# Expansion Waves Behaviour during Liquified $CO_2$ Depressurization in a Divergent Cross-Section Vessel

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## 1 Abstract

Recent developments in carbon capture and storage have led to an increased concern about the safety of $CO_2$ transport systems. Hazards that arise from the accidental release of liquid $CO_2$ during its transportation include rapid phase change with explosive evaporation and expansion. Therefore, it is essential to research the mechanisms and the dynamics affecting these process developments. The presented work investigates the phase transition mechanisms occurring during liquified $CO_2$ depressurization from a double-membrane installation with a high-pressure conical vessel. It provides experimental results and analysis describing the effect of the divergent cross-section and liquid volume fraction on expansion wave behavior. Results indicate a considerable pressure increase at the vessel's bottom after the evaporation wave has passed due to the over-expansion effect. Its peak values were proportional to the increase in liquid volume fraction (LVF). Besides, the rarefaction wave velocities were nearly constant in all vessel height regions. In contrast, they were varied for evaporation wavefront.

## 2 Introduction

Transport and storage of liquified $CO_2$ involve serious hazards associated with pressure container malfunction due to different detrimental situations such as heating, a projectile hit, or corrosion [1, 2]. The catastrophic container failure due to explosive evaporation proceeded from rapid decompression of a liquified gas which, in certain conditions, may characterize as boiling liquid expanding vapor explosion (BLEVE) [3]. If the pressure of a pure liquified substance decreases below its saturation pressure, it potentially develops into a superheated or metastable liquid. This state encompasses the region between the liquid saturation and spinodal curves. The phase transition occurs when the liquid approaches or surpasses its superheat limit temperature (SLT). The depressurization rate controls the degree of superheat. When it is low, heterogeneous nucleation develops at the container's surface or liquid's impurities. Consequently, the possibility for severe explosion is dwindled.

According to Reid [4], a BLEVE occurs once the liquid expands to its SLT, and the phase change is governed by homogeneous nucleation. However, Zhang et al. [5] pointed out that BLEVE may be developed without the liquid temperature exceeding its SLT. They also mentioned that explosive evaporation could be promoted due to the formation of solid-phase nuclei as liquid $CO_2$ pressure falls rapidly to the atmospheric pressure. During $CO_2$ depressurization in a vertical vessel, the phase transition

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occurs in a narrow zone symbolizing the evaporation wavefront. It moves into metastable liquid downwards, and its propagation is strictly dependent upon the degree of superheat.

Several experimental studies have examined the dynamics influencing evaporation wave's emergence and propagation during decompression of different liquified substances. Das et al. [6], Hill [7], and Reinke et al. [8] are among the studies that have observed the evaporation wave and measured its front velocity. The research group for process safety, combustion, and explosion laboratory at the University of South-Eastern Norway, for many years, investigated liquid $CO_2$ depressurization. Small-scale experiments on BLEVE have been conducted on cylindrical test tubes by Bjerketvedt et al. [9] and Wei Ke [10]. Tosse et al. [11] and Hansen et al. [12] have analyzed the development of the evaporation wave intensively during liquified $CO_2$ depressurization. Most of the stated research described an evaporation wave propagating with almost steady velocity. However, the mentioned studies and most experimental research on liquified gas depressurization have been performed in constant-area ducts or tubes. Therefore, this small-scale experimental study aims to provide results and analysis of rarefaction and evaporation wave features during liquified $CO_2$ decompression in a conical-shaped vessel. It focuses on the effect of divergent cross-section on expansion waves behaviour and determination of their velocities.

## 3 Experimental configuration and procedure

A stainless steel (AISI 316) vertical conical-shaped vessel and two slip-on flanges constituted the central assembly parts of a double-diaphragm installation. These components are reinforced on an aluminum structure and opened to an atmospherically vented chamber. The vessel has a volume of $480 \cdot 10^3$ $mm^{3,}$ and each of the flanges' cylinder volumes is $510 \cdot 10^3$ $mm^3$. The high-pressure reservoir (the conical vessel) was filled with liquid $CO_2$, whereas the medium-pressure MP section (mid flange) with vapor. Industrial-grade liquid and gaseous cylinders were independently provided $CO_2$ to HP and MP sections. A high-pressure HP diaphragm was pressed between the high-pressure reservoir and the medium-pressure MP section. A second diaphragm separated the MP section from the upper flange and opened to chamber pressure. The initial pre-ruptured condition in the HP vessel was 5.2-5.8 MPa, while it was 2.6-2.9 MPa in the MP section. The temperature was ambient in all sections. Figure 1 shows the setup components and a close-up image of the conical vessel and slip-on flanges fixed above it.

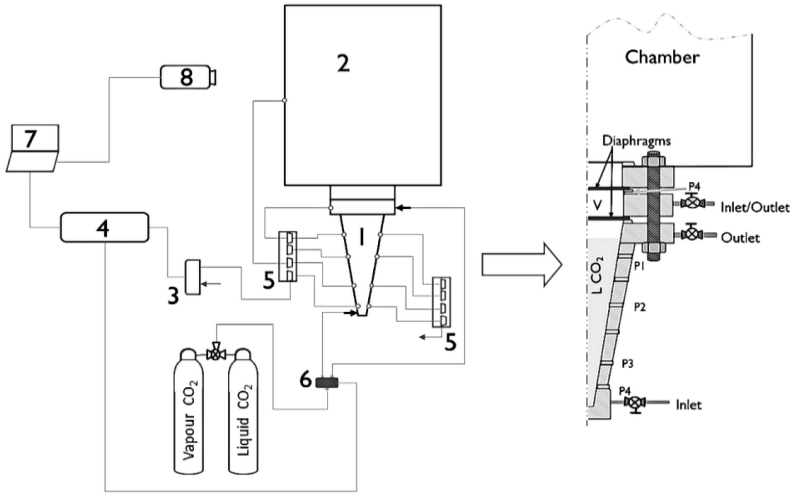


Figure 1: Schematic drawing of the experimental setup: 1. conical vessel, 2. chamber space, 3. hub, 4. Triggering unit, 5. data acquisition system, 6. 3-way valve, 7. PC, 8. Photron camera. An enlarged segment of the conical vessel and flanges on the right-hand side.

A Quantum composers 9500 series pulse generator initiated the experiments by triggering a three-way valve to increase the pressure in the MP section. As a result, the MP diaphragm ruptured, and the MP section's pressure fell to atmospheric in milliseconds. Subsequently, the HP diaphragm burst due to the

grown pressure difference between its sides. Pressure and temperature histories during the expansion inside the vessel were recorded with Pressure sensors Kulite XTM-190-2000G (P1-P4) and k-type thermocouples (T1-T3 ). Besides, a pressure sensor P5 of the same type was attached to the MP section. One Kulite XTM-190-100G sensor was attached in the middle of the chamber. Besides, a high-speed camera (Photron Fastcam SA-1) captured the evolution of the released multi-phase mixture through the chamber's transparent polycarbonate walls.

## 4 Results and Discussion

A series of experiments were performed with different liquid volume fractions (LVF): 0, 35, 52, and 73%. Diaphragm thickness for the set separating HP vessel from MP flange was 1.6 mm, and the set pressed between flanges was 1.5 mm. The pre-ruptured state in the vessel was saturated $CO_2$ at the temperature range of 19-21 °C. Figure 2 illustrates 65 ms of pressure histories inside the conical vessel (a), in the MP section (b), and overpressure in the chamber (c) during the depressurization of 73% LVF $CO_2$.

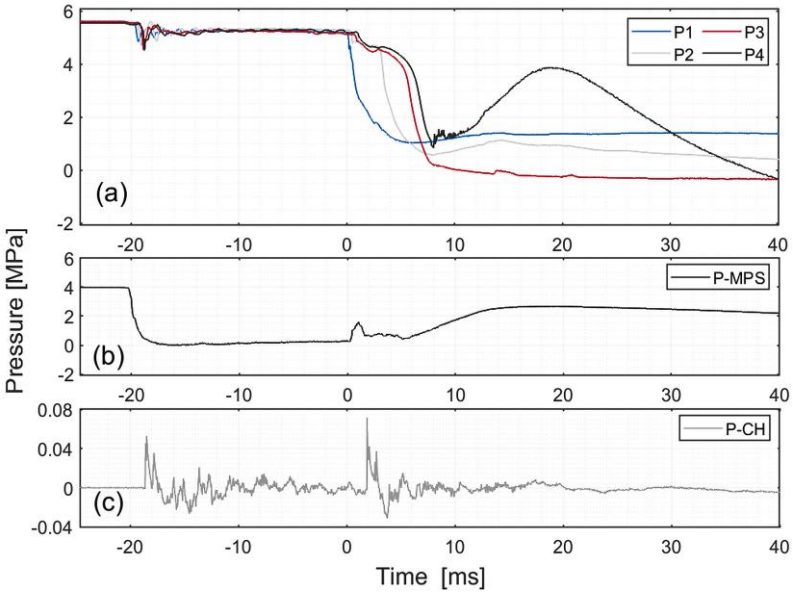


Figure 2: Pressure records during 65 ms of $CO_2$ depressurization in a conical vessel for 73% LVF, (a) inside the vessel, (b) in the MP section, and (c) overpressure in the chamber space.

A shock wave has arisen due to the MP diaphragm rupturing and proceeding upwards in the chamber space. Wherein the recorded overpressure was 0.051 MPa. While a rarefaction wave moved downwards, it hit the HP diaphragm and reflected into the chamber. After the MP diaphragm has ruptured, about 20 ms was required for the HP diaphragm to destabilize. Meanwhile, the diaphragm underwent bulging and cracks due to increased pressure difference and the waves hitting its surface. When it burst, a second shock wave initiated and traveled upwards. It passed through the MP section, raising the pressure to about 1.6 MPa. Besides, the recorded overpressure in the chamber was 0.072 MPa. The shock wave was followed by the contact surface that primarily divided vapor and liquid. Simultaneously, a rarefaction wave propagated downwards through the vapor headspace and the liquid. As a result, the liquified $CO_2$ went through isentropic expansion. The phase transition ensued during the passage of the evaporation wave behind the rarefaction wave towards the vessel's bottom. Figure 3 presents the pressure histories inside the vessel during 30 ms of $CO_2$ decompression for different LVFs (0, 35, and 52%). Time 0 indicates the HP diaphragm rupture. The first steep pressure drop corresponds to the rarefaction wave traveling through the liquid. Subsequently, the $CO_2$ liquid became superheated. The pressure lines in the metastable state fluctuated slightly and nearly plateaued. Metastable state duration depended on the LVF. It varied from about 4.1ms for 35% to 4.7 ms for 73% LVF.

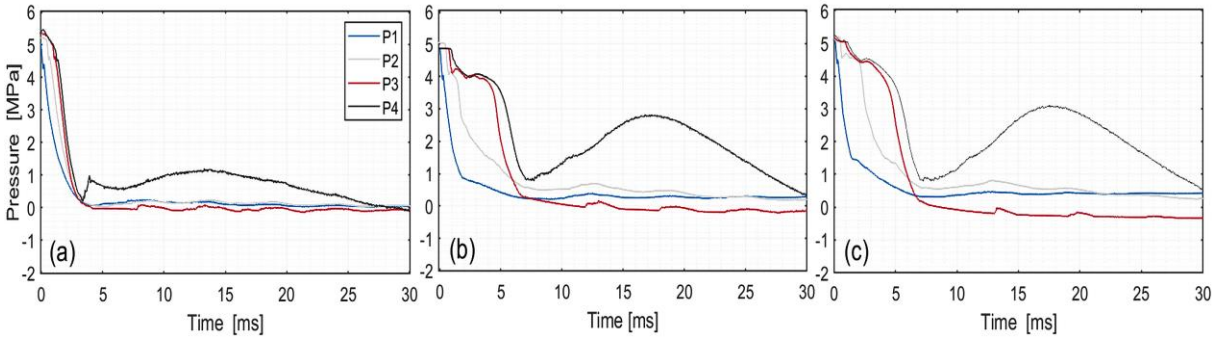


Figure 3: Pressure-time diagrams of $CO_2$ depressurization in the HP vessel for LVFs 0, 35, and 52% in (a), (b), and (c), respectively.

Figures 2 (a) and 3 show that the bottom sensor P4 has distinctive reading lines with pressure rise after reaching about 1 MPa. Then it started rising along with an onset fluctuation. It peaked and then dropped to atmospheric pressure. Figure 4 compares P4 readings for the above-indicated LVFs. The pressure peak value increased with the LVF, so it was around 1.2, 2.8, 3.1, and 3.9 MPa for 0, 35, 52, and 73%, respectively. The observed fluctuation on P4 lines is due to the reflection of the expansion wave on the vessel's bottom. It also intensified with increasing LVF, as shown in Figure 4.

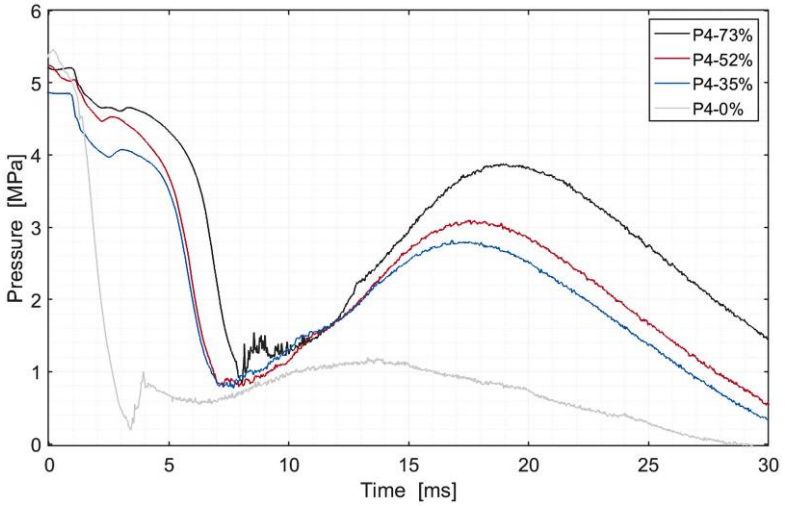


Figure 4: comparison of pressure transducer P4 recordings during 30 ms of $CO_2$ depressurization in the conical vessel for LVFs 0, 35, 52, and 73%.

The pressure surge in P4 signifies a dramatic phenomenon resulting from the potential consequence of over-expansion. After the evaporation wave had rapidly passed through and the pressure fell to about 1 MPa, the formed two-phase mixture moved upwards. Then, a heavier part of this mixture was drawn back towards the bottom with high velocity due to low pressure. While its movement decayed at the vessel's bottom, the pressure rose again. As the pressure increased, reaching its peak and falling to atmospheric, the expanded two-phase mixture flowed toward the vessel's exit.

The expansion wave velocities were determined graphically by analyzing the pressure records along the length between sensors' positions (zones P1-P2, P2-P3, and P3-P4). For this purpose, The pressure readings were illustrated on the height-time diagram, as shown in Figure 5. The rarefaction and evaporation waves' path went through the sites where the pressure sharply decreased. The exact time turning points were defined by drawing tangent lines on both sides of the turning curves. Then, connecting the tangent lines' junction to the mid-point on the line passed through the tangency points.

The locus of intersection of these connecting lines with the pressure curves demonstrated the time turning points at which pressures change.

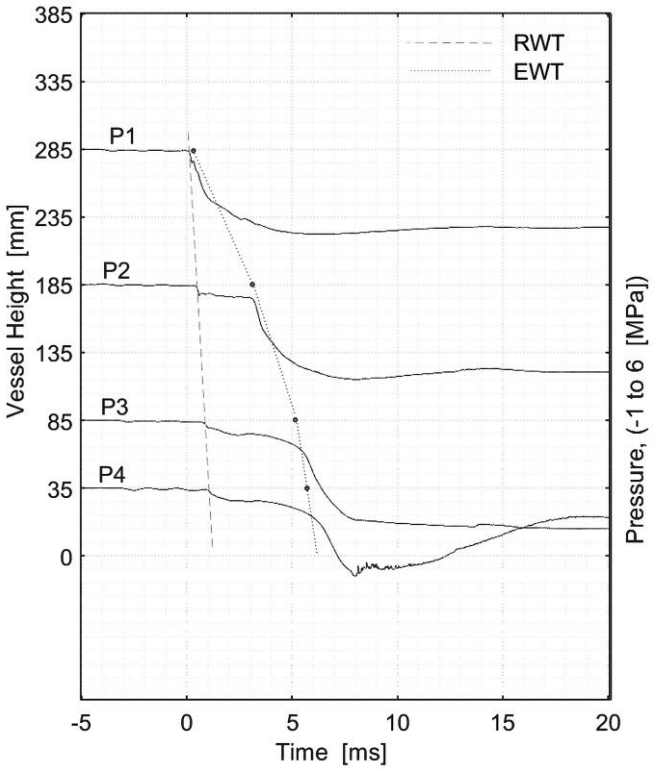


Figure 5: Synchronized pressure transducer recordings plotted on vessel's height axis during 25 ms of $CO_2$ depressurization in the conical vessel for 73% LVF. The diagram illustrates wave trajectories of rarefaction (RWT) and evaporation (EWT).

Results from calculated rarefaction wave velocities have slightly differed in the various height zones. So, the average rarefaction wave velocities were 246.7, 271.7, and 293.3 $ms^{-1}$ for the LVFs 35, 52, and 73%, respectively. However, the evaporation wave velocities varied along the three vessel's regions. For the LVFs 35, 52, and 73%, the corresponding calculated wavefront velocities in the region P3-P4 were about 89, 92.6, and 106.8 $ms^{-1}$. There were about 37.8, 56, and 73 $ms^{-1}$ in the region P2-P3. The wavefront velocity for 73% VLF in zone P1-P2 was 36.8 $ms^{-1}$. The presented numbers signify that the rarefaction waves propagated inside the vessel with nearly constant speed. However, differing from the previously mentioned studies, the evaporation wavefront swiftness increased as it propagated downwards. This trend implies that the wavefront speeded up as the vessel's cross-section area diminished. In addition, it decreased with LVF reduction. The highest evaporation wavefront velocities were in the region close to the vessel's bottom (zone P3-P4) and for LVF of 73%. The observed trend of the pressure at the vessel's bottom is different from the results of the previous experiments conducted in ducts with a constant cross-sectional area, for instance, in experimental studies by Ciccarelli et al. [13], Reinke [14], Chaves [15], and Hansen et al. [12]. This difference could be attributed to the nearly steady evaporation wave velocity in constant cross-section ducts. In contrast, the velocity increased as the cross-sectional area decreased in the conical-shaped vessel. Simultaneously, the subsequent expanded two-phase mixture propagated towards a regularly increasing cross-sectional area.

## 5 Conclusion

The small-scale experimental investigation of the expansion waves during $CO_2$ decompression in a conical vessel has shown that the rarefaction wave velocities were nearly constant over the vessel's

height for various LVFs. While the evaporation wavefront velocities increased as it propagated toward the vessel's bottom with reducing cross-section area and LVF. One of the more significant findings from this study is the pressure rise after the evaporation wave reached the vessel's bottom. This occurrence arose from the over-expansion effect when the pressure at the bottom fell sharply, and subsequently, the downstream two-phase mixture was drawn down. After its inertia at the vessel's bottom, the pressure rose gradually, and the two-phase mixture propagated upwards to the vessel exit.

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