Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 4712 – 4723

Energy Procedia

GHGT-11

Vertical CO_2 release experiments from a 1 liter high pressure vessel

Corina Hulsbosch-Dam[a], Arjen de Jong[a], John Zevenbergen[a], Rick Peeters[a], Mark Spruijt[a]*

[a]*TNO, The Netherlands*

Abstract

High-speed CO_2 release experiments from a pressurized vessel have been conducted for a range of storage pressures nozzle diameters. The experiments are conducted to validate and develop models for accidental releases of CO_2 during transport. In cooperation with DNV-KEMA lab (Groningen, The Netherlands), medium scale experiments with a 500 liter tank have been designed and performed in spring of 2012. The results of this experiment are reported in a separate GHGT paper by Ahmad et al. [5]. In preparation of these experiments, some optical measurement techniques have been tested in a smaller set-up of a 1 liter vessel, carried out at the TNO Rijswijk facility. These preparatory experiments will be discussed in the current document. A number of optical techniques are evaluated in relation to the observed phenomena. The tested techniques are: HD resolution standard optical camera, HS (high speed) camera and IR (infra-red) camera. In addition some experiments were performed using the PIV (Particle Image Velocimetry) technique, which is reported in a separate paper by de Jong et al. [4].

Keywords: CO_2 release; infra-red, high pressure

1. Experimental set-up

High-speed CO_2 release experiments from a pressurized vessel have been conducted for a range of storage pressures nozzle diameters. Figure 1 shows a schematic representation of the total set-up. A 1 liter, thick walled, stainless steel vessel is placed on a table top. The vessel is closed with a pneumatic

* Corresponding author. Tel.: +31-8886-62076.
E-mail address: Mark.Spruijt@TNO.nl.

doi:10.1016/j.egypro.2013.06.380

valve. The typical opening time of the valve is 0.2 sec. The nozzle is directed upward. The nozzle diameter is varied in the experiments: ½” and ¼”. In the background of the film material a grid of 15 by 15 cm is visible to give an indication of the length scales of the release process.

The pressure inside the vessel is measured prior to experiment. The initial pressures for the experiments with each nozzle are: 60, 80, 100, 120, 150 en 180 bar. The pressure is measured during the filling of the vessel and before the opening of the valve. The release process that follows is too fast for the manometer to register. The vessel is filled in several stages in order to prevent high temperature and pressure fluctuations after filling. The pressure and temperature are allowed to settle before the valve is opened to start the release.

The measurement techniques that are used during the release are all optical: normal (HD) camera, high speed (HS) camera and infra-red (IR) camera. The last two were positioned adjacent to each other at one side of the vessel. Unfortunately not all methods were available for all experiments, an overview of the used methods is shown in Table 1. The HD, IR and HS images are all taken for the same experiment. PIV measurements are performed for experiments with the same initial conditions, however, at a different time. The PIV results are reported in a separate paper by de Jong et al. [4].

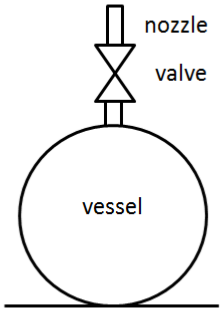

Figure 1 Schematic overview of experimental set-up.

Table 1 Overview of used camera techniques for the complete set of experiments of two nozzle sizes and varying initial pressure.

	¼ ” nozzle	½” nozzle
60 bar	HD, IR	HD, IR, HS, PIV
80 bar	HD, IR	HD, IR, HS
100 bar	HD, IR	HD, IR, HS, PIV
120 bar	HD, IR	HD, IR, HS
150 bar	HD, IR, HS	HD, IR, HS, PIV
180 bar	HD, IR	HD, IR, HS

The experiments were performed in a bunker at the TNO facilities (Rijswijk, the Netherlands). During the experiments no people were present in the same room as the vessel. The used room has a large venting capacity. In between the subsequent experiments the room is well ventilated. This allows to work safely with the quantities CO_2 involved.

2. Optical equipment

Next to a standard HD resolution video camera, the following optical equipment has been used:

2.1. IR camera

The used camera is a MWIR (Mid-Wavelength InfraRed) camera from FLIR Systems, type Titanium SC7000 (560M). Its original range is 1.5-5.1 µm, during the measurements a filter is used decreasing the range to 3.5-5.1 µm.

The camera registers the MWIR radiation from objects. Different materials or surfaces radiate IR with different efficiency. If this efficiency or emissivity is known the real temperature of an object can be determined. In order to do this it is necessary to correct for transmission losses and radiation generated in the atmosphere.

CO_2 gas absorbs and radiates around 4.2-4.3 µm. Based on the images of the jet it is hard to determine the real temperature of the jet. The jet is not a solid object and its emissivity is unknown. Other complicating factors are the phase changes of CO_2 that occur in the jet, the mixing with the surrounding air and the atmosphere between the jet and the camera.

So no temperature data can be obtained from the IR images, however, the general shape and behavior of the jet can be studied.

2.2. HS camera

The used HS camera is: IDT Y4-S3 from IDTVision. It has a maximum frame rate of 5100 fps at a resolution of 1024 x 1024 pixels.

Due to the high frame rate during recording the lighting of the scene is very important in order to get good quality images. A system with 12 LEDs (http://www.idtvision.com/lighting/index.php?show=4) was used. During the experiments the position of the LEDs relative to the camera and the nozzle was optimized.

3. Results and discussion

3.1. General observations

For most releases, after opening the valve a whistle tone is audible even outside the (thick walled) room with the vessel. This first long tone can be followed by a second, shorter whistle tone. The second tone is only present for releases starting from pressures of 100 bar and higher. These sounds correspond to a first strong jet leaving the vessel, followed by one or more narrower jets. These jets can be observed in the film images.

During the outflow the pressure inside the vessel reduces to atmospheric pressure. The initial and end pressure is measured by a manometer. Post-experiment, when the valve is closed again, the pressure starts to increase again up to 25 bar. The hypothesis for this phenomenon is that some solid CO_2 is formed during the cooling that accompanies the expansion of the release. After the closing of the valve the solid CO_2 inside the vessel starts to heat up and sublimates, which leads to an increasing pressure inside the vessel. When, after the main release, the valve is not closed this pressure build up is not observed.

3.2. Camera images: HD, IR, HS

The main information about the experiments is visual and is recorded by 3 different camera techniques. In this section the 3 techniques will be compared to each other for two release experiments: 180 bar ½” and 100 bar ½”. These experiments have been chosen based on the fact that they have good

HS images. The 180 bar experiment was the last experiment to be performed in the series and as such has the best illumination for the HS images.

The settings for the 100 bar experiment were also used for the series of experiments with PIV that were performed at a later time, see section 5.

An attempt has been made to synchronize the three films. As they all have different fps, see Table 2, this is not a straight forward procedure. This means that there are 200 HS images for every single HD image. The last image before any sign of the jet is visible is given t=0 sec. For subsequent frames the time is determined based on the frame rate. This procedure introduces an error or uncertainty in the exact synchronization of the images. The maximum time difference between the camera images using this method is 0.04 sec.

Table 2 Frame rates for the different techniques.

Method	Frame rate (fps)
HD	25
IR	100
HS	5000

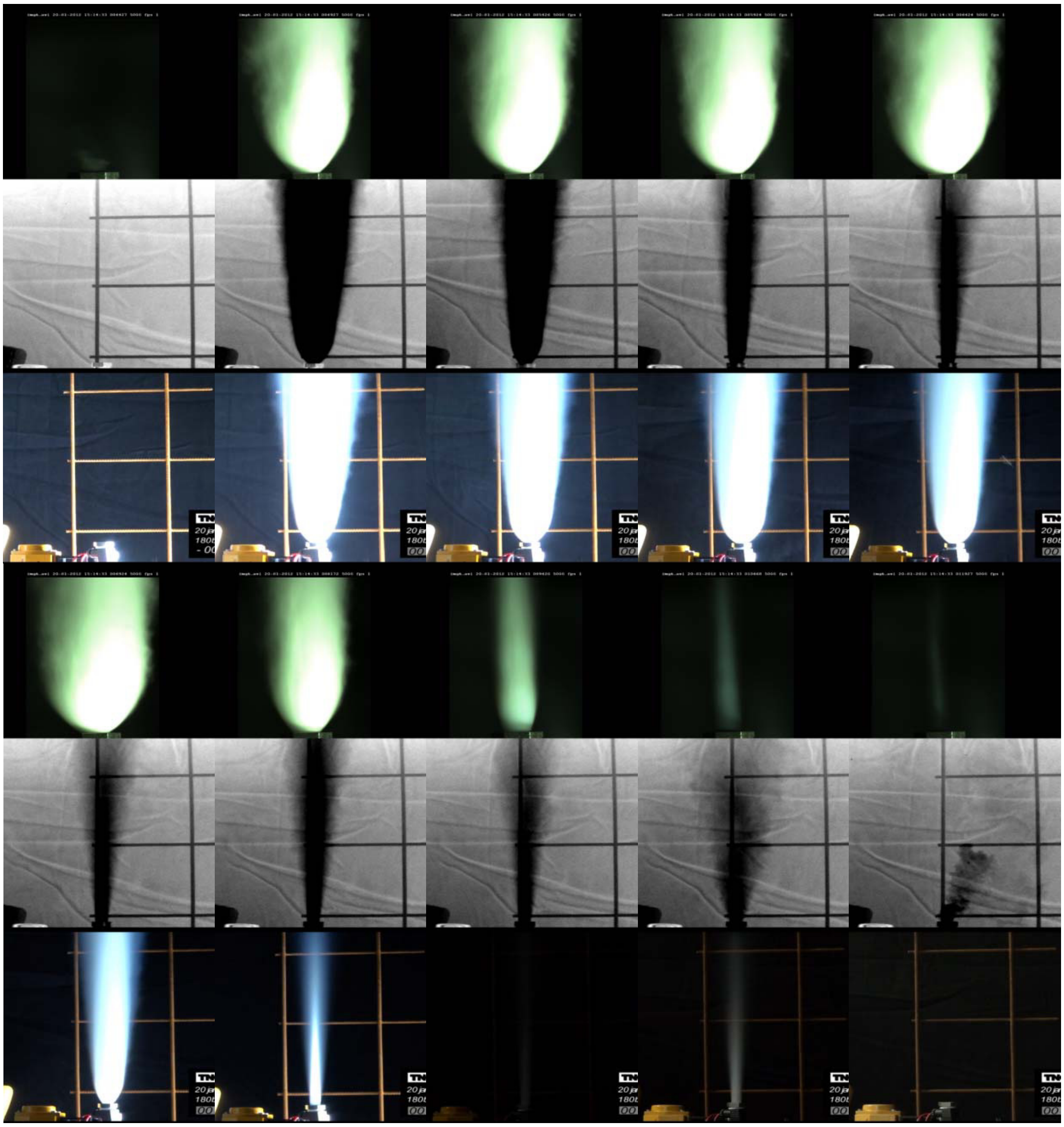

Figure 2 Camera images (180 bar, ½" nozzle) at: t= 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.00, 1.25, & 1.50 sec.
Top: HS; centre: IR; bottom: HD. Please note that the IR and HD images are compressed in the vertical direction: in reality the grid at the background is square (15 by 15 cm).

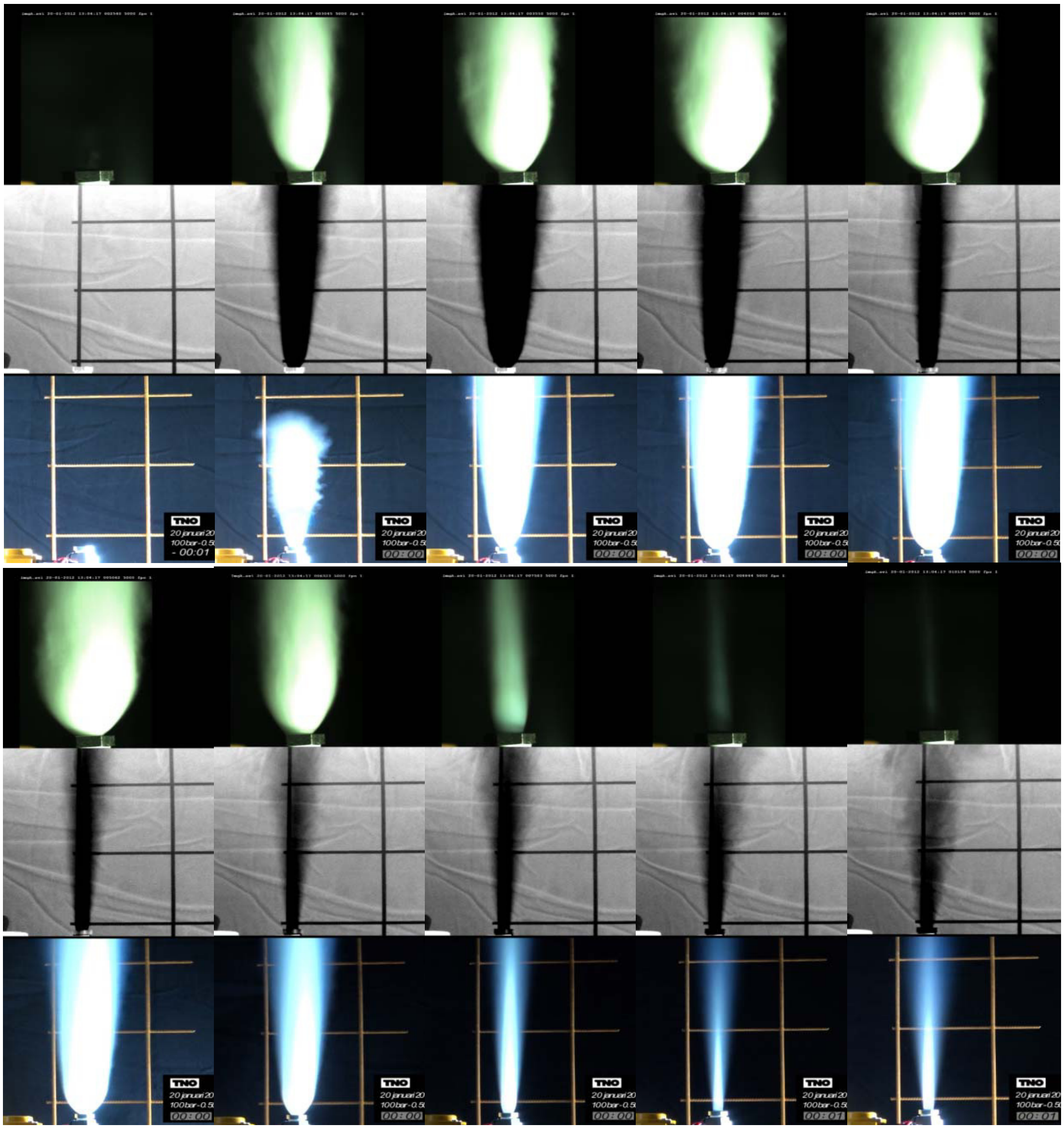

Figure 3 Camera images (100 bar, ½”) at: t= 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.00, 1.25, 1.50 seconds.
Top: HS; centre: IR; bottom: HD. Please note that the IR and HD images are compressed in the vertical direction: in reality the grid at the background is square (15 by 15 cm).

3.3. Differences between imaging techniques

As stated before, to obtain an exact overlap of timing of the different recording techniques is quite hard due to the very different frame rates. The result can be that the increasing and decreasing of the jet in the different techniques is not exactly timed when based on counting frames. This means that at a single chosen time the HD camera can still show a wide jet, whereas the IR camera already shows a decreasing width of the jet. In a frame just before the IR could also still give a wide jet and in a next frame the HD camera could give a more narrow jet.

The IR and the HD have similar scales, which can be concluded based on the visible grid in the background of the images. The HS camera has a more zoomed in view, which results in a wider jet, but also a smaller height of the jet that is recorded.

As said, the lighting is very important for the HS images. The position of the Led's is such that right hand side of the jet is lit completely. The left hand side is only partly visible. This causes an apparent asymmetry of the jet that is not present in reality as can be seen in the other techniques. The HS images have a good time resolution to follow the development of the jet. Especially in the build-up of the jet in the first 0.1 sec (not shown in the figures).

In the infra-red images the jet appears as a dark area against a lighter background. The CO_2 absorbs part of the background radiation. The jet is also cold which leads to a lower emission of IR radiation. The images show a sharp edge to the jet close to the nozzle, whereas further away from the nozzle a more diffuse jet is visible. By comparing the IR with the other camera's one can distinguish the mixing with air in the upper regions of the jet in the third flow regime.

One interesting observation that can be made with the IR camera is the 'smoke' rising from the nozzle after the main release has finished. The other techniques do not show this part of the process. Most likely, this 'smoke' is the last (optically transparent) CO_2 that is slowly evaporating from the vessel without a large pressure difference to drive the flow. Another option is that the 'smoke' is visualizing the motion of the cooled air around the cold nozzle, however, this option is not very realistic as cold air normally does not rise.

In the HD images the CO_2 jet appears as white against the dark background. The white color of the jet is caused by the CO_2 droplets and particles just above the nozzle. After entrainment of air also water vapor from the air may form droplets and ice particles due to cooling and this will help to visualize the jet.

In IR, the jet looks smaller. This could be due to the differences in light emission: reflection of visible light versus absorption of IR light in the jet core.

The infra-red camera shows other features compared to the visual cameras, like a smaller jet, mixing with air in the upper regions and CO_2 leakage after the high pressure release. The fact that CO_2 absorbs IR light provides extra information that the optical cameras do not capture. CO_2 does not radiate as a black body, but has spectral lines that make it more difficult to quantify the temperature of the opaque region of the jet. Moreover, the semi transparent mixing region consisting of a mixture of CO_2 and air will partly absorb the emissions from the jet core. Therefore, no attempt to evaluate the jet temperature or concentration based on infra-red data has been made.

3.4. Description of outflow process for 100 bar ½ inch

Both initial pressures show comparable outflow behavior, see Figure 2 and Figure 3. After the opening of the valve the build-up of a strong jet is visible. The diameter of the jet increases to a maximum value and then decreases. This can be quantified by measuring the diameter of the jet. For the 100 bar release the jet diameter at the height of the first horizontal rod has been measured, see figure 4. The whole outflow process for the ½" nozzle take about 2 seconds. After that no more CO_2 is observed leaving the vessel.

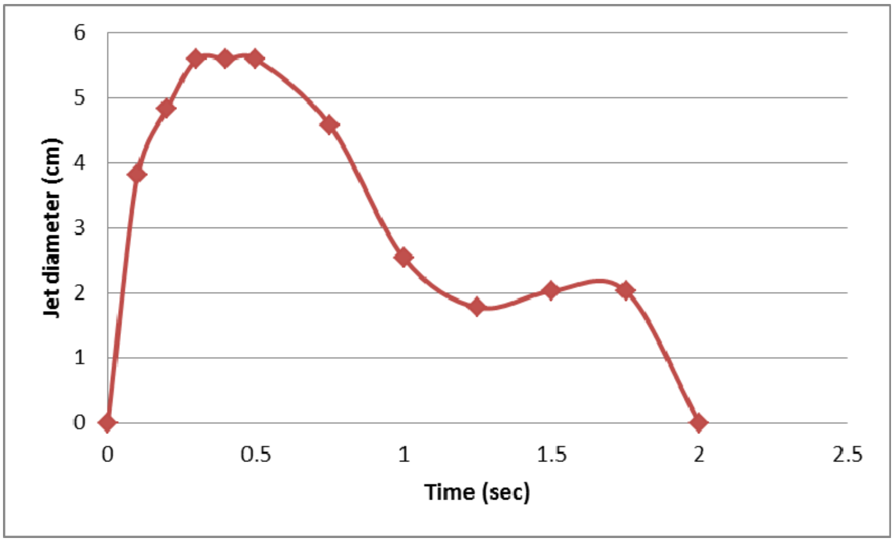

Figure 4: Jet diameter as a function of time for 100 bar ½" release. The diameter is measured at the height of the first horizontal line of the grid behind the set-up. (Diameters are measured in the HD images.)

The most characteristic shape of the jet in the images is the shape just above the nozzle. Instead of a slowly widening jet, there is an immediate side-ward motion just outside the nozzle. This gives an almost parabolic shape to the jet. All three imaging techniques show this shape in the initial stages of the release.

Based on figure 4, three different flow regimes can be observed:

- Regime 1: 0 to 0.8 sec, An expanded cloud
- Regime 2: 0.8 to 1.4 sec, high speed release including particulate matter
- Regime 3: 1.4 to 1.8 sec, slow down

The slow down regime was deduced from Particle Image Velocimetry data by de Jong et al. [4].

4. Effect of Initial pressure

For the two nozzle sizes, ¼ inch and ½ inch, the jet diameter as a function of time during the release is plotted for several initial pressures in Figure 5 and Figure 6. For the ¼ inch 80, 150 and 180 bar show a similar profile for the jet diameter. The jet builds up to a maximum value of 6 cm and then slowly decrease to a low value which is present for some time at the end of the release.

For the ½ inch nozzle the picture is different. The jet diameter slowly builds up when the initial pressure is increased from 60 bar to 80 bar and then to 100 bar. The results for 100, 120 and 150 bar are very similar: A strong first jet with a diameter of 6 cm. Then a second plateau is visible at a lower value of 2 cm and after 2 seconds the jet suddenly is finished.

The smaller width for the 180 bar experiment is unexpected. After closer inspection of the whole HD video footage it is found that the contrast in the images during that time period is too low to actually see a jet. So it is concluded that the difference in jet width for the 180 bar experiment is not a physical effect but rather a measurement error. The 180 bar data should therefore not be used for analysis

Initial pressure does not influence the release much. The measured diameters are nearly equal. This is most clear for the ¼ inch nozzle (Figure 5). The following process could be happening. Directly after opening the valve the pressure inside the vessel decreases very fast. The pressure drops to the equilibrium pressure. The pressure drop from initial pressure to equilibrium pressure is a very fast process, it is not visible in the shown images. After reaching the equilibrium pressure the release for all initial pressures is nearly identical.

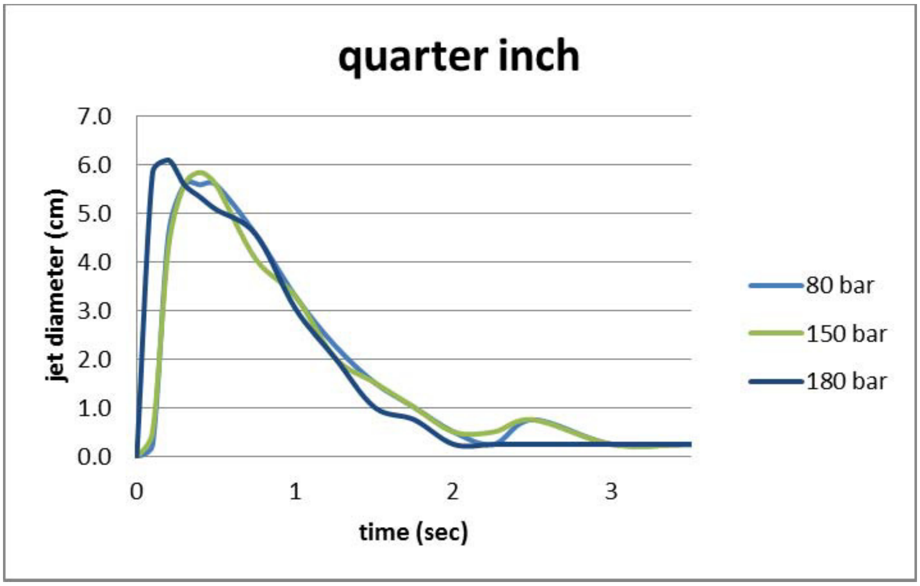

Figure 5 Jet diameter for ¼ inch nozzle, with 80, 150, and 180 bar as initial pressure.

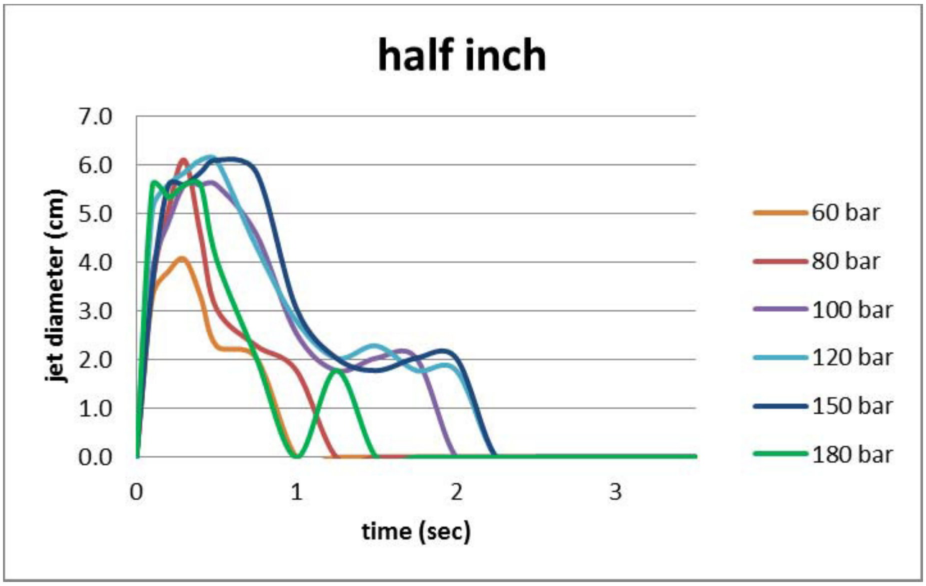

Figure 6 Jet diameter for ½ inch nozzle, with 60, 80, 100, 120, 150, and 180 bar as initial pressure.

The ½ inch nozzle gives a slightly different result. For 60 bar the maximum jet diameter is not reached, and for 80 bar the maximum diameter is only present for a short time.

4.1. Effect of nozzle diameter

For two different initial pressures (80 and 150 bar) the effects of varying the nozzle diameter have been studied. The focus is on the duration of the outflow process and on the jet diameter as a function of time. This information is taken at several times during the release. The images that have been used to obtain quantitative data are shown in figures 2 and 3.

Figure 7 and 8 show the jet diameter as a function of time. The diameter has been measured from the HD images. The diameter of the jet is obtained by relating the diameter of the jet to the width of the grid in the images (15 cm).

The two figures show that using a larger nozzle diameter the maximum value for the jet diameter is not influenced. The fact that the jet diameter is much larger than either nozzle diameter could be of influence here. When the nozzle diameter is increased., only the maximum jet diameter is present for a shorter period of time Also the total duration of the release shorter than for the smaller nozzle: approximately 1.0-1.5 sec for the ½ inch nozzle and 2.0-3.0 sec for the ¼ inch nozzle. These effects are visible for both initial pressures of 80 and 150 bar.

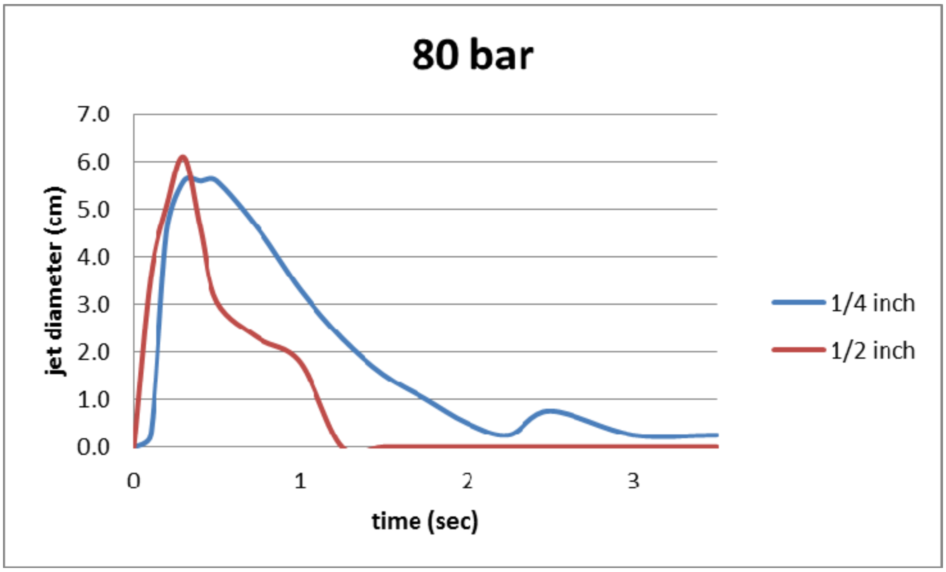

Figure 7 Jet diameter as a function of time for two nozzle sizes: ¼ and ½ inch. The initial pressure is 80 bar.

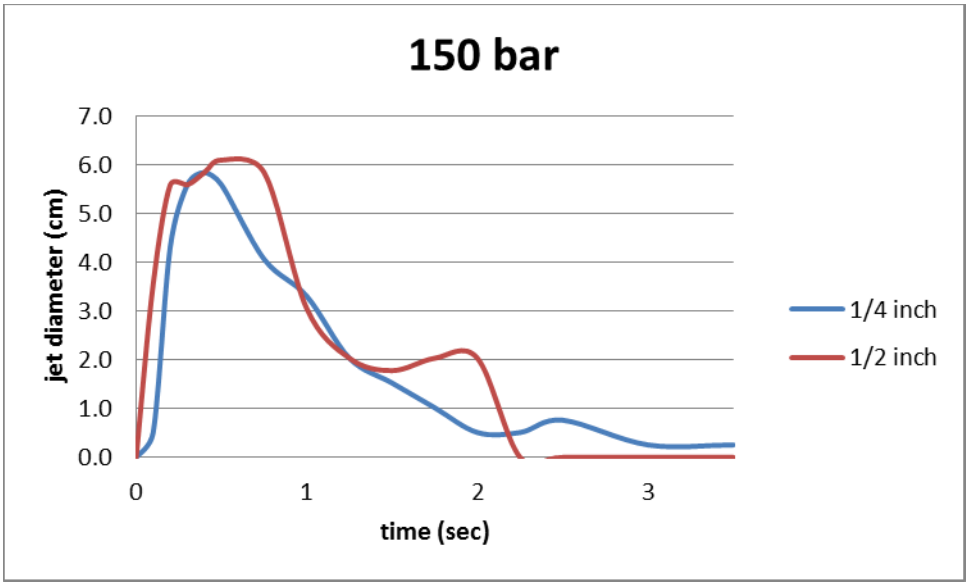

Figure 8 Jet diameter as a function of time for two nozzle sizes: ¼ and ½ inch. The initial pressure is 150 bar.

5. Conclusions

The following conclusions on the physics of the release can be made:

- Initial pressure has little effect on duration of release
- Nozzle diameter has a larger influence

These are important implications for safety studies. If general applicable, then initial pressure is not so much important as long as it is above the vapor pressure and the CO_2 is stored and transported as a liquefied pressurized gas. What is important, however, is the hole diameter that occurs during an accident, or the hole diameter that is used in a safety study.

During the release, three flow regimes can be identified. This first one shows a wide expanded jet, whereas the second longer period shows a more straight jet. In the third regime, the jet slows down. The differences between the first and second regime could be due to reaching the equilibrium pressure of the CO_2 inside the canister, as is indicated by the similarities of between different pressure releases. Compared to other releases [5], the vertical positioning of the nozzle could influence the amount of liquid CO_2 pushed through the nozzle and thereby the jet exit speed.

For the optical measurement techniques the following conclusions can be made. The implemented IR HS and HD camera's all give different view on release process:

- HS: focus on fast changes during the start of the experiment
- HD: recording of optical image, what is seen by the human eye
- IR: Different physics are recorded due to the absorption of CO_2 in the IR range

Acknowledgements

This research has been carried out in the context of the CATO-2 program. CATO-2 is the Dutch national research program on CO_2 Capture and Storage technology (CSS). The program is financially supported by the Dutch government (Ministry of Economic Affairs) and the CATO-2 consortium parties.

The authors would like to thank Koen Benoist, Henny Veerman and Jakko Moorhof for their helpful contribution to the research.

References

[1] Kim, Y.J., Okamoto, K. and Ko, H.S., Study on Concurrent Measurements of Velocity and Density Distributions for High-Speed CO_2 Flow, Journal of Visualisation, Vol 12, No 3, 2009, pp 203-215

[2] Ko, H.S., Kim,Y.J., Kwon,O.C., Okamoto, K., Analysis of Simultaneous Velocity and Density Distributions for High-speed CO_2 Flow Using Particle Image Velocimetry and Digital Speckle Tomography, Key Engineering Materials, Vol 326, 2006, pp 55-58

[3] Peltier III, D.W., Performing Particle Image Velocimetry in a Supersonic Wind Tunnel using Carbon Dioxide as the Seed Material, PhD thesis, Air Force Institute of Technology, June 2007,

[4] de Jong, A.T. and Spruijt, M.P.N., Particle Image Velocimetry for quantification of high pressure CO_2 release, GHGT-11, November 2012

[5] Ahmed, M. ,Buit, L., Florisson, O.,Hulsbosch-Dam, C.E.C., Bogemann-van Osch, M.,Spruijt, M.P.N., Davolio, F., Experimental Investigation of CO_2 Outflow from a High Pressure Reservoir, GHGT-11, November 2012