Zhang, Wenbiao, Yan, Yong, Shao, Ding, Liu, Shi and Wang, Tao (2018) ***Experimental investigations into the transient behaviours of CO2 in a horizontal pipeline during flexible CCS operations.*** **International Journal of Greenhouse Gas Control, 79 . pp. 193-199. ISSN 1750-5836.**

Experimental investigations into the transient behaviours of CO_2 in a horizontal pipeline during flexible CCS operations

Wenbiao Zhang[1], Yong Yan[2*], Ding Shao[1], Shi Liu[1], and Tao Wang[3]

1 School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, P.R. China
2 School of Engineering and Digital Arts, University of Kent, Canterbury, Kent CT2 7NT, U.K.
3 KROHNE Ltd. Wellingborough, NN8 6AE, U.K.

* Correspondent author: y.yan@kent.ac.uk

Abstract

Power plants with CCS facilities should be operated flexibly because of the variability in electricity demand. Load change, start-up and shutdown will occur during flexible CCS operations. It is necessary to investigate the transient behaviours of CO_2 flow in the pipeline during these operations for optimized operation of CCS plants. However, very limited experimental data for gas-liquid two-phase CO_2 under CCS conditions are available. As a result, experimental observations of the CO_2 transient behaviours were conducted on a CO_2 gas-liquid two-phase flow rig. Load change, start-up and shutdown of a CO_2 flow process were replicated on the rig. Coriolis flowmeters and high-speed imaging equipment were used to observe the mass flow rate, thermophysical properties and flow regimes of the CO_2 flow. There are significant discrepancies in the mass flow rate of two-phase CO_2 between the test value and the reference value during the load change. During the start-up operation, the flow regime transits from liquid slug flow to gas bubbly flow and the mass flow rate from the Coriolis flowmeter presents two-step changes. In addition, the depressurization and evaporation of liquid CO_2 in the pipeline were observed during the shutdown operation.

Keyword: Carbon capture and storage; Flexible operation; CO_2 flow; Transient behaviour

1. Introduction

It is well known that electricity generation from fossil fuel power plants is a major source of CO_2 emissions, which makes power plants the first point of interest for implementation of low emissions technologies such as CCS (Leung et al., 2014). Although it is assumed by IEA GHG and others that power plants with CCS will operate at base load, power plants are increasingly required to balance the power grid by compensating for the intermittent electricity supply from renewable energy resources such as solar stations and wind farms. As a result, in many cases CCS plants will need to be operated flexibly (Abdilahi et al., 2018; Dowell and Staffell, 2016; Mechleri et al., 2017; Tait et al., 2016). Load change, start-up and shutdown will occur during flexible CCS operations. CCS technology has three parts, which are capture, transport and storage, and pipelines are considered to be the most viable solution for large volume CO_2 transportation (Onyebuchi et al., 2018). Transient conditions occur in the pipeline during flexible CCS operations, which result in phase transition of CO_2, flow instability and hydrate formation (Uilhoorn, 2013). It is therefore necessary to investigate the transient behaviours of CO_2 in the pipeline for the optimization of CCS operations and earlier work on the numerical simulations of transient CO_2 flow are available. In addition, knowledge on transient behaviours of CO_2 will enable an in-depth understanding of the CO_2 flow characteristics and subsequent optimal design of the CO_2 transport pipelines under flexible CCS conditions. There has been some work on the modelling of CO_2 flow characteristics in recent years. Chaczykowski and Osiadacz (2012) carried out the simulations of transient flows in pipelines containing dense phase and supercritical CO_2-rich mixtures. The transient conditions of block valve closure and variable CO_2 production rates were selected as case studies. The results showed that the type and quantity of impurities had a significant influence on the hydraulics of the pipeline transportation system under transient conditions. Aursand et al. (2013) reviewed current research challenges related to the transient flow modelling of multiphase CO_2-rich mixtures in pipes. Although numerical simulations have been conducted to analyze the transient behaviours of CO_2 flow in the pipeline, there have no experimental investigations to date to validate the transient numerical models.

Experimental investigations into CO_2 transient behaviours in CCS pipelines require appropriate measurement devices. The Coriolis mass flowmeter (CMF) was recognised as one of the most promising technologies for fiscal metering in CCS (Collie et al., 2016; Hunter and Leslie, 2009). CMF is a flow measuring device that depends on the vibration between the fluid and its inner tubes to create Coriolis acceleration on the fluid and to sense the reaction on the tubes. CMF measures the mass flow rate of the fluid based on the time delay between the two pick-up sensors with high accuracy, rangeability and repeatability (Wang and Baker, 2014). In addition to the mass flow rate, the density of the fluid can also be determined from the resonant frequency of the tubes and the temperature of the fluid. With increased acceptance in industry, CMF has been widely applied in single-phase and multiphase flow measurement (Wang and Baker, 2014). Wang et al. (2018) reported that the CMF combined with soft computing models can measure the mass flow rate of gas-liquid two-phase CO_2 with a relative error of $\pm 2\%$ over the range from 250 kg/h to 3200 kg/h. In addition, for flow measurement in transient conditions, the dynamic response of the CMF is important. It was found from experimental investigations on a water flow test facility that, with appropriate flow tube design, improved meter drive and signal processing procedures, high dynamic performance CMF was achievable (Cheesewright and Clark, 2004; Clark and Cheesewright, 2006). Pope and Wright (2014) investigated the performance of the CMFs in transient helium gas flows and proved that CMFs satisfy the requirement from the International Organization of Legal Metrology Recommendation 139. However, the thermophysical properties of the fluid in above reported work are quite different from CO_2 under CCS conditions. Experimental investigations into CO_2 transient behaviours using CMFs are required to validate the CMF performance during flexible CCS operations. Nazeri et al. (2016) studied transient conditions on a CO_2 flow rig under start and stop operations using a CMF, but their work focused on gaseous CO_2 flow in a 6 mm bore pipeline, the flow characteristics of which are far from those under CCS conditions. Gas-liquid two-phase CO_2 is expected in CCS pipelines due to the thermophysical properties of CO_2 and the transportation conditions. Moreover, flow regimes of two-phase CO_2 fluctuate significantly due to the changes in the flow dynamics and thermophysical properties of CO_2 during the transient conditions. In order to visualize the highly dynamic characteristics of transient CO_2 flow, high-speed imaging is utilized in conjunction with CMFs in this study.

2. Experimental method

The experimental method in this paper is given in Fig. 1. Three different operation modes of load change, start-up and shutdown in the CO_2 transportation pipeline during flexible CCS operations were created on the experimental rig. During each operation mode, the mass flow rate, density, temperature and pressure of the two-phase CO_2 flow from the CMF and the pressure transducer were recorded. In addition, images of the CO_2 from high-speed imaging equipment were also captured. As a result, the mass flow rate, thermophysical properties and the flow regimes of two-phase CO_2 flow in the pipeline were varied and observed under a range of flexible CCS conditions.

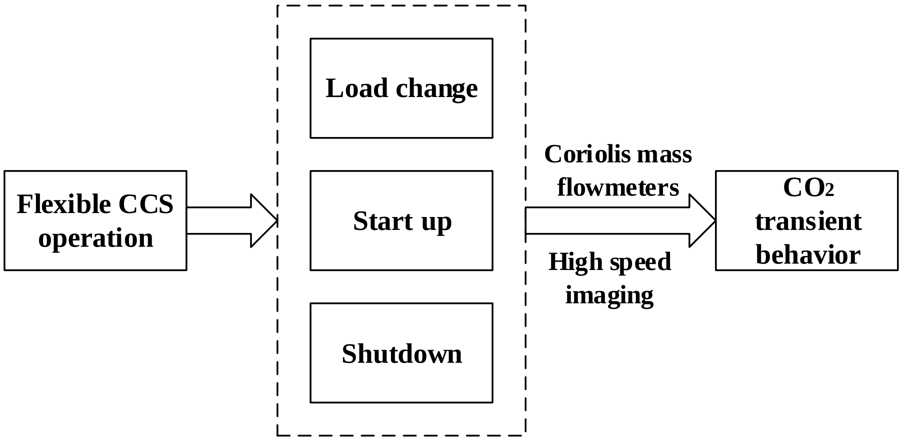


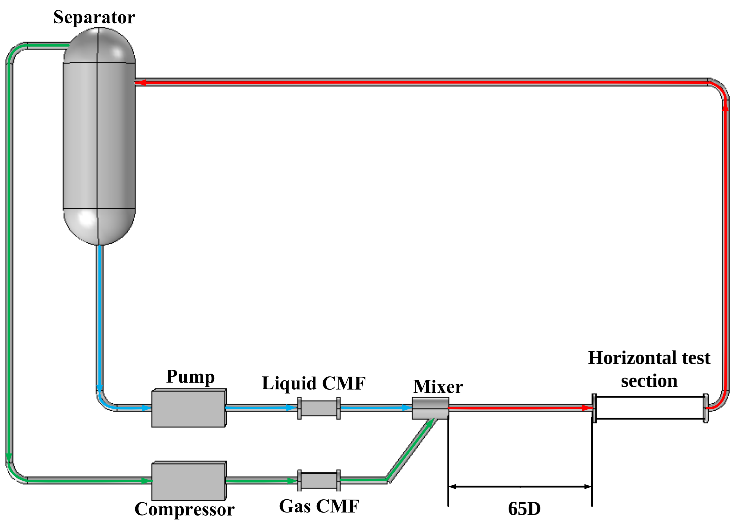
Fig. 1. Experimental method

3. Experimental setup and test conditions

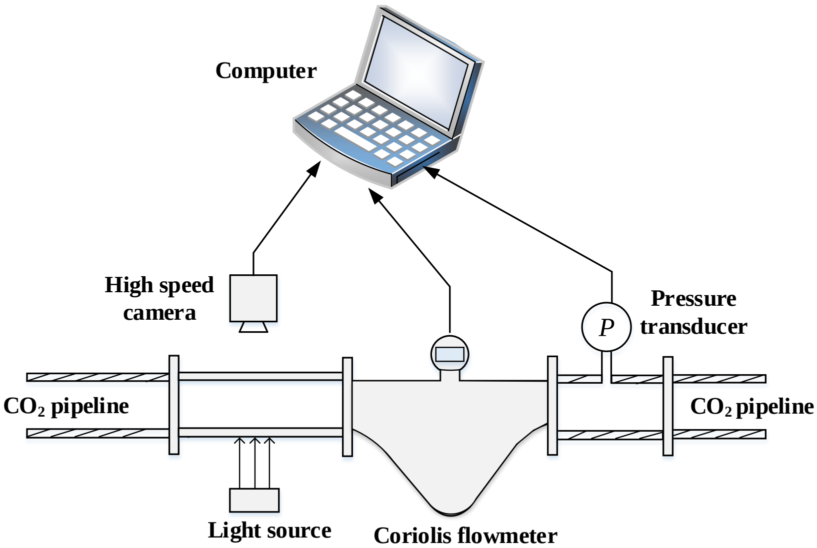
Experimental investigations were conducted on a 25 mm bore horizontal test section of the CO_2 gas-liquid two-phase flow rig at North China Electric Power University, as shown in Fig. 2 (a). CO_2 is stored in a separator which also serves as a supply vessel. From the separator, the liquid CO_2 flow is driven by a piston pump while the gas CO_2 flow is driven by a compressor. Both flows are controlled separately and mixed at a downstream mixer. After the horizontal and vertical test sections, the gas-liquid two-phase CO_2 returns to the separator. The distance between the horizontal test section and the mixer is 65D (D=25 mm). The CO_2 flow in the horizontal test section is fully developed. Two independent CMFs are installed on the liquid and gas CO_2 flow sections to provide references. The measurement uncertainty for liquid phase and gas phase CO_2 is 0.16% and 0.3%, respectively.

A CMF, a high-speed imaging equipment and a pressure transducer were installed in series on the horizontal pipeline, as shown in Fig. 2 (b) and (c). The CMF installed on the horizontal test section was KROHNE OPTMASS S15. XFC 300 Data Logger was used to record and monitor the mass flow rate, density and temperature of CO_2 flow during each test. A transparent acrylic pipe was also installed in the horizontal test section in order to visualize the liquid phase and gas phase CO_2 in the pipe. The transparent acrylic pipe was specially designed to withstand the high pressure (up to 100 bar) on the two-phase flow rig. A high speed camera (Photron FASTCAM Mini UX 50) and the lens (AF-S NIKKOR, focal length 50 mm, maximum aperture f/1.4) were applied to capture the images of CO_2 flow. The camera was placed at the same height as the pipe centerline and a continuous white light source was carefully positioned to obtain the clear pictures of CO_2 flow. During the experiments the images of CO_2 flow regimes and corresponding mass flow rate, density, pressure and temperature of CO_2 flow under the test conditions were recorded and analyzed.

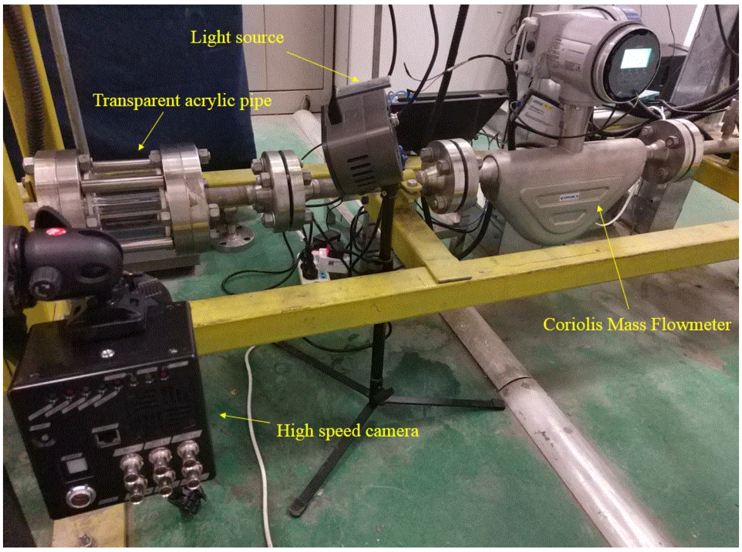
In order to study the transient behaviours of CO_2, the operation modes of load change, start-up and shutdown of a CO_2 flow process were replicated on the test rig. In the load change operations, two groups of experiments were conducted. Firstly, the gas flow rate changed while the liquid flow rate was fixed. The step change in the gas flow rate was accomplished by increasing or decreasing the working speed of the air compressor. In the second group of the experiments, the step increase or decrease was introduced to the liquid flow rate in the liquid loop while keeping the gas flow rate constant. When the load changed, a step change in the mass flow rate of liquid phase or gaseous CO_2 was observed. While the piston pump in the liquid phase loop was suddenly started or closed to create the start-up and shutdown modes, transient CO_2 two-phase flow regimes in the pipeline were observed.



(a) Layout of the CO_2 gas-liquid two-phase flow rig



(b) Schematic diagram of the horizontal test section



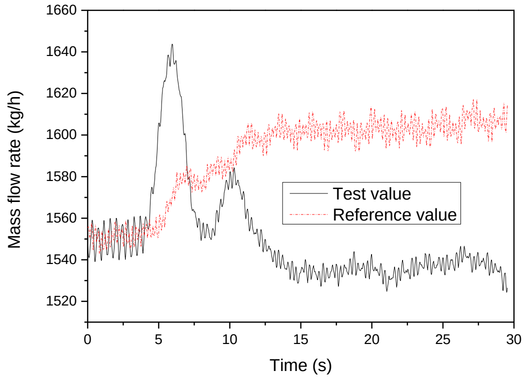
(c) Photo of the horizontal test section

Fig. 2. Experimental setup

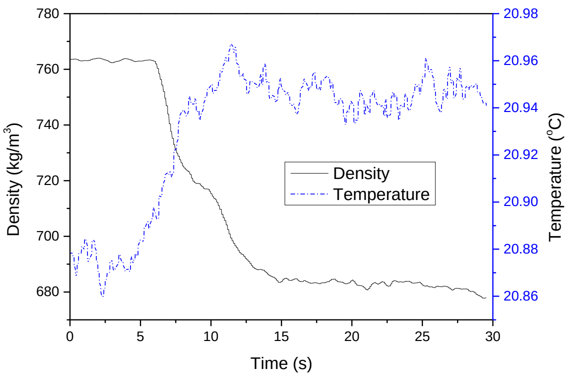
4. Results and discussion

4.1. Load change

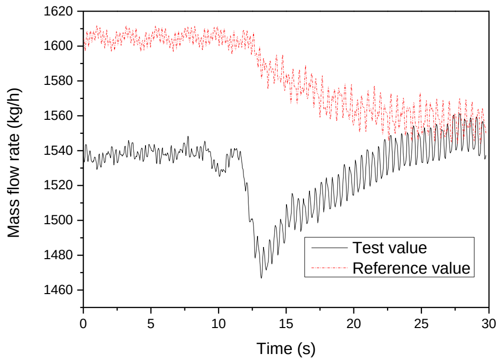
Fig. 3 shows the transient behaviours of two-phase CO_2 flow during the load change operations in the horizontal pipeline. The mass flow rate of liquid phase was fixed at 1500 kg/h while the mass flow rate of gas phase experienced the step increase or decrease. As shown in Fig. 3 (a) and (c), it is found that the overshoot and undershoot of CO_2 mass flow rate from the test meter occur during the transient changes. Due to the compressibility of gaseous CO_2, large variations in gas flow rate affect the vibration between the fluid and its conveying pipe in the CMF, which results in the overshoot and undershoot of the mass flow rate during the step increase and decrease. Meanwhile, in comparison with the reference value, which is the sum of the results from the CMFs in the liquid and gas single-phase loops, there are significant discrepancies in CO_2 mass flow rate between the test value and the reference value during the transient changes. The absolute error and relative error of the results from the CMF are given in Fig. 4. The maximum absolute error and relative error are -87.89 kg/h and 5.44% during the step increase, while the maximum absolute error and relative error are -122.43 kg/h and 7.67% during the step decrease, which cannot meet the requirement of 1.5% measurement uncertainty specified in the European Union Emissions Trading Scheme under all expected CCS conditions (Hunter and Leslie, 2009). In order to accurately measure the total mass of CO_2 flow, the errors during the transition should be compensated using the soft computing method (Wang et al., 2018; Yan et al., 2018). In addition, since the gaseous CO_2 has a higher temperature and a lower density in comparison with liquid phase CO_2, the density and temperature of two-phase CO_2 flow change correspondingly during the step increase or decrease of the gas mass flow rate (Fig. 3 (b) and (d)). Meanwhile, density and temperature readings from the CMF are good indicators for measuring the gas void fraction of two-phase CO_2 flow.



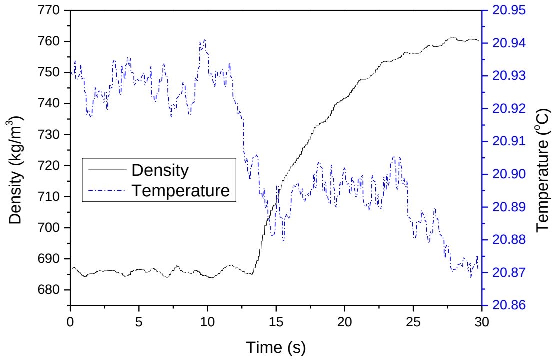
(a) Mass flow rate variation during step increase



(b) Corresponding density and temperature change during step increase

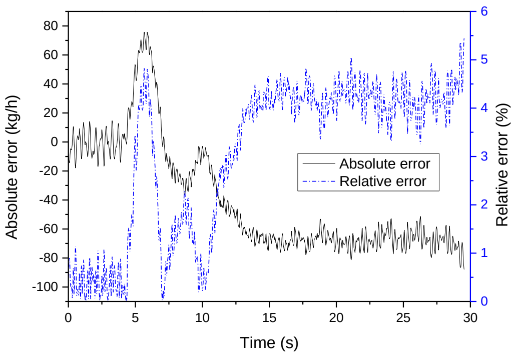


(c) Mass flow rate variation during step decrease

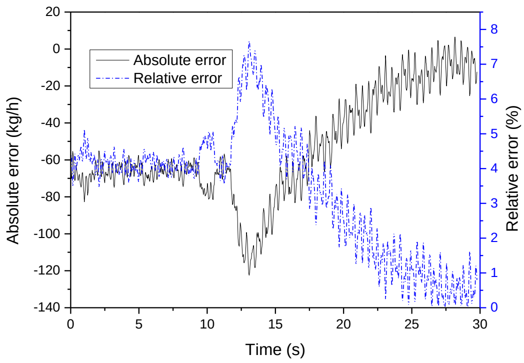


(d) Corresponding density and temperature change during step decrease

Fig. 3. Transient behaviours of the two-phase CO_2 flow during the step increase or decrease of gas mass flow rate.



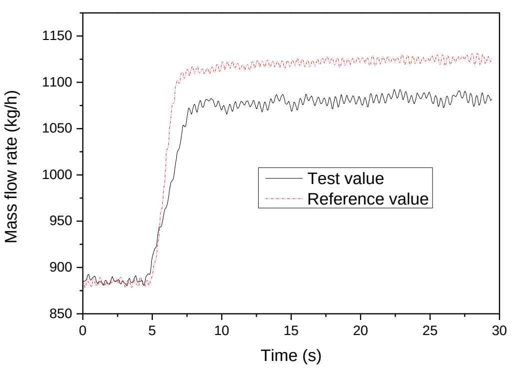
(a) Step increase



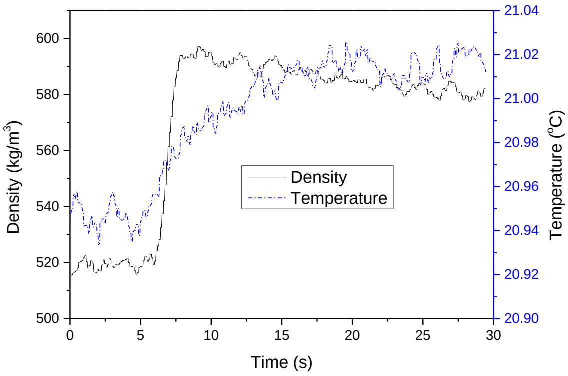
(b) Step decrease

Fig. 4. Absolute error and relative error between the test value and the reference value during the step increase or decrease of gas mass flow rate.

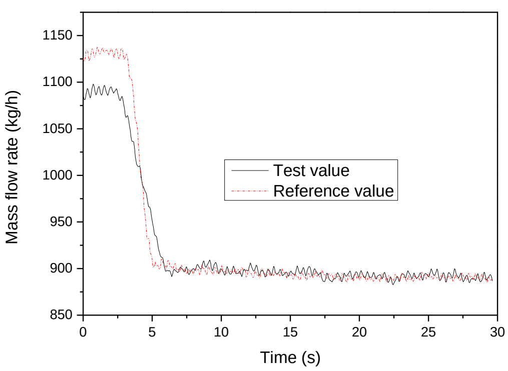
The liquid CO_2 is incompressible and the variations in the liquid mass flow rate do not affect the operation of the CMF. As shown in Fig. 5, there are smooth transitions of CO_2 mass flow rate between the start point and the final point during the step increase or decrease of liquid mass flow rate when the gas mass flow rate is fixed at 120 kg/h. Because the CMF has good dynamic response, the test value and reference value have a similar trend. However, due to the sudden changes in the gas volume fraction of two-phase CO_2, there are also obvious absolute and relative errors of the results from the CMF, as shown in Fig. 6. In addition, the density and temperature of CO_2 flow present step increase or decrease when the liquid mass flow rate changes.



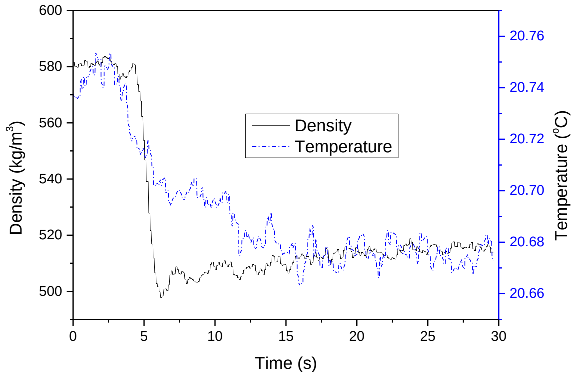
(a) Mass flow rate variation during step increase



(b) Corresponding density and temperature change during step increase

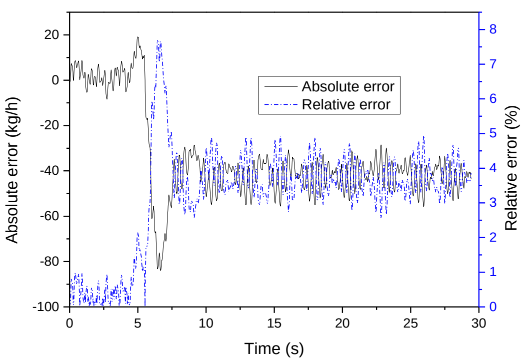


(c) Mass flow rate variation during step decrease

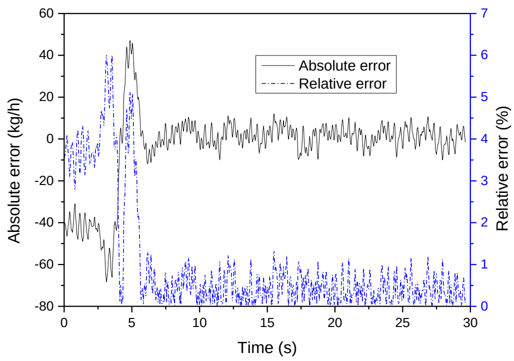


(d) Corresponding density and temperature change during step decrease

Fig. 5. Transient behaviours of the two-phase CO_2 during the step increase or decrease of liquid mass flow rate.



(a) Step increase

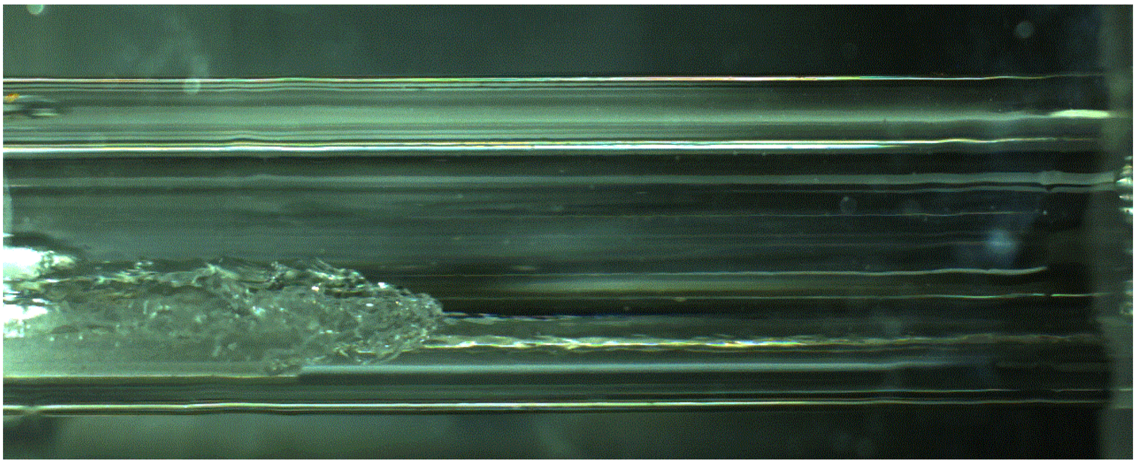


(b) Step decrease

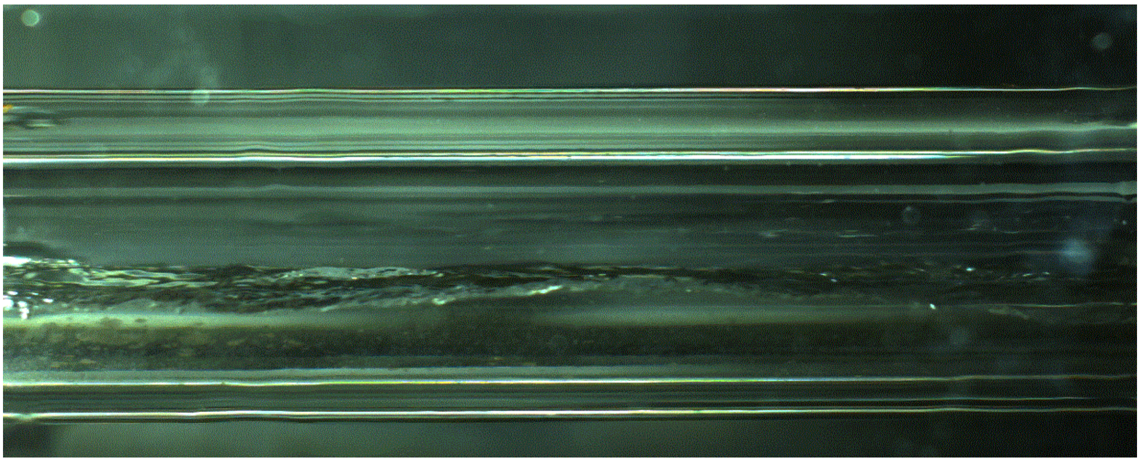
Fig. 6. Absolute error and relative error between the test value and the reference value during the step increase or decrease of liquid mass flow rate.

4.2. Start-up

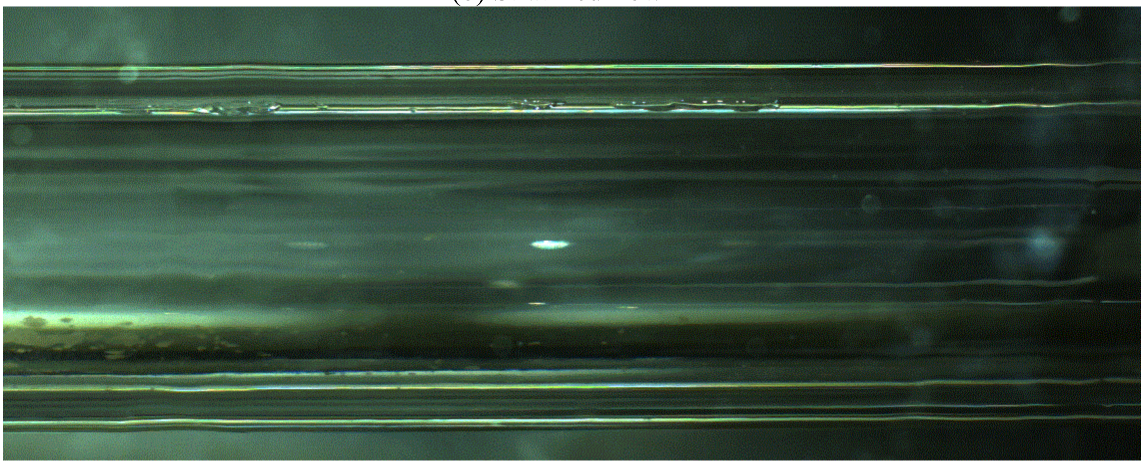
In the start-up operations, the pipe was initially filled with the gaseous CO_2. With the start of the piston pump in the liquid phase loop, liquid slug of CO_2 was found in the horizontal test section of the pipeline, as shown in Fig. 7 (a). After that, the flow regime changed to stratified flow and the liquid level of CO_2 gradually increased (Fig. 7 (b)). Finally, the liquid phase filled the entire pipe, except for small gas bubbles existing at the top of the pipeline (Fig. 7 (c)). During the start-up process, the mass flow rate measured from the CMF in the horizontal test section presents two-step changes, as shown in Fig. 8. In addition, it is found that the density from the CMF gradually increases together with the second step change of the mass flow rate. Considering the flow images from the high speed camera, it is supposed that the second step change is related to the occurrence of the liquid slug in the horizontal pipeline. In addition, the first step change of the mass flow rate is caused by the flow of gaseous CO_2. With the start of the pump in the liquid phase loop, the pressure wave is generated in the pipeline and the wave forces the stationary gaseous CO_2 to flow through the CMF in the horizontal test section before the arrival of the liquid slug.



(a) Liquid slug flow



(b) Stratified flow



(c) Gas bubbly flow

Fig. 7. Flow regime transition during the start-up operations

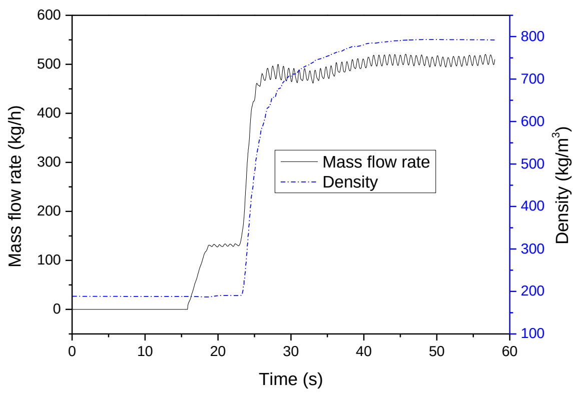
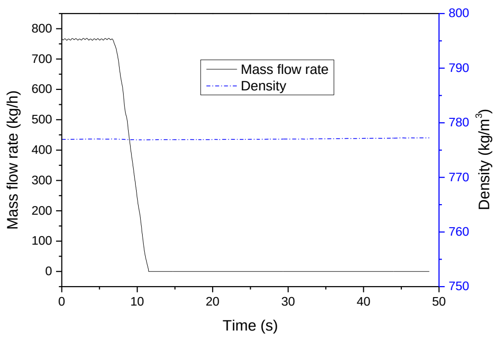


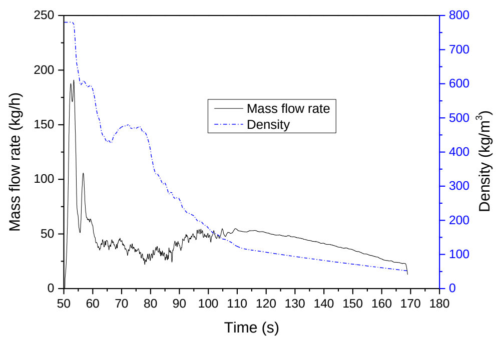
Fig. 8. Mass flow rate and density of the CO_2 flow in the horizontal pipeline during the start-up operations

4.3. Shutdown

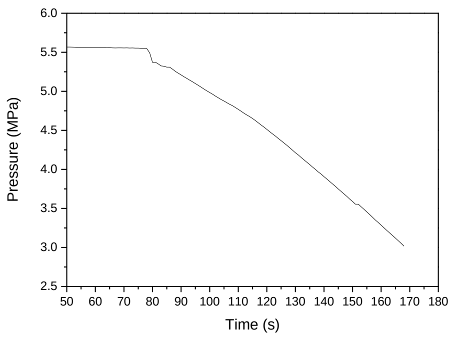
The transient behaviours of CO_2 flow during the shutdown operations are given in Fig. 9. The pipeline was initially filled with liquid phase CO_2 with the mass flow rate of 750 kg/h. The piston pump in the liquid phase loop was suddenly stopped and the mass flow rate of liquid phase CO_2 dropped to zero in less than 5 seconds, as shown in Fig. 9 (a). In order to accelerate the depressurization process in the shutdown operations, a regulating value was opened to release the liquid phase CO_2 into the atmosphere. Corresponding variations in mass flow rate, density, pressure and temperature of CO_2 flow in the horizontal pipeline are shown in Fig. 9 (b)-(d). Due to the large pressure drop between the pipeline and the atmosphere, the CO_2 flow was forced to move and the mass flow rate of CO_2 presented a large increase after opening the regulating value (Fig. 9 (b)). With the drop of the pressure in the pipeline (Fig. 9 (c)), the mass flow rate gradually decreased. Meanwhile, the evaporation of the liquid phase CO_2 occurred, small gaseous CO_2 bubbles were generated and the liquid level of CO_2 dropped, which resulted in the density drop of the CO_2 flow (Figure 9 (b)). In addition, due to the endothermic effect associated with the evaporation, the temperature of the CO_2 flow decreased (Fig. 9 (d)).



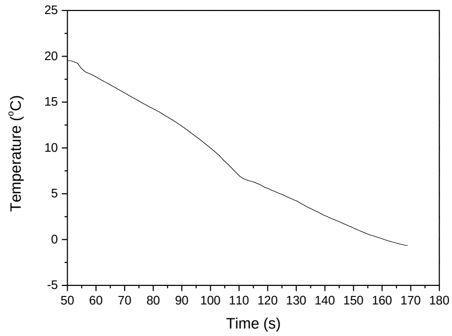
(a) Mass flow rate and density change after stopping the pump



(b) Mass flow rate and density change after opening the valve



(c) Pressure fluctuation after opening the valve



(d) Temperature fluctuation after opening the valve

Fig. 9. Transient behaviours of the CO_2 flow during the shutdown operations.

5. Conclusions

The transient behaviours of the CO_2 flow during flexible CCS operations including load change, start-up and shutdown processes have been investigated on the CO_2 gas-liquid two-phase flow rig using dedicated instrumentation. The following conclusions are drawn from the experimental results:

(1) There are significant discrepancies between the mass flow rate readings and the reference values during the load change operations, especially when there is a step increase or decrease in the mass flow rate of gaseous CO_2. This is mainly due to the sudden change of gas volume fraction in the two-phase flow.

(2) The flow regimes of liquid slug flow, stratified flow and gas bubbly flow are generated after the start of the liquid phase pump. Meanwhile, two-step changes in the mass flow rate and corresponding variations in the density of CO_2 flow were observed. Such an interesting observation for start-up operations clearly indicates the transition from a gaseous phase to a liquid phase inside the pipeline.

(3) After the stop of the liquid phase pump and the release of CO_2 flow into the atmosphere, the depressurization and evaporation of liquid CO_2 in the pipeline were observed. This shutdown process can be identified by the graduate reduction in the density of CO_2 flow and the fluctuation in CO_2 mass flow rate.

The significant discrepancies of CO_2 mass flow rate from the CMFs during the load change operations lead to significant errors in the fiscal metering of CCS. In order to solve the above problem, the flow compensation of the CMFs with a dynamic neural network will be investigated in the near future.

Acknowledgements

The authors would like to acknowledge the financial support of the UK CCS Research Centre (www.ukccsrc.ac.uk) in carrying out this work. The UK CCSRC is funded by the EPSRC as part of the RCUK Energy Programme. This work is also supported in part by Beijing Natural Science Foundation (No. 3162031) and Fundamental Research Funds for the Central Universities (No. 2017044).

References

Abdilahi, A.M., Mustafa, M.W., Abujarad, S.Y., Mustapha, M., 2018. Harnessing flexibility potential of flexible carbon capture power plants for future low carbon power systems: Review. Renew. Sust. Energ. Rev. 81, 3101–3110.

Aursand, P., Hammer, M., Munkejord, S.T., Wilhelmsen, O., 2013. Pipeline transport of CO_2 mixtures: models for transient simulation. Int. J. Greenh. Gas Control 15, 174–185.

Chaczykowski, M., Osiadacz, A.J., 2012. Dynamic simulation of pipelines containing dense phase/supercritical CO_2-rich mixtures for carbon capture and storage. Int. J. Greenh. Gas Control 9, 446–456.

Cheesewright, R., Clark, C., Hou, Y.Y., 2004. The response of Coriolis flowmeters to pulsating flows. Flow Meas. Instrum. 15, 59–67.

Clark, C., Cheesewright, R., 2006. Experimental determination of the dynamic response of Coriolis mass flow meters. Flow Meas. Instrum. 17, 39–47.

Collie, G.J., Nazeri, M., Jahanbakhsh, A., Lin, C.W., Maroto-Valer, M.M., 2016. Review of flowmeters for carbon dioxide transport in CCS applications. Greenh. Gases 7, 10–28.

Dowell, N.M., Staffell, I., 2016. The role of flexible CCS in the UK's future energy system. Int. J. of Greenh. Gas Control 48, 327–344.

Hunter, L., Leslie, G., 2009. National physical laboratory (NPL): A study of measurement issues for carbon capture and storage (CCS). TUV NEL Ltd, Glasgow, U.K., Tech. Rep. 2009/54.

Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. Renew. Sust. Energ. Rev. 39, 426–443.

Mechleri, E., Fennell, P.S., Mac Dowell, N., 2017. Optimisation and evaluation of flexible operation strategies for coal- and gas-CCS power stations with a multi-period design approach. Int. J. of Greenh. Gas Control 59, 24–39.

Nazeri, M., Maroto-Valer, M.M., Jukes, E., 2016. Performance of Coriolis flowmeters in CO_2 pipelines with pre-combustion, post-combustion and oxyfuel gas mixtures in carbon capture and storage. Int. J. Greenh. Gas Control, 54, 297–308.

Onyebuchi, V.E., Kolios, A., Hanak, D.P. Biliyok, C., Manovic, V., 2018. A systematic review of key challenges of CO2 transport via pipelines. Renew. Sust. Energ. Rev. 81, 2563–2583.

Pope, J.G., Wright, J.D., 2014. Performance of Coriolis meters in transient gas flows. Flow Meas. Instrum. 37, 42–53.

Tait, P., Buschle, B., Ausner, I., Valluri, P., Wehrli, M., Lucquiaud, M., 2016. A pilot-scale study of dynamic response scenarios for the flexible operation of post-combustion CO_2 capture. Int. J. of Greenh. Gas Control 48, 216–233.

Uilhoorn, F.E., 2013. Evaluating the risk of hydrate formation in CO_2 pipelines under transient operation. Int. J. of Greenh. Gas Control 14, 177–182.

Wang, T., Baker, R., 2014. Coriolis flowmeters: a review of developments over the past 20 years, and an assessment of the state of the art and likely future directions. Flow Meas. Instrum. 40, 99–123.

Wang, L.J., Yan, Y., Wang, X., Wang, T., Duan, Q.S., Zhang, W.B., 2018. Mass flow measurement of gas-liquid two-phase CO_2 in CCS transportation pipelines using Coriolis flowmeters. Int. J. Greenh. Gas Control 68, 269–275.

Yan, Y., Wang, L.J., Wang, T., Wang, X., Hu, Y.H., Duan, Q.S., 2018. Application of soft computing techniques to multiphase flow measurement: A review. Flow Meas. Instrum. 60, 30–43.