PRONTO

PROCESS NETWORK OPTIMIZATION

Multiphase flow facility case study technical report

Benchmark with heterogeneous data

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Executive summary

This is a supplementary technical report for the Multiphase Flow Facility Case Study to facilitate the understanding of the process and the experiment and give support to get started with the benchmark dataset. The report starts with a brief overview of the facility, describing tests under different operating conditions and induced faults. Heterogeneous data was collected from various sources, including process data, high frequency ultrasonic data, high frequency pressure data, alarm, event and change data and videos. Each data acquisition system is described in detail. All tested scenarios are introduced; the operation sequences conducted to induce the faults manually and corresponding observations during the experiment are included. We continue with a summary of the dataset and it is stored for each of the tested scenarios. Some issues that may arise during data analysis and algorithm validation, and our recommendations of how to deal with them, are presented afterwards.

The work was conducted within the PRONTO project, which has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 675215, for which the authors are grateful. The benchmark case fits the scope of PRONTO, as the collected datasets are suitable for algorithm development and validation of fault detection, fault identification, fault classification, fault severity evaluation, monitoring of fault evolution and prognostics using both quantitative and qualitative data from disparate sources. The datasets can be used to generate and visualize information-rich statistics concerning equipment condition and process performance.

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Overview

Multiphase flow facility

The benchmark case study is conducted on a multiphase flow facility in the Process System Engineering lab of Cranfield University. In this experiment, water and air are mixed to flow through the horizontal section and then separated. A number of different testing scenarios are implemented in order to generate data for both normal and faulty states. Figure 1 provides an overview of the configuration of pipelines and instrumentation of the test facility. The feed air and water flows are the inputs to the facility and their flow rates are controlled for implementing different operating conditions. Input flows are mixed in the mixing zone and directed through a horizontal pipeline to the 2” vertical riser, which has an S shape section connected midway along the riser. After reaching the top of the riser, the mixed flow is separated by two separators in sequence; the water flow returns to the storage tank and the air flow is exhausted to atmosphere after separation. The facility is instrumented with various pressure, flow rate, temperature and density sensors; all of the 17 process variables recorded in the tests are shown in Figure 1. The high frequency pressure sensors are distributed along the pipelines from the mixing zone to the riser top while the ultrasonic sensor is located at the riser top, as shown in Figure 1. Additionally, two transparent sections are installed on the riser bottom and top for observation of the flow regime. For more detailed information, such as additional tags and control loops, please refer to DeltaV Screenshots section in Appendix.

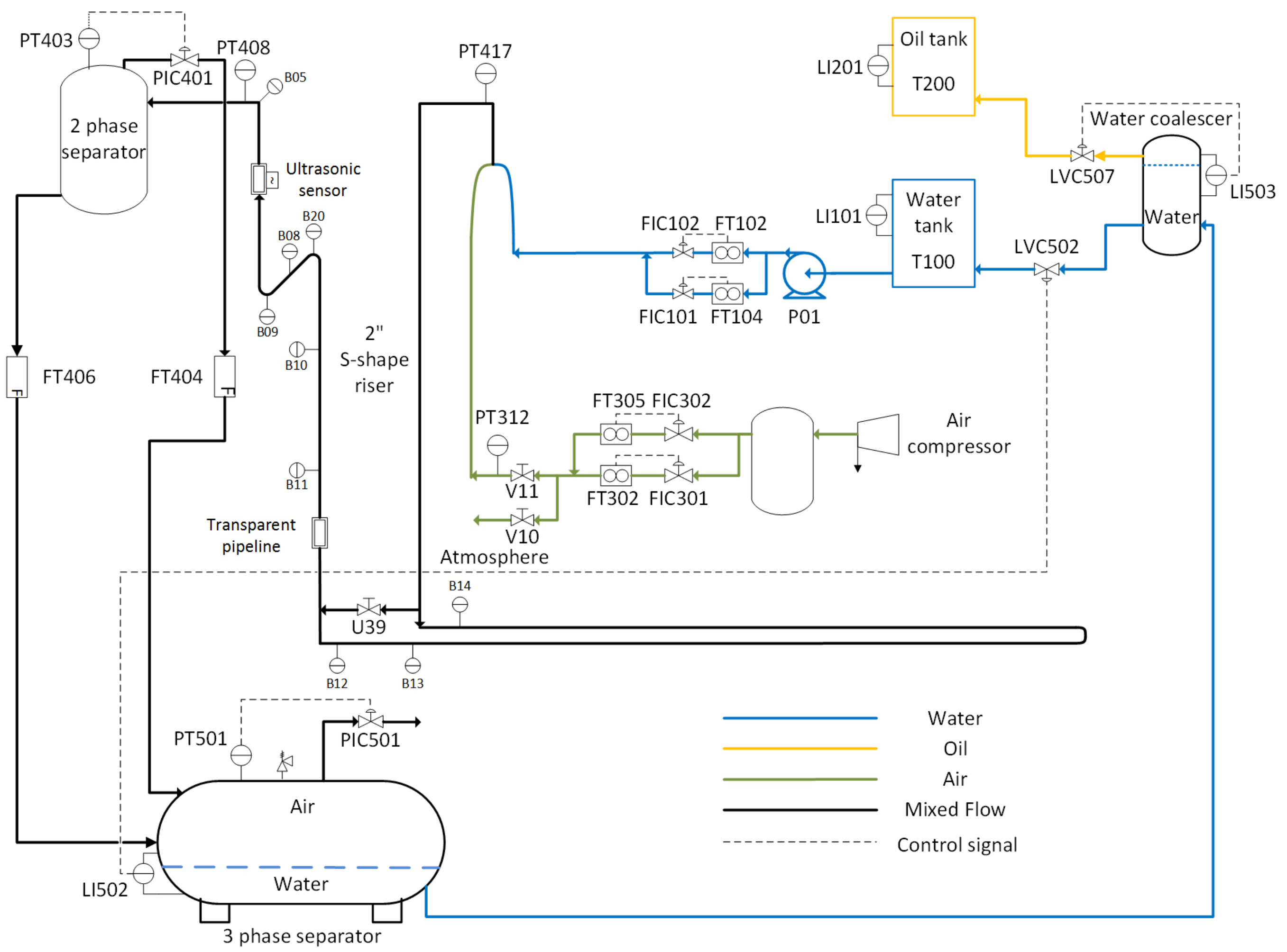

Figure 1. Process schematic

Measurement specification

Sensors measuring different variables with different sampling rates have been installed on the test facility in order to obtain real-time data for both on-line monitoring and further off-line data analysis. Sensor readings are collected and stored along with their time stamps and alarm information during each experiment. Table 1 summarizes the data recorded in this case study.

Table 1 Data availability through the experiment

Measured variable	Sampling rate	Availability	Platform
Process variables	1 Hz	Continuous	DeltaV
Alarm, event, change logs	Event driven	Discrete event	DeltaV
Doppler ultrasonic sensor	10 kHz	60 s	LabView
High frequency pressure sensors	5 kHz	60 s	LabView
Videos	-	30-60 s	Camera

Measurement availability

In this section an overview of the data types available throughout the experiment, a summary of which can be found at Table 1, are given.

Process data

Process data was collected using DeltaV, which is a SCADA system provided by Emerson Process Management. It is responsible for the control of the process and provides a way to retrieve process data. DeltaV samples all of the connected sensors at 1 Hz. The selected process variables are listed in Table 2 with their corresponding tag and unit.

Table 2 Process variables

Sensor tag	Measured process variable	Unit
FT305/302	Input air flow rate	Sm^3/h
FT305	Input air temperature	°C
PT312	Air delivery pressure	barg
FT102/104	Input water flow rate	kg/s
FT102	Input water temperature	°C
FT102	Input water density	kg/m^3
PT417	Pressure in the mixing zone	barg
PT408	Pressure at the riser top	barg
PT403	Pressure in the top separator	barg
FT404	Top separator output air flow rate	m^3/h
FT406	Top separator output water flow rate	kg/s

PT501	Pressure in the 3-phase separator	barg
PIC501	Air outlet valve 3-phase separator	%
LI502	Water-oil 3- level phase separator	%
LI503	Water coalescer level	%
LVC502-SR	Water coalescer outlet valve	%
LI101	Water tank Level	m
FIC302/PID1/OUT.CV	Inlet air flow rate controller 1 valve opening	%
FIC302/PID1/SP.CV	Inlet air flow rate controller 1 set point	Sm^3/h
FIC302/PID1/PV.CV	Inlet air flow rate controller 1 process value	Sm^3/h
FIC301/PID1/OUT.CV	Inlet air flow rate controller 2 valve opening	%
FIC301/PID1/SP.CV	Inlet air flow rate controller 2 set point	Sm^3/h
FIC301/PID1/PV.CV	Inlet air flow rate controller 2 process value	Sm^3/h
FIC102/PID1/OUT.CV	Inlet water flow rate controller 1 valve opening	%
FIC102/PID1/SP.CV	Inlet water flow rate controller 1 set point	kg/s
FIC102/PID1/PV.CV	Inlet water flow rate controller 1 process value	kg/s
FIC101/PID1/OUT.CV	Inlet water flow rate controller 2 valve opening	%
FIC101/PID1/SP.CV	Inlet water flow rate controller 2 set point	kg/s
FIC101/PID1/PV.CV	Inlet water flow rate controller 2 process value	kg/s

Alarms, events and changes

Alarms, events and changes were logged during the whole operation of the process. The alarm data consist of two types of alarms: critical value alarms monitor if sensor measurements exceed their critical values; module alarms indicate the health state of the sensors and their connectivity to the DeltaV system. The event data consist of logs of I/O related sensor failure events. Change data consist of a log of changes that the user made to the system or to the process, such as adjusting a valve position, acknowledging an alarm, changing the set point of a control valve and changing the critical value for a sensor.
The data is stored in .csv format, the timestamp of the logs are in decreasing order. One log consists of the parameters described in Table 3.

Table 3 Alarm, event and change log parameters

Parameter name	Parameter description
Date/Time*	Date and time in decreasing order (in ms second accuracy)
Event Type	Alarm/Event/Change
Category	Instrument/Process/User/Device
Area	Test Section/Metering Section/Separation/Area A (user changes)
Node	Name of the information node: Node1/JJ45Q0J
Unit	Empty field
Module	Tag names
Module Description	Description: e.g “Air flow rate controller via FR302”
Parameter	A parameter of the alarm/event/change if applicable
State	Active/Inactive/Acknowledged/Unacknowledged
Level	Info/Advisory/Warning/Critical
Desc1	Description 1 (extended tag names)
Desc2	Description 2 (Error code/new values/etc.)

In case of some sensor tags, only module alarms were enabled. The alarm interface for sensor tag FIC301 air flowrate controller is shown below on Figure 3 as an example. Although there is a list of possible alarms listed under the Alarms tab only the Module Alarm was enabled with a critical priority. We are currently investigating the case of Module Alarms to have a better understanding on which occasion they are getting triggered.

One may refer to the Alarm settings in DeltaV.xlsx in Technical Documents folder for further information about the alarm settings for the tags. As shown in Figure 4, the alarm limits are presented in meters for water and oil tank levels. For the alarm limits in percentage, their scales are provided for converting percentages into real values for the limits. Other information, such as the enabling status, is also included in the Remarks column.

Tagnames	HiHi Alarm	Hi Alarm	Lo Alarm	LoLo Alarm	Remarks
Separation					
LI101 (m)	1.6	1.4	0.2	0.1	water tank level, scale 0~2m
LI201 (m)	1.6	1.6	0.11	0.1	oil tank level, scale 0~1.8m

Figure 4. Alarm information

Doppler ultrasonic data

A Continuous Wave Doppler Ultrasound non-invasive, clamp-on sensor was used for the experiment. The sensor has two crystal transducers. One of the transducers emits an ultrasonic signal at 500 KHz, while the other transducer receives the reflected signal from the multiphase flow. The received output signal is then conditioned by the sensor electronics, which provides the Doppler frequency shift as an output voltage signal in the range of ± 10V. The Doppler ultrasonic data was recorded with LabView at a 10 KHz sampling rate for 60 seconds for all flow rates, valve openings and seeded fault scenarios during steady state operation. The recordings were manually synchronized with the process data from DeltaV. The ultrasound beam angle is directed in a 58 degree with respect to the pipe axis of the vertical riser. The sensor provides the Doppler frequency shift in the form of an output voltage signal. Assuming that all the scatterers have the same velocity v, then the Doppler shift f_d of the transmitted ultrasound is given by

$$f_{\mathrm{d}} = 2f_{\mathrm{t}}\frac{v}{c}\cos\theta \qquad \rightarrow \qquad v = \frac{f_{\mathrm{d}}c}{2f_{\mathrm{t}}\cos\theta}$$

where f_{d} is the Doppler frequency shift, f_{t} is the transmitted ultrasound frequency, v is the flow velocity average, c is the velocity of sound in the liquid and θ is the angle between the flow velocity and the ultrasound beam.

High frequency pressure data

For all tested scenarios, high frequency pressure data was recorded using LabView at a 5 kHz sampling rate for 60 seconds during steady-state operation. The location of the 9 pressure sensors is given in Figure 2, while the sensors are listed in Table 4. The measurements are given in units of barg. The recordings were manually synchronized with the process data from DeltaV. System times of LabView computers and DeltaV computer were synchronized in advance and the action of recording was synchronized by hand according to the system time. As there are no process measurements through the horizontal pipeline, vertical riser and S-shape riser in the DeltaV system, the high frequency pressure data provides a better insight into the pressure fluctuations at the horizontal pipeline and the riser.
Table 4 provides an overview of the collected pressure variables, their tag names on the process schematic and their corresponding tag names in the .csv files.

Table 4 Pressure variables		
Sensor tag	Measured pressure variable	Excel tag
B14	Before horizontal line	P4
B13	After horizontal line, before riser base	P5
B12	Riser base	P6
B11	Vertical riser after transparent pipe beyond riser base	P7
B10	The middle of vertical riser, before S shape	P8
B20	Top of S shape	P13
B08	Middle of inclining part of S shape	P14
B09	Bottom of S shape	P15
B05	After S shape riser and riser top	P17

Videos

The 2" pipeline has a transparent section at both the top and the bottom of the riser. Videos were taken for a period of 30-60 seconds during different tested scenarios, for educational purposes and to provide a better understanding of the flow regimes.

TESTED SCENARIOS

The experiment was conducted under 5 different scenarios. In addition to normal operating conditions, 4 different incipient or intermittent faults were tested. These faults were designed to simulate real process malfunctions, such as leakage, blockage or incorrect operation of the system. In the following section a detailed description is given for each tested scenario.

Normal operating conditions (0912 Test9)

When developing algorithms and methods for process monitoring, a representative normal training dataset is essential for the success of the algorithms. In this benchmark case study normal data was collected with a continuous, stable flow regime. The corresponding air and water flow rate combinations are shown in Table 5. 13 normal datasets were recorded. The high frequency measurements were taken once the flow stabilized. Videos are recorded from the transparent section at the riser top.

Slugging (0912 Test10)

Slugging is an intermittent fault. The liquid builds up at the bottom of the riser blocking the gas flow. The pressure increases at the riser bottom till it is sufficient to push the air and water slug up to the riser top, at which point the water falls down and the cycle starts again. 7 slugging datasets were collected through the experiment, the set points of which are shown in Table 4. Videos are recorded from the transparent section at the riser top.

Operation sequence

The sheet named Operation Log 0912 in Operation log.xlsx records the operations (set point changes of input flow rates) during the flow condition test. As a demonstration of operation sequence during the flow condition test, input water (FT102/104) and air flow rates (FT305/302) after preliminary pre-processing are presented in Figure 5.

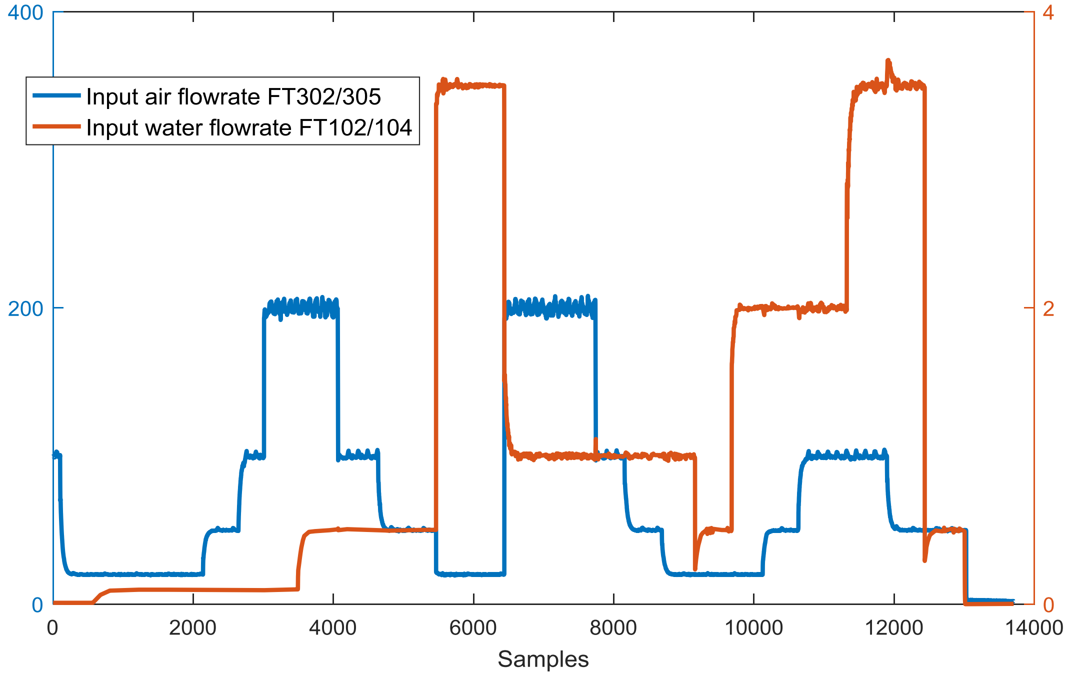

Figure 5. Input flow sequences for flow condition test

For each flow combination, data was recorded only after the flow regime stabilized; this was typically 5-7 minutes after adjusting the set point of input flow rates. The high frequency pressure and ultrasonic measurement were collected for 1 minute along while the flow regime video recorded at the riser top. Afterwards, the input flow rate was adjusted and the same procedure was repeated.

Expected outcome / Observed outcome

Table 5 presents the operating conditions (normal or slugging) determined by observing the flow regimes in pipelines under different combinations of input water and air flow rates. The operation log also specifies the operating conditions which were expected (presented in separate sheets) ahead of the experiment according to the flow regime map obtained in a similar experimental set up on the same rig.

Table 5 Operating conditions

		Water flow rate (kg/s)				
		0,1	0,5	1	2	3,5
Air rate (sm^3/h)	20	slugging	slugging	slugging	slugging	normal
	50	slugging	slugging	slugging	normal	normal
	100	normal	normal	normal	normal	normal
	200	normal	normal	normal		

Figure 6 shows time-series plots of selected data from different sources for the slugging case of 20 Sm^3/h air, 0,1 kg/s water flow rate. The data is scaled to have values between zero and 1 to represent the data trends. The top three signals are process variables sampled at 1 Hz. The fourth signal shows the ultrasonic sensor sampled at 10 kHz, the fifth signal is a module alarm, which is triggered twice during the 60 second measurement period. The last signal shows a pressure signal sampled at 5 kHz.

Normal operating conditions (Test11)

Since more healthy data under the same flow conditions are preferred as the training set for detecting the manually seeded faults (leakage, blockage and diverted flow), extra process measurement data under these two flow conditions specified by Table 6/8/10 without any fault are collected in a follow-up experiment. The operation log of this day can also be found in Operation log.xlsx. The alarm and event log was also collected for this period.

Air leakage (0911 Test4/5/6)

The aim of this seeded fault scenario is to simulate a gradually developing air leakage in the input air pipeline. By opening valve V10 manually the air is partially leaked to the atmosphere. The valve was opened gradually simulating an incipient leakage with the valve positions being recorded along with the data. The set points of the air and water flow rates chosen for the air leakage tests are shown in Table 4 (“normal & faults”). Two tests were carried out, with high frequency measurements being taken once the flow had stabilized at its given set point for the selected valve position.

Figure 7. Manual valve V10 used for simulating air leakage

Operation sequence

Data was obtained for two healthy flow conditions for air leakage fault, as shown in Table 6. All tests were conducted after the flow condition stabilized.

Table 6 Flow conditions for air leakage test

	Test5	Test4/6
Air flow rate (sm^3/h)	120	150
Water flow rate (kg/s)	0.1	0.5

For each test, valve V10 was opened gradually; the valve openings are shown in Table 7. Once the flow regime had stabilized after adjusting V10, high frequency pressure and ultrasonic sensor measurements were collected simultaneously for 1 min and if the phenomena were deemed interesting, videos of the flow regime at riser bottom and riser base were recorded.

Table 7 Valve opening sequences for air leakage test

	Valve opening (°)							
Test4	0	10	20	30	15*	25	40	90
Test5	0	5	10	15				
Test6	0	5	10	15	20	25		

*: The valve opening was reduced because a significant change was observed when it was switched from 20° to 30°: the flow in the pipeline disappeared due to insufficient air. Therefore, 25° valve opening was tested in Test4 and a smaller step size was selected in Test6.

All tests were stopped when a full air leakage was observed, i.e. there was no air in the riser. Higher input air flow rate in Test6 resulted in a larger final valve opening when the air was fully leaked.

Observed outcome

At the beginning of each test with a fixed air and water flow rate the valve was fully closed resulting in normal flow conditions. With the development of the air leakage, the flow regime in the riser shifts from normal to slugging. As the amount of input air is reduced an intermittent cyclic behaviour appears: first there is normal flow present, then the flow disappears, then water appears with big air bubbles, then the cycle starts again. This behaviour is very similar to severe slugging, although the reason behind it is not only due to the reduced air flow rate but also due to the pressure drop caused by the leakage. Once all of the input air leaked out, the pressure drops and only the water stays, leading to a continuous liquid only flow regime. Videos were recorded from the transparent section at the riser top to study this phenomenon.

Air blockage (0907 Test2/3)

The aim of this fault scenario is to simulate a gradually developing blockage in the input airline by manually closing valve V11. Initially for each set point with a fixed air and water flow rate the valve was fully open with normal flow conditions. The valve was then gradually closed. Similarly to the case of air leakage fault, the set points are shown in Table 8. The high frequency measurements were taken once the flow stabilized at its given set point for the selected valve position.

Figure 8. Manual valve V11 used for simulating air blockage

Operation sequence

The input airline blockage test was conducted under two healthy flow conditions, specified by Table 8. The same valve opening sequence of V11 for both conditions were used, from fully opening (90°) to 10°. Once the flow regime stabilized after adjusting V11, high frequency pressure and ultrasonic sensor measurements were acquired simultaneously for 1 min. There is no video record for this tested scenario. The sheet named Operation Log 0907 in Operation log.xlsx records the operations along with brief descriptions of observations.

Table 8 Flow conditions for air blockage test

	Test2	Test3
Air flow rate (sm^3/h)	120	150
Water flow rate (kg/s)	0.1	0.5

Table 9 Valve opening sequences for air blockage test

	Valve opening (°)								
Test2	90	80	70	60	50	40	30	20	10
Test3	90	80	70	60	50	40	30	20	10

Observed outcome

The flow regime for air blockage is different from the leakage case: as there is no pressure drop in the system the flow remains continuous, although mild slugging is observed.

Diverted flow (0911 Test7/8)

The aim of this fault scenario is to simulate a case of a mixed diverted flow. In real processes this fault could be caused by the incorrect operation of the system. The U39 bypass valve was gradually opened. The mixed flow is partially directed straight to the riser and partially directed into the horizontal pipeline before joining the riser. The set points are the same, as for the previous seeded faults, as shown in Table 4. The high frequency measurements were taken once the flow stabilized at a certain set point with a certain valve position.

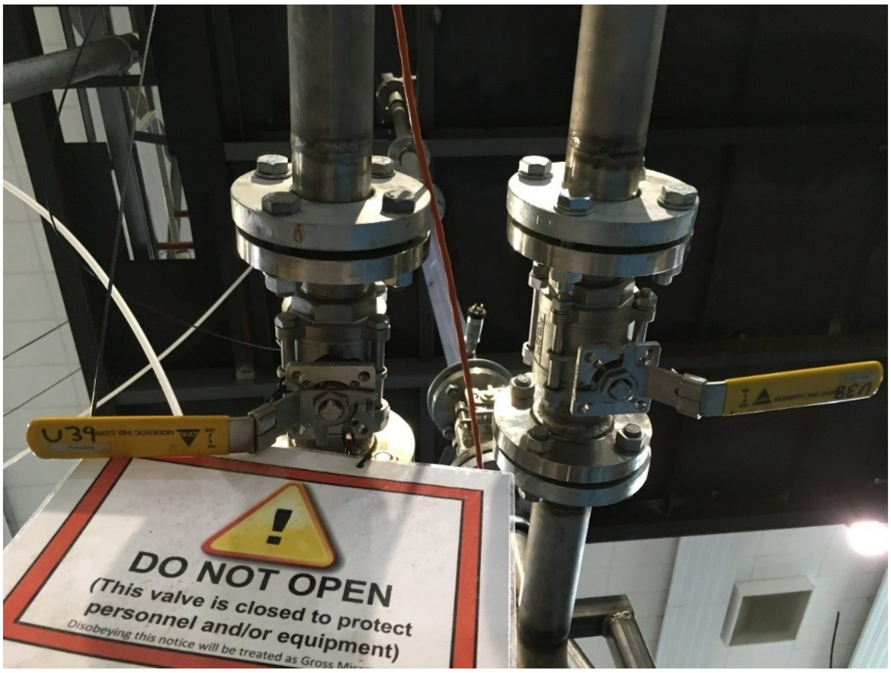

Figure 9. Manual valve U39 used for simulating diverted (U38 is open in normal conditions)

Operation sequence

The valve opening and brief descriptions of observations can be found in "Operation Log 0911" in Operation log.xlsx. U39 was opened gradually while U38 remained unchanged. Once the flow regime stabilized after adjusting U39, high frequency pressure and ultrasonic sensor measurements were collected simultaneously for 1 min and if the phenomena were deemed interesting, videos of the flow regime at riser bottom and riser base were recorded.

Table 10 Flow conditions for air blockage test

	Test7	Test8

Air flow rate (sm^3/h)	120	150
Water flow rate (kg/s)	0.1	0.5

Table 11 Valve opening sequences for air blockage test

	Valve opening (°)							
Test7	5	10	15	20	30	40	50*	60
Test8	10	20	30	40	45	50	60	

*: high frequency measurements/videos were not collected in this valve opening, as the flow regime did not change significantly. However, the process data and alarms/events log are collected indifferently. Operation log records the time of valve adjustments.

Observed outcome

This seeded fault is different from the previous two faults, as there is no change in the flow regime in the riser and it is not observable at the riser top. However, at the riser bottom, at the transparent section the change is visible. With increasing the opening of U39 the air disappears from the transparent section showing that most of the air flow is directed straight to the riser. As the diverted flow fault is introduced between the beginning of the horizontal pipeline and the riser base, the high frequency pressure sensors are able to detect the change in the flow. Videos were recorded from the transparent section at the riser bottom.

Datasets

Data summary

Table 12 Data summary

Fault	No.	Process data	High-freq pressure	Ultrasonic data	Alarms & Events	Videos
Air Blockage	Test2	0907Testday2	0907Test2	0907Test2_UT	0907Testday2_AlmEvt	N/A
	Test3		0907Test3	0907Test3_UT		
Air Leakage	Test4		0907Test4	0907Test4_UT		
	Test5	0911Testday3	0911Test5	0911Test5_UT	0911Testday3_AlmEvt	0911Test5_VID
	Test6		0911Test6	0911Test6_UT		0911Test6_VID
Diverted Flow	Test7		0911Test7	0911Test7_UT		0911Test7_VID
	Test8		0911Test8	0911Test8_UT		0911Test8_VID
Flow conditions	Test9	0912Testday4	0912Test9	0912Test9_UT	0912Testday4_AlmEvt	0912Test9_VID
	Test10		0912Test10	0912Test10_UT		0912Test10_VID
	Test 11	0626Testday5	-------------	--------------------	0626TestDay5_AlmEvt	---------------------
File type		.csv	.csv	.csv	.csv	.mp4

Table 12 summarizes the data sets collected from aforementioned tested scenarios. The process data and alarms/events logs are continuously available for a whole day of test. High frequency measurements (pressure and Ultrasonic sensor) are available in 60-sec length segments that were recorded after every adjustment specified by operating sequences in previous section and operation logs. Videos at riser top and riser bottom are also available when a significant change in flow regime was observed.

Dataset layout

Once the zip file is downloaded and extracted the user will find the following folder structure in the root directory:

C0: Normal and Slugging conditions	Test 9 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor • Videos	Test 10 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor • Videos	Test 11 • Alarms and Events • Process Data
C1: Air Blockage	Test 2 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor	Test 3 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor	
C2: Air Leakage	Test 4 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor • Videos	Test 5 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor • Videos	Test 6 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor • Videos
C3: Diverted flow	Test 7 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor • Videos	Test 8 • Alarms and Events • High Frequency Pressure • Process Data • Ultrasonic Sensor • Videos	
Pre-processed data: labelled and pre-processed data files			
Operation logs: the operation logs are in one Excel file, operation logs for different days are under different tabs			
Technical documents: Alarm settings in DeltaV, Technical report: Folder containing this report			
Photos: photos named after equipment			
README.txt: important copyright information about the usage of the dataset			
Extra data: as listed in Table 13 in the Appendix			

Figure 10. Dataset layout

Remarks for data analysis

Switching between two input valves

According to Fig 1, two parallel valves and corresponding control loops are applied to control the input water and air flow rates. For each individual time point, only one valve controls each input flow; switching between the two valves depends on the set point: VC102/301 is used when the input water/air flow rates are relatively high; otherwise, VC101/302 is used for smaller flow rates. The following switching rules apply for most tests. Moreover, the control valves for larger flow rates also have a larger variance of the controlled variables.

$$V_{water} = \begin{cases} VC102 & if\ SP_{water} \geq 1\ kg/s \\ VC101 & otherwise \end{cases}, \quad V_{air} = \begin{cases} VC301 & if\ SP_{air} > 150\ sm^3/h \\ VC302 & otherwise \end{cases}$$

As shown in Figure 2 and Table 3, it is reasonable to combine the two FT readings as one input flow rate measurement for both water and air. One may observe that the reading of the FT on one control valve is not zero when the other valve is controlling the process. Therefore, a simple summation may not be the best way of combining the readings.

Distinguishing between healthy/slugging conditions

It is necessary to highlight that, in the flow condition test, the expected and observed operating conditions are not always consistent with each other. The results in Table 4 are obtained by observing the flow regimes during testing, while the occurrence of slug should be determined by calculating superficial velocity of the fluid in the pipeline. Therefore, the flow conditions presented in Table 4 are only the suggestions of the authors and one is encouraged to conduct other clustering/classification methods on the data sets for better labelling of the flow combinations.

Dealing with the ultrasonic data

For some measurements, instead of 60 seconds being recorded, a 70-second measurement is available. This is due to a data acquisition issue in LabView. For simplicity the last 10-second measurement can be ignored for those cases if the aim is to process the data together with the high frequency pressure data, however they were not removed from the datasets. The .csv files contain three columns: the first column is the timestamp in seconds; the second column is the Doppler frequency shift, recorded in the form of an output voltage signal. The readings from the third column are not used for analysis.

Dealing with high frequency data

The .csv file for the pressure data contains a row with ‘Offset” values and a row with “Slopes” values. These values should be used for the calibration of the raw variables in the following way:

$$X_{\mathrm{calibrated}} = \mathrm{Slopes} \cdot X_{\mathrm{raw}} + \mathrm{Offset}$$

This calibration step is needed for each of the measurement values.

The first column of the .csv file is time stamp, given in seconds, counted from the timestamp mentioned in the header of the file. The .csv files contain 20 measurements altogether, however

only those 9 which are listed in Table 4 should be considered for data analysis. The other measurements either contain zero values or false readings.
It has to be noted that the synchronization between the ultrasonic and high frequency pressure data recordings was conducted through manual triggering of the data acquisition. A 0.5 -1 second difference is possible at the start time of these measurements.
The authors propose to extract features for each second from the high frequency data. In this way the features can be processed together with the process data and the synchronization issue will not cause problems. Possible feature extraction methods include: moving average, standard deviation for window, spectrum decomposition, etc.

Alarms and events

Alarm, event and changed data is stored in .csv format with a decreasing timestamp. The data are stored for each experiment day in two files. The first file contains all the alarms, events and changes, whilst the second file contains only the alarms from the same day.
The authors note that the alarm data may converted into binary vectors ahead of further processing.

Data segmentation

The data sets are collected according to different acquisition parameters. The process data is available continuously at a lower sampling rate (1 Hz) while high frequency pressure and ultrasonic measurements are collected in 60-sec segments at much high sampling rates after each adjustment. Videos may or may not be taken simultaneously when the high frequency measurements are collected. The operation and alarm/event logs are event-triggered.

The authors recommend that the dispersed data sets should be segmented properly in order to allow them to be combined for analysis. For example, the 60-sec length segments of process data, which are synchronized with high frequency measurements, can be obtained by comparing their time stamps using operation logs. Other segment approaches can be considered as well.

Timestamps

The format of time stamp in process data is “mm/dd/yyyy hh:mm”. Microsoft Excel may interpret it incorrectly; however, it should not influence data importing into other software.
One may also notice that the time stamps in 0911Testday3.csv after 09/11/2017 16:20:00 are not interpretable. Nevertheless, sensor readings are still reliable despite of the time stamp issue.

Acknowledgments

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Appendix

Extra process data

In addition to the process variables relevant to the tested scenarios in this case study (specified by Table 2), extra process variables (specified by Table 13) are also collected from DeltaV system and stored in the similar format for potential usages such as controller performance assessment. These extra process data files can be found in the "*Extra Data*" folder of the shared drive.

Table 13 Extra data summary

Tag	Description
PIC401/PID1/OUT.CV	2-phase separator pressure control valve opening
PIC401/PID1/PV.CV	2-phase separator pressure control valve process value
PIC403/PID1/OUT.CV	2-phase separator inlet valve opening
PIC403/PID1/PV.CV	2-phase separator inlet valve process value
LI405/OUT.CV	Oil-gas interface 3-phase separator
LIC402/PID1/OUT.CV	2-phase separator liquid level control valve opening
LIC402/PID1/PV.CV	2-phase separator liquid level control valve process value
PIC501/PID1/PV.CV	3-phase separator pressure control valve process value
LVC502-SR/PID1/PV.CV	3-phase separator water-oil interface control valve process value
LIC507/PID1/OUT.CV	Water coalescer oil-water interface control valve opening
LIC507/PID1/PV.CV	Water coalescer oil-water interface control valve process variable
LI505/OUT.CV	Oil coalescer oil-water interface level
LVC504/PID1/OUT.CV	Oil coalescer oil-water interface control valve opening
LVC504/PID1/PV.CV	Oil coalescer oil-water interface control valve process variable
LI101/OUT.CV	Water storage tank level
LI201/OUT.CV	Oil storage tank level
LI504/OUT.CV	3-phase separator oil-water interface
TT313/OUT.CV	Input air temperature
PUMP1_SUPPORT/CURRENT.CV	Water pump current
PUMP1_SUPPORT/MOTOR_SPEED.CV	Water pump motor speed
PUMP1_SUPPORT/FREQ_SETPOINT.CV	Water pump frequency set point