Experimental study of CO₂ releases from a saturated liquid reservoir

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Abstract

To improve the tools used in safety assessments for handling transport and storage of CO₂ experimental results are used as a reference. The present study measures mass flux, temperature of the jet and particle sizes of a release from a liquid CO₂ reservoir. In a release to the atmosphere from a liquid reservoir with a pressure of 6 MPa and 293 K, the jet formed consists of gas and solid particles. In the experiments the CO₂ is released through nozzles of 0.25 mm, 0.5 mm, 1 mm and 2.5 mm diameters. Both high speed imaging and laser diffraction is used for particle characterization. The results show that the jet core temperature is 205 K close to the release and increases after 100 diameters. The measured mass flux decreases with increasing nozzle diameter. The average mass flux is 38 g/s mm². The high speed imaging shows particle sizes of 20-80 μm with velocities up to 100 m/s at the edges of the jet. It was not possible to measure particles in the jet core with high speed imaging. The laser diffraction experiments show a clear particle size concentration of about 1 μm.

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1. Introduction

CO₂ Capture and Storage (CCS) involve processing and transport of large amounts of CO₂ in dense liquid phase. Current tools for safety assessment have contributed to the successful design and operation...
of CO₂ compression and transport systems worldwide. To achieve even safer operation of such installations and to increase authority and public confidence it is important to reduce the uncertainty even more in the predictions of what happens if CO₂ is accidentally released.

Several experimental projects are going on to establish experimental data related to safety distances. However, the thermodynamics and fluid dynamics involved in a sudden release of CO₂ is complex, both to measure and to model numerically. Even if validated models for heavy gas dispersion exist in general, the distance downwind to the point where all the CO₂ dry ice is sublimated might be significant for a large release. The phase transition in the expansion zone might have a significant impact on the dispersion further downstream. Local geometry and wind conditions will also have a very important impact. Therefore experimental results are necessary to validate and further improve the numerical models. Statoil has put a significant effort in financing research activities to obtain such data. Pressurized liquid CO₂ is also a safety hazard in terms of accidental vessel ruptures which can result in a BLEVE (Boiling Liquid Expanding Vapor Explosion) [1], but also in cases where a vessel is partially ruptured leading to a CO₂ jet. It is important to understand the mechanics of such jet, both to be able to calculate realistic leak rates and to assess the risk factor to the immediate surroundings. When liquid CO₂ is released through a nozzle, the rapid expansion quickly cools the liquid. Depending on the initial conditions, equilibrium between gas and liquid droplets or solid particles will occur inside the jet. During the release of CO₂ in the present research, solid particles (dry ice) were formed inside the jet.

Liu et al. [2] used a high speed camera and microscopic lens to examine the agglomeration process of dry ice in a jet. The dry ice was formed by expanding liquid carbon dioxide through an expansion nozzle. They used a glass tube to keep the temperature inside the jet low. They found particles with a size distribution of 40 to 400 μm. The velocity of the particles was relatively low (in the order of 1-20 m/s) compared to the experiments presented in this article.

Liu et al. [3] also used laser diffraction analysis to measure the size distribution of the particles. Using this method, they found particles with a diameter around 1μm. They found some variations with the size of the particles with the distance from the nozzle opening.

2. Experimental setup

The experimental rig used in the present research consisted of a nozzle connected to a bottle of CO₂ with a riser tube. A pneumatically controlled valve was used to control the flow of CO₂ from the nozzle. The gas bottle was hanging in a loading cell, so that continuous measurements of the total weight of the
bottle were obtained. These measurements were used to calculate mass flow. A temperature element with a diameter of 1 mm was used to measure the temperature inside the jet. A schematic overview of the experimental setup is shown in fig. 1. Two different measurements techniques were used to analyze the composition of the jet. High speed imaging was used to measure particle size and velocity of particles inside the jet. A laser diffraction analyzer was used to measure the size distribution of the same particles.

A schematic view of the nozzle geometry can be found in fig 2 a) and a photograph of the different nozzles is found in fig 2 b).

2.1. High speed imaging

A high speed camera of type Photron APX-RS was used to take photographs of the jet. Close-up images of the jet were taken using a Navitar 12X zoom lens to measure the size and velocity of particles inside the jet. These images were taken using laser pulses from a LED Laser of type Oxford Laser Firefly-300 as lighting source. A 70 mm lens and white light was used to take photographs of the shape of the jet.

2.2. Particle image velocimetry

When measuring particle velocities in the order of 100 m/s on a length scale of 5 mm, the frame rate has to be at least in the order of 50 kfps if no special techniques are used. By firing laser pulses in pairs, and pairing images, a much lower frame rate can be used (see fig 1 c)). The laser used in these experiments can fire pulses only microseconds apart. This is sufficient to determine the position of a particle in two subsequent pictures and, since the time difference is known, the velocity of the particle can be determined.

2.3. Laser diffraction analysis

A series of experiments was conducted using laser diffraction analysis (HELOS, Sympatec GmbH). This is a method that is based on the light scattering properties of particles. The sample (in this case the CO₂ jet) is fed through a laser beam, and the scattering of light is measured. Based on some assumptions, the size distribution of the particles is found by the scattering measurement.
3. Results and discussion

3.1. Overview and shape of jet

Fig. 3 shows an overview of the jet shapes for four different nozzles. The jet from the 0.25 mm nozzle is asymmetric. This is probably caused by some foreign object inside the nozzle throat, or structural damage to the nozzle.

3.2. Mass flow

The experimental results for mass flow were used to calculate a mass flux (kg/m²s). The mass flux for each nozzle and the average mass flux is shown in fig. 4 a). The mass flux decreases with increasing nozzle diameter.

3.3. Temperature measurements

All temperature measurements were done with the 1 mm nozzle. In the temperature measurements, the temperature reached a stable level after some seconds. This stable level was used as the jet temperature. Fig. 4 b) shows the temperature in the jet plotted with distance from the nozzle opening. The plot shows that the temperature varies little in the zone 0 - 100 mm from the nozzle opening.

High speed images of the temperature element shows a cone of solid CO₂ growing on the temperature element. The cone evaporated quickly after the experiment, leaving no moisture. This shows that it was in fact dry ice and not water from the surrounding air. The boiling temperature of CO₂ at atmospheric pressure is 195 K while the lowest temperature measured in the jet is 205 K. This corresponds to the boiling point of CO₂ at approximately 2.3 times atmospheric pressure (0.23 MPa).
It is possible that the presence of the temperature element causes a stagnation of the flow and a locally high pressure. This can also account for the small rise in temperature close to the nozzle opening, as the higher local velocity will lead to a higher stagnation pressure. After 100 mm the temperature increases due to entrainment of the surrounding air.

3.4. Close-up images of jet

The 1 mm nozzle was used in the investigation of particle sizes and velocities. A selection of photographs is shown in fig. 5. In close-up images of the jet, the center of the jet was totally opaque. It is possible that the density of particles is much higher in the center of the jet than in the outer region. However, large density fluctuations in the jet may also cause total dispersion of the laser beam.

Table 1. Particle size distribution in the jet from the 1 mm nozzle. Image position refers to fig. 5.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Image position</th>
<th>Diameter [μm]</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a)</td>
<td>35</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
<td>a)</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>a)</td>
<td>26</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>a)</td>
<td>32</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>a)</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>6</td>
<td>b)</td>
<td>78</td>
<td>67</td>
</tr>
<tr>
<td>7</td>
<td>b)</td>
<td>26</td>
<td>29</td>
</tr>
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<td>8</td>
<td>b)</td>
<td>37</td>
<td>50</td>
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<td>9</td>
<td>b)</td>
<td>35</td>
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</tr>
<tr>
<td>10</td>
<td>b)</td>
<td>20</td>
<td>53</td>
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<tr>
<td>11</td>
<td>c)</td>
<td>39</td>
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<td>12</td>
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</tr>
<tr>
<td>15</td>
<td>c)</td>
<td>23</td>
<td>46</td>
</tr>
</tbody>
</table>
In the outer region of the jet, small particles with a diameter of roughly 20-80 microns were observed. Table 1 shows the diameter and velocity of some of these particles. It is possible that the large particles observed in the outer region of the jet are dry ice that has been formed on the nozzle wall and not by sublimation of liquid carbon dioxide.

3.5. Laser diffraction analysis

In the laser diffraction analysis, the 0.25 mm and 0.5 mm nozzles were used. In the measurements with the 0.5 mm nozzle, some beam steering was encountered. This is a phenomenon that occurs when the jet has a significantly different refraction index than the air around it. It shows up as coarse particles in the upper channels on the laser diffraction analyzer [3]. The particle distribution is therefore limited at 20 μm, since high speed images of the jet shows small concentrations of larger particles in the jet. What is clear in fig. 6 is that there is a peak of particles with a characteristic size around 1 μm. From these

![Fig. 5. Close-up images of the jet from the 1 mm nozzle; (a) Nozzle opening; (b) 20 mm from nozzle opening; (c) 60 mm from nozzle opening; (d) 180 mm from nozzle opening. The large object in d) is a needle used for positioning and camera focus. All four images are 5.3 x 5.3 mm in the focus plane. This corresponds to a pixel size of 5.22 μm.](image-url)
measurements, it is likely that the opaque center of the jet seen in fig. 5 consists mainly of particles with a
diameter in the order of 1 μm. This is consistent with earlier research by Liu et al. [3].

4. Conclusions

- The temperature in the core of a CO2 jet seems to be constant out to a certain point.
- The core of the jet is opaque, leaving high speed imaging ineffective to determine its composition.
- Some larger particles (20 – 80 μm) were observed in the outer part of the jet.
- Laser diffraction analysis shows a clear peak of particles with a size around 1μm in the jet.

Further experiments are planned in order to obtain better measurements of the composition of a CO2
jet. It seems clear that high speed photography with back lighting is not sufficient to determine the
composition of the jet core, both because of the high dispersion of light through the core and because of
the small length scales of particles. Laser diffraction measurements with exact positioning in the jet are
needed to determine how the particle distribution develops downstream from the nozzle. Further work
will enable the development of numerical models for CO2 jets to be used in risk assessment.

Acknowledgements

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References

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