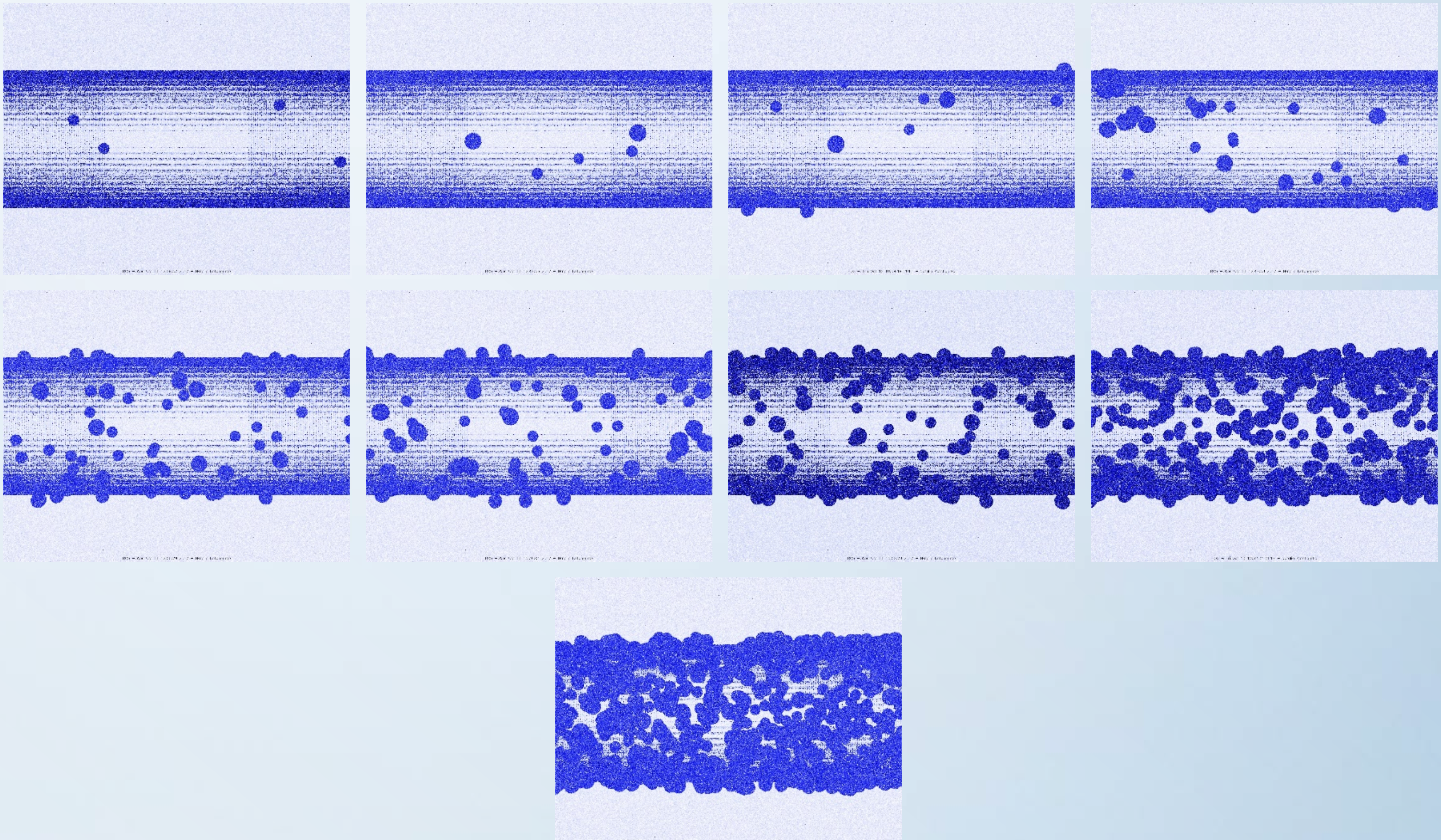
Influence of the particle density: R = 0.5

Influence of particle density for liquid hydrogen particle radius R = 0.5. Number of particles from left to right: 5, 10, 25, 50, 100, 150, 200, 500, 1000, 5000, 10000.



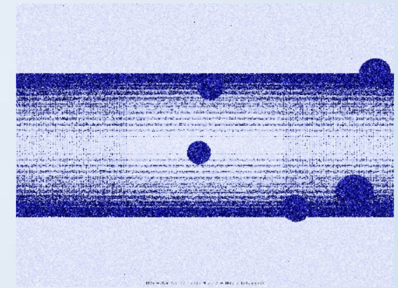
Influence of the particle density: R = 2

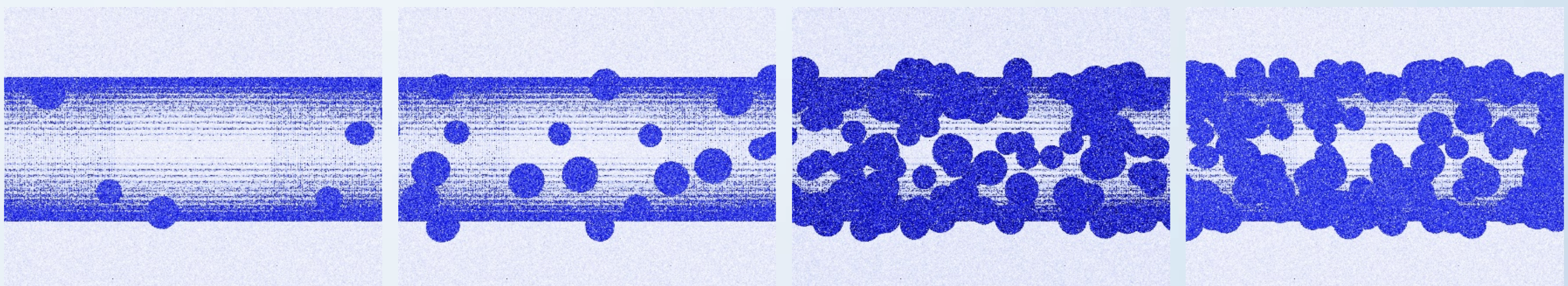
Influence of particle density for liquid hydrogen particle radius R = 2.
Number of particles from left to right: 5, 10, 25, 50, 100, 150, 200, 500, 1000.



Influence of the particle density

Influence of particle density
for liquid hydrogen particle radius R = 4.
Number of particles from left to right: 5, 10, 25, 50, 100, 150, 200.

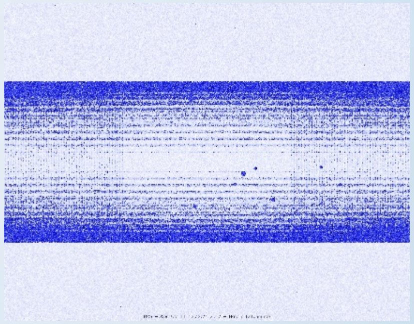


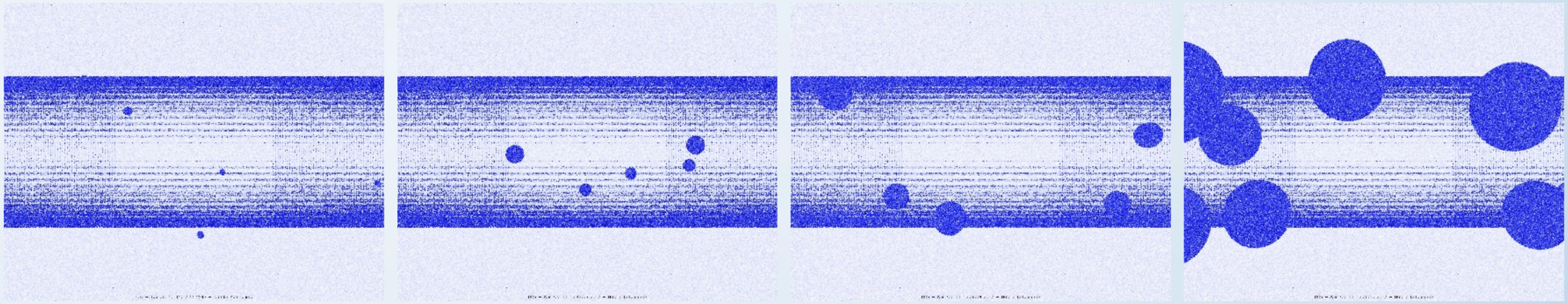


The density of the droplets should not exceed the definite level, when the droplet images begin to overlap and therefore obscure the picture details

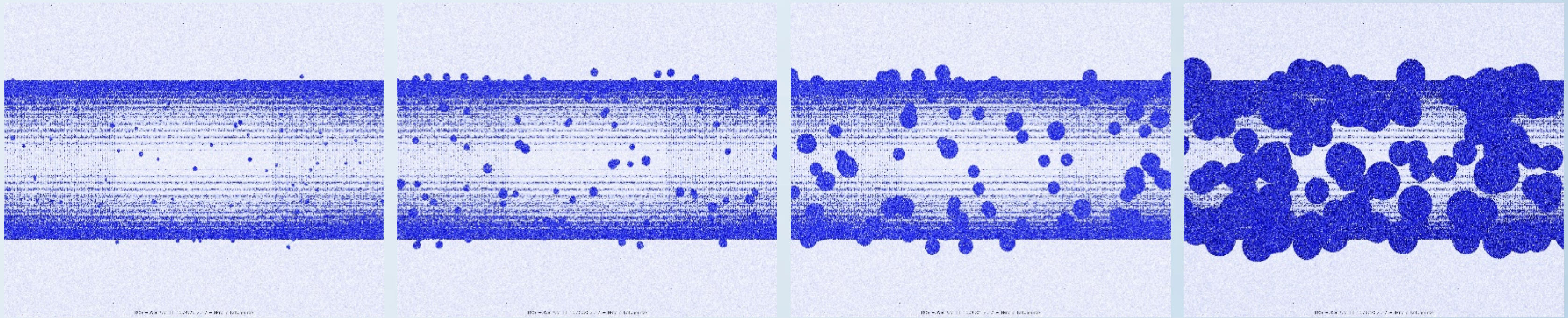
Influence of the particle size

Influence of the particle size for liquid hydrogen. Number of particle N = 10. Particle size (R) from left to right: 0.5, 1, 2, 4, 10.



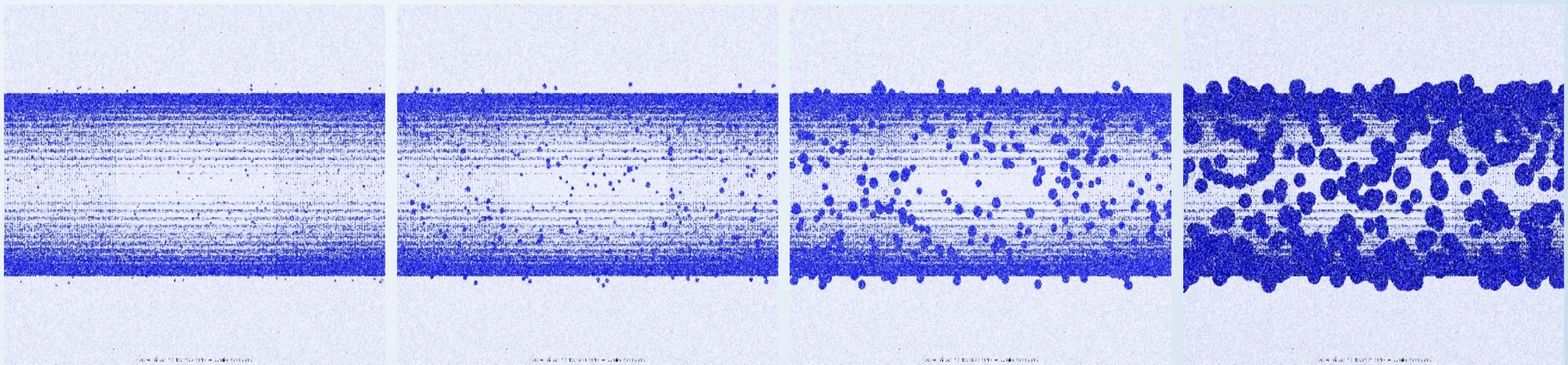


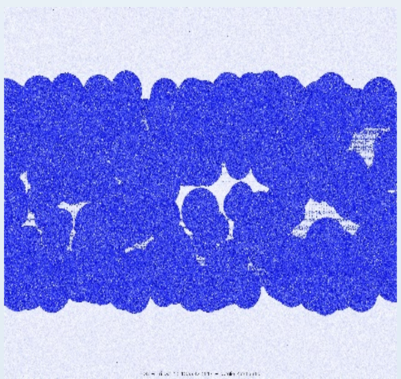
Influence of the particle size for liquid hydrogen. Number of particle N = 150. Particle size (R) from left to right: 0.5, 1, 2, 4.



Influence of the particle size: N = 500

Influence of the particle size for liquid hydrogen. Number of particle N = 500. Particle size (R) from left to right: 0.25, 0.5, 1, 2, 4.

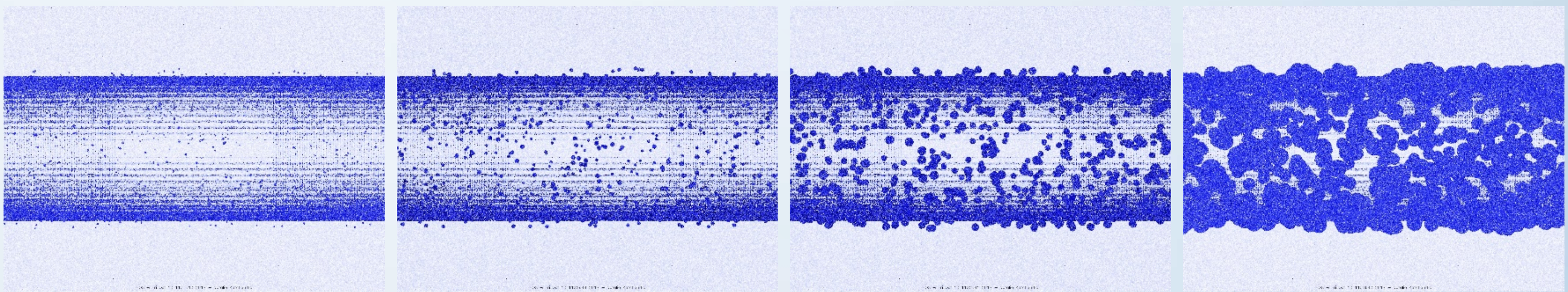




Generally, for the BOS method, the maximum displacement, that can be measured with accuracy according to spatial resolution constraints, should not exceed half of the interrogation area. Thus, the size of one particle that can be visualized must exceed at least 2 pixels. The obtained results fully confirm the theoretical expectations

Influence of the particle size: N = 1000

Influence of the particle size for liquid hydrogen. Number of particle N = 1000. Particle size (R) from left to right: 0.25, 0.5, 1, 2.

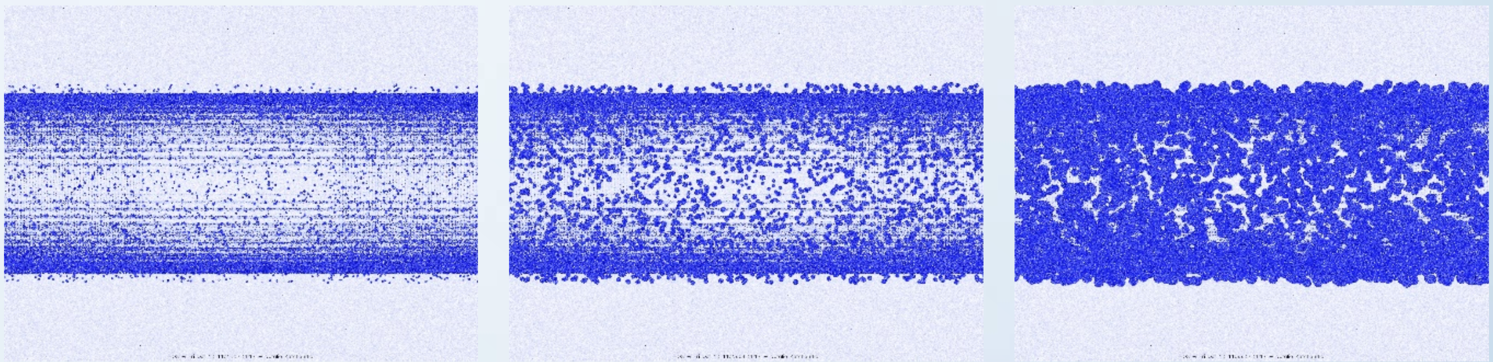


Notice, that typically the POV Ray scene is free of natural noises and, in comparison with the real experiment, can give more detailed information on the presence of particles of small size.

Sensitivity of the BOS method by evaluation of POV-Ray scene depends only on spatial arrangement of the POV-Ray scene and the characteristics of the selected background

Influence of the particle size

Influence of the particle size for liquid hydrogen. Number of particle N = 10000. Particle size (R) from left to right: 0.25, 0.5, 1, 2.



Analysis of the presented scenes demonstrated that the BOS technique is very well suited for the determination of the droplets presence, their sizes and the total number (droplets density).

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Influence of the droplet material

According BOS theory, the values of the ray displacement is proportional to the value of the refractive index .

Material of the droplets can be distinguished by the colors on the BOS image.

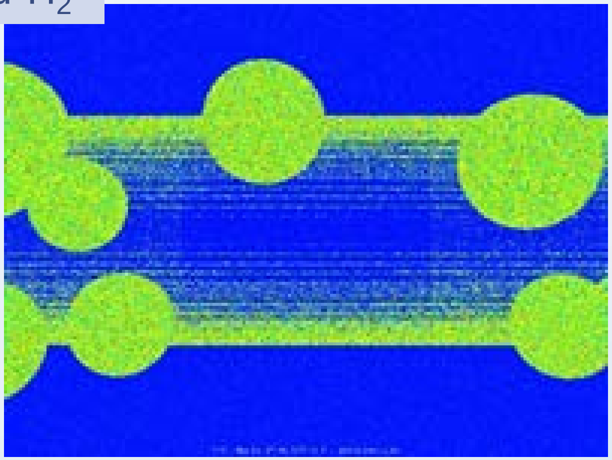
Material	Refractive index n
Air	1.0002926
Liquid H_2 (Hydrogen)	1.0974
Liquid CH_4 (Methane)	1.286

- Two liquid material, liquid hydrogen (refractive index n = 1.0974)and liquid methane (refractive index n = 1.286), were tested.
- During program application these data were replaced by the normalized ones, the necessary normalization is connected with the fact that POV Ray program uses refractive index for gaseous air equal to 1.0.

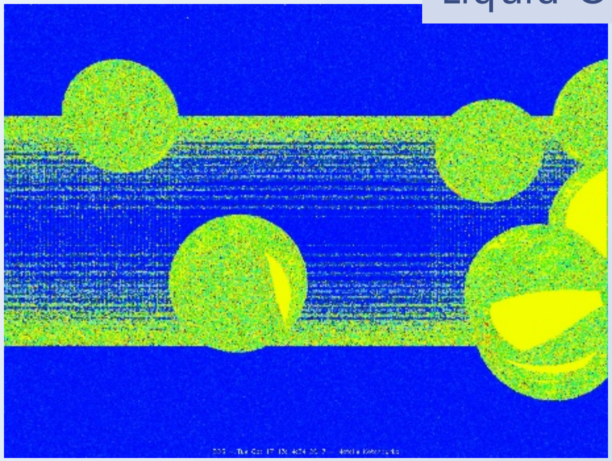
Influence of the droplet material

Influence of the droplet material on the droplet identification. Number of particle N = 10. Particle size R = 10. Liquid hydrogen particle left and liquid methane particle right.

Liquid H_2



Liquid CH_4

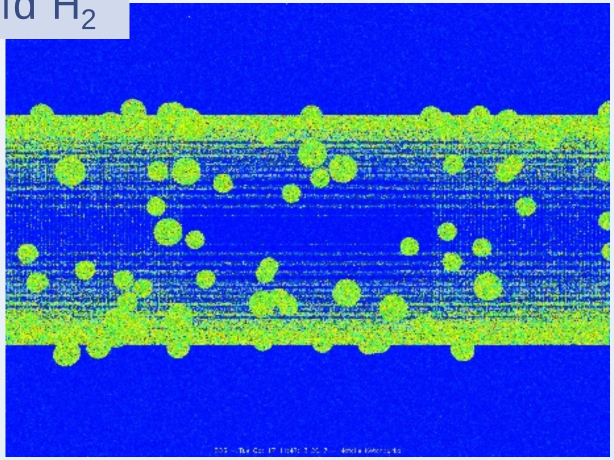


In the droplets located in the image foreground, the color difference is clear visible. For the droplets located deeper in the line of seeing due to perspective distortion, the effective displacement value is reduced and the effect reduces as well.

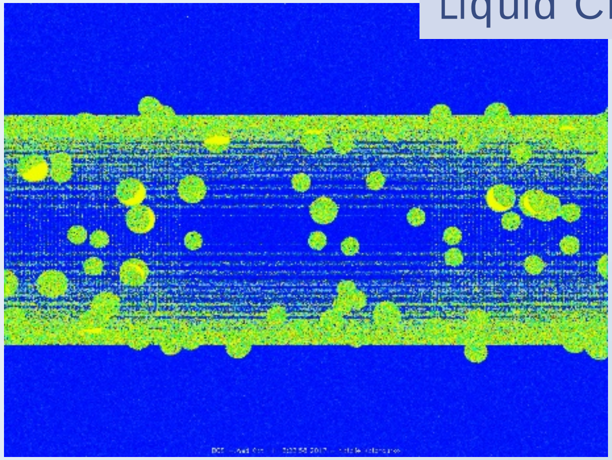
Influence of the droplet material

Influence of the droplet material on the droplet identification. Number of particle N = 100. Particle size R = 2. Liquid hydrogen particle left and liquid methane particle right.

Liquid H_2



Liquid CH_4



Possible reduction of the perspective distortion could diminish the negative consequences and potentially should provide results that are more confident. Preliminary trials with replacement of the perspective camera to orthographic demonstrated the peripheral droplets remains undisturbed.

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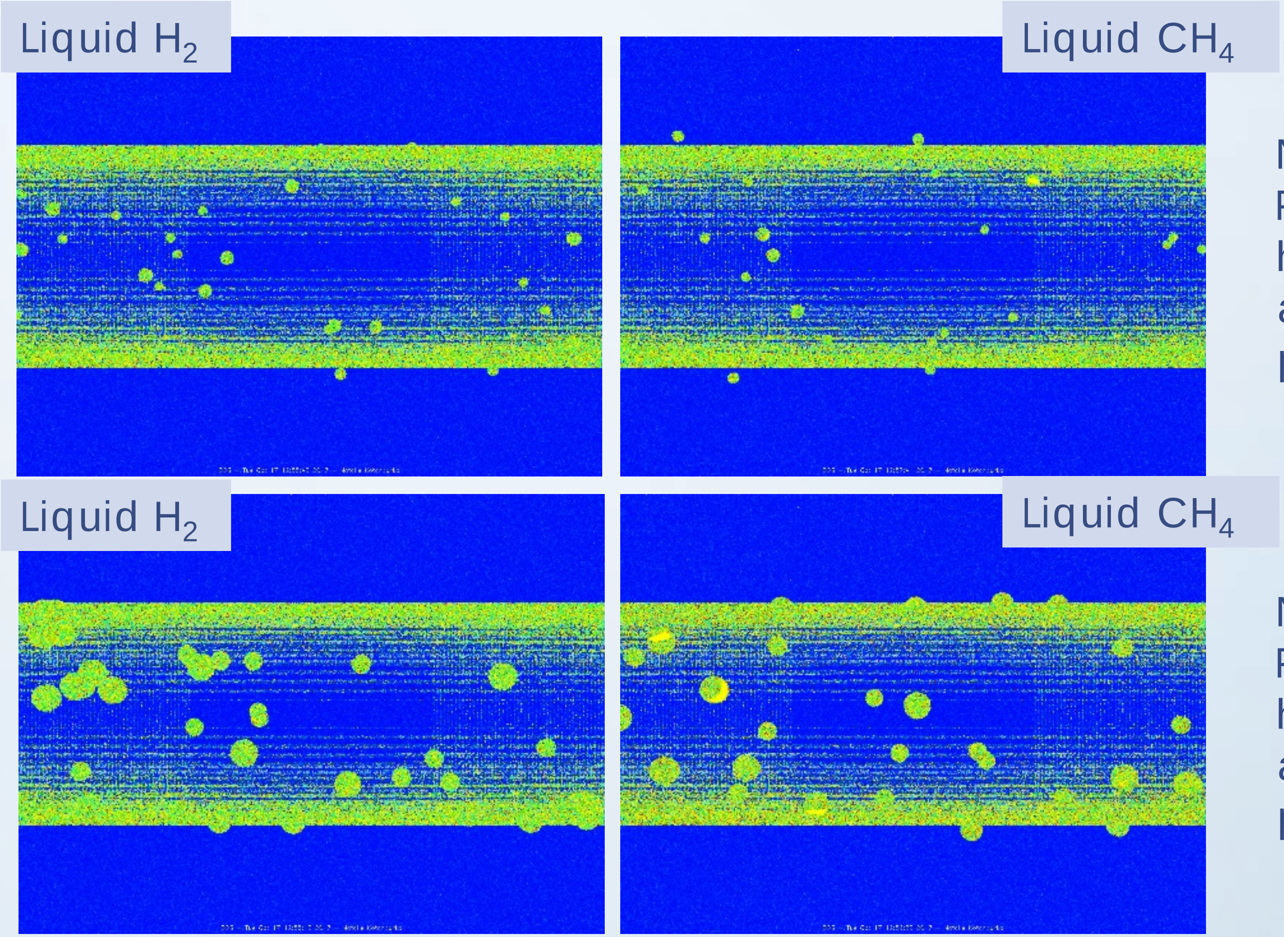
Influence of the droplet material



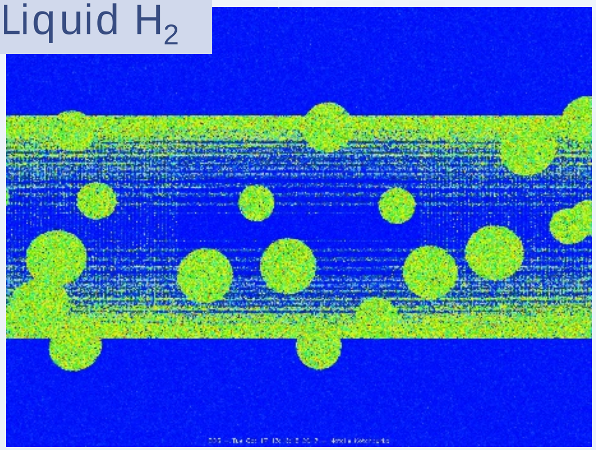
Number of particle N = 50. Particle size <u>R = 1</u>. Liquid hydrogen particle left and liquid methane particle right.

Number of particle N = 50. Particle size <u>R = 2</u>. Liquid hydrogen particle left and liquid methane particle right.

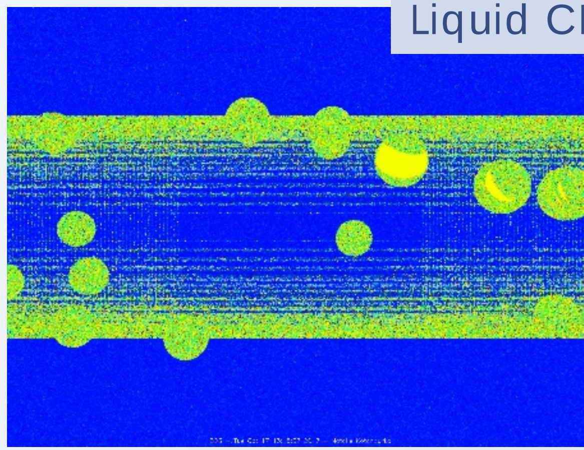
Depending on the BOS processing conditions for every concrete arrangement, it is possible to determine minimal droplet radius, for which it is still possible to distinguish the droplet material. This is clearly seen by comparing BOS images with particle sizes R = 1 and R = 2 and different particle density.

Influence of the droplet material

Liquid H_2

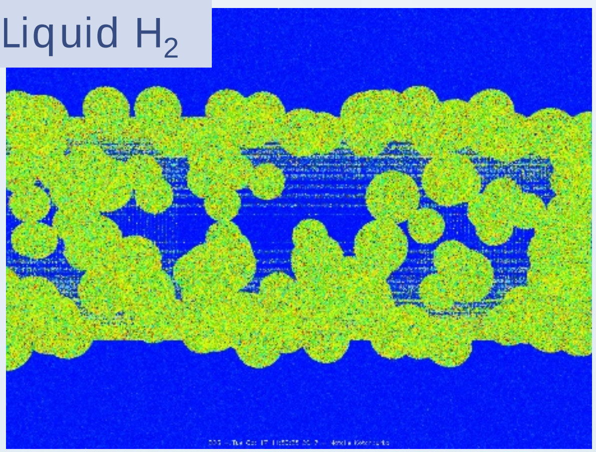


Liquid CH_4

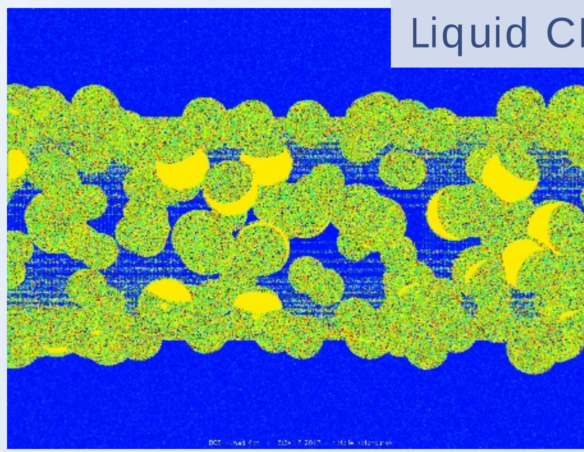


Number of particle N = 25. Particle size R = 4. Liquid hydrogen particle left and liquid methane particle right.

Liquid H_2



Liquid CH_4



Number of particle N = 200. Particle size R = 4. Liquid hydrogen particle left and liquid methane particle right.

Increase of particles number gives possibility to identify particle material in case if all droplets are of the same material.

Summary

- Proposed and implemented method for the coupled work of BOS software together with rendering software POV Ray demonstrated that such numeric tool can be valuable mean for the preparation/optimization of the experiments and post-test processing and results interpretation.
- Obtained results clearly demonstrated: that the BOS technique can be successfully applied to the multi-phase systems and is able to identify the major system properties, such as number and size of condensed materials, and with relatively high level of confidence to determine the droplet material.

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Thank you for attention!