EXPERIMENTAL STUDY OF CO_2 TWO-PHASE FLOW REGIME IN A LARGE DIAMETER PIPE

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Abstract

An experimental study was carried out on two-phase CO_2 flow in Equinor's multiphase flow rig in Porsgrunn, Norway. This facility was recently upgraded for CO_2 applications. This paper presents the experimental results on two-phase regimes of CO_2 flow in a pipe close to horizontal inclinations. One of the main discoveries from this work is that hydrodynamic slug flow is not observed. The flow regime information will be used as an input to the model development of flow assurance tools for CO_2 applications.

Keywords: *CO_2 two-phase flow, Flow regimes, X-ray measurement*

1. Introduction

Long distance transport in pipelines is found to be an effective part of the solution for storage of CO_2, for instance Snøhvit CO_2 pipeline operated by Equinor Energy AS since 2008. Operation of CO_2 transport systems has currently been restricted to single phase (gaseous or liquid) flow in the flowline. Such restrictions limit the selection of the storage site (may exclude low pressure reservoirs), and sometimes require complex system design as well as operational procedures.

To allow two-phase flow in transport and injection systems can facilitate and reduce the cost for storage in low pressure reservoirs. The existing commercial flow assurance softwares were developed based on laboratory studies and tuned against operational data of oil and gas transport lines and production systems. It is believed that many physical models in these softwares are still applicable for some flow scenarios of CO_2 transport and injection systems. However, due to large differences in thermodynamics and physical properties between CO_2 and oil & gas fluids, some flow models as well as some aspects of numerical methods in the existing software need to be tested against dedicated experimental data and the available field operational data.

In this context, a research program ECOTS JIP (Extending CO_2 Transport Solution) was established in 2020. The main objectives of this program are:

- Enabling Equinor's multiphase phase flow rig in Porsgrunn for CO_2 applications
- Experimental study of CO_2 flow with various flow conditions.

In previous studies [1,2], extensive experimental study of various two-phase flow phenomena was carried out at IFE's CO_2 flow loop in Norway. The results from these studies provide first-hand information of CO_2 flow behaviour in conditions relevant for CO_2 transport and injection system. IFE's CO_2 rig has a test section with internal pipe diameter of 44 mm and a length of 13 m. The experimental results from a larger scale facility are essential to validate the scaling behaviour of the flow model. Equinor's multiphase flow rig in Porsgrunn has been used extensively for validation of multiphase flow models for oil and gas applications. It is found that this facility is the largest in the world that has both temperature and process controls critical for CO_2 fluid systems.

In this work, the experimental results from ECOTS JIP on the two-phase flow regimes will be presented. The flow regimes of two-phase flow are critical input to the concept development of the flow models.

2. Experimental facility

Equinor's multiphase flow rig is a closed loop designed for three-phase flow tests with crude oil and natural gas fluid system. It has been in operation since 1996.

In 2020, this rig was upgraded to handle CO_2 fluid. Process safety and HSE related issues had a large focus in the upgrade.

Figure 1 shows the schematic of the flow loop in Porsgrunn. The flow loop consists of a main separator, gas compressor, liquid pump, heat exchanger for both liquid and gas phase and test section. The main separator ensures accurate phase flow rate control. The CO_2 fluid in the main separator is maintained at saturated condition with CO_2 vapor filled in the upper part of the separator, and liquid CO_2 at bottom. CO_2 vapor needs to be cooled downstream the compressor so that similar vapor and liquid temperatures are achieved at their merging location. This minimizes the mass transfer between vapor and liquid.

The flow loop has a 200 m long test section, in which a section of 80 meter is inclinable within the range of -5 to 10 degrees. Pipe internal diameter is 0.0779m. The pipe material is duplex steel, and the whole loop is insulated. The rig has the following operational window for CO_2 flow tests

- Maximum liquid rate: 40 m^3/h
- Maximum vapor rate: 100 m^3/h;
- Pressure: 45-65 bar
- Temperature: 10 -26 ^oC

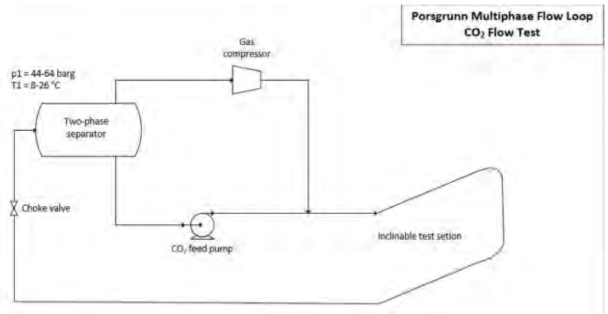


Figure 1**:** Sketch of Equinor's multiphase flow rig in Porsgrunn

This facility is equipped with advanced instrumentations as follows:

- Coriolis meter for both vapor and liquid mass flow rate measurement
- 5 absolute pressure sensors
- 11 thermal-couples for temperature measurement at different locations
- 6 differential pressure transducers
- 7 narrow-beam Gammas
- 1 X-ray
- Two pipe sections with transparent materials (sight glass) for video recording.

The narrow beam Gamma is mounted at the centre-line of the pipe in a vertical direction. It measures the average fluid density along the beam diameter. This average density can be converted into liquid holdup if an ideal stratified flow is observed. The transient measurement with sampling rate of up to 20 Hz provides the information of vapor-liquid flow geometry, a large variation of narrow beam measurement indicates either stratified flow with large wave interface or gas-liquid slug flow.

The X-ray system is a mono camera system, measuring liquid holdup and fluid distribution in two- or three-phase flow. A principle sketch of the system used in the flow loop is shown in Figure 2. The camera can obtain up to 190 images per second with resolution of 75 μm. This X-ray system has been in operation for oil and gas application since 2015.

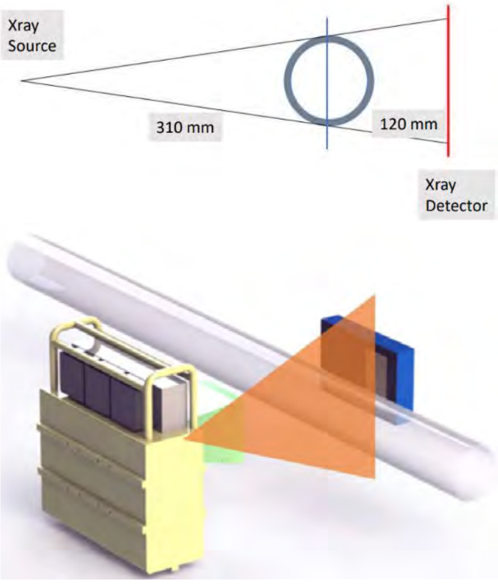


Figure 2 Schematic of the X-ray mono camera system. Upper: source-camera configuration. Bottom: 3D layout.

3. Experimental observations

The experiments of two-phase CO_2 fluid were carried out under steady-state conditions. Pure CO_2 fluid was used in the experiments. Under a defined pressure in the main separator, all instruments should show stable parameter values during a period of 10 minutes. These parameters are: vapor and liquid mass flowrate, temperature at different locations, pressure and differential pressure sensors, readings from Gammas and X-ray. During the experiments, the choke valves downstream the gas compressor and liquid pumps were used to control the mass flowrate of each phase, and the cooling of vapor phase downstream the compressor was imposed to ensure the desired temperature for vapor phase achieved.

The experiments were carried out with following conditions:

- System pressure: 45, 50 and 60 bar, with corresponding temperatures: 10, 15 and 22 ^oC.
- Liquid superficial velocity (Usl): 0.1, 0.2, 0.3, 0.4 0.5, 1, 1.5 and 2.0 m/s.
- Vapor superficial velocity (Usg): 0.1, 0.2, 0.25,0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0 and 4.0 m/s.
- The test section inclinations are: -5, -1, 0, 1, 5 and 10 degrees.

The information from three different measurements were used to identify the flow regime:

- Direct observation via transparent windows, video was recorded for most of the cases.

- Transient measurement from narrow beam-Gamma, which gives mixture density at the pipe centreline.
- X-ray measurement of the liquid holdup profile (distribution) across pipe

Figure 3 shows typical flow geometries from the video recorded through transparent window. Under the flow condition with low Usg and Usl, a clear stratified gas-liquid flow is observed with and without presence of vapor bubbles at the gas-liquid interface, depending on the mixture flowrate. A smooth vapor-liquid interface without bubble generation is observed with very low mixture velocity. Increase in mixture flow rate leads to increased mixing intensity, and generation of more bubbles. In these pictures, secondary flow is observed along the pipe wall, this is simply due to that fact that the diameter of transparent window is slightly smaller than the main pipe (0.065 m vs. 0.0779m ID).

Both Gamma and X-ray measurements show very stable liquid holdup behaviour with time. The X-ray measurements provide the holdup profile along the pipe cross-section (horizontally from bottom to top of the pipe). Figure 4 and Figure 6 show the X-ray measurement for two series of tests with Usl = 0.5 m/s and Usl = 2.0 m/s, respectively. These two series of tests have the same system pressure (60 bar) and pipe inclination (1 degree upward flow). These two series represent two extreme situations: gas dominated and liquid dominated flow. The time series measurement shown in these figures have 30 seconds. The red colour represents liquid dominant measurement, and the blue colour indicates gas/vapour dominant measurement. The time-averaged distribution of liquid holdup gives quantitative representation of phase distribution in a pipe as shown in Figure 5 and Figure 7.

The measurements give the following observations on the flow regime:

- The volume fraction of phases segregated with relatively smooth interfaces. The slug type of the flow geometry is not identified in any of the tests carried out. This is also consistent with the experimental observations from IFE'e test loop [2], which has smaller a pipe diameter (44 mm ID).
- For the cases with relatively low mixture flow rate, stratified gas-liquid flow regime is observed. Bubbles are generated at the interface. Increase in mixture flowrate and system pressure leads to more bubble generation. If liquid flowrate is significantly higher than the gas flowrate, a pure liquid layer is observed at the bottom part of the pipe, the top part of the pipe is filled with the strong mixing flow layer (bubble flow layer). This bubbly flow layer has low liquid volume fraction. The interface at these two layers exhibits wavy structure, indicating strong mixing intensity. Smooth interface is observed only for very low mixture velocity situations.
- With high mixture flowrate, the gas-liquid is well mixed with very small bubbles.
- High system pressure gives a large gas-liquid density ratio, this leads to more bubble generation.
- For liquid dominated flow condition, there is a trend of liquid layer, and the dispersion process begins at the upper part of the flow.
- For vapor dominated flow condition, there is a trend of vapor layer, and the dispersion process occurs at the bottom part of the flow.

(a) Low Usg & low Usl (b) Low Usg & moderate Usl

(c) High Umix (d) Moderate Usg & low usl

Figure 3 Flow geometry observed from transparent window (sight glass)

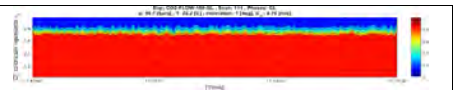
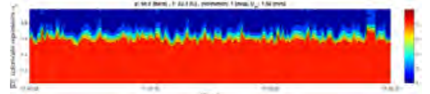
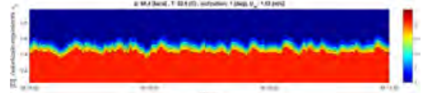
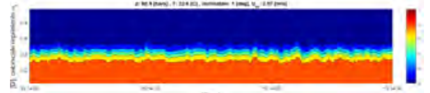
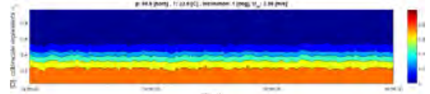
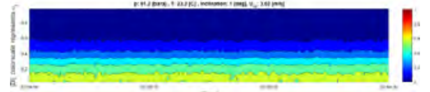
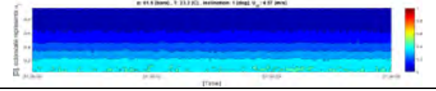
Usl=0.5m/s Usg =0.33m/s	
Usl=0.5m/s Usg =0.57m/s	
Usl=0.5m/s Usg =1.0m/s	
Usl=0.5m/s Usg =1.6m/s	
Usl=0.5m/s Usg =2.0m/s	
Usl=0.5m/s Usg =3.0m/s	
Usl=0.5m/s Usg =4.0m/s	

Figure 4 X-ray measurement of liquid holdup profile across the pipe, color scale gives the liquid holdup. Test conditions are 1 degree upward pipe and P = 60 bar

The following flow regimes are summarised from the experimental observations:

- Stratified flow with bubbles generated at the interface (ST) (Figure 3a)
- Stratified flow with bubble & churn flow at the top layer and liquid layer at the bottom (ST/Ch)(Figure 3b)
- Bubbly flow (BB)(Figure 3c)
- Stratified flow with gas layer at the top and bubbly flow at the bottom (ST/BB)(Figure 3d).

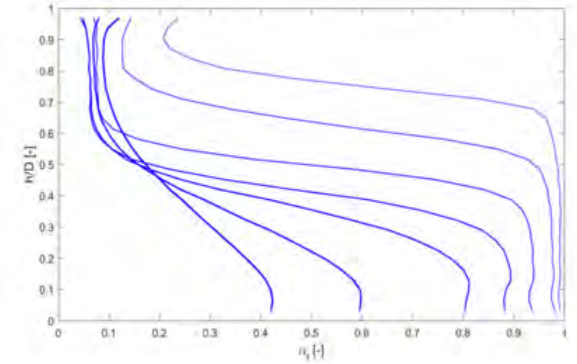


Figure 5 Time-averaged liquid holdup profile from X-ray for the tests with Usl = 0.5 m/s, Usg varies from 0.3 to 4.0 m/s, 1 degree upward pipe and P = 60 bar.

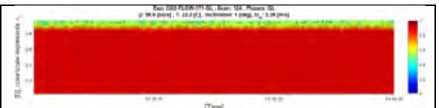
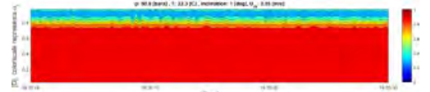
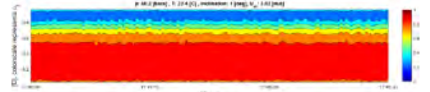
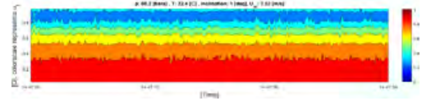
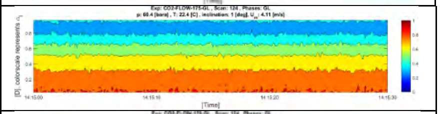
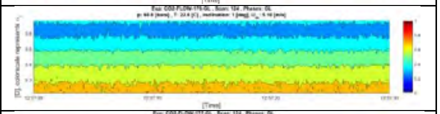
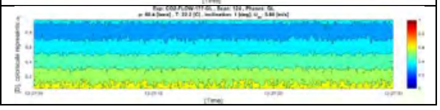
Usl = 2.0 m/s Usg= 0.33 m/s	
Usl = 2.0 m/s Usg = 0.6 m/s	
Usl = 2.0 m/s Usg = 1.0 m/s	
Usl = 2.0 m/s Usg = 1.6 m/s	
Usl = 2.0 m/s Usg = 2.0 m/s	
Usl = 2.0 m/s Usg = 3.0 m/s	
Usl = 2.0 m/s Usg = 4.0 m/s	

Figure 6 X-ray measurement of liquid holdup profile across the pipe, color scale gives the liquid holdup. Test conditions are 1 degree upward pipe and P = 60 bar

The two-phase flow regimes can also be illustrated in a flow regime map in terms of vapor-liquid superficial velocity. Figure 8 shows the flow regime map for the flow condition of 60 bar and 1 degree upward inclination. Similar flow regime maps were observed for other flow conditions in the test program. The pipe inclinations (within the range or -5 and 10 degrees) have little impact the flow regime boundary.

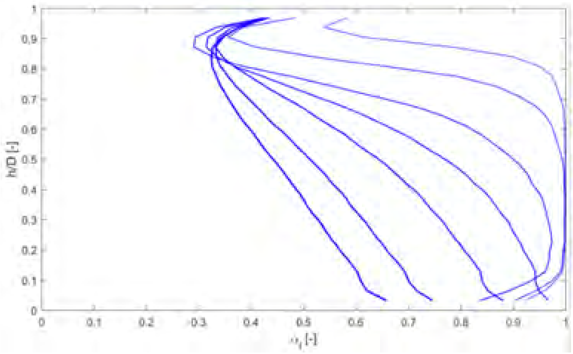


Figure 7 Time-averaged liquid holdup profile from X-ray for the tests with Usl = 2.0 m/s, Usg varies from 0.3 to 4.0 m/s, 1 degree upward pipe and P = 60 bar.

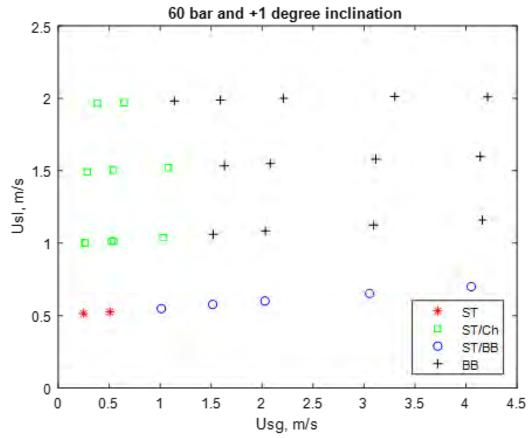


Figure 8 Flow regime map for the flow with 1 degree upward inclination and P = 60 bar.

4. Summary

The multiphase flow rig in Porsgrunn has been upgraded to carry out two-phase flow studies of pure CO_2. This is currently the largest test facility in terms of pipe diameter and pipe length for CO_2 applications in the world. The facility is a closed system with both temperature and pressure control, and is equipped with advanced instrumentation for accurate measurement of various physical parameters.

This paper presents the experimental observations of two-phase CO_2 flow regimes in a near horizontal pipe configuration. Both direct observation via class window and X-ray measurement shows that the flow regimes observed are: stratified flow with and without bubble generation at vapor-liquid interface, stratified flow with liquid layer at bottom and bubbly flow at top, stratified flow with gas layer at top and bubbly flow at bottom, and dispersed bubbly flow. The hydrodynamic slug flow which is one of the typical flow regimes for oil and gas flow system is not observed. This may be due to relatively small gas-liquid density ratio and very small surface tension of CO_2 fluid system.

Acknowledgements

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References

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