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The Effect of Swirl on Spark Assisted Compression Ignition (SACI)

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ABSTRACT

Auto ignition with SI compression ratio can be achieved by retaining hot residuals, replacing some of the fresh charge. In this experimental work it is achieved by running with a negative valve overlap (NVO) trapping hot residuals. The experimental engine is equipped with a pneumatic valve train making it possible to change valve lift, phasing and duration, as well as running with valve deactivation. This makes it possible to start in SI mode, and then by increasing the NVO, thus raising the initial charge temperature it is possible to investigate the intermediate domain between SI and HCCI. The engine is then running in spark assisted HCCI mode, or spark assisted compression ignition (SACI) mode that is an acronym that describes the combustion on the borderline between SI and HCCI.

In this study the effect of changing the in-cylinder flow pattern by increased swirl is studied. This is achieved by deactivating one of the two intake valves. The effect of the increased turbulence is studied both on the initial slow heat release originating from the spark plug and on the following HCCI combustion.

The early SI flame development is highly dependent on the flow field so by increasing the turbulence the flame expansion speed is affected, also at high residual rates. Also, HCCI combustion rate has been shown to slow down as turbulence is increased. As high reaction rate is an issue for HCCI combustion this means that it could be possible to reduce the reaction rate and simultaneously increase the possible usage of SACI combustion by increasing the turbulence.

Synchronized simultaneous pressure and high speed chemiluminescence measurements are conducted making it possible to reproduce fully resolved cycles from the onset of the spark throughout the entire combustion event. From the chemiluminescence images it is possible to calculate a flame expansion speed. The effect on combustion in terms of auto ignition timing, combustion duration and the amount of heat released in the different combustion modes is investigated using heat release analysis. LDV measurements are conducted to support the turbulence effects on SACI combustion.

INTRODUCTION

Throughout the last decades Homogeneous charge compression ignition (HCCI) has been the subject of intensive research that is now branching into two main paths. Diesel HCCI with partially premixed combustion (PPC) and gasoline HCCI with different strategies of residual usage to reach auto ignition temperature, also often refered to as controlled auto ignition (CAI) combustion. In the latter concept the strategy is to run the engine in SI mode when high output power is required and in HCCI mode at low and part load to keep up efficiency. The proposal for using negative valve overlap (NVO) to reach HCCI combustion in an SI engine environment was first published by Willand et al. in 1998 [1]. The first presented results of NVO HCCI combustion by Lavy et al [2] followed in 2000. Cycle to cycle mode switches from SI to HCCI and vice versa has been demonstrated on multi cylinder engines [3] showing the possibility of such a concept.

Recent research has shown the potential of using spark assistance to aid gasoline HCCI combustion at some operating conditions, and even extend the operating regime into regions where unsupported HCCI combustion is impossible. The first reports of combustion stability effects by usage of a spark with NVO HCCI were published by Koopmans et al [4]. Later experiments have shown the possibility to also affect combustion timing [5] and to cancel oscillating behaviour in combustion timing at low temperature conditions [6]. Spark assistance is also investigated when going towards higher possible loads as described by Urushihara et al. [7].

This implies that the usage of spark assisted HCCI or spark assisted compression ignition (SACI) could help to expand the usable operating regime for NVO HCCI as well as to assist during mode switching events. However more knowledge is needed on the nature of the spark effects and the influence of the ensuing HCCI combustion. This since HCCI combustion normally is run highly diluted with air or residuals, an environment that a normal SI flame would not be expected to endure.

There are ways to increase the performance of SI combustion at unfavourable conditions. Prior SI combustion experiments with the current combustion chamber have shown great improvement in lean burn capability with maintained combustion stability at lean conditions [8]. This has been accomplished by both inlet valve deactivation and late intake valve closing (IVC). The deactivated inlet valve changed the tumbling in-cylinder flow to a swirling motion with increased turbulence intensity and thus faster burn rate. The outcome was even more pronounced with late IVC.

The turbulence is shown in Figure 1 for the case of two inlet valves, and for inlet valve deactivation in Figure 2, both with standard valve timings. The measurements are conducted from one side to the other in the pent-roof, passing the spark plug location. The increase in turbulence is significant. At lean conditions the burn duration of 0 to 10 % heat released could almost be halved.

The above results encourage investigation of SACI combustion at conditions with elevated turbulence levels to further increase the usefulness of SACI combustion.

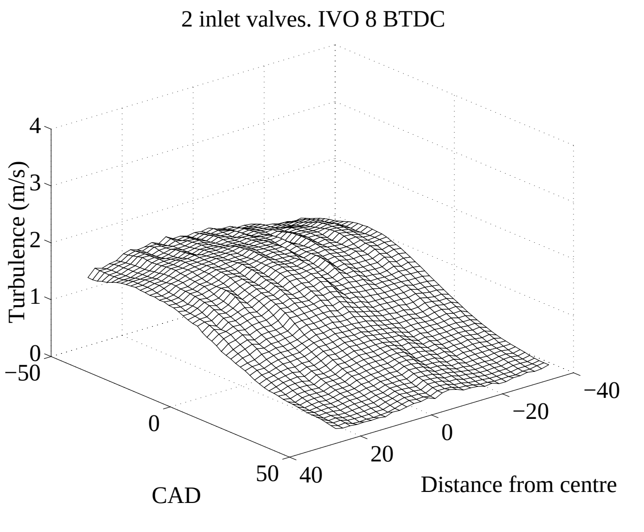

Figure 1. Turbulence for two valve inlet strategy [8].

It is generally accepted that the HCCI combustion process is controlled by chemical kinetics, thereby the effects of turbulent mixing should not affect the chemical reactions and the heat release process since the local chemistry is an order of magnitude faster than turbulence effects.

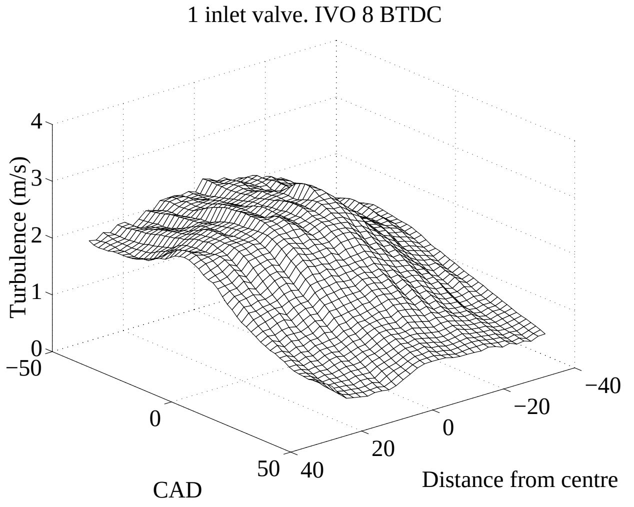

Figure 2. Turbulence for inlet valve deactivation strategy [8].

Earlier experiments have however shown a decreased HCCI combustion burn rate for geometry generated turbulence [9, 10]. For inlet generated turbulence in a lean burn HCCI engine without residuals [11] only minor changes in combustion behaviour could be seen and only small moderations of the intake temperature was needed to maintain the combustion timing.

For HCCI combustion with NVO, some stratification between the trapped hot residuals and the fresh charge can be expected. This means that both temperature and gas composition is inhomogeneous. Thereby the effect of turbulence could be increased. To investigate the role of turbulence for SACI combustion inlet port deactivation is used. Turbulence intensity is measured using Laser Doppler Velocimetry (LDV). The effect on the early flame development is studied with high speed broad band chemiluminescence imaging and the auto ignition timing by pressure and heat release analysis.

EXPERIMENTAL SETUP

ENGINE SETUP

The experimental engine is based on a Volvo D5, which is a passenger car sized five cylinder compression ignition (CI) engine. The engine is converted to single cylinder operation with a bowditch piston extension. The remaining four pistons are motored and are equipped with counter weights to compensate for the extra weight of the piston elongation on the operated piston. A 58 mm diameter quartz glass is fitted in the piston extension resulting in a flat piston crown. The optical access is approximately 51 % of the total combustion chamber area. Also small vertical windows are mounted perpendicularly in the pent-roof giving see-thru access to the vicinity of the sparkplug. The combustion chamber is of SI type with a high pent-roof, four valve design. More engine specifications can be found in Table 1.

Table 1

Displacement	0.48 Liters
Valves per cylinder	4
Bore	81 mm
Stroke	93.15 mm
Combustion chamber	Pent-roof
Compression ratio	9:1
Valve timings	Fully flexible
Speed	1200 rpm

The Engine is fitted with a pneumatic valve train system supplied by Cargine Engineering [12]. The system features fully flexible valve lift, duration and timing as well as deactivation individual for each valve. The engine with the valve actuators mounted on the cylinder head is shown in Figure 3.

In this work a symmetrical NVO is used, meaning exhaust valve closing (EVC) at the same CAD before top dead centre (BTDC) as intake valve opening after top dead centre (ATDC). Intake closing and exhaust opening have been fixed at -160 and 160 CAD ATDC respectively. For all cases a lift height of approximately 8 mm is used with an opening and closing ramp of approximately 25 CAD at 1200 rpm.

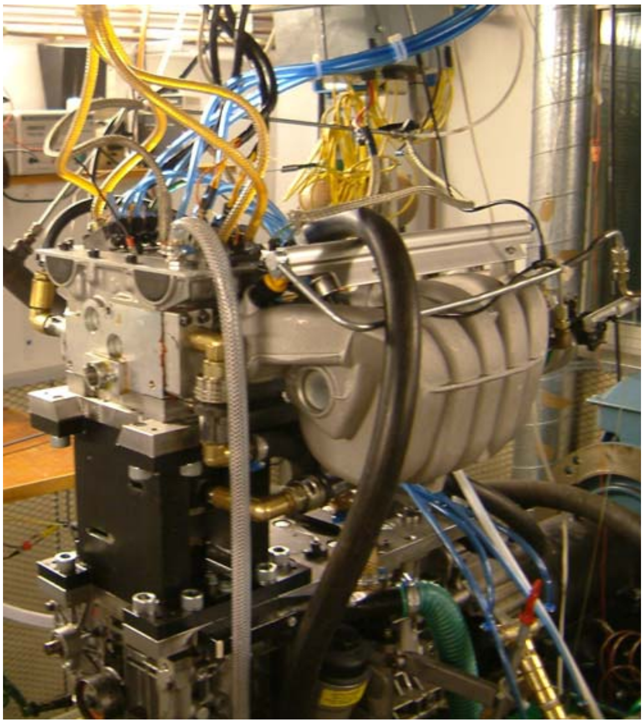

Figure 3. Single cylinder engine with optical access and pneumatic free valve train.

MEASUREMENT SYSTEM

Pressure is monitored with a Kistler 6117B combined sparkplug and pressure sensor with a sample rate of 5 per CAD. The piezo electric pressure sensor is flush mounted in the sparkplug. Emissions are monitored using a Horiba MEXA 8120, measuring NO_x, CO, HC, CO_2 and O_2.

The fluid flow is measured by a 2-component Dantec-fibre flow LDV system at a wavelength of 488 and 512 nm respectively, thus giving two dimensional velocity information. The setup consists of an Ar-ion laser, colour separator and fibre transferring of the laser beams to a probe with a beam expander. An f 310 lens is used to focus the beams near the spark plug through the optical access to the combustion chamber pent-roof. The backscattered light from the seeding particles is collected and transferred back to two photo multiplier (PM) tubes where it is converted to an electric signal. This signal is digitized and analysed with fast Fourier transformation (FFT) by burst spectrum analysers (BSA) to obtain valid velocity data. The BSAs are run with an external frequency generator giving a maximum mean data rate of 150kHz. A polystyrene-latex dispersion with a mean size of 0.46 μm is used as seeding and is added upstream of the intake manifold by a set of Hudson Up-Draft nebulizers.

Combustion is seen by chemiluminescence imaging from below through the piston crown using a Phantom high speed framing camera running synchronised with the engine, taking 2.5 images per CAD. This corresponds to 18000 Hz at 1200 rpm. At this framing rate, image resolution is limited to 304 x 304 pixels, giving a pixel size of 0.2 mm. The camera is used in combination with a Hamamatsu high speed gated image intensifier. This allows short exposure times with less smearing of the images. For all cases an exposure time of 12 μs has been used. A 105 mm f 2.8 macro lens is used and apertures have been kept in the range from 5.6 to 11 depending on operating conditions.

In general both the spark plasma and the main bulk combustion are very bright whereas the early combustion has very low chemiluminescence intensity. Apertures and gains have been balanced to see the early combustion, still not saturating the camera during high rate of heat release (RoHR).

For each operating point in the sweeps simultaneous pressure and image acquisition is conducted. Ten chemiluminescence cycles are captured at each point together with 1000 consecutive pressure cycles.

FUEL

Due to optical constrains the engine is run with a somewhat low compression ratio (CR = 9:1) and a cooling water temperature of 70° C. Because of the usage of seeding particles it was not desired to heat the inlet air, therefore a fuel blend with lower octane number than normal has to be used. A blend of 40 % ethanol and 60 % n-heptane (mass percentage) is used. The choice of ethanol instead of iso-octane is due to that the former seems to cancel the low temperature reactions (LTR) normally associated with n-heptane. The LTR usually occurs at around 20 CAD BTDC and could smear any early reactions originating from the spark plug. No LTR were observed for these operating conditions even during tests with 10 % ethanol and 90 % n-heptane.

IMAGE PROCESSING

The images obtained with the high speed camera have an extremely low noise level. This makes it possible to calculate, with good precision the perimeter of a burning structure from the intensity image. Similarly the projected flame area can be obtained. The process is outlined in [Figure 4].

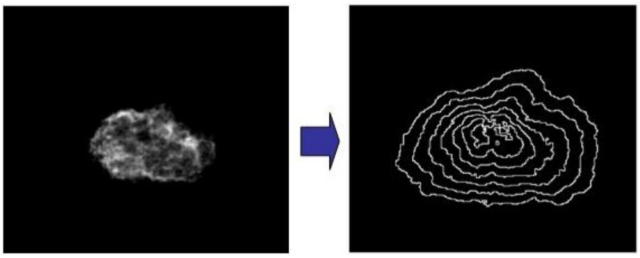

Figure 4. Left: Early flame originating from the spark plug. Right: Obtained perimeter for growing flame, image showing every fifth calculated perimeter (2 CAD separation)

A mean expansion speed is calculated according to Heywood [13] with the assumption that the flame is growing as a sphere, although it is here calculated in two dimensions, thus a circle. Therefore the perimeter of each flame image is calculated as the perimeter of a circle with the same area as the projected area of the flame

By applying Equation 1 using the differential area between two images and calculating the time step, then dividing it with the calculated flame perimeter length (L), a mean expansion speed of the flame is obtained.

Equation 1. Mean expansion speed

$$u_f = \frac{dA/dt}{L} \qquad L = \text{Perimeter length}$$

RESULTS

TURBULENCE INFLUENCE

The high influence of turbulence on SI combustion is well known. Increasing turbulence level wrinkles the growing flame, increasing the flame surface, thus the expanding flame area. Further it is well documented that the turbulence level increases with inlet port deactivation with the combustion chamber geometry used in this study. The question that remains is if turbulence plays the same role for residual diluted SACI combustion. For NVO HCCI and SACI combustion the state of the residuals in the current cycle depends highly on the previous cycle both in terms of composition and temperature. This could indeed influence the conditions for the growing flame as it has been seen to give rise to oscillation of the HCCI combustion timing [14].

To investigate the effects of turbulence LDV measurements are conducted 1.5 mm away from the edge of the spark plug gap just upstream of the mean tumble flow. The engine is run at stoichiometric conditions with wide open throttle (WOT) in SACI mode with both inlet valves activated and a NVO of 200 CAD

From the velocity data obtained by the LDV measurements turbulence information are calculated according to Johansson [15]. For each measurement point 120 cycles of velocity data are collected, the calculated position of CA at 1 % heat released is then correlated against the turbulence level using a linear correlation coefficient according to Equation 2.

Equation 2. Linear correlation coefficient

$$R(i,j) = \frac{C(i,j)}{\sqrt{C(i,i) \times C(j,j)}}$$

Figure 5 shows the Correlation coefficient of the relation between CA 1 % heat released and the turbulence level for 120 cycles as a function of crank angle. Three different measurement points are shown all at the same distance (y) from the spark gap (upstream of the mean flow), but at different depth (x). According to statistic theory the correlation is not very high but it does exist. For all three measurement points the trend is the same that the correlation decays closer to TDC.

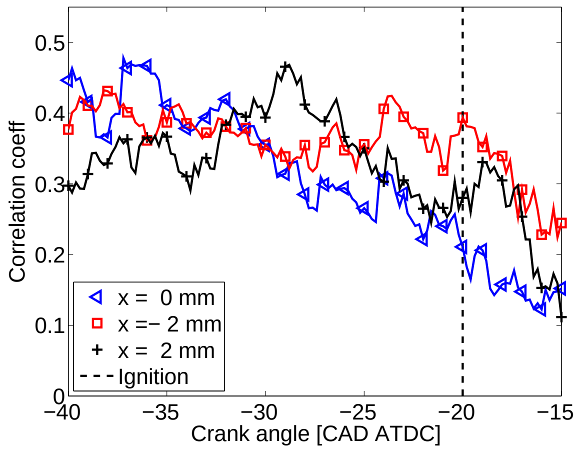

Figure 5. Correlation coefficient of relation between timing of CA 1 % heat released and turbulence over CAD.

The nature of the correlation is presented in Figure 6. This is at the crank angle of spark discharge shown by the black dashed line in Figure 5 for the measurement at x = -2 mm.

When fitting a second order polynomial to the turbulence scatter an earlier position of CA 1 % burned is seen for increased turbulence levels. The correlation coefficient at this position is 0.39. This behaviour is consistent if looking at both different crank angles and measurement points. At higher turbulence levels the effect is the opposite and the flame growth is delayed. This effect is however not as pronounced for all measurement points.

The retarded flame growth for very high turbulence levels could be due to increased heat losses when the early flame is too heavily wrinkled with high area to volume ratio.

It can be concluded that the turbulence level plays an important role for the early flame propagation in SACI combustion with high residual rates.

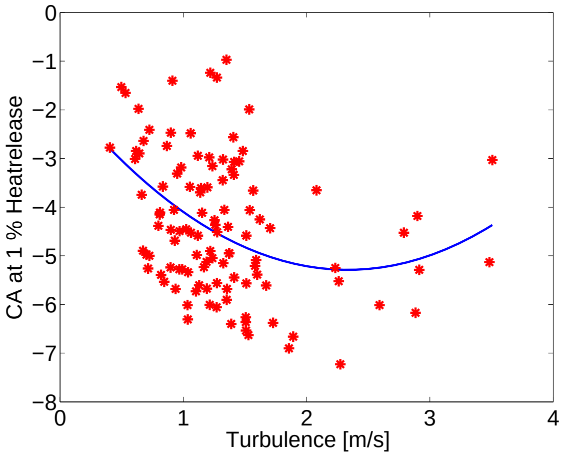

Figure 6. Correlation between CA at 1 % heat released and turbulence at -20 CAD ATDC, corr. coeff = 0.39.

FLAME EXPANSION SPEED

As the residual rate is increased by increasing the NVO the flame speed decays. The calculated flame expansion speed for an increased NVO is shown in Figure 7. The engine is run with constant spark timing at – 19 CAD ATDC. All points are run stoichiometric at constant fueling so for increased NVO, higher residual rates are balanced by reduced throttling i.e. increased intake pressure until 200 CAD NVO where the engine is run practically un-throttled.

Due to the low octane fuel some of the charge burns with HCCI combustion already at low NVO. The HCCI part of the SACI combustion increases with increased NVO, and full HCCI is reached at 200 CAD NVO with a slightly lean charge. The engine load at 202 CAD NVO is 3.3 bar $IMEP_{net}$. As the NVO is decreased also load decreases due to increased pumping losses.

As explained in [16] the possibility to still have flame propagation at these residual diluted conditions is thought to be due to elevated temperature of the residuals pushing the limit of where the heat losses from the early flame to the surroundings is too high. This is combined with the fact that the slower SI combustion with SACI can be accepted since it is followed by the onset of HCCI combustion, keeping down the total burn duration.

The effect of swirl is investigated by inlet valve deactivation while simultaneously recording in-cylinder pressure information and taking high speed videos of broad-band chemiluminescence. To ensure that the results are valid, the measurements are started with a reference case with both inlet ports activated. Then one port at a time is deactivated. Finally the reference case is run again.

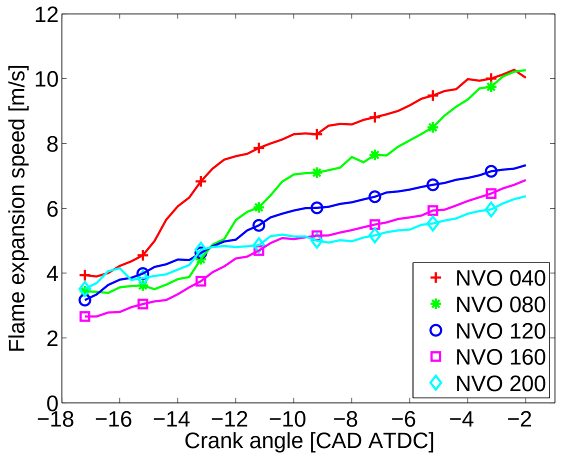

Figure 7. Calculated flame expansion speed for increased NVO.

Figure 8 shows the mean expansion speed for a NVO of 40 CAD. The calculation of flame expansion speed starts some CADs after the spark is set of as soon as a growing flame can be detected, and is terminated before either the flame grows bigger than the quartz glass or auto ignition occurs, whichever comes first. For the 40 CAD NVO a clear effect of increased turbulence by inlet valve deactivation can be seen. When both inlet valves are active and the in cylinder flow consists of a pure tumble flow pattern the same expansions speeds can be seen for both reference cases, reaching around 10 m/s which corresponds well to the calculated speed in the NVO sweep shown in Figure 7. With intake valve deactivation already the early flame development has increased in velocity compared to the reference cases and stays higher all the way reaching around 12 m/s before the calculation has to be terminated. Chemiluminescence images of single cycles for the 40 CAD NVO case can be seen in Appendix A for the reference case and in Appendix B for intake valve deactivation. If looking at TDC approximately 19 % of the heat is released in the reference case whereas 33 % when using valve deactivation.

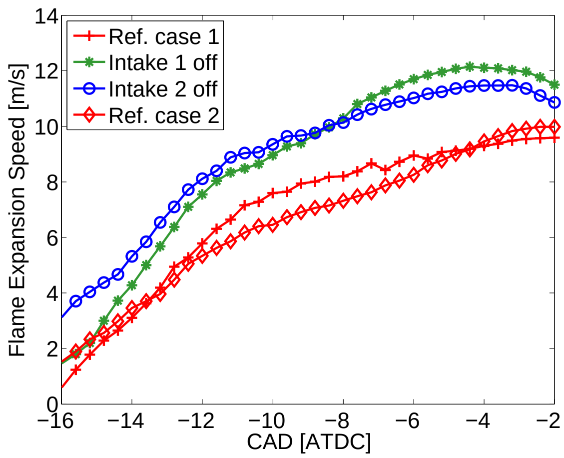

Figure 8. 40 CAD NVO, stoichiometric conditions.

At 202 CAD NVO, WOT and stoichiometric conditions the engine is still run in SACI mode, but with the greater part of the charge burning in HCCI mode. Figure 9 shows the calculated mean expansion speeds from -16 to -2 CAD ATDC. The calculation is terminated due to auto ignition as opposed to flame size in this case.

Again we can see a strong distinction between the tumble flow and the high turbulent swirling flow. The cases with valve deactivation show a mean expansion speed around 2 m/s greater than for the reference cases. The choice of valve for deactivation has only a minor influence on the flame expansion speed. This comes as no surprise since the inlet ports are symmetric. However when looking directly on the high speed videos the different rotational directions are obvious.

Appendix C shows pictures from one of the high speed videos of the reference cases with both inlet valves active. Appendix D shows snap shots from a move where inlet valve 1 is deactivated. When comparing the images at -2 CAD, the larger flame for the swirl case is obvious. At this point the flame in the valve deactivation case has reached the edge of the visible region and the reference case shows the first signs of auto ignition.

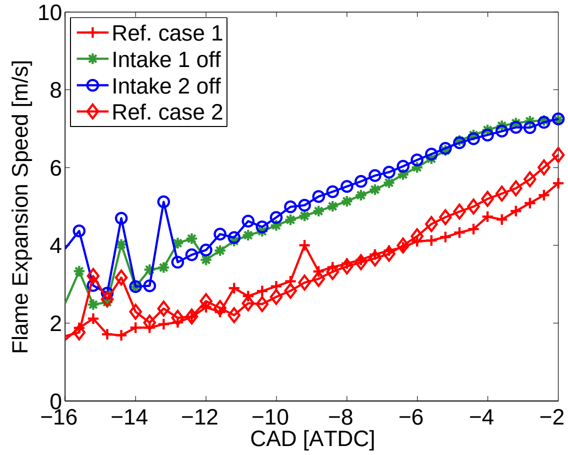

Figure 9. 202 CAD NVO, stoichiometric conditions.

EFFECTS ON AUTO IGNITION

The positive effect on flame growth by valve deactivation and increased turbulence seems straightforward; the remaining question is how does it affect the latter part of SACI combustion i.e. the HCCI combustion.

From the calculated heat release rate it is possible to estimate the auto ignition timing and the ratio of combustion prior to auto ignition. Hyvönen et al. [17] defined the initial slow heat release (ISHR) as shown in Equation 3.

Equation 3. Initial slow heat release

$$ISHR = \frac{Q_{threshold}}{Q_{\max}} \cdot 100[\%]$$

Since HCCI combustion is generally much faster than SI combustion a break point ($Q_{threshold}$) is calculated by finding the maximum difference of the derivative (2nd derivative) of the rate of heat release (RoHR). This is done here by fitting a moving polynomial of a finite length to the derivative. This way any noise can be suppressed to get more reliable results. The break point will indicate the point where combustion speed changes the most. This calculation predict the auto ignition well for SACI combustion, however when the amount of ISHR is low, the initial HCCI combustion can also be rather slow before the reaction rate increases, this can not be detected by the calculation, the amount of the charge burning in SI mode will then be over predicted.

Combustion timing and ISHR

If we apply the ISHR calculation to the calculated heat release information at three different operating conditions as shown in Figure 10 we can distinguish different behaviours depending on which combustion mode is superior.

For low NVO when the ISHR is high (here above 40 %) the faster flame development with valve deactivation will result in an advanced combustion timing towards TDC as shown in Figure 11 with a higher temperature thus slightly faster auto ignition and lower amount of ISHR.

At high residual rates as for the 202 CAD NVO case the ISHR instead increases although the flame expansion speed is increased. At the same time combustion timing is retarded. These trends correspond well with what can be seen from single cycle chemiluminescence information in Appendix C and B from this measurement point.

One explanation of the retarded combustion timing at high residual rates could be that the stratification between the hot inert residuals and the fresh stoichiometric charge is lowered by the increased mixing of the swirling motion thereby lowering the reactivity of the total charge. Auto ignition can be expected to occur in the border between the hot residuals and the fresh charge. Increased mixing with the fresh charge will lower the temperature, delaying auto ignition. This would then also be in agreement with Christensen [18] regarding temperature in-homogeneities.

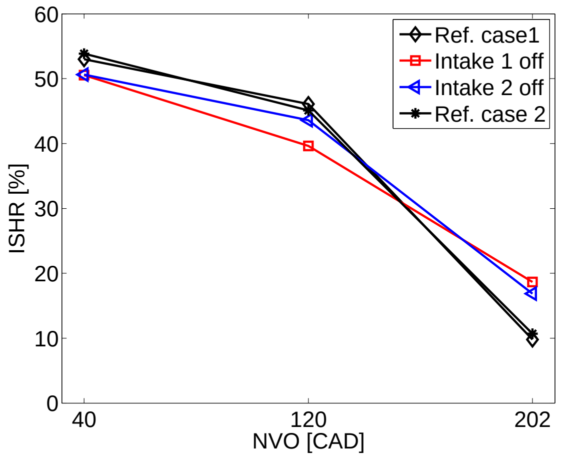

Figure 10. ISHR as a function of NVO for different inlet valve strategies.

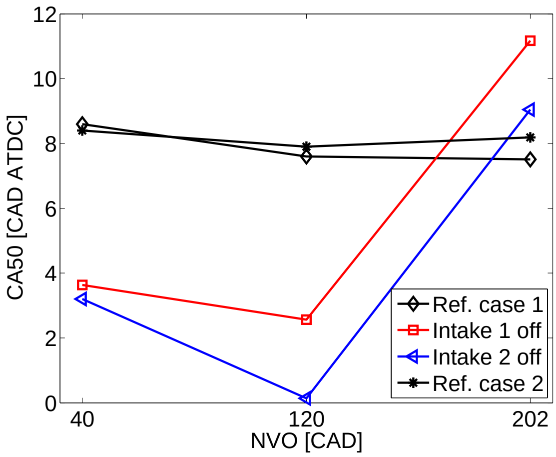

Figure 11. CA50 as a function of NVO for different inlet valve strategies.

<u>Burn duration</u>

Besides the turbulence effect on the auto ignition process the influence on the HCCI combustion duration is of interest. Figure 12 shows the combustion duration from the calculated point of auto ignition to CAD 90 % heat released. For the low NVO case the HCCI combustion duration is decreased, however it should be kept in mind that in this case CA50 is advanced much closer to TDC which in itself would lead to shorter combustion duration.

For the measurement point at 202 CAD NVO the HCCI burn duration is increased by approximately 25 %. At the same time the amount of fuel burned with HCCI is decreased. The calculated amount of ISHR changes from 10 to 20 % and combustion timing is slightly retarded with valve deactivation.

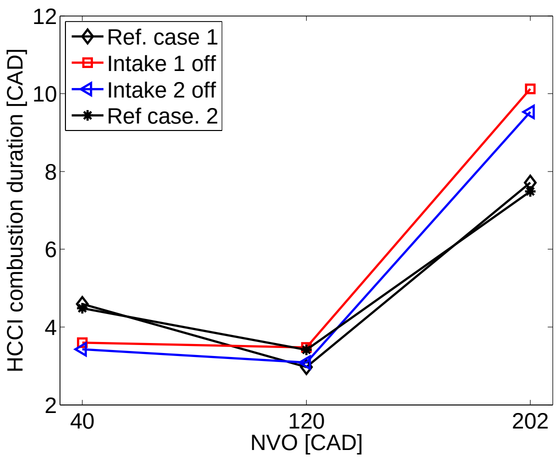

Figure 12. Combustion duration from calculated point of auto ignition to CA 90 % heat released.

<u>Auto ignition location</u>

The turbulence increase from valve deactivation affects not only the auto ignition timing and duration. The auto ignition location is also altered. The early flame growth is faster with the increased turbulence, however the altered flow field also transports the whole burning structure. This can be clearly seen in the chemiluminescence images in appendix E through G. Appendix E shows SACI combustion at 210 CAD NVO at a load of 2.2 Bar $IMEP_{net}$ with both inlet valves active with an air fuel equivalence ratio (λ) of 1.01. Appendix F and G is run with inlet valve deactivation. Unfortunately λ dropped to 0.94 in these cases, therefore comparisons to the reference case regarding flame growth and auto ignition timing should be done with great care. At this low load the first chemiluminescence originating from the spark is more stretched and does not really look like the growing flames shown previously. Since the intensity of these images is very low the reason could be insufficient gain of the acquisition system. As the combustion continues a more flame like structure can again be recognized, clearly following the swirling flow. The auto ignition location can be seen to move from the right side of the combustion chamber in appendix F with inlet valve 1 deactivated to the left side when inlet valve 2 is deactivated in appendix G.

SUMMARY AND CONCLUSIONS

Increased turbulence by inlet valve deactivation has been shown to influence SACI combustion in both of the two combustion modes. The interpretation of the results from the initial SI combustion is relatively straight forward. To fully understand the influence on the auto ignition process requires more knowledge of the residual stratification and its response to the mixing process caused by valve deactivation. Still a number of conclusions can be drawn.

- With valve deactivation an advanced, faster early flame expansion speed at high residual rates is seen to be related to increased turbulence levels.
- Using inlet valve deactivation thus increasing the turbulence levels increases the flame expansion speed at both high and low NVO i.e. high and low residual rates.
- The increase in flame expansion speed at high NVO by increased turbulence suggest the possibility of reaching lower loads in SACI mode by valve deactivation.
- For SACI combustion at high NVO the auto ignition is delayed by increased turbulence.
- The amount of ISHR increases as the turbulence is increased at high residual rates.
- The burn duration from calculated auto ignition until 90 % burned increases with valve deactivation at high NVO, however combustion timing is simultaneously slightly delayed.
- Increased mixing of the fresh charge and the hot residuals by the highly turbulent swirling flow is thought to be responsible for the delayed auto ignition and longer burn duration.
- The induced swirling motion captures the whole burning structure, moving the following auto ignition location in an almost symmetrical manner relative to the inlet ports.

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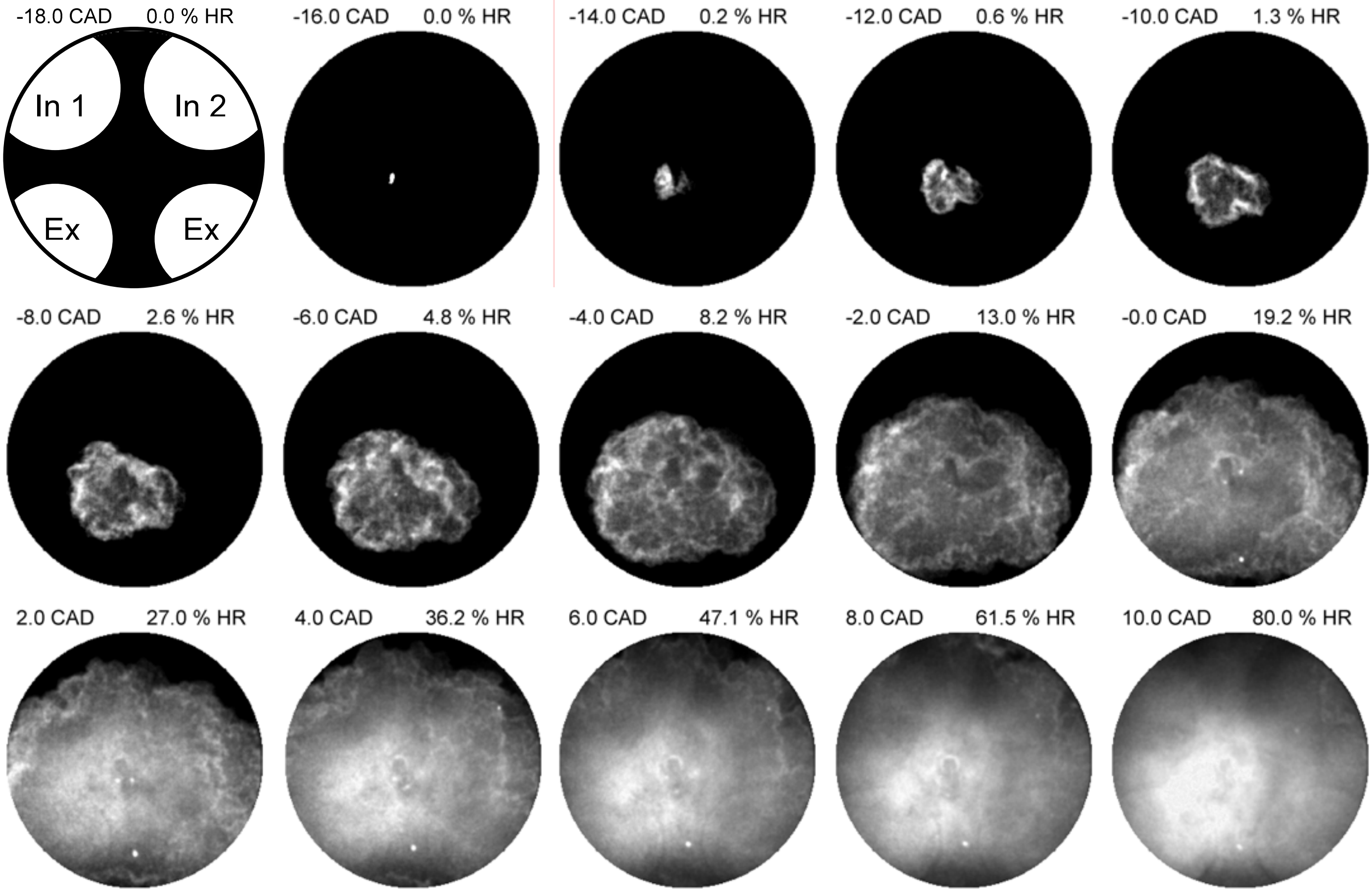
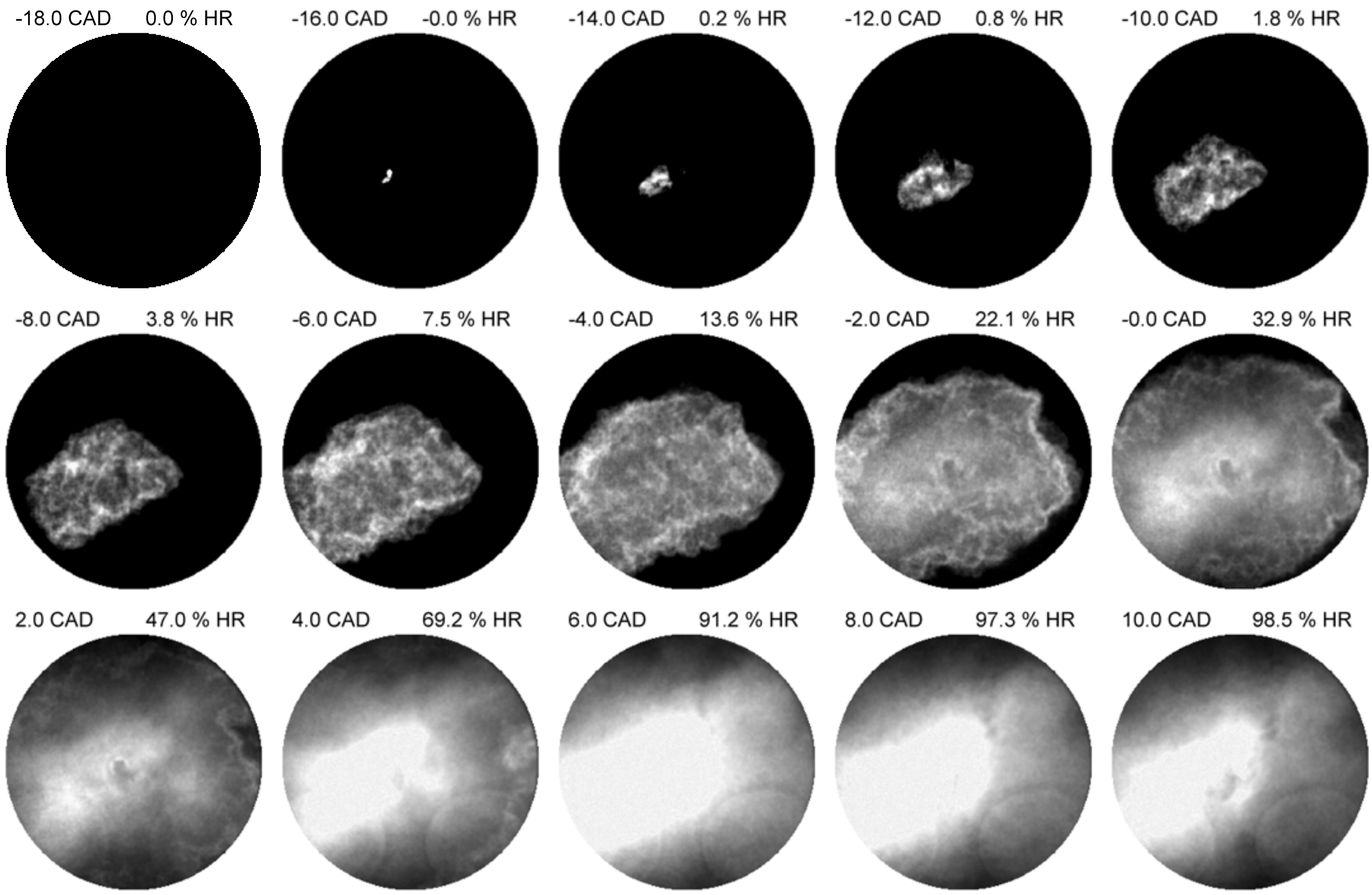
DEFINITIONS, ACRONYMS, ABBREVIATIONS

CAI	Controlled Auto Ignition
CI	Compression Ignition
EVC	Exhaust Valve Closing
FFT	Fast Fourier Transform
HCCI	Homogenous Charge Compression Ignition
ISHR	Initial Slow Heat Release
IVC	Inlet Valve Closing
IVO	Inlet Valve Opening
LDV	Laser Doppler Velocimetry
NVO	Negative Valve Overlap
RoHR	Rate of Heat Release
SACI	Spark Assisted Compression Ignition
SI	Spark Ignition
TDC	Top Dead Center
WOT	Wide Open Throttle

APPENDIX A
40 CAD NVO, both inlet valves active

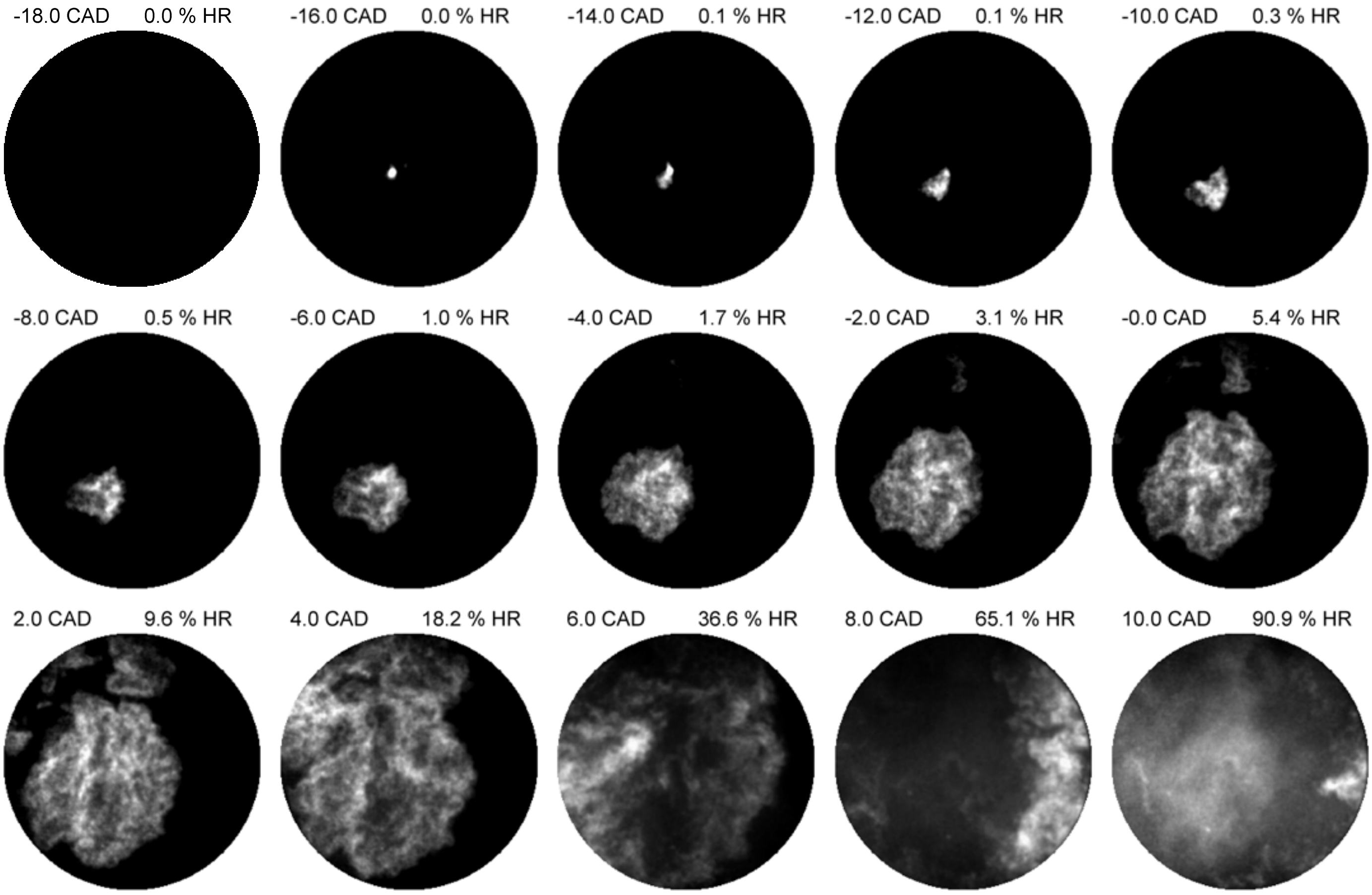


APPENDIX B
40 CAD NVO, inlet valve 1 deactivated



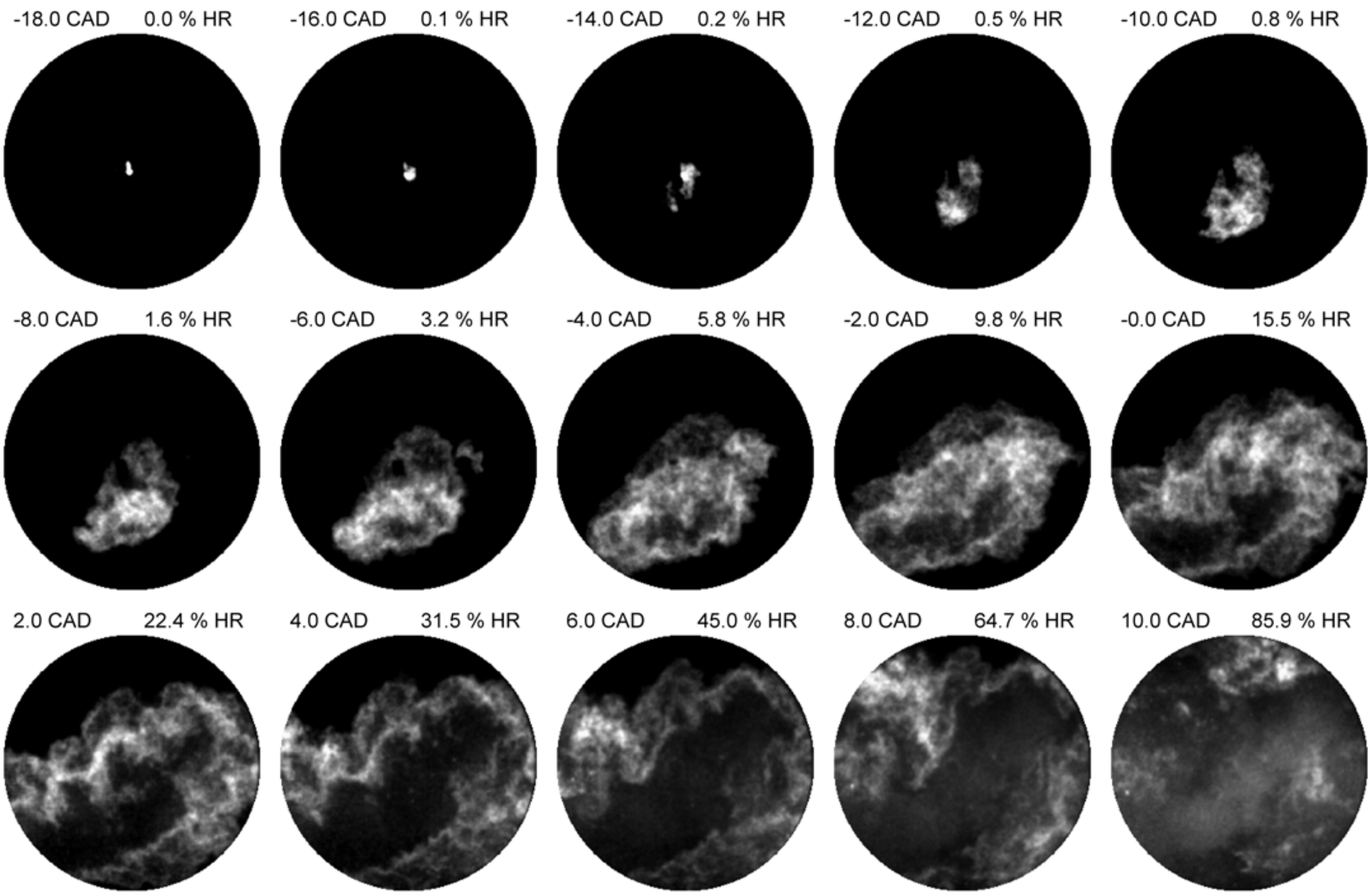
APPENDIX C

202 CAD NVO, both inlet valves active



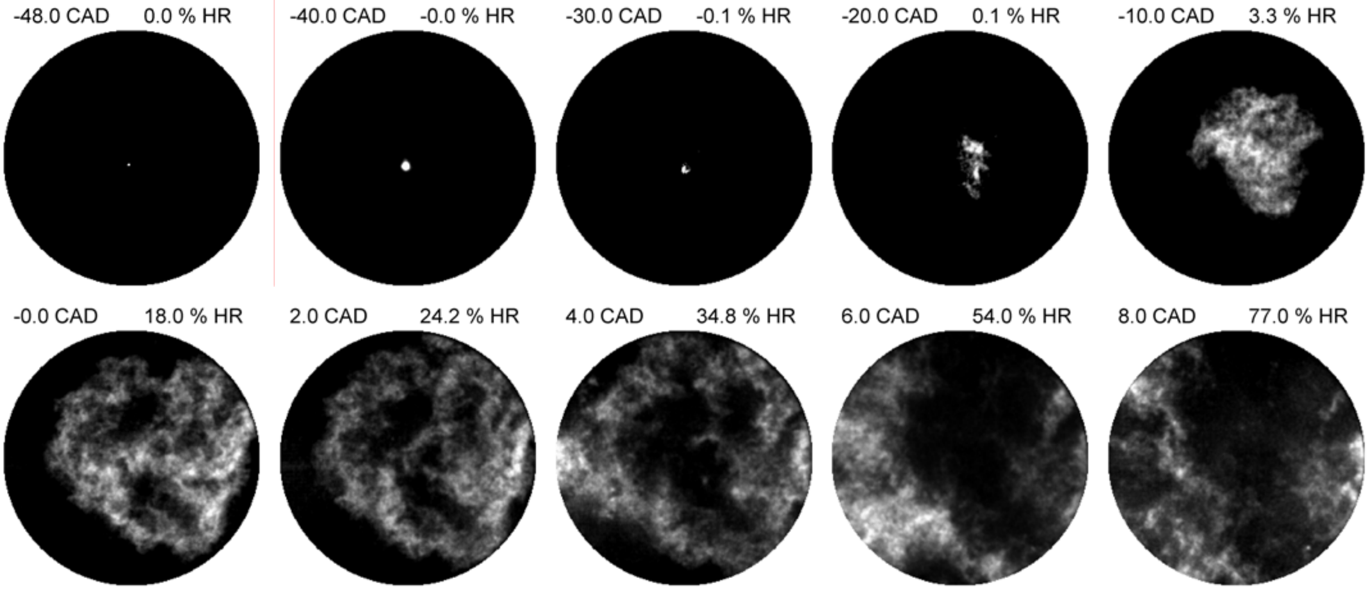
APPENDIX D

202 CAD NVO, one inlet valve deactivated



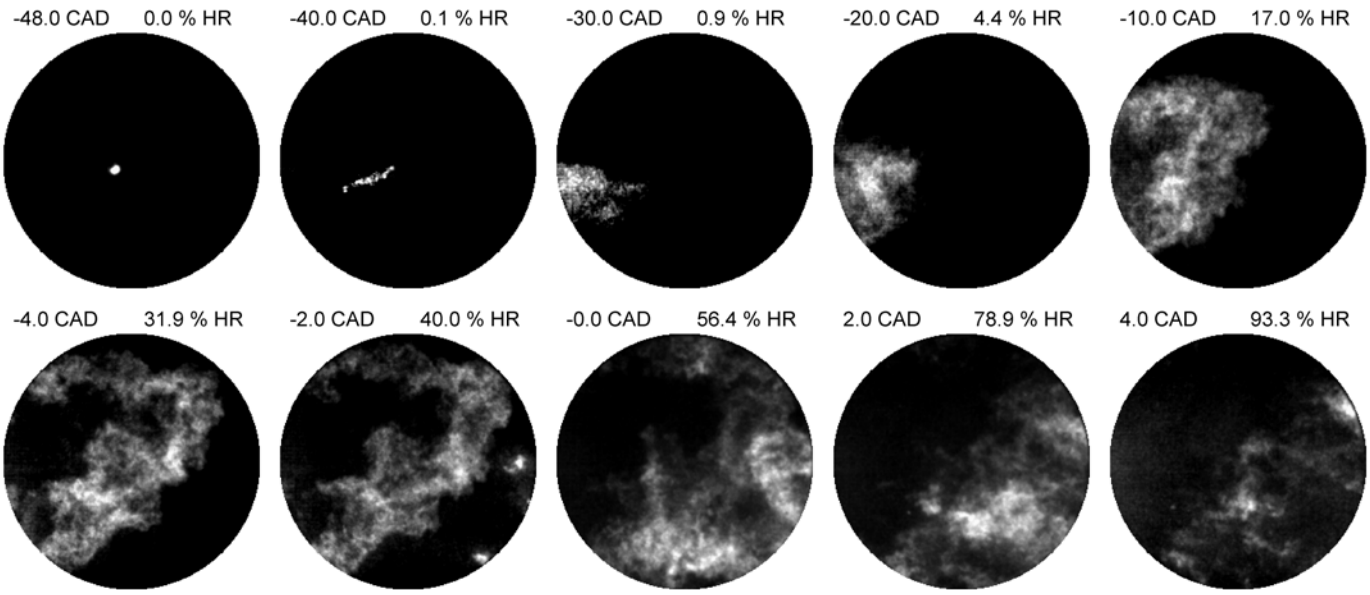
APPENDIX E

210 CAD NVO, both inlet valves active



APPENDIX F

210 CAD NVO, Inlet valve 1 deactivated



APPENDIX G

210 CAD NVO, Inlet valve 2 deactivated