EXPERIMENTAL INVESTIGATION OF SPRAY BEHAVIOUR AND SPRAY INTERACTION FOR DIESEL MULTIPLE INJECTION APPLICATION

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ABSTRACT

Multiple injections is believed to be one way to meet the stricter emission legislation for diesel engines. However, when two or more injections are injected close to each other interactions take place both in the injection equipment and in the cylinder into which fuel is injected. A spray following a previous one will go into the trails of the former spray, and how much interaction there will be depends on, for instance, swirl in the cylinder. This study is focused on the sprays from multiple injections, and in particular spray interaction.

The experiments were carried out in Chalmers high-pressure high-temperature (HP/HT) spray rig equipped with a standard common rail system. An injector with a single hole nozzle with hole diameter of 0.15 mm was used. The measurement techniques used were Mie scattering and LIF.

The measurements showed that penetration depends on the density of the air in the spray rig and that the second injection penetrates faster than the first one, that penetration of the first injection stops when injection stops, but continues when the second injection starts. For a low injection pressure it takes a longer time for injection to be visible and penetration is slower. Also, if the time between injection signals (from the control system) was too small injection never stopped and the double injection became a single one.

1. INTRODUCTION

The use of multiple injections is believed to be one way to meet the stricter emission legislation for diesel engines. However, difficulties may appear when two or more injections are injected close to each other because of interactions that take place. The fast opening and closing of the injector generates pressure waves which cause the pressure to fluctuate in the pipes of the injection system as well as in the injector that make an accurate fuel addition difficult [1]. Also, the spray following a previous one will go into the trails of the former spray, how much interaction there will be depends on, for instance, swirl in the cylinder. This study is focused on the sprays from multiple injections, in particular spray interaction, and also on spray behaviour during injector opening and injector closing.

2. EXPERIMENTAL SETUP

The experiments were carried out in Chalmers high-pressure high-temperature (HP/HT) spray rig. Pressures and temperatures in the spray rig were chosen to correspond to conditions in the cylinder during compression, 24, 44 and 61 bar and 120 and 440 °C in different combinations were used which gives both non-evaporating and evaporating conditions. A standard common rail system controlled by a solenoid valve together with a single hole nozzle with hole diameter of 0.15 mm was used. The injection pressure was normally 1350 bar, and the injection sequence was 1.0 ms injection followed by another injection of 1.0 ms. The time between the injections, here called “dwell”) was usually 0.75 ms, but in one case it was varied. The measurement techniques used were Mie scattering and laser induced fluorescence (LIF). An Nd:YAG laser with 10 Hz pulses was used. The LIF and the Mie signals were captured by using two ICCD-cameras.

Four experimental investigations were made:

- Case 1 – non-evaporating *vs.* evaporating conditions, i.e. the temperature in the spray rig was changed but the other operating parameters (injection sequence, injection pressure, spray rig pressure) were left constant.
- Case 2 – injection pressure variation, i.e. two injection pressures were used, the other parameters were unchanged.
- Case 3 – different duration between first and second injection (here called “dwell”), i.e. from 0.5 ms to 1.25 ms in steps of 0.25 ms
- Case 4 – different spray rig pressure (non-evaporating spray)

3. RESULTS

The general behaviour of a spray was investigated by Magnusson et al. [2]. They found that at the tip of a spray both liquid and vapour was present, in a non-evaporating as well as in an evaporating case, indicating that spray penetration is similar to liquid penetration. Thus it can be assumed that if injection is stopped spray penetration stops. Figure 1 illustrates the spray penetration for a double injection, based on Mie-scattering experiments in the HP/HT-rig. It is seen that penetration of the liquid of the first injection stops when the needle is closed (around 0.8 ms). It is also seen that the second spray penetrates faster than the previous in accordance with earlier findings [3], probably because of gas movements started by the first injection.

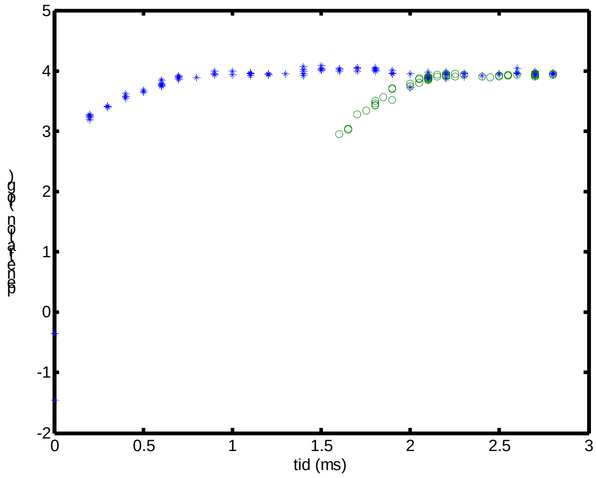

Figure 1. Spray penetration for a double injection; the stars and the circles represents the first and the second injection respectively. Time in ms along the horizontal axis, penetration in the vertical direction.

When the control system of the Common Rail injection system sends a signal to the solenoid to start an injection it takes some time before injection starts, in our case at least 0.2 ms. Also, when closing begins injection goes on until the needle is closed, here around 0,5 ms. This means that when the control system orders an injection sequence of 1 ms injection, "dwell" 0.75 ms and a second injection of 1.0 ms, this does not mean that this is the way injection takes place. In fact, injection #1 will last from 0.2 ms to 1.5 ms (if we assume that the numbers given previously can be used). Injection #2 will then start at 1.95 ms (1.75+0.2) and go on until 3.25 ms. (Remember that the numbers used here are an example, the real values varies depending on injection system and operating conditions.) Another thing that may happen is that if the time between two injections is too short the needle never closes completely and the injection never stops. For our equipment that has happened with a "dwell" of 0.5 ms (but not always).

In Figures 2-4 the Mie and LIF measurements of Cases 1-3 are presented, the results of Case 4 are only stated but some of the measurements used for that care is also used in the other cases. The times chosen corresponds to just after needle opening (0.5 ms), later during the same injection (0.8 ms), just after the start of the second injection, similar to the first time (1.0+0.75+0.5 =2.25 ms), and later during the second injection. The pictures represent instantaneous values, no averaging has been performed. Thus, the sequence of results shown are from different sprays and there is a variation from spray to spray.

All pictures show an area of approximately 1000×450 mm. The laser light comes from the right, that is why the signals are stronger on that side.

3.1. Case 1 – non-evaporating (temp. 120 °C) *vs.* evaporating conditions (temp. 440 °C)

Penetration is faster in the high temperature case than in the low temperature case and the reason is the difference in density (20 *vs.* 11 kg/m^3). It is also seen that in the evaporating case the liquid from the first injection disappears before the second injection starts so the liquid encounters only vapour.

For the non-evaporating conditions it seems that the second injection reaches about the same distance as the first (look at the dark areas of the LIF pictures and compare 0.8 and 2.5 ms). However, in order to be able to make a correct comparison the results of the second injection should have been captured at 2.55 ms, not 2.50 ms. So the results from Figure 1 saying that the second injection penetrates faster holds.

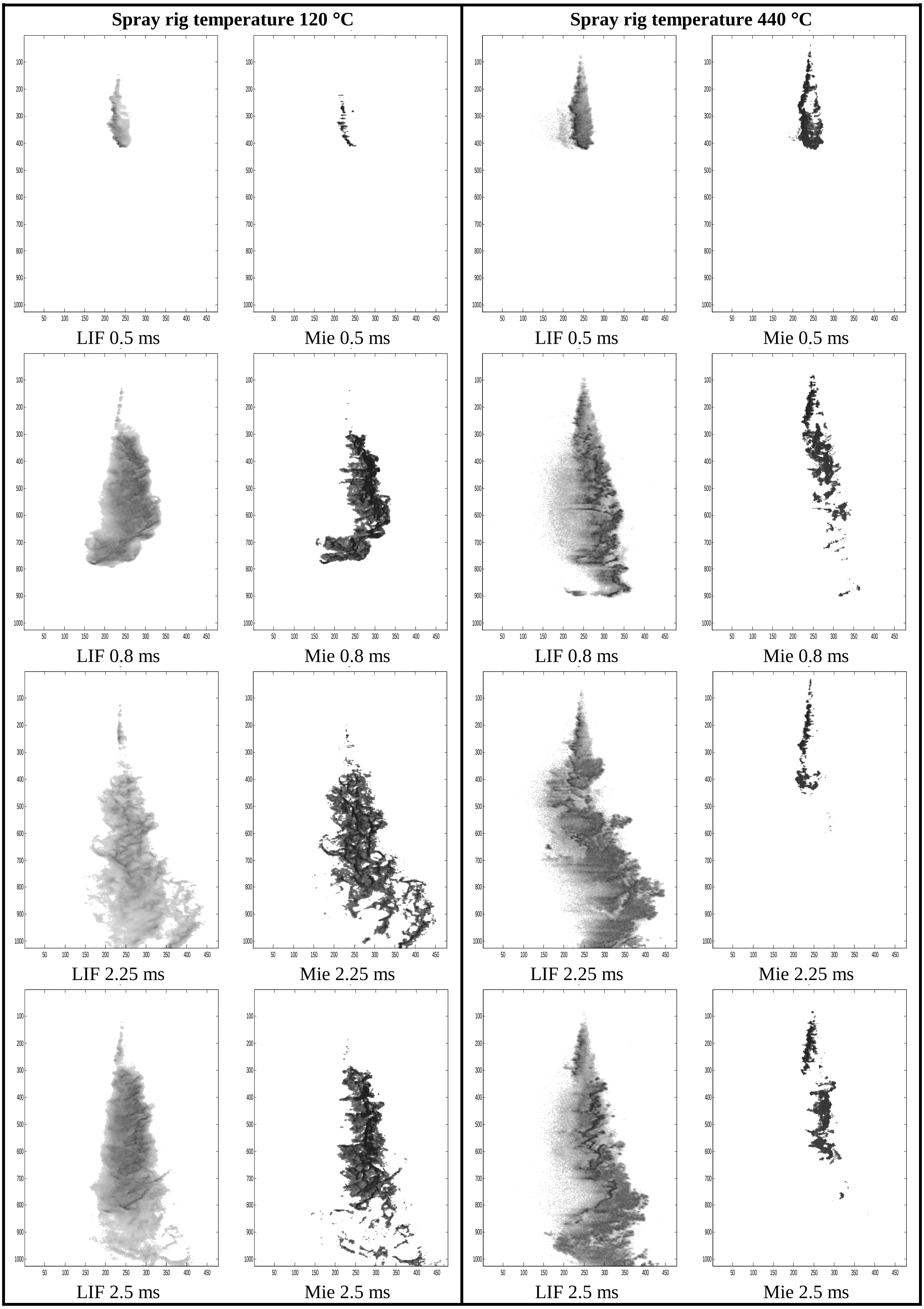

Figure 2. Results of Case 1 – non-evaporating (temperature 120 °C) *vs.* evaporating conditions (temperature 440 °C) Other operating conditions: Injection sequence 1.0 ms injection, 0.75 ms “dwell”, 1.0 ms injection, Injection pressure 1350 bar, Spray rig pressure 24 bar

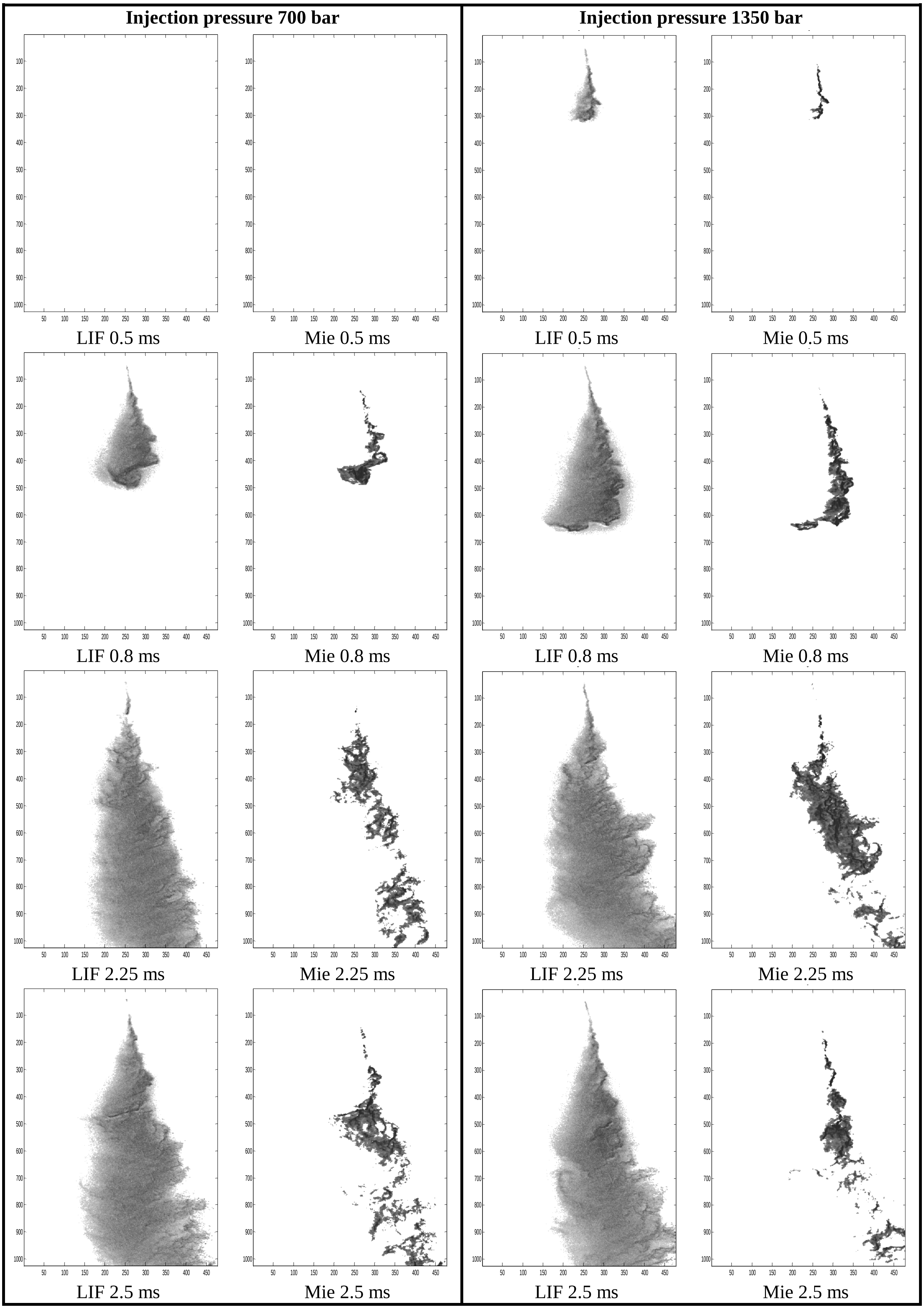

Figure 3. Results of Case 2 – injection pressure variation
Other operating conditions: Injection sequence 1.0 ms injection, 0.75 ms "dwell", 1.0 ms injection,
Spray rig pressure 44 bar, Spray rig temperature 120 °C (non-evaporating)

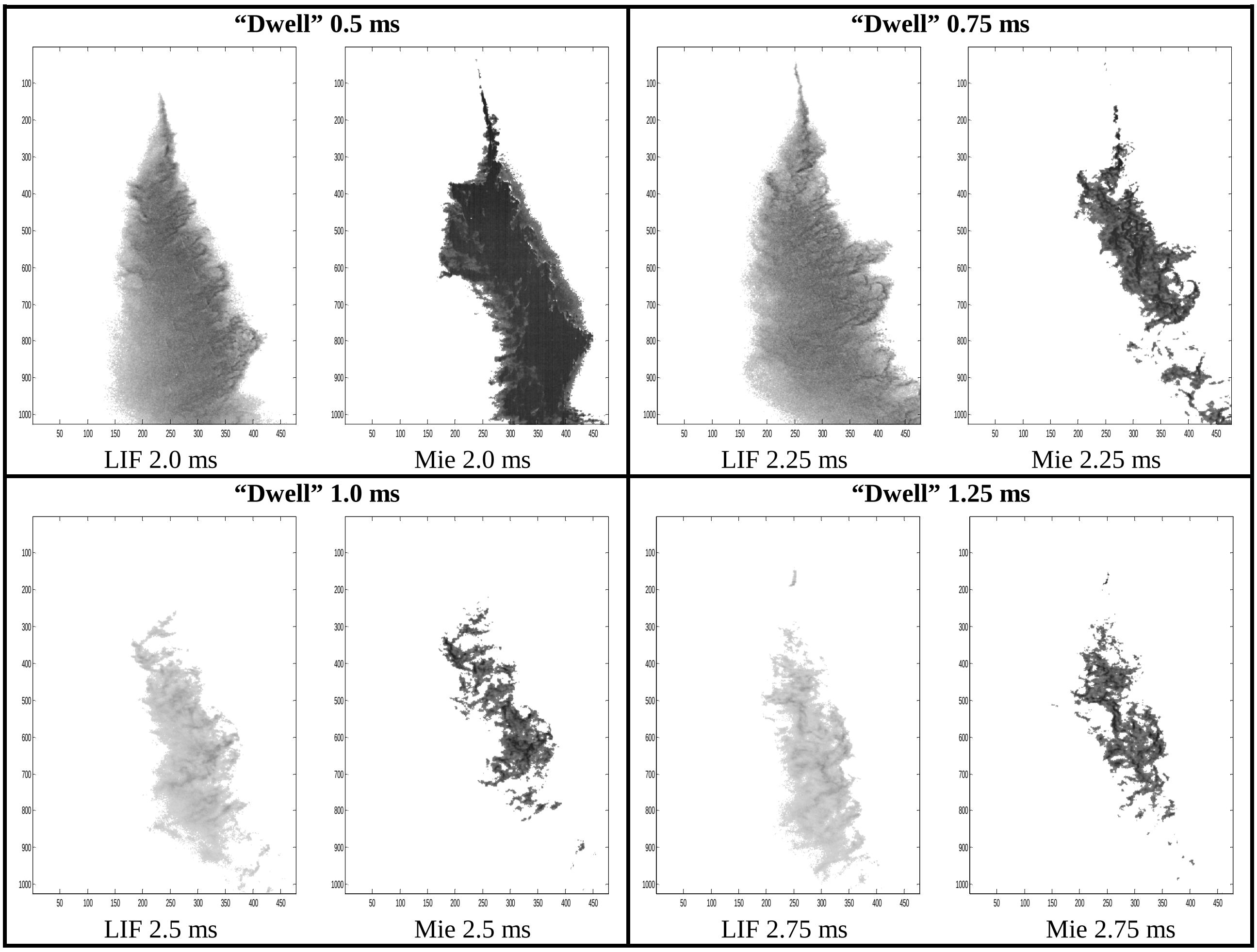

Figure 4. Results of Case 3 – different duration between first and second injection (“dwell”)
Other operating conditions: Injection sequence 1.0 ms injection, different “dwell”, 1.0 ms injection,
Injection pressure 1350 bar, Spray rig pressure 44 bar, Spray rig temperature 120 °C (non-evaporating)

3.2. Case 2 – injection pressure variation

Here it is seen that injection starts faster and with a stronger penetration when the driving force, *i.e.* the injection pressure, is larger. For the 700 bar case injection is not visible in neither the 0.5 ms nor the 2.25 ms pictures, whereas it is observed when the injection pressure is 1350 bar.

3.3. Case 3 – different duration between first and second injection (“dwell”)

For this case only the time corresponding to 0.5 ms after start of second injection is shown. For the cases with a long “dwell” the signal from the first spray is very weak, as if both the liquid and the vapour have dispersed to the surrounding air. Note that the air in the spray rig is moving downwards with a very low velocity (close to 0.1 m/s) and no turbulence is present. So if this would be in a cylinder where turbulent gas movements are present the dispersion would have been ever stronger.

In the case where the duration between the injections was only 0.5 ms it is likely that the needle never closed completely, but that injection went on continuously. Thus the strong signal from the Mie scattering measurements in this case.

3.4. Case 4 – different spray rig pressure (non-evaporating spray)

- Injection sequence 1.0 ms injection, 0.75 ms “dwell”, 1.0 ms injection
- Injection pressure 1350 bar
- Spray rig pressure 24, 44 and 61 bar
- Spray rig temperature 120 °C (non-evaporating)

There are no separate figure for this case but the 24 and 44 bar cases can be seen in Figures 2 and 3. The only clear effect of increasing the pressure in the spray rig is that penetration is slower. It can be seen from comparing Figure 2 and Figure 3 and the result from the 61 bar experiment confirms this.

4. CONCLUSIONS

Experiments with double injections in a high pressure high temperature spray rig show that

- penetration depends on the density of the air in the spray rig,
- the second injection penetrates faster than the first one,
- penetration of the first injection stops when injection stops, but continues when the second injection starts,
- for a low injection pressure it takes a longer time for injection to be visible and penetration is slower,
- if the time between injection signals (from the control system) is too small injection never stops and the double injection becomes a single one.

5. REFERENCES

1. R. Ehleskog and S. Andersson, Numerical and Experimental Investigation of Fuel Properties Influence on the Dynamic Behaviour of a Diesel Injection System, VAFSEP 2004, Dublin, pp. 60-65, 2004.
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3. G. Wigley and G. Pitcher, An Investigation of Pilot Injection with a High Pressure Common Rail Diesel Injection System, ILASS- Europe '98, UMIST, Manchester, pp. 256-261, 1998.