Measurements done for leak detection in pipeline systems and FAIR dataset produced

Rahul Jayaraj
5935156
M.Sc. Mechanical Engineering (EFPT)
TU Delft

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Abstract

Leaks in water distribution systems create massive impact monetarily and socially. Even if pipelines are regularly maintained, the chances of leaks to be present are not zero. Accurate leak detection and response ensures minimizing of the impacts caused by the leak. This paper provides a dataset which includes measurements done using sensors (absolute pressure sensor, differential pressure sensor, flow meter, temperature sensor, level sensors and wave height meters) with leaks (two plastic taps of different flow coefficients, K_v) being introduced in an existing PVC pipe loop built with various heads. Two experimental setups were used to create the total data set. This dataset is published with the intent of assisting the advance in leak detection research along with digital/machine learning model creation and validation.

1 Introduction

Leaks are one of the most predominant losses faced by water distribution systems across the globe. It is estimated that every year around 6.2-25% of water transported through the pipelines are lost to leaks in Europe [12]. Studies suggest the range of loss of potable water through leaks in pipelines is between 15-35% in the United States [12] and is between 3-7% in the Netherlands [14]. Leaks also occur on wastewater lines, leading to contamination of the surrounding area, and to heating and cooling pipeline systems, which leads to losses in efficiency and increase in power consumed. Leakage could occur in a pipe due to faulty connections, worn-out gaskets, improper maintenance, excess pressure on the inside and external forces. The excess pressure produced inside could be due to transient events like sudden valve closures along the pipeline, which leads to water hammer effects. As the flow rate through the pipe increases, sudden closing or opening of valves in the system creates larger pressure fluctuations. These pressure fluctuations can damage the inside of the pipes and create leaks. Leakage in the distribution system results in the loss of pressure and velocity of the flow. Most of the time for big networks of pipes, a visual inspection is required to attest the absence of a leakage. But small leaks and sub surface leaks, are often difficult to locate due to the pipelines being buried in the soil. To detect such leaks in pipelines and networks, different types of sensors are typically used to monitor changes in parameters like flow rate and pressure at different locations.

Though there are extensive research undertaken on leak detection there is an evident lack of data which could be used by the research community to model algorithms which could be used to detect leaks in similar systems [10]. Most of the research done on leak detection were for oil and gas pipelines [17]. Amongst the published work, it was seen that complicated network topology of the pipeline system, with variation in potential head due to varying levels of pipe elevations were lacking and amongst the studies done, the impact of multiple leaks in the pipe line system were not realised for such complicated topology. The objective of this paper is to provide a set of controlled lab data on a pair of induced leaks and the subsequent impact in the flow conditions in a pipeline system, in the FAIR (Find-able, Accessible, Interoperable, and Reusable) format [9]. The dataset is also made into a format that follows the FAIR principles, for achieving the following,

1. Find-ability - To make the data and metadata easily find-able by both humans and computers. The data recorded in the measurements done within this paper is ensured to follow a nomenclature of naming the files for ease of access and understanding.

2. Accessibility - Once the required data is found, the user needs to know how they could be accessed, possibly including authentication and authorisation. The measured data is categorized and sorted in different folders, and are shared on a network, which ensures the freedom of access. The folder structure created is also made to be simple and understandable for the user.

3. Interoperability - The data generated should be easy to manage and ready for integration with other data sources if needed. Additionally, it must be compatible with applications or workflows used for analysis, storage, and processing. The data is recorded in 3 different formats in the measurements done, which are the .asc, .dat and .raw formats (ASCII, DATA and RAW formats respectively). The data is recorded in a tab separated, columnar format in the respective files.

4. Re-usability - The primary aim of FAIR is to maximize data reuse. To accomplish this, both metadata and data must be thoroughly described, enabling them to be replicated or integrated across various contexts. Readme files in ".txt" are also included to explain the method of measurements done and the conditions involved with each set of measurements.

The controlled lab data set in FAIR format, have a couple of potential applications. This includes creating a data base that could be used to create a digital twin for the experimental set up. It is also used for the creation of an IoT-based system for reading the measurement data in real-time in the digital twin system. This system could then be used to run the simulations for the comparison of real time data measured.

2 Experimental setup

2.1 Experimental setup

We have performed the experiments in the Beta loop, a pipe network specifically designed for slurry flow experiments at Deltares, Delft, The Netherlands. Deltares is an independent knowledge institute which works on research in fields including water, sub surface/sub-soil, infrastructure and hydraulic engineering. Figure 1 shows a schematic of the Beta loop. It consists of pipes made of polyvinyl chloride (PVC) of DN100. The pipe system consists of a supply line and a return line.
Two different experimental setups were used for the experiments, which are as follows:

2.1.1 Experimental setup - 1

The Beta loop starts at a polyethylene (PE) tank of volume 5000 L, which acts as the supply of the clear water for the experiments done. The tank sits on the reference level (here, the ground), reaching to a height of 2.5 m. A PVC pipe line called the supply line starts from the tank. The supply line begins with two pipe lines starting from a height of 35 cm from the reference to the center of the pipe, separated by 115 cm on the tank. All elevations measured to system components in the Beta loop were done from the reference level (ground in the lab) to the center of the component, which is the center of the pipe here. These pipes merge to form a Y-section, at a distance of 1.7 m, into a single pipe of same diameter (DN100)(4.2 mm thickness) and lead to a variable frequency centrifugal wastewater pump (Flygt NT 3153 - Xylem). This is depicted in the Figure 3a. The pump has a maximum pumping capacity of 800 m^3/hr, which can be varied using a potentiometer to control the voltage of operation. The supply line then rises to a height of 1 m (from reference level to the center of the pipe) and continues to a main control valve (MCV) (which is made up of a butterfly valve, connected to a pro-gear valve actuator), in the pipe network to further control the flow through the pipes. The supply line eventually reaches a section with an elevation and a subsequent depression, as seen in Figure 1. This particular section is made of transparent PVC of diameter DN100 (5.3 mm thickness) and reaches a height of 2.9 m, making a 30° angle on either side of the supply line, before reaching the lower point of 0.17 m from ground level, where the clear section ends. This transparent section is marked as "Clear section" in Figure 3b. The PVC pipe section restart from that point on the supply line with a diameter DN100 (5.3 mm thickness), and continues till it reaches the end of the supply line length which is 90 m horizontally (measured from the tank surface) at 0.17 m above ground level. The supply line turns back at the end of the loop to start the return line section of the Beta loop. The return line runs at an elevation of 1 m from the ground level and reaches 6.7 m away from the Beta loop where it increases its elevation to 1.9 m from ground level, where the thickness of the pipe reaches 4.2 mm again. The return line then ends the loop back at the tank, by diverging as two pipes, creating a Y-section similar to the beginning of the supply line, at a distance of 2.5 m from the tank. The water level in the tank is maintained above the supply level end height of 2.9 m to ensure there would not be any air bubbles introduced into the flow. The wrapped sections in Figure 1, represent the regions of the Beta loop (both the supply line and return line) where optical fiber cables are wrapped as a part of the DAS sensor measurements. Drains are present in supply line to empty the Beta loop when not in use. The symbols indicated in Figure 1 are described in Table 1.

Table 1: Description of the components represented in Figure 1

Symbols used	**Details**
Pa, Pb, P1...P6	Absolute pressure sensors
T1, T2, T3	Temperature sensors
Q1, Q2	Flow meters
DP	Differential pressure sensor
V1, V2 ... V6	Butterfly valve

The list of main supply line components of the Beta loop are given in Table 3.

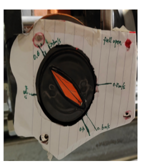
2.1.2 Experimental setup - 2

The "clear section" marked in subsubsection 2.1.1 is replaced by a depressed section, as marked in Figure 2. The transparent section is replaced by PVC of DN100 (thickness 4.2 mm). Every other component and construction within the Beta loop remains the same as in subsubsection 2.1.1. The symbols indicated in Figure 2 are described in Table 2.

Table 2: Description of the components represented in Figure 2

Symbols used	**Details**
Pa, Pb, P1...P6	Absolute pressure sensors
T1, T2, T3	Temperature sensors
Q1, Q2	Flow meters
DP	Differential pressure sensor
V1, V2 ... V6	Butterfly valve
Z1, Z2, Z3, Z4	Optical fibre wrapped section for DAS sensor

Table 3: Beta loop supply line components placed in series with the pipeline

Image	Components	Product detail	Specifications
	Tank	Polyethylene tank-5000L(Flygt)	• Diameter - 1.6 m • Height - 2.5 m • Supply side pipe elevation - 0.35 m • Return side pipe elevation - 1.9 m
 	Main control valve (MCV)	• Progear valve actuator - X series • Euro valve Butterfly valve - EVS DN 50-1400	• Maximum pressure - 10/16 bar
	Pump	Xylem - Flygt NT 3153	• Rated power - 15 kW • Impeller diameter - 197 mm • Number of blades - 2 • Operation range - (0 - 10) V

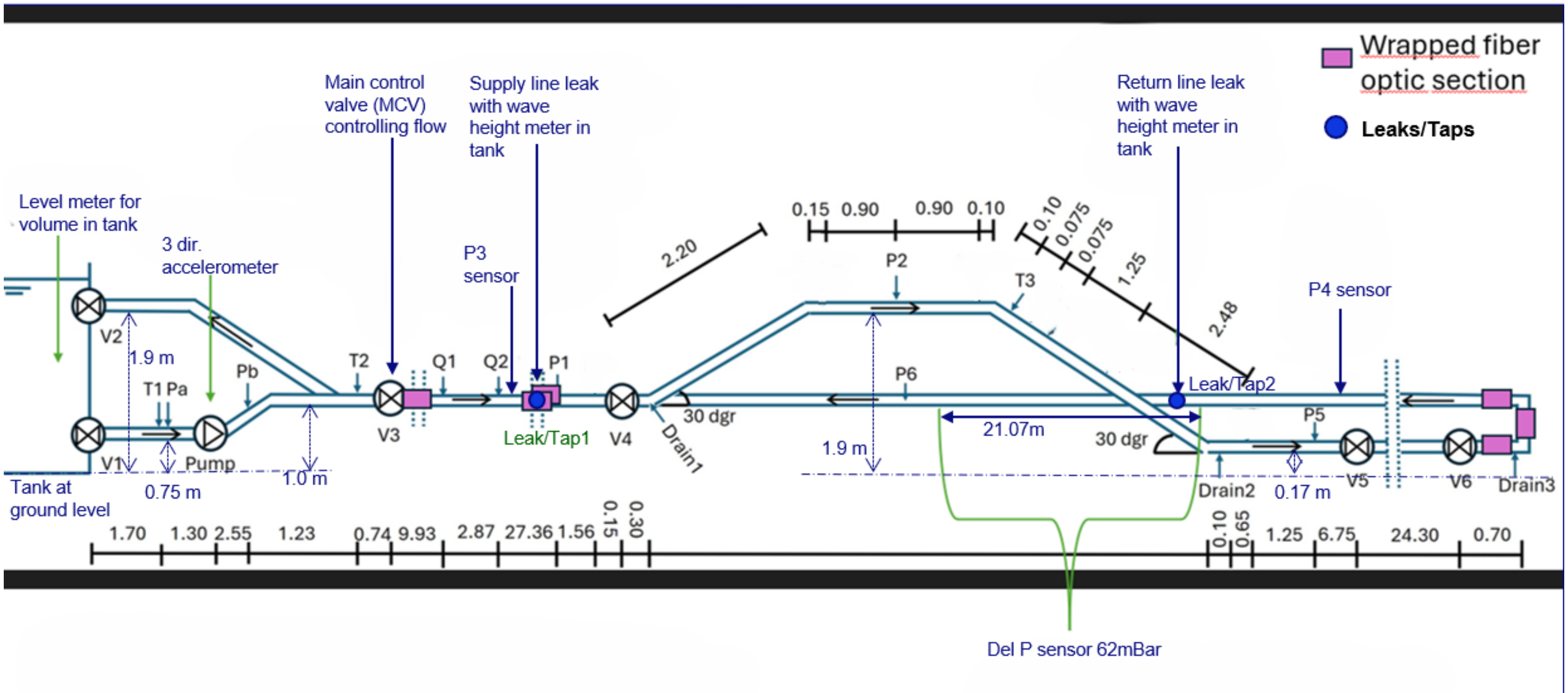


Figure 1: Schematic representation of the Beta loop setup - 1 with two leaks

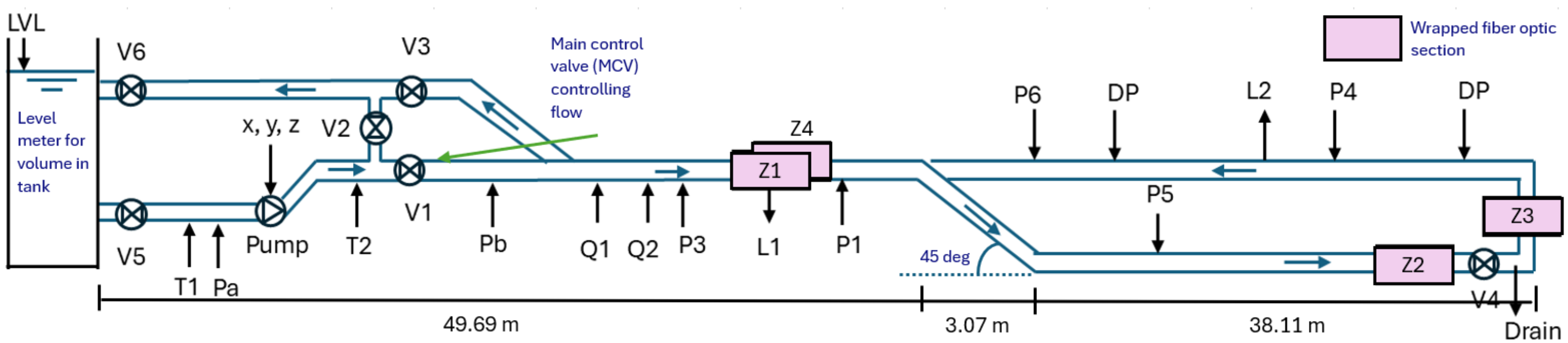
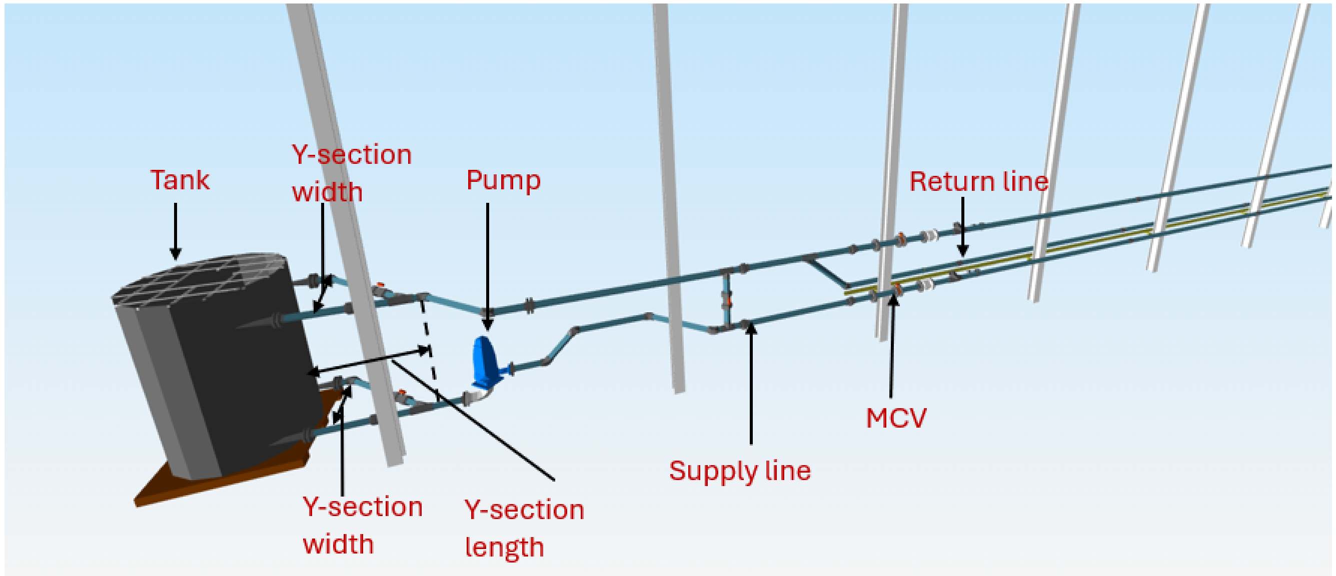
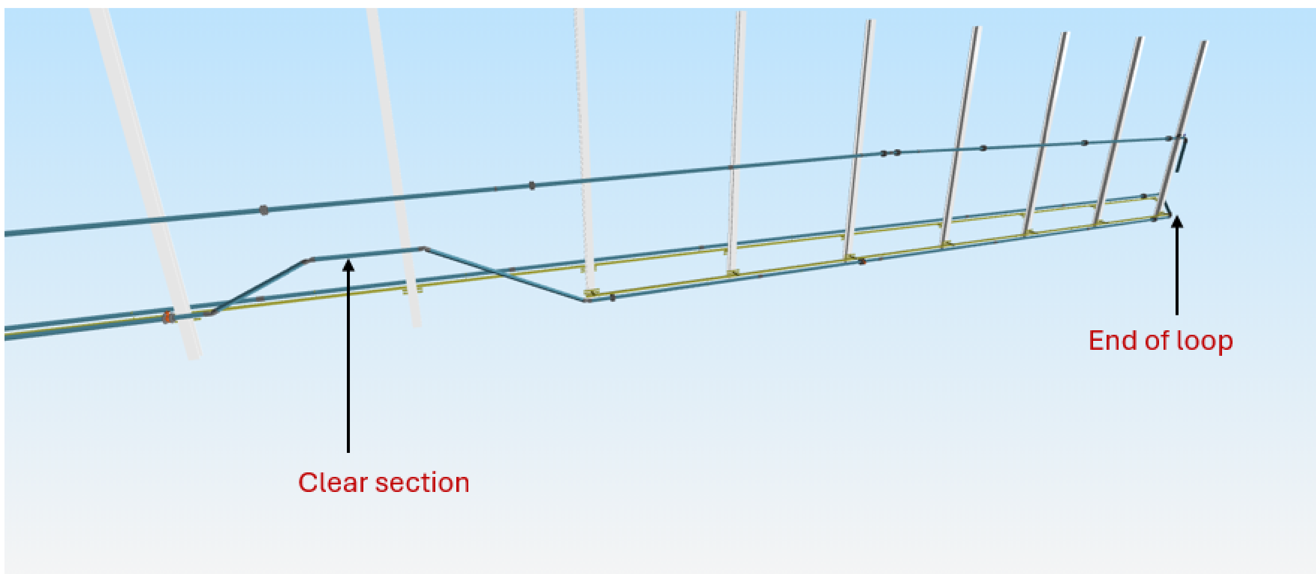


Figure 2: Schematic representation of the Beta loop setup - 2 with two leaks



(a) 3D view of start of Beta loop - 1



(b) 3D view of the end of Beta loop - 2

Figure 3: 3D drawing of the Beta loop

2.2 Taps for introducing leaks

The leaks are introduced by means of two taps (made in-house) of 10 mm in diameter placed in the supply and return line of the Beta loop. The taps are introduced to ensure fine control of the amount of water leaked out of the pipeline system. The taps are used to study at what leak rate does the sensor start to pickup the pressure and velocity fluctuations caused by the leak in the pipe. The maximum outflow rate of the tap is measured for each flow condition in the pipe line and the number of rotations to turn the tap off was noted to control the leak rate by rotation of the tap head, to study various leak rates. A pair of measuring vessels with wave height meter sensors are used to measure the amount of water leaked through the system over time, per tap. the details of the collecting vessels used are mentioned in subsection 2.3. A no-leak condition (NL) is also tested, where both the taps are closed to compare as a benchmark condition.

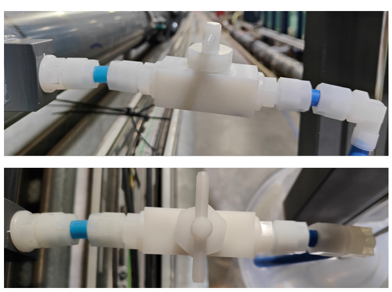
The pair of taps used belong to two different kinds.

1. Tap 1 is a simple on/off tap (with a ball valve mechanism), which completely turn on by a single 90° turn.
2. Tap 2 is a simple turn-able tap (with a screw down/ gate valve mechanism), which requires 7.5 revolutions to be completely open.

Tap 2 was made as a simple turn-able tap to ensure a finer control of the leak. This is to ensure to control the leak rate as required by the turn of the tap, which is used to measure the impact of the leak rate on the flow.

2.2.1 Leak configuration used in experimental setup-1

In experimental setup-1 the taps are directly connected to the Beta loop. The images of taps used in Beta loop setup are given in Figure 4.


(a) Tap 1

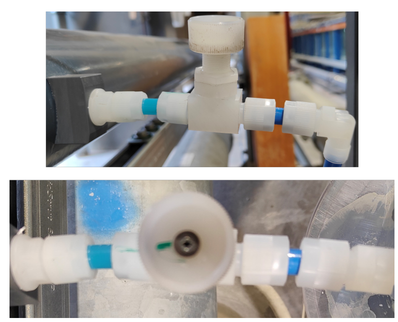

(b) Tap 2

Figure 4: Taps introduced in experimental setup - 1: Top- side view, Bottom - top view

2.2.2 Leak configuration used in experimental setup-2

In experimental setup-2 the taps are connected to a solenoid valve, which in turn is connected to the Beta loop. The images of taps used in Beta loop setup are given in Figure 5.

2.2.3 Solenoid valve used

In experimental setup-2 of the Beta loop, the taps are connected to the PVC pipes through solenoid valves for instantaneous discharge through the taps. Figure 6, shows the solenoid valve used in the setup-2 with its specifications stated in Table 4. The solenoid valves are activated with the help of independent switches as shown in Figure 7.

(a) Tap 1 (b) Tap 2

Figure 5: Taps introduced in experimental setup - 2: side view

Figure 6: Solenoid valve

Table 4: Description of the solenoid used [7]

Features	**Details**
Name	Festo VZWF-B-L-M22C-G34-275-1P4-6
Design structure	Diaphragm valve forced
Nominal size	27.5 mm
Flow rate (K_v)	7.5 m^3/h
Switching on/off time	275/290 ms

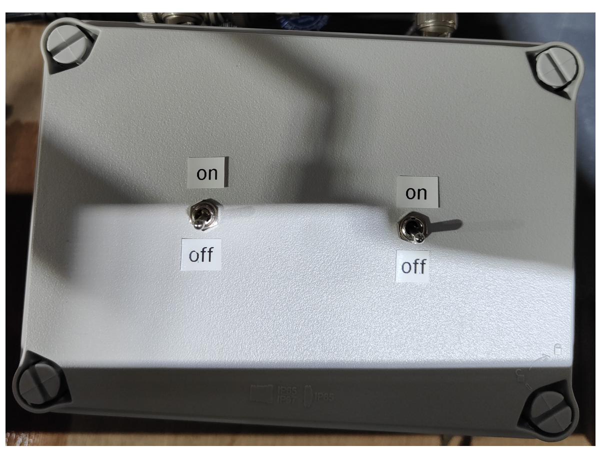


Figure 7: Switches for activating the solenoid valves (Left switch for tap 1, right for tap 2)

2.3 Vessels for collecting leak flow

Two collecting vessels of diameter 19 cm and height 90 cm were made with a removable lid attached with a PVC mount for a wave height sensor. These are used to collect the leaked water during the experiments and measure the amount of leakage. These collecting vessels also have a venting tap attached near to the base of it to empty it after each trial. The tubes connected to the venting taps lead to the nearest drain. The taps for each collecting vessel are connected to the bottom of the collecting vessel with the help of a tube (blue) of 10 mm diameter to avoid splashing. Another reason for adding the tube is to ensure that proper mixing of the leak happens in the collecting vessel, with out any impact of temperature-gradient induced buoyancy in the collecting vessel. The components used in the collecting vessel set up are shown in figure Figure 8. Even though the tubes are used for the aforementioned purposes, there is a drawback for using them. The water leaked out of the tubes, collected in the collecting vessel, exerts a pressure to the exit side of the tube. This pressure acts against the pressure inside the Beta loop which pushes the leak out through the tap. Thus, a reduction in leak rate occurs due to the water column's presence. The wave height meter used, has a electrode length of 1 m. Due to the wave height meter being attached on top of the PVC mount, there is a clearance or gap present below the bottom of the wave height meter. There exists approximately 2.5 cm worth of gap between the bottom of the collecting vessel and the bottom of the wave height meter. At the start of a leak measurement, a minimum level of water (approximately 2.5 cm or till just above the start of the electrode of the wave height meter) needs to be present to fill this gap. This is done to ensure immediate measurement of water level change in the collecting vessel, when the taps are opened.

Figure 8: Collecting vessel at tap 1

2.4 Sensors and meters

The flow in the Beta loop and the associated parameters to it are measured using various sensors and meters. These sensors undergo a conversion of signals, to convert the data measured in volts to the required units. The conversion follows a quadratic equation which is,

$$U_{out} = C_2 U_{in}^2 + C_1 U_{in} + C_0 \tag{1}$$

where,

U_{out}, is the sensor reading in required unit.
U_{in}, is the sensor reading in volts.
C_0, C_1, C_2, are the conversion coefficients found for the sensors used.

The sensors used in the experimental setup-1 and experimental setup-2 are given below.

2.4.1 Wave height meter

A wave height meter (developed in-house at Deltares) [4] was placed in the two measuring vessels, to track and measure the amount of water leaked at the leak locations, over time. An image of the same is given in Figure 9. The wave height meter is developed for measuring dynamically varying liquid levels or wave heights and is used here combined with an amplifier. The probe of the wave height meter is constructed of two parallel stainless steel rods, mounted underneath a small box. This box contains electronics for sensor excitation, signal detection, amplification and galvanic isolation. The rods act as the electrodes of an electric conduction meter. A platinum reference electrode is included to compensate the surface elevation measurement for the effect of varying electrical conductivity of the fluid. The analogue output signal is linearly proportional to the liquid level between the sensor rods. The probe used here is of 1 m in length for the measuring vessels and the specifications are as given in Table 5. The wave height meters are used in both experimental setup-1 and experimental setup-2.

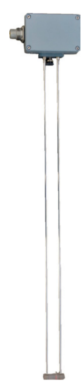


Figure 9: Wave height meter

Table 5: Description of the wave height measurement system [4]

Sensor features	**Details**
Wave height electrodes	• Rods, stainless steel, type 316, 4 mm diameter • Electrode spacing 24.3 mm • Electrode length 1000 mm
Reference electrode	Platinum
Liquid medium	• Medium conductive liquids non-aggressive to mentioned materials • Minimum required conductivity 0.1 mS/cm • Sensitivity variation <1 % for 0.1 to 2.0 mS/cm
Accuracy	0.5% of measuring range, best straight line
Output	0.4 V/cm level variation (standard: -20 to +20 VDC for 100 cm liquid level change)
Frequency response	>15 Hz
Dimensions	Including electronics 675 mm long (standard length)
Conversion coefficients	$C_0 = 0$, $C_1 = 5$, $C_2 = 0$

2.4.2 Level meter

A level meter (Temposonics, G-series analog) [16], as shown in Figure 10, is used to track the level of water in the tank during measurements. It consists of a long probe constructed of stainless steel, with a position magnet sliding on the probe, which works on the principle of magnetostriction. The profile or rod-shaped sensor housing protects the sensing element in which gives rise to the measurement signal. The sensor head accommodates the complete modular electronic interface with active signal conditioning. The position transmitter, a permanent magnet,fixed at the mobile machine part, drives contactless over the sensors stroke and starts measuring through the housing wall. The analogue signal measured in the sensor is linearly proportional to the liquid level present in the tank. The details of the specification of the level meter is further described in Table 6. The level height meters are used in both experimental setup-1 and experimental setup-2.

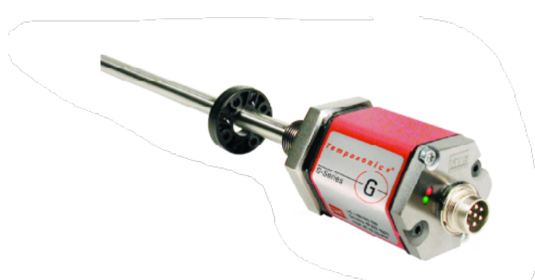


Figure 10: Level meter

Table 6: Description of the level measurement system [16]

Sensor features	Details
Sensor details	• Aluminium sensor heads • Stainless steel 1.4301/AISI 304 rod with flange • Position magnet- ring magnets, U-magnets
Accuracy	• Linearity $< 0.02\%$ (minimum $\pm$ 50 μm) • Repeatability $< 0.001\%$ (minimum $\pm$ 2.5 μm) • Hysteresis $<$ 4 μm • Ripple $< 0.01\%$
Output	175.941 mm/V level variation (standard: -10 to +10 V)
Update time	$<$ 1 ms
Dimensions	The rod is 1750 mm long
Conversion coefficients	$C_0 = 0$, $C_1 = 175.941$, $C_2 = 0$

2.4.3 Flow meter

Two flow meters were used in series on the supply line to measure the flow in the Beta loop

- A electromagnetic flow meter (OPTIFLUX 2300 C, Krohne) [11] was used to measure the flow rate through the pipes, and was placed after the main control valve (MCV). The Krohne flowmeter uses the principle of Faraday's law of induction where an electrically conductive fluid, while flowing inside an electrically insulated pipes through a magnetic field, creates a voltage, which is subsequently measured.
- A second electromagnetic flow meter (Proline Promag 55S, Endress & Hauser) [6] also makes use the same principle stated above.

The two flow meters are used to verify and check the flow for every measurement done. The Krohne flow meter is intended for measurement of only pure water flow, while the E&H flow meter is used to measure the flow rate of fluid flows including slurry, pure water etc. The two flow meters are used in both experimental setup-1 and experimental setup-2.

(a) Krohne flowmeter

(b) Endress & Hauser flowmeter

Figure 11: Flowmeters in series on the supply line

Table 7: Flow meter details

	Krohne [11]	**Endress & Hauser [6]**
Product details	• Electromagnetic flow sensor: Optiflux 2000 • Signal converter for electromagnetic flowmeters: IFC 300	• Electromagnetic Flow Measuring System: Proline Promag 55S
Measuring range	-12 to +12 m/s	0.01 to 10 m/s
Accuracy	• Measuring error - IFC 300: 0.2% of the measured value ±1 mm/s • Repeatability - ±0.1% of the measured value, minimum 1 mm/s	• Measuring error - volume flow: ± 0.5 % or ±1 mm/s • Option error - ± 0.2 % or ±2 mm/s
Output	21.5625 $m^3/h/V$ (<20 V DC)	13.1125 $m^3/h/V$ (<24 V DC)
Conversion coefficients	C_0 = -479.166750, C_1 = 239.583375 , $C_2 = 0$	$C_0 = 437.5$, $C_1 = 218.75$, $C_2 = 0$

2.4.4 Absolute pressure sensor

Absolute pressure sensors (PDCR5031, GE) [8] were placed before and after the pump and before and after the induced leaks 1 and 2 and at other locations along the Beta loop, to measure the changes in pressure introduced in the flow due to the pump and the leaks. The pressures sensors are connected to the Beta loop via two sided valves, which are opened to the side where the pressure sensor is connected, and closed to the other side, while measuring data. This closed side is opened to vent out air at the beginning of every experiment. An example of the pressure sensor system used is represented in Figure 12, with its specifications in Table 8. The absolute pressure sensors are used in both experimental setup-1 and experimental setup-2.

Figure 12: Absolute pressure sensor, connected to the two sided valve

Table 8: Absolute pressure sensor details [8]

Sensor features	**Details**
Product detail	UNIK 5000/ PDCR 503
Measurement range	Gauge ranges: 70 mBar and 70 bar
Accuracy	Combined effects of non-linearity, hysteresis and repeatability: ±0.04% FS (full scale) BSL (Best straight line)
Output	1.25 bar/V (0-10 V)
Conversion coefficients	C_0 = 0, C_1 = 0.5 , C_2 = 0

2.4.5 Differential pressure sensor

A differential pressure sensor (Rosemount 3051 CD) [5], of range -62 to 62 mBar was used, as shown in Figure 13. It has two connections to it, which are connected via tubes to either side of leak 2, with the upstream connection being 5.46 m from the tap and the down stream connection to the differential pressure sensor being 7.68 m. The differential pressure sensor was used at this point to observe the drop in pressure across a length of the pipe, during measurements done with or without the leak. The pressure difference between the points of connections are found and relayed as voltage difference and is calibrated to give out units in mBar while measuring. The details of the differential pressure sensor used are given in Table 9. The differential pressure sensors are used in both experimental setup-1 and experimental setup-2.

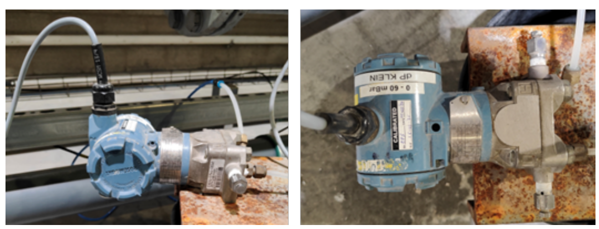


Figure 13: Differential pressure sensor

Table 9: Differential pressure sensor details [5]

Sensor features	**Details**
Product detail	Rosemount 3051 CD pressure transmitter
Measurement range	-62.16 mBar to 62.16 mBar
Accuracy	Reference accuracy 0.04 % of span
Output	75mBar/V (4-20 mA)
Conversion coefficients	C_0 = -15, C_1 = 7.5 , C_2 = 0

2.4.6 Temperature sensor

A pair of temperature sensors (STS-PT100, Ametek) [1] were placed before and after the pump to monitor the change in the temperature of the water due to pumping. The temperature sensor used is represented by Figure 14. Another temperature sensor was also present in the descending section of the clear part of the Beta loop. This temperature sensor was used in a previous experiment for measurement. The specifications of the temperature sensor used is given in Table 10. The temperature sensors are used in both experimental setup-1 and experimental setup-2.

Figure 14: Temperature sensor

Table 10: Temperature sensor details [1]

Sensor features	**Details**
Product detail	Amatek STS-PT100 temperature sensor
Measurement range	-50°C to 400°C
Accuracy	• Repeatability - 0.002°C • Hysteresis - 0.01°C at 0 °C • Stability - 0.014°C at 0 °C
Output	6.25°C/V
Conversion coefficients	C_0 = -12.5, C_1 = 6.25 , C_2 = 0

2.4.7 Accelerometer

Three accelerometers (DS4030, Measurement specialities inc.) [13] for each axes (x, y and z) were attached to the pump to measure the vibrations produced by the pump during its operation. The accelerometer used is represented in Figure 15 with its specifications defined in Table 11. The accelerometers are used in both experimental setup-1 and experimental setup-2.

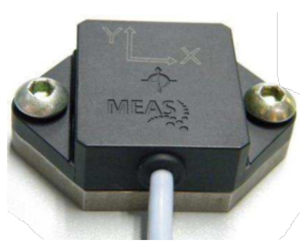


Figure 15: Accelerometer

Table 11: Accelerometer details [13]

Sensor features	**Details**
Product detail	Measurement specialities inc. DS4030 accelerometer
Measurement range	-2g to +2g
Accuracy	• Non linearity - $< \pm$ 0.5 % • Transverse sensitivity - $<$ 3 %
Output	• Zero acceleration output - 2.5 $\pm$ 0.1 V • Full scale output voltage - $\pm$ 2 VDC
Conversion coefficients	• x : C_0 = -2.479770, C_1 = 0.991512, C_2 = 0 • y : C_0 = -2.429210, C_1 = 0.977026 , C_2 = 0 • z : C_0 = -2.468990, C_1 = 0.986676 , C_2 = 0

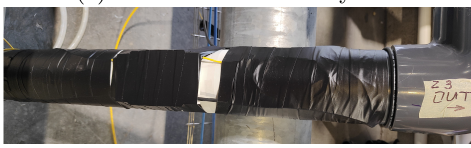
2.4.8 iDAS (intelligent distributed acoustic sensor)

The iDAS (intelligent distributed acoustic sensor) by SILIXA, uses phase difference occurring due to Rayleigh back scattered light due to dynamical strain effects along an optical fibre, to measure flow characterisation. The iDAS system is introduced as a part of a Co-UD lab project [2] done by Deltares in collaboration with Silixa (UK). The optical fibres used are wound in 3 different positions, Z1, Z2, Z3, and Z4 as marked in Figure 2. In Z1 optical fibres are wound around the PVC supply line tightly without any gap between subsequent winding. In Z2 section, the optical fibres are spread apart while winding across the Beta loop. In Z3 section, the optical fibres are placed longitudinally (along the axis of flow) on the Beta loop. In Z4 section,optical fibres are wound around the PVC supply line tightly without any gap between subsequent winding. Sections Z1 and Z2 are present on the supply line and section Z4 is present on the return line, parallel to section Z1. Section Z3 is present in the region where the Beta loop end the supply line and starts the return line. The optical fibre wrapped sections of the Beta loop are represented in Figure 17. The data from the iDAS are measured and stored separately, compared to the other sensors attached to the Beta loop. The optical fibres used are of 800 μm diameter. The iDAS is used in only experimental setup-2 and is used compared to all the other sensors used in the Beta loop. The data measured from iDAS is controlled and post processed by SILIXA.

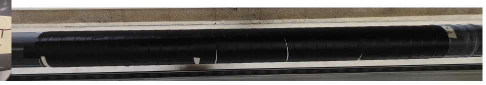
Figure 16: iDAS (intelligent distributed acoustic sensor)

(a) Section Z1 of iDAS system

(b) Section Z2 of iDAS system



(c) Section Z3 of iDAS system



(d) Section Z4 of iDAS system

Figure 17: Optical fibre wrapped sections used in iDAS measurement

Table 12: iDAS details [15]

Sensor features	**Details**
Product detail	iDAS intelligent distributed acoustic sensor
Sensing range	45 km
Sampling frequency	400 Hz to 100kHz
Acoustic sensitivity	<0.001 Hz to 50 kHz

2.5 Recording software used

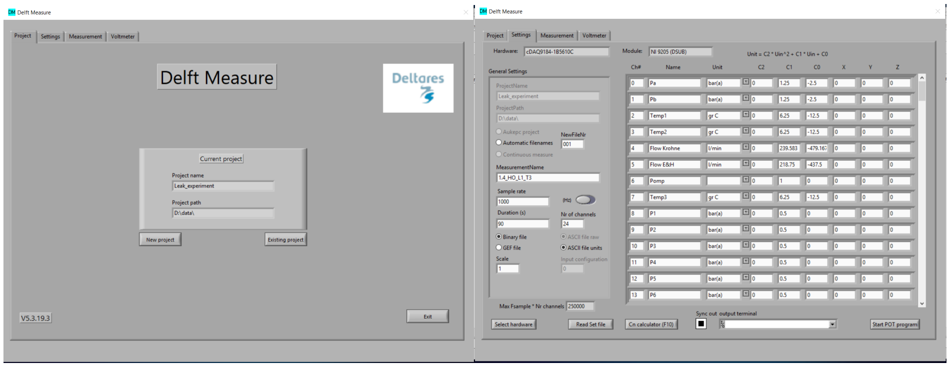
A signal recording software called "Delft measure" [3] is used for recording the sensor signals. Delft measure is an in-house developed software, from Deltares. For the Beta loop setup, we use an Ethernet connection from the junction-box with all sensors connected to it, to a workstation which runs the Delft measure as means of data recording. The software has 4 tabs in its window, as represented in Figure 18. The top left panel of Figure 18 is the project tab, shown in Figure 18a, which opens up on opening the software. This is where we set the root directory of the files to be saved, as well as naming the project. The settings tab, as shown in Figure 18b, is where the signals from the sensors are received and listed. The settings tab also converts the signals received in volts to required units using conversion parameters, according to the sensor used. The signals are then recorded as, .raw (voltage), .asc and .dat files. These are, respectively,

1. RAW files, which store the collected raw data from the sensors, without conversion to required unit.
2. ASCII files, which consists of tab separated columns of time series data of the converted units of sensors.
3. DATA files, which consists of tab separated columns of time series data of the converted units of sensors.

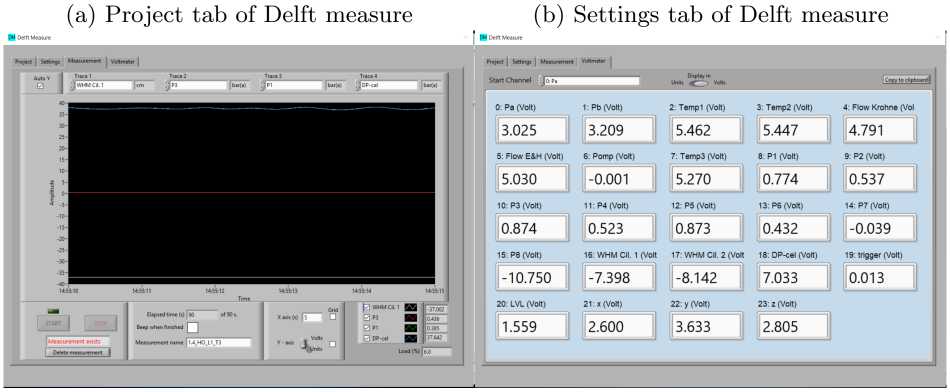
The conversion settings are saved as .set files. The signals can be recorded in the required sampling rate and duration, depending on the measurement done. There is also the option of recording the data of limited number of channels out of the entire set of channels connected at the moment.

The signals can be viewed in real time, as traces (up to 4 maximum) in the measurement tab, as seen in Figure 18c. These signals can be viewed in corresponding voltages recorded or the in the required units for each sensor. The voltmeter tab, given as Figure 18d, allows us to watch the real time variation of the required signals recorded in the requested units/voltages.

The iDAS uses a separate controlling software and is accessed separately, by SILIXA.



(a) Project tab of Delft measure (b) Settings tab of Delft measure



(c) Measurement tab of Delft measure (d) Voltmeter tab of Delft measure

Figure 18: Delft measure software

2.6 Pump control

The pump in the Beta loop system starts at 2.05 V, with an "inactive" range of 0 - 2.05 V and has an operation range of 2.05 - 10 V. This means the pump starts up only after reaching an input voltage of 2.05 V, and there is zero discharge between the input voltage range of 0 - 2.05 V. The discharge rate from the pump can be regulated by controlling the input voltage to the pump, which can be done in two different methods:

1. Through a pump control GUI, which goes through a voltage profile prescribed by the user, as illustrated in Figure 19. Here the voltage profile is written on a notepad file, to follow a particular pattern of ramp up, hold and ramp down of the pump, in specified times. The sequence can be loaded and executed using the buttons seen in Figure 19.

2. Through manual increment in voltages through a potentiometer, indicated in Figure 20. The potentiometer is set at a default value of 0. There are two dials connected to the knob of the potentiometer, where one dial has markings with a least count of 0.1 V and the other with a least count of 1 V, which can be seen through a window. On turning the potentiometer knob, the first dial starts turning from 0 - 0.9 V, after which the second dials moves by 1 unit or 1 V.

The pump control can be switched from manual potentiometer control to the GUI control by the flip of a switch, present in Figure 20

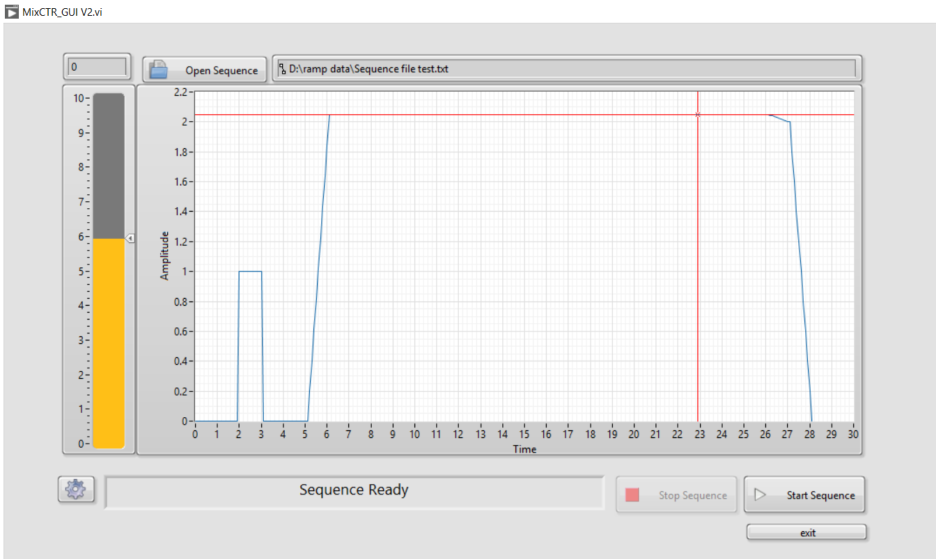


Figure 19: Pump control GUI

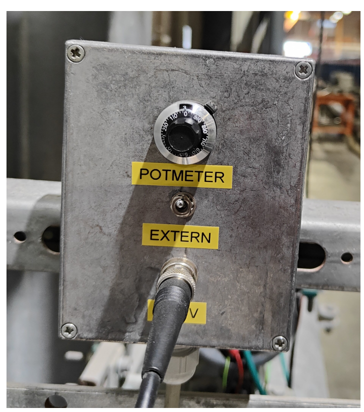


Figure 20: Pump control: Potentiometer

3 Methods of operation for measurement

In this section we explain about the procedure done for measurement of data for experimental setup-1. The measurements done include those done to investigate the characteristics of the Beta loop and those done to measure the impact of leaks to the Beta loop.

3.1 General steps to be followed while operating the Beta loop

The following steps are to be followed while doing any trials/ measurements on the Beta loop to ensure reduction of errors and safe operation.

Step 1: Check the water level in the tank, using the static reading of the level meter from Delft measure. If the water level is below/close to the return line level at 1.9 m, fill the tank with the hose attached to it.

Step 2: The absolute pressure sensors are connected to the Beta loop with the help of valves. These valves have to be opened at the beginning of each trial to vent any air trapped in the loop and then subsequently after all the air is vented out.

Step 3: The clear section of the Beta loop has to be checked visually for trapped residual air bubbles that needs to be vented.

Step 4: The pump is operated at required voltage and the main control valve is kept fully open (FO) or half open (HO).

Step 5: The collecting vessels for the leaks are to be emptied until reaching a level of approximately 2.5 cm from the bottom of the vessel or until there is a minimum height of water which reaches just till the start of the wave height meter in the collecting vessel. The emptying taps of the collecting vessels are ensured to be closed before the experiment.

3.2 Method for determining the operating range of the Beta loop

3.2.1 For experimental setup-1

The operation range of the pump for the Beta loop setup were to be determined. This was done through the following steps,

Step 1: The first step is to determine the criteria of operation of the Beta loop. The criteria of operation include,

- Range of voltage of operation of the pump: As mentioned in subsection 2.6, the pump starts up at a voltage of 2.05 V. It is decided to keep the operating range between 2.05 V - 5 V to ensure safety of the equipment and user.
- Minimum/ maximum pressure to be allowed in the Beta loop : The pressure fluctuations are to be limited between the range of -0.3 bar and +5 bar to ensure safety of the equipment and user. This range was decided based on previous experiments done on the Beta loop. Since the Beta loop is made of PVC rated 10 bar, but the clear/ elevated section is made of a different material whose pressure rating is lower than the PVC, the +5 bar upper limit was decided. Also, as the PVC pipes are not rated for a negative pressure, but the minimum allowable pressure of operation in previous experiments done in the Beta loop was -0.3 bar, it was chosen as the lower limit of operation.
- Minimum/ maximum flow allowed in the Beta loop: This corresponds to the input voltage range mentioned above.
- Minimum/ maximum water level allowed in the tank: The water in the tank is to be ensured to $>$ 1.9 m.

Step 2: The next step is to check the amount of time required for the ramp up and ramp down of the pump safely. Ramp up times and ramp down times ranging between 60 s and 10 s, by steps of 10 s were evaluated for 3V, 4V and 5V. The ramp down measurements were done separately, while the ramp up measurements were done as a single measurement, for each input voltage. Figure 21 references one such measurement done.

- For the ramp up measurement, the pump was initially ramped up to a certain voltage in the required time, is then maintained a constant for a period of 30s to allow the flow to settle. The pump is then ramped down in 60 s. This cycle is repeated for all ramp up times. It is noted that for all ramp up times, the flow seemed to stabilize, by visual inspection of the live signal on Delft measure, within 20 s. The criteria for deciding stability was observing the live signal on Delft measure, and checking whether the signals settles around a mean value of flow measured. The ramp down time in each of the ramp up measurements were kept at 60 s. An example of this trial for 3 V is given in Figure 21a.
- For the ramp down measurements, the pump is ramped up to the desired voltage in 60 s and is then allowed to remain for a period of 30 s to allow the flow to settle. The pump is then ramped down in the required time and the experiment is repeated. An example of this trial for 3 V is given in Figure 21b.

The measurement matrix chosen for ramp up and ramp down time measurements are given in Table 13.

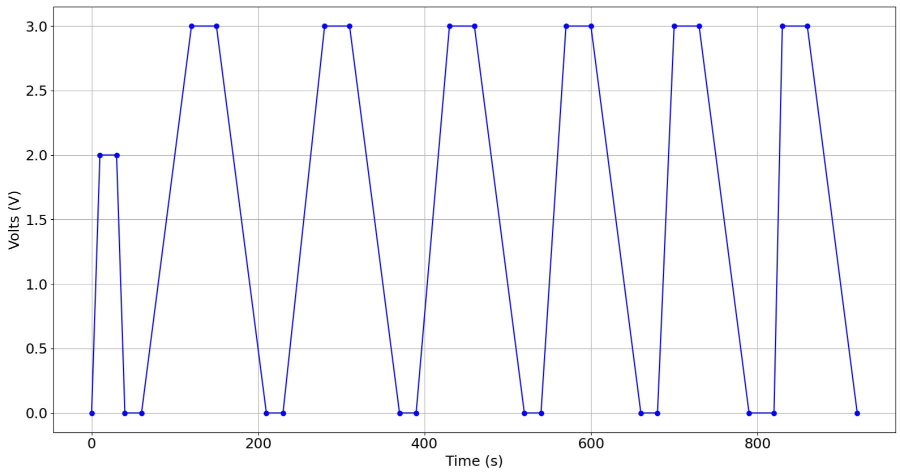
Table 13: Measurement matrix for ramp up and ramp down times in experimental setup - 1

Voltage input (V)	**Time for ramp up/ramp down**
3	60 s, 50 s, 40 s, 30 s, 20 s and 10 s
4	60 s, 50 s, 40 s, 30 s, 20 s and 10 s
5	60 s, 50 s, 40 s, 30 s, 20 s and 10 s

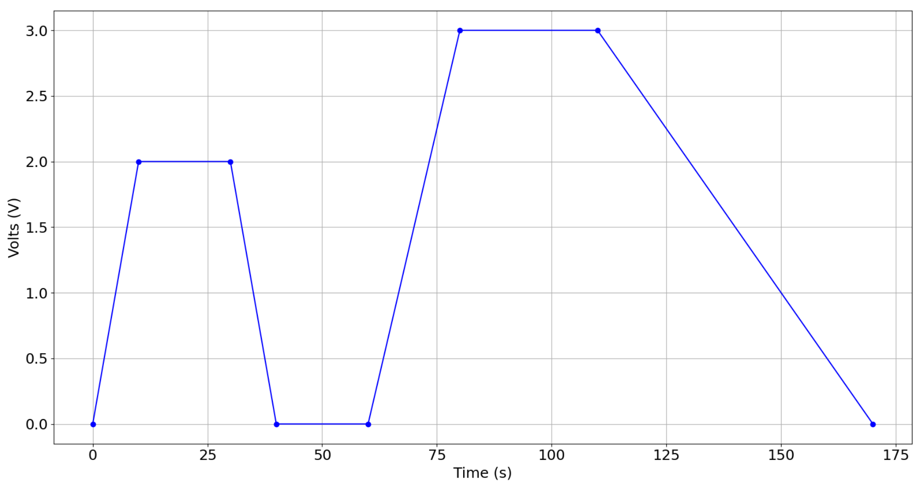
Step 3: As per the operation range of voltage decided in step 1, we maintain the voltage of the pump between 2.25 V-5 V. A set of measurements where, the operating voltage of the pump was varied from 2.25 V - 5 V and the corresponding flow rates were noted from the flow meters, were done. These flow rates were then converted to bulk flow velocities through the Beta loop using the equation, $v = \frac{Q}{A}$, where, Q, is the flow rate through the Beta loop at a particular pump operation voltage, in m^3/hr, v, is the bulk velocity of the flow, in m/s and A, is the area of cross section of the Beta loop. A step size of 0.25 V was taken during measurement. These trials were repeated twice, where in one set of measurements the main control valve (MCV) was fully opened and in the second set of measurements, the MCV was opened half-way. The measurement matrix chosen for bulk velocity determination is given in Table 14, which gives rise to 30 Reynold's number regimes.

Table 14: Measurement matrix for bulk velocity determination for experimental setup - 1

Voltage input (V)	**MCV position**
2.25 - 5	HO
2.25 - 5	FO



(a) Ramp up profile for 3 V



(b) Ramp down profile for 3 V at 60 s of ramp down time

Figure 21: Example of pump profiles used for testing operation ranges for experimental setup - 1

3.2.2 For experimental setup-2

For experimental setup-2 a set of bulk velocities were decided initially, which are given in Table 15.

Step 1: The first step was to find the corresponding frequency input that is obtained by controlling the potentiometer rotation. The first measurement is taken for 5 min at 100 Hz, after the first bulk velocity required is obtained in the Beta loop. The input frequency can be seen on the control panel next to the potentiometer, as given in Figure 22.

Step 2: The next step is to repeat step 1 for all velocities previously decided in the measurement matrix in Table 15, while noting the input frequency that correspond to the bulk velocity needed in the Beta loop.

Figure 22: Control panel of pump

Table 15: Measurement matrix for input frequency determination for experimental setup - 2

Bulk velocity	**MCV position**
0	FO
0.8	FO
1.0	FO
1.2	FO
1.4	FO
1.6	FO
1.8	FO
2.0	FO

3.3 Determining the friction factor of a sample section of Beta loop

The pressure drop across the differential pressure sensor, whose ends are connected at a distance of 21.07 m across tap 2 on the return line, was measured and was converted to friction factor value of the PVC pipe using the Darcy-Weisbach equation given below,

$$\Delta P = f_D \frac{\rho v^2}{2} \frac{L}{D} \tag{2}$$

where,

ΔP, is the pressure drop across the length of the pipe, in Pa.
f_D, is the Darcy friction factor (-).
ρ, is the density of the fluid, in kg/m^3.
v, is the bulk velocity of the flow in m/s.
L, is the length of the section of pipe under consideration in m.
D, is the diameter of pipe under consideration in m.

The following procedures were taken to calculate the friction factor of the sample section of the pipe.

3.3.1 For experimental setup-1

Step 1: Fix the operating voltage of the pump at a constant value between the operating range of 2.5 - 5 V. The main control valve (MCV) is kept fully open for the measurement.

Step 2: The data is recorded for 90 s (based on time required to fill the collecting vessel, by using the tap 1, with no flow in the Beta loop) at a 1000 Hz (estimated from previous measurements on Beta loop), where the main parameters of interest recorded were the differential pressure sensor reading across tap 2. Using the temperature sensor connected upstream, (marked as T2 in Figure 1) the corresponding density at that temperature is found, for calculating Reynold's number.

Step 3: The differential pressure sensor data, the temperature sensor data (T2) and the flow meter data (obtained in L/min, which is converted to m/s using the equation mentioned in (**Step 3:**) of subsection 3.2) is averaged over the entire measurement period of 90 s. These average values along with the corresponding density of the T2 value is used to find the friction factor according to Equation 2.

Step 4: The voltage is increased by a step of 0.25 V and the previous steps are repeated until 5 V.

Step 5: The error factor involved in the measurement is calculated using the accuracy offered for the measurement instruments, offered by the manufacturer, to calculate the error in calculation of the Reynold's number as well as the friction factor. The error factor is measured using Equation 3 ,

Given a function $f = f(x, y, z)$

$$df = \frac{\partial f}{\partial x}dx + \frac{\partial f}{\partial y}dy + \frac{\partial f}{\partial z}dz \tag{3}$$

where, the quantities $\frac{\partial f}{\partial x}$, $\frac{\partial f}{\partial y}$ and $\frac{\partial f}{\partial z}$, refer to the fractional errors of x, y and z.

Step 6: Finally the Moody plot, or a plot of the friction factor and the Reynold's number, was made. The measured value was plotted along side a theoretical Moody's plot, with the error factors of measurement of the Reynold's number and the friction factor in the plot. The measurement matrix for the friction factor determination is given in Table 16.

Table 16: Measurement matrix for friction factor determination experimental setup - 1

Voltage input (V)	**MCV position**
2.25 - 5	FO

3.3.2 For experimental setup-2

Step 1: The data measured in subsubsection 3.2.2, is used to calculate the friction factor across the differential pressure sensor in Figure 2, using Equation 2. This means the measurement matrix is the same as Table 15.

Step 2: The error factor of measurement remains same as stated for the friction factor measurement of experimental setup-1.

Step 3: The Moody plot (Friction factor vs Reynold's number) along with theoretical Moody's diagram is plotted.

3.4 Method of measurement of Tap 2 flow rate per rotation or tap 2 operating profile

Since tap 2 attached to the return line of the Beta loop is a rotating tap, where a turn of the cap opens the tap more thus causing more flow rate to progress through it.
The rate of "leak" or flow through the tap 2 with each rotation of the cap of the tap, creates a tap 2 operating profile. This can be done by the following steps:

Step 1: Fix the operating voltage of the pump at a constant value (here done at 4V), using the potentiometer. The main control valve (MCV) is kept fully open for the measurement.

Step 2: The Tap 2 is opened to a required degree of rotation. Since the tap opens fully at 7.5 revolutions, the tap 2 is opened by 0.5 revolution for each measurement. The first measurement is done at 1 revolution, as there is no discharge below 1 revolution of the tap.

Step 3: Delft measure is used to record the data for 90 s at 1000 Hz of acquisition rate. The main parameter of interest is the flow rate per voltage (here, a constant) and the leak rate by tap 2. The leak discharged from tap 2 is collected in a collecting vessel which has a wave height meter attached to it (WHM Cil 2) which measures the discharge rate in cm.

Step 4: The taps are closed after each measurement and the collecting vessel is drained before the next measurement. The measurement matrix for determining the tap 2 operating profile is given in Table 17.

Table 17: Measurement matrix for determining tap 2 operating profile

Voltage input (V)	**Revolutions of tap 2 cap considered**
4	1 revolutions - 7.5 revolutions

3.5 Method for leak measurement

3.5.1 For experimental setup-1

Before starting any experiment on the Beta loop the steps mentioned in subsection 3.1, are to be followed and ensured. During the initial trials of measurement of bulk velocities for corresponding input voltage to the pump, it was observed that the collecting vessel got filled almost to the brim if the leak was allowed to progress for 120 s, at an input voltage of 5 V. Thus a maximum recording time of 90 s was decided for every signal recorded for the leak, to account for avoiding any spillage. To have a good amount of data to consider an average, over any period of time $\leq$ 90 s, 1000 Hz was chosen as the sampling rate for the signals recorded.

Out of the 30 input voltage & MCV combination measurements, mentioned in subsection 3.2, 12 combinations spread into two categories of MCV fully open and MCV half-way open were chosen to be studied. This was done to limit the number of measurements to an achievable and discernible number. Each of the corresponding voltages was achieved by ramping up the pump in 20s, maintaining the flow

Table 18: Input voltage and MCV condition chosen for leak determination experimental setup - 1

Voltage input (V)	**MCV position**
2.5	HO & FO
3.0	HO & FO
3.5	HO & FO
4.0	HO & FO
4.5	HO & FO
5.0	HO & FO

for a long period of time with a constant pump operating voltage (for 200s) and finally ramped down in 20s at the end of each trial. The measurements were decided to be done in the following way for each input voltage-MCV combination as,

1. No taps/leaks opened i.e. reference condition.

2. Continuously open tap measurements, with the taps being opened before measurement and the collecting vessel having the blue tube from the tap with a length of 1 m. The different combinations of tap openings considered are:
   (a) With only Tap 1 opened.
   (b) With only Tap 2 opened fully.
   (c) With only Tap 2 opened to halfway.
   (d) With both Taps opened fully.
3. Impulsively open tap measurements, with the taps being opened during measurement and the collecting vessel having the blue tube from the tap with a shortened length of 0.25 m. The different combinations of tap openings considered are:
   (a) With only Tap 1 opened.

It was decided to have two separate set of tap opening methods, i.e. for the tap being open before the recording of the measurement and during the measurement. This was to also study the effect of a leak which exists against a leak that is introduced while measuring respectively.

1. **Measurement method for reference conditions**

Step 1: The reference conditions were measured for each input voltage before the leak measurements were conducted. This was done by ramping the pump in 20s, allowing the flow to stabilize itself after reaching the set voltage for 20s, and then recording the data for a sample length of 90s and a sampling rate of 1000 Hz. The measurement matrix given in Table 19, gives a summary of the reference measurements done.

Table 19: Measurement matrix for reference measurement experimental setup - 1

Voltage input (V)	**MCV position**
2.5	HO & FO
3.0	HO & FO
3.5	HO & FO
4.0	HO & FO
4.5	HO & FO
5.0	HO & FO

2. **Measurement method for continuously open tap measurements**

Step 1: The taps are initially turned on and then the pump is allowed to ramp up and reach the steady state flow with the help of the pump control GUI. After the pump reaches a steady flow as mentioned above, when the flow stabilizes itself after 20 s after reaching the set voltage, the data is recorded using Delft measure for the trial, for a sample length of 90s and a sampling rate of 1000 Hz.

Step 2: The taps are turned off at the end of 90s of recording time and the collecting vessels are drained before moving on to the next trial. The measurement matrix for the continuously open tap measurement, is given as Table 20.

3. **Measurement method for impulsively open tap measurements**

Step 1: The pump is allowed to ramp up and reach the steady state flow with the help of the pump control GUI. After the pump reaches a steady flow as mentioned above, (when the flow stabilizes itself after 20s after reaching the set voltage as stated in subsection 3.2) the data is

Table 20: Measurement matrix for continuously open tap measurement experimental setup - 1

Voltage input (V)	MCV position	Taps opened
2.5	HO & FO	Tap 1, Tap 2, Tap 2 halfway open, Tap 1 + Tap 2
3.0	HO & FO	Tap 1, Tap 2, Tap 2 halfway open, Tap 1 + Tap 2
3.5	HO & FO	Tap 1, Tap 2, Tap 2 halfway open, Tap 1 + Tap 2
4.0	HO & FO	Tap 1, Tap 2, Tap 2 halfway open, Tap 1 + Tap 2
4.5	HO & FO	Tap 1, Tap 2, Tap 2 halfway open, Tap 1 + Tap 2
5.0	HO & FO	Tap 1, Tap 2, Tap 2 halfway open, Tap 1 + Tap 2

recorded using Delft measure for the trial, for a sample length of 90s and a sampling rate of 1000 Hz. After the data recording starts, the tap 1 is turned on at a random point in time (before the recording sample length time of 90s ends) and the leak is allowed to progress for 30s before the tap is switched off.

Step 2: After the recording sample length time of 90s ends, the collecting vessels are drained before moving on to the next trial.

Step 3: The transient leak trials were repeated thrice for each input voltage. The measurement matrix for the impulsively open tap measurement, is given as Table 21.

Table 21: Measurement matrix for Impulsively open tap measurement experimental setup - 1

Voltage input (V)	MCV position	Taps opened	Number of repeats
2.5	HO & FO	Tap 1	3
3.0	HO & FO	Tap 1	3
3.5	HO & FO	Tap 1	3
4.0	HO & FO	Tap 1	3
4.5	HO & FO	Tap 1	3
5.0	HO & FO	Tap 1	3

3.5.2 For experimental setup-2

Before starting any experiment on the Beta loop the steps mentioned in subsection 3.1, are to be followed and ensured. In this measurement, the velocities determined in subsubsection 3.2.2 are used. The measurements are decided to be done as impulsively open tap measurements, with the tap being opened for a time period of 90 s and then closed, all within a total measurement time of 15 min in the Delft measure system ad 5 min in the iDAS system. The different combinations of tap openings considered are:

- Only tap 1 open.
- Only tap 2 open (fully open)
- Both taps opened fully.

1. **Measurement method for reference conditions**

Step 1: The reference or no taps open condition are measured for a time period of 15 min for all bulk velocities (at 100 Hz) decided in subsubsection 3.2.2, by adjusting the input frequency using the potentiometer.

Step 2: The iDAS system is activated 5 minutes after the measurement is started in the Delft measure system. The iDAS system is stopped after 5 minutes of measurement. The Delft measure system is stopped along with the measurement 15 minutes after starting.

Step 3: The measurements are repeated over three days, where all the reference measurements are repeated each day.

Table 22: Measurement matrix for reference measurement in experimental setup-2

Bulk velocity	MCV position	Number of iterations done
0	FO	3
0.8	FO	3
1.0	FO	3
1.2	FO	3
1.4	FO	3
1.6	FO	3
1.8	FO	3
2.0	FO	3

2. **Measurement method for impulsively open tap measurements**

Step 1: The initial bulk velocity decided in subsubsection 3.2.2, is achieved , by adjusting the input frequency using the potentiometer and the measurement is started in the Delft measure system. The measurement sampling rate was kept at 1000 Hz.

Step 2: The iDAS system is switched on 5 minutes after the Delft measure system is started.

Step 3: Within 1 min, the switch operating the solenoid of tap 1 is activated, initiating the flow. The flow through the tap is allowed to proceed for 90 s after which the switch of the solenoid of tap 1 is switched off.

Step 4: The rest of the recording of the measurement is allowed to proceed until a total time of 5 min in the iDAS system. The iDAS system is switched off after this.

Step 5: The Delft measure system is switched off after 15 minutes of total recording time.

Step 6: The steps 1-5 are repeated for all the bulk velocities decided in subsubsection 3.2.2.

Step 7: The steps 1-6 are repeated for tap 2 and tap 1 + tap 2 combination and the data is recorded.

Step 8: The steps 1-7 are repeated thrice over a span of three days, with each measurement set of the day containing a measurement of tap 1 opened, tap 2 opened and tap 1 + tap 2 opened. The measurement matrix for the impulsively open tap measurement is given in Table 23.

Table 23: Measurement matrix for Impulsively open tap measurement for experimental setup-2

Voltage input (V)	MCV position	Taps opened	Number of repeats
2.5	FO	Tap 1, Tap2 , Tap 1 + Tap 2	3
3.0	FO	Tap 1, Tap2 , Tap 1 + Tap 2	3
3.5	FO	Tap 1, Tap2 , Tap 1 + Tap 2	3
4.0	FO	Tap 1, Tap2 , Tap 1 + Tap 2	3
4.5	FO	Tap 1, Tap2 , Tap 1 + Tap 2	3
5.0	FO	Tap 1, Tap2 , Tap 1 + Tap 2	3

3.6 Method of measurement for calculation of K_v of the taps

The resistance offered by both the taps are measured by varying the operating voltage of the pump at 3V, 4V and 5V (and thus at varying bulk velocities) and measuring the pressure drop across the length of the taps. This means finding the pressure drop between the inside of the tap, which lies in the Beta loop and the outside of the tap. We consider the reading of the pressure sensor upstream of each tap (P3 corresponds to upstream pressure sensor of Tap 1 and P4 corresponds to upstream pressure sensor of Tap 2). Subsequently, we use the Darcy-Weisbach equation, stated in Equation 2 to extend the pressure profile from the upstream taps, to the point where the tap/leak is present and using the amount of water leaked in 30s. This is then used in the following equation to calculate the K_v or the flow factor/flow coefficient of the taps. It is described as the flow rate through the tap per square root of the unit pressure loss across the inside and outside condition of the tap.

$$K_v = \frac{Q'}{\sqrt{\Delta P}} \tag{4}$$

where,

ΔP, is the pressure drop across the tap,
between the inside of the tap and outside of the tap.
K_v, is the flow coefficient in $m^3/(h\ bar^{0.5})$.
Q', is the flow rate through the tap in m^3/h.

The following methods are used to calculate the K_v values of the taps attached to the Beta loop,

3.6.1 For experimental setup-1

The data measured in the steady leak trials, from subsubsection 3.5.1 is considered for this method. The data obtained for 3, 4 and 5 V for the leak measurements for tap 1 and tap 2 at fully opened MCV conditions are taken and the leaks are gathered in the collecting vessel from the taps using the blue tube attached.

Step 1: For a constant voltage of supply to the pump, starting at 3 V, we consider the measurements recorded in subsubsection 3.5.1 . The main parameters of interest recorded were the absolute pressure sensor readings across the tap 1 (P3 and P1 in Figure 1), tap 2 (P4 and P6 in Figure 1) and the wave height meter measurements done in both the collecting vessels at tap 1 and tap 2.

Step 2: A random point in the signal was chosen between the signal recording time of 0 s and 90 s. The value of P3, P1, P4, P6 , the wave height meter measurement of in the collecting vessels is taken as an average over a period of ± 1 s on either side of the random point in time of the signal chosen to get the necessary values of the parameters of interest.

Step 3: The pressure on the supply side of the taps were then found using (2), by interpolating from the value of P3 for tap 1 and P4 for tap 2. Due to the presence of the additional water column during measurement, the pressure exerted by the water column is calculated using the height of the water column measured at the random point chosen, and then using the following equation to convert the height of head of water to pressure at the bottom of the collecting vessel, near the exit of the blue tube.

$$p' = \rho g h \tag{5}$$

where,

p', is the pressure caused by the water column collected in Pa,
g, is the acceleration due to gravity = 9.81 m/s ^{2}.
h, height of the water column collected in m.

This p' is then used as the exit pressure condition to calculate ΔP.

Step 4: The height difference introduced during the period of ± 1 s on either side of the random point in time of the signal chosen, per 2 s is taken as the leak rate in m^3/h i.e. Q'.

Step 5: The steps 1 - 4 are repeated for all measurements recorded in subsubsection 3.5.1, with MCV fully open. The K_v value for the individual taps were calculated using Equation 4. The measurement matrix for the K_v calculation is the same as the one for continuously open tap measurement, i.e. Table 20.

3.6.2 For experimental setup-2

The data measured in the impulsively open tap trials done in subsubsection 3.5.2 is considered in this method.

Step 1: The data for the first bulk flow velocity (of measurement time 15 min), where the taps are opened for 90 s individually are considered.

Step 2: The pressure existing at the inside region of the taps were then found using (2), by interpolating from the value of P3 for tap 1 and P4 for tap 2. The exit pressure condition of the outside of the taps are kept as atmospheric (gauge pressure = 0).

Step 3: A random point in the signal was chosen between the signal recording time of tap opening and tap closing. The value of P3, P1, P4, P6 , the wave height meter measurement of in the collecting vessels is taken as an average over a period of ± 10 s on either side of the random point in time of the signal (between the time the taps were opened and closed) chosen to get the necessary values of the parameters of interest.

Step 4: The height difference introduced during the period of ± 10 s on either side of the random point in time of the signal chosen, per 20 s is taken as the leak rate in m^3/h i.e. Q'.

Step 5: Steps 1-4 are repeated for all individual tap opening measurements (i.e. tap 1 open or tap 2 open) as given in subsubsection 3.5.2 and the K_v value for the individual taps were calculated using Equation 4. The measurement matrix used here for K_v calculation is the same as in Table 23.

4 Data description and nomenclature used

The data measured for all the trials done are stored as ACSII (.asc), DATA (.dat) and RAW (.raw) formats. The .asc stores the sensor data in the required units of measurement while the .dat and .raw files store the direct voltage measurement of the sensors. The setting used in Delft measure software is recorded in settings along with the calibration details including conversion constant from the voltages measured by the sensors to required units, are stored as setting (.set) files.

4.1 Data indices

The data stored in the .asc, .dat and .raw files are tab separated columns with the following column names, which make up the 24 channels in use in Delft measure, with the description of what they represent.

4.2 File naming convention used for determining the operating range of Beta loop measurement data

4.2.1 For experimental setup-1

The data is recorded for 3 separate purposes in subsection 3.2. This includes determining an appropriate ramp up rate, a ramp down rate and values of bulk velocities and Reynold's number corresponding to the each voltage value chosen as the input voltage of the pump. The following nomenclature was used in naming the trials.
Here the data are recorded at various duration, based on the total duration of time taken for pump profile built on the GUI to be ramped up, held constant and ramped down. The naming convention begins with the input voltage to which the pump is ramped up or ramped down to. It is then followed by the name of the process; whether the measurement is done for ramp up or ramp down process. Finally the file name ends with the state of the main control valve (MCV), being kept fully open (FO) or half-way open (HO). For ramp down measurements, the time taken to ramp down the pump is

Table 24: Data indices recorded

Column name	Description
T (ms)	Time measurement in milliseconds.
Pa	Time series measurement of pressure sensor Pa.
Pb	Time series measurement of pressure sensor Pb.
Temp1	Time series measurement of temperature sensor T1.
Temp2	Time series measurement of temperature sensor T2.
Temp3	Time series measurement of temperature sensor T3.
Flow Krohne	Time series measurement of flow measurement from Krohne flowmeter.
Flow E&H	Time series measurement of flow measurement from E&H flowmeter.
Pomp	Pump profile input from the GUI.
P1, P2 ... P6	Time series measurement of absolute pressure sensors P1, P2 ... P6.
WHM Cil. 1	Time series measurement of wave height meter in collecting vessel at Tap 1.
WHM Cil. 2	Time series measurement of wave height meter in collecting vessel at Tap 2.
DP-cel	Time series measurement of differential pressure sensor across Tap 2.
LVL	Time series measurement of level meter measurements in the tank. The measurements recorded starts from the top of the sensing element (near the housing). This means that the level of water in the tank = the height of the tank - the level sensor reading in a measurement.
x, y and z	Time series measurement of accelerometer readings in the x, y and z axes.
P7, P8, trigger, Lucht Instel. and Lucht Outp.	Residual of old measurements done in the setup, which include sensors which are not used in the current measurements done. P7 and P8 were pressure sensors that were previously used, and currently disconnected from the Beta loop. Lucht Instel. and Lucht Outp. are devices which were used to inject and eject air out of the transparent section of the Beta loop. Trigger corresponds to the signal sent to the Lucht Instel. and Lucht Outp. sensors for their activation.

Table 25: File naming convention for operating range measurement for experimental setup-1

File format	`[(Required voltage input)V]_[ramping process]_[MCV position]_[time taken for ramping]`
	`[(Required voltage input)V]_[bulkvelocity]_[MCV position]`
Required voltage input	3V, 4V or 5V
Process identifier	rampup, rampdown or bulkvelocity
MCV position	FO or HO
Time taken for ramping	10 s, 20 s, 30 s, 40 s, 50 s or 60 s
eg	`3V_rampdown_FO_40s`
	`4V_rampup_FO`
	`5V_rampup_HO`
	`2.05-5V_bulkvelocity_FO`

given at the end of the file for better identification. For the measurement done on the calculation of bulk velocity of flow, as per item **Step 3:** of subsection 3.2, we have a file name which begins with the input voltage range chosen, followed by the an identification name of the process as ”bulkvelocity” and finally ending with the state of the main control valve (MCV), being kept fully open (FO) or half-way open (HO).

4.2.2 For experimental setup-2

The measurement done as per subsubsection 3.2.2, has been named as given in Table 28. Here the file name starts with the fluid used, which is water, represented by W0.The file name is then followed by the the state of taps being opened during measurement, which is represented as give in Table 26.

Table 26: Operating tap identifier for experimental setup-2

Taps opened	**Represented by**
No taps were open	L0
Tap 1 was open fully	L1
Tap 2 was open fully	L2
Tap 1 +Tap 2 were opened fully	L3

The file name is then followed by which leak is operated during measurement, which is stated in Table 27.

Table 27: Bulk flow velocity identifier for experimental setup-2

Bulk velocity in Beta loop (m/s)	**Represented by**
0	F0
0.8	F1
1.0	F2
1.2	F3
1.4	F4
1.6	F5
1.8	F6
2.0	F7

The file name finally ends with the repetition number done for the measurement, which is C1 for this measurement, i.e. only 1 measurement iteration is carried out.

Table 28: File naming convention for operating range measurement for experimental setup-2

File format	`[Fluid]_[Leak]_[Flow velocity]_[Measurement repetition]`
Fluid	W0
Leak	L0, L1, L2 or L3
Flow velocity	F0, F1...F7
Repetition	C1, C2.. Cx
eg	`W0_L0_F1_C1`
	`W0_L0_F2_C1`

4.3 File naming convention used for friction factor measurement data

4.3.1 For experimental setup-1

The following naming convention was used in naming the friction factor measurements.

Table 29: File naming convention for friction factor measurement for experimental setup - 1

File format	`[(Required voltage input)V]_[ff]_[MCV position]`
Required voltage input	2.25V to 5V
Process identifier	ff
MCV position	FO
eg	`2.25V_ff_FO`
	`3V_ff_FO`

Here the data are recorded with the values of the corresponding voltages used to control the pump. This is followed by file identification mark of "ff", representing friction factor measurement. It is to be noted that all the measurements are done with the main control valve (MCV) in the fully opened condition, represented by FO at the end of the file name.

4.3.2 For experimental setup-2

The same files and file naming conventions used in subsubsection 4.2.2 are used in friction factor calculation for experimental setup-2.

4.4 File naming convention used for Tap 2 flow rate per rotation or tap 2 operating profile

The following naming convention was used in naming the friction factor measurements. Here the data

Table 30: File naming convention for tap 2 operating profile measurement

File format	`[(Required voltage input)V]_[OP]_[MCV position]` `_[Number of revolutions of tap]`
Required voltage input	4V
Process identifier	OP
MCV position	FO
Number of revolutions of tap	1 to 7.5
eg	`4V_OP_FO_2.5`
	`4V_OP_FO_6.5`

are recorded with the values of the corresponding voltages used to control the pump, which is kept as 4V. This is followed by file identification mark of "OP", representing operating profile measurement. It is to be noted that all the measurements are done with the main control valve (MCV) in the fully opened condition, represented by FO which is added after "OP". Finally the number of revolutions of the cap of the tap is represented at the end of the name.

4.5 File naming convention used for leak measurement data and for K_v measurement

4.5.1 For experimental setup-1

The following naming convention was used in naming the measurements.

Table 31: File naming convention for leak measurement for experimental setup-1

File format	`[(Required voltage input)V]_leak operated_MCV position _Transience trial`
Required voltage input	2.5V to 5V
Leak	L1, L2h, L2, L1L2 , or L0
MCV position	HO/FO
Transient leak	T#
eg	`2.5V_L2h_HO`
	`4V_L1L2_FO`
	`3V_L0_HO`
	`3.5_L1_FO_T1`

The file naming convention of the leak measurement begins with the input voltage supplied to the pump. It is followed by the which taps are being opened for the measurement, where,

Table 32: Taps opened and their representation in the naming convention for for experimental setup-1

Tap opened	Represented by
Tap 1	L1
Tap 2 opened fully	L2
Tap 2 opened half-way (turned 3.5 times)	L2h
Tap 1 and Tap 2 opened fully	L1L2
No taps were opened (Reference condition)	L0

The main control valve (MCV) position follows next; it could be fully open (`FO`) or half-way open (`HO`). If the measurements considered were for the impulsively opened taps, then an additional suffix follows the name as `T` followed by the trial number (eg. T_1, T_3 etc.).

4.5.2 For experimental setup-2

The measurement done as per subsubsection 3.5.2, has been named as given in Table 33. Here the file name starts with the fluid used, which is water, represented by W0.The file name is then followed by the the state of taps being opened during measurement, which is represented as give in Table 26. The file name is then followed by which leak is operated during measurement, which is stated in Table 27. The file name finally ends with the repetition number done for the measurement, which is M1, M2 or M3 for this measurement, i.e. whether it is the first, second or third iteration of the measurement respectively.

Table 33: File naming convention for leak measurement for experimental setup-2

File format	`[Fluid]_[Leak]_[Flow velocity]_[Measurement repetition]`
Fluid	W0
Leak	L0, L1, L2 or L3
Flow velocity	F0, F1...F7
Repetition	M1, M2, M3
eg	`W0_L0_F1_M1`
	`W0_L0_F2_M1`

5 Results

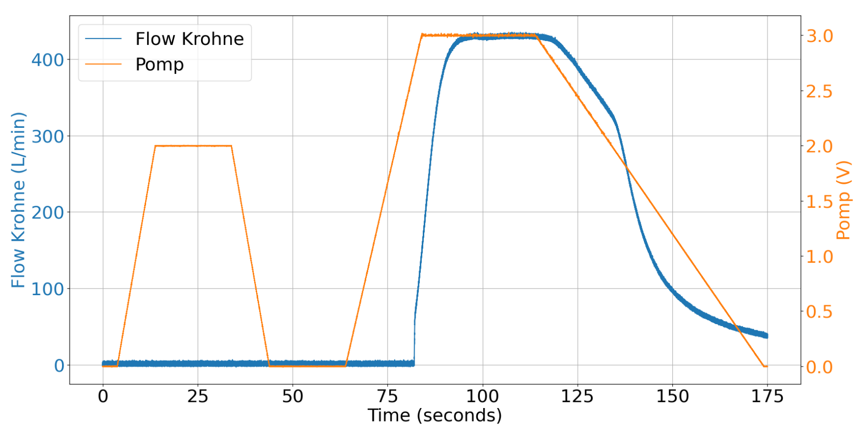
5.1 Operating range of the Beta loop

5.1.1 For experimental setup-1

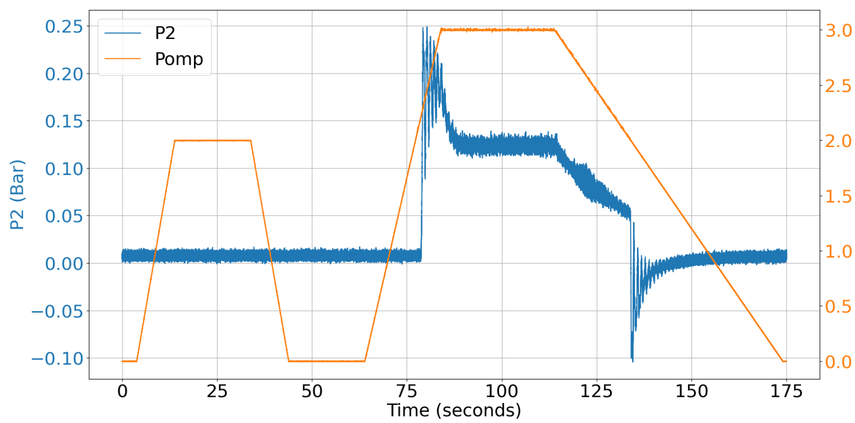
The ramp-up and ramp down profile measurements for fully opened and half-way opened main control valve (MCV) was recorded. Based on the effect of the flow measured (as described as Flow Krohne and Flow E&H in the data), the pressure sensor plot (at P2, on top of the clear section of the Beta loop, as indicated in the Figure 1) and input pump profile (described as POMP in the data recorded) the time taken for the pressure pulses formed during ramping up and ramping down were observed. It was decided to take 7 s/ V as an average ramp up and ramp down time for the operating range of voltages i.e. between 2.05 V - 5 V. Samples of signals measured in a ramp up and ramp down measurements are represented in Figure 24 and Figure 23 respectively. As per the measurements done based on subsection 3.2, which correspond to the "`2.05-5V_bulkvelocity_FO`" measurements done, we have the bulk velocity (v) values, which correspond to the given set of Reynold's numbers, for both fully opened and half-way opened main control valve (MCV), which are listed in the table of summaries given in Table 34. The sample of a signal measured in the "`2.05-5V_bulkvelocity_FO`" measurements, is represented in Figure 25.

Table 34: Comparison of MCV Half-way and Fully Open at Different Voltages for for experimental setup-1

Voltages	**MCV (Half-way open)**		**MCV (Fully open)**	
	Velocity (m/s)	**Re ($\times 10^4$)**	**Velocity (m/s)**	**Re ($\times 10^4$)**
2.5	0.7	7.5	0.9	9.4
3.0	0.8	9.1	1.1	11.4
3.5	1.0	10.8	1.2	13.4
4.0	1.1	12.4	1.4	15.5
4.5	1.3	14.0	1.6	17.5
5.0	1.4	15.7	1.8	19.6

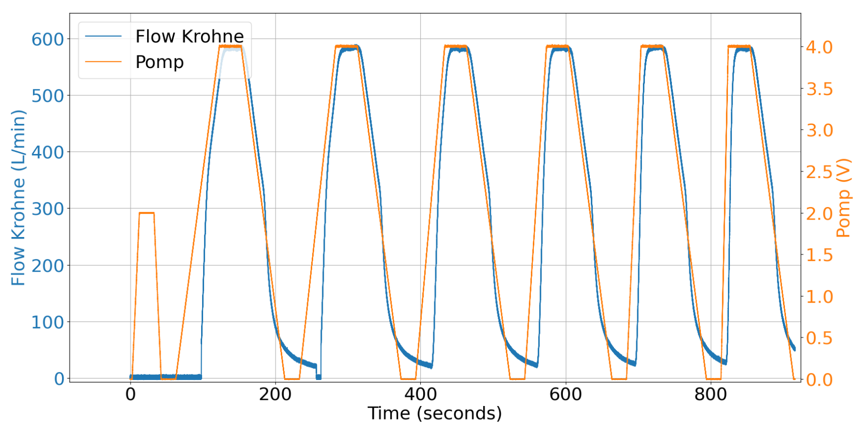


(a) Krohne flowmeter signal (Flow krohne) vs Pump input (Pomp) for the measurement 3V_rampdown_HO_60s

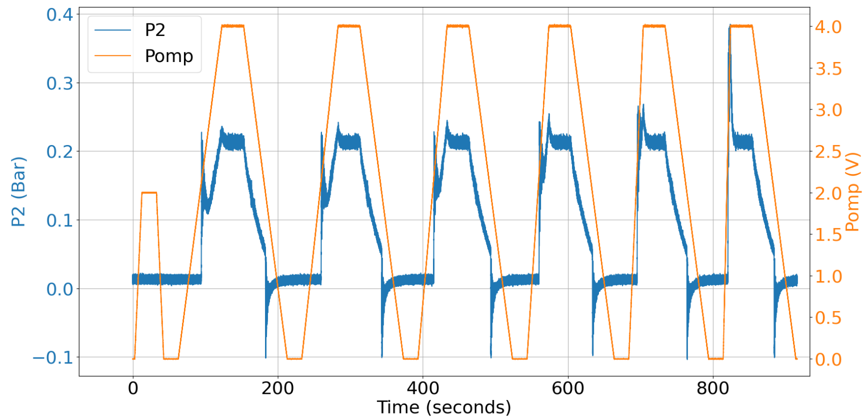


(b) Pressure sensor on top of transparent section (P2) vs Pump input (Pomp) for the measurement 3V_rampdown_HO_60s

Figure 23: Signals recorded in the measurement 3V_rampdown_HO_60s for experimental setup-1

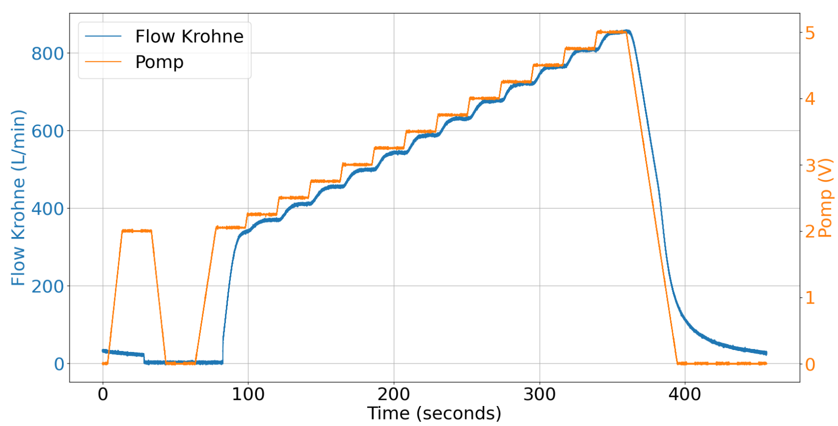


(a) Krohne flowmeter signal (Flow krohne) vs Pump input (Pomp) for the measurement 4V_rampup_HO

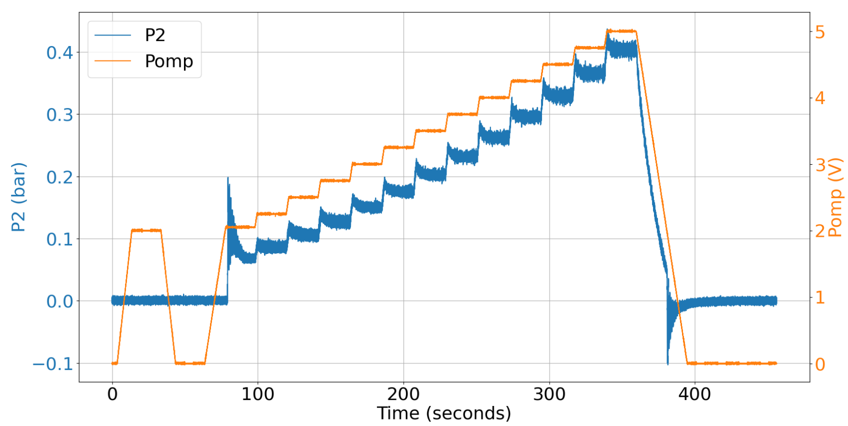


(b) Pressure sensor on top of transparent section (P2) vs Pump input (Pomp) for the measurement 4V_rampup_HO

Figure 24: Signals recorded in the measurement 4V_rampup_HO for experimental setup-1



(a) Krohne flowmeter signal (Flow krohne) vs Pump input (Pomp) for the measurement 2.25-5V_bulkvelocity_FO



(b) Pressure sensor on top of transparent section (P2) vs Pump input (Pomp) for the measurement 2.25-5V_bulkvelocity_FO

Figure 25: Signals recorded in the measurement 2.25-5V_bulkvelocity_FO for experimental setup-1

5.1.2 For experimental setup-2

The corresponding input frequencies to the pump were noted for each bulk flow velocities decided. This is stated in Table 35. A sample measurement for the sensor P4, for the bulk velocity 0.8 m/s with no taps being open is given in Figure 26.

Table 35: Bulk flow velocity Vs input frequency measured in experimental setup-2

Bulk velocity in Beta loop (m/s)	Input frequency (Hz)
0	0
0.8	11.8
1.0	14.6
1.2	17.4
1.4	20.2
1.6	22.9
1.8	25.7
2.0	28.4

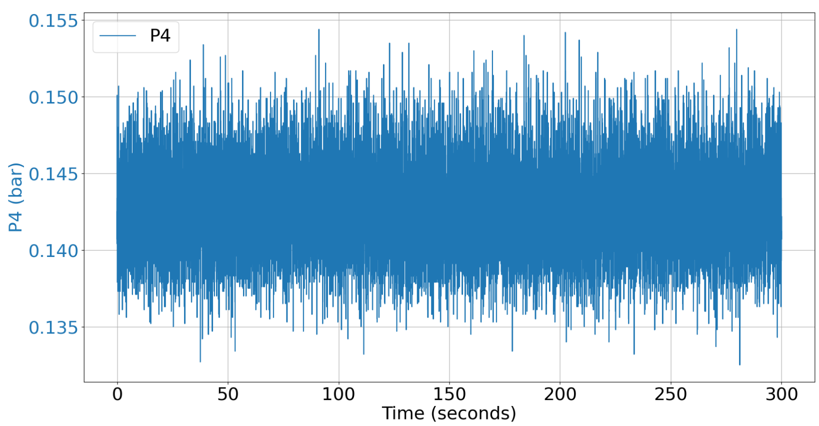


Figure 26: Data of P4 sensor in the measurement W0_L0_F1_C1 for experimental setup-2

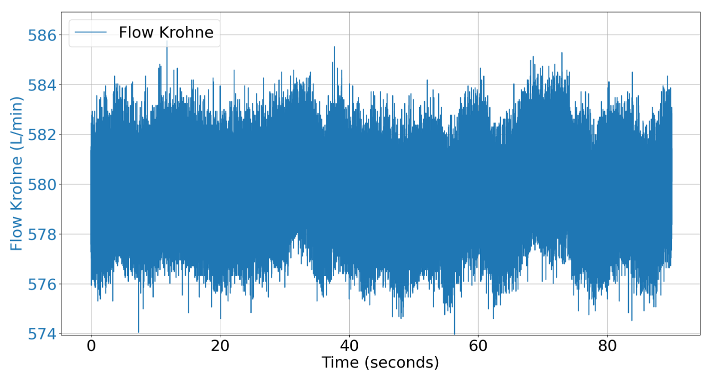
5.2 Friction factor of the Beta loop

5.2.1 For experimental setup-1

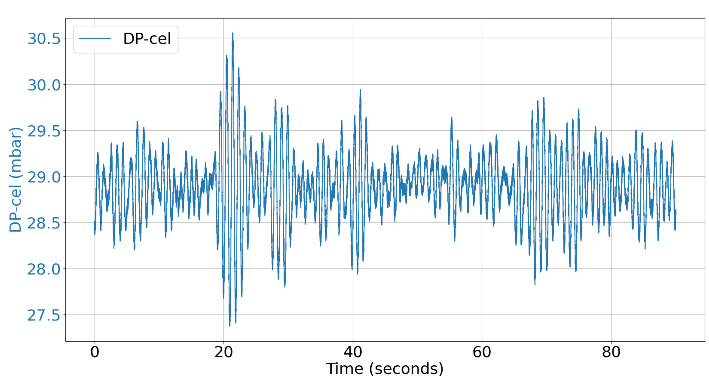
The friction factor for a sample length of the Beta loop was measured only for a condition with fully opened main control valve (MCV). The measurement done at a input pump voltage of 3.5V is represented in Figure 27. As per the measurements and calculations done on the basis of subsection 3.3, we get the following plot in Figure 28. The error factors measured, as per Equation 3 are given in Table 36. The moody plot obtained for a sample length (21.07 m) lies at a relative roughness of 2e-4. This corresponds to a roughness value of 0.02 mm. This is approximately 1.3 times larger roughness than roughness of a new PVC pipe. The increase in roughness measured could also be attributed to the presence of pipe joints, the presence of tap 2 etc. which are present between the terminals of the differential pressure sensor.

Table 36: Error factors in calculation of friction factor for experimental setup-1

	Error(%)
Reynold's number (Re)	5.2
Friction factor	4.3



(a) Krohne flowmeter signal (Flow krohne) signal for the measurement 3.5_ff_FO



(b) Differential pressure sensor (DP-cel) signal for the measurement 3.5_ff_FO

Figure 27: Signals recorded for the measurement 3.5V_ff_FO for experimental setup-1

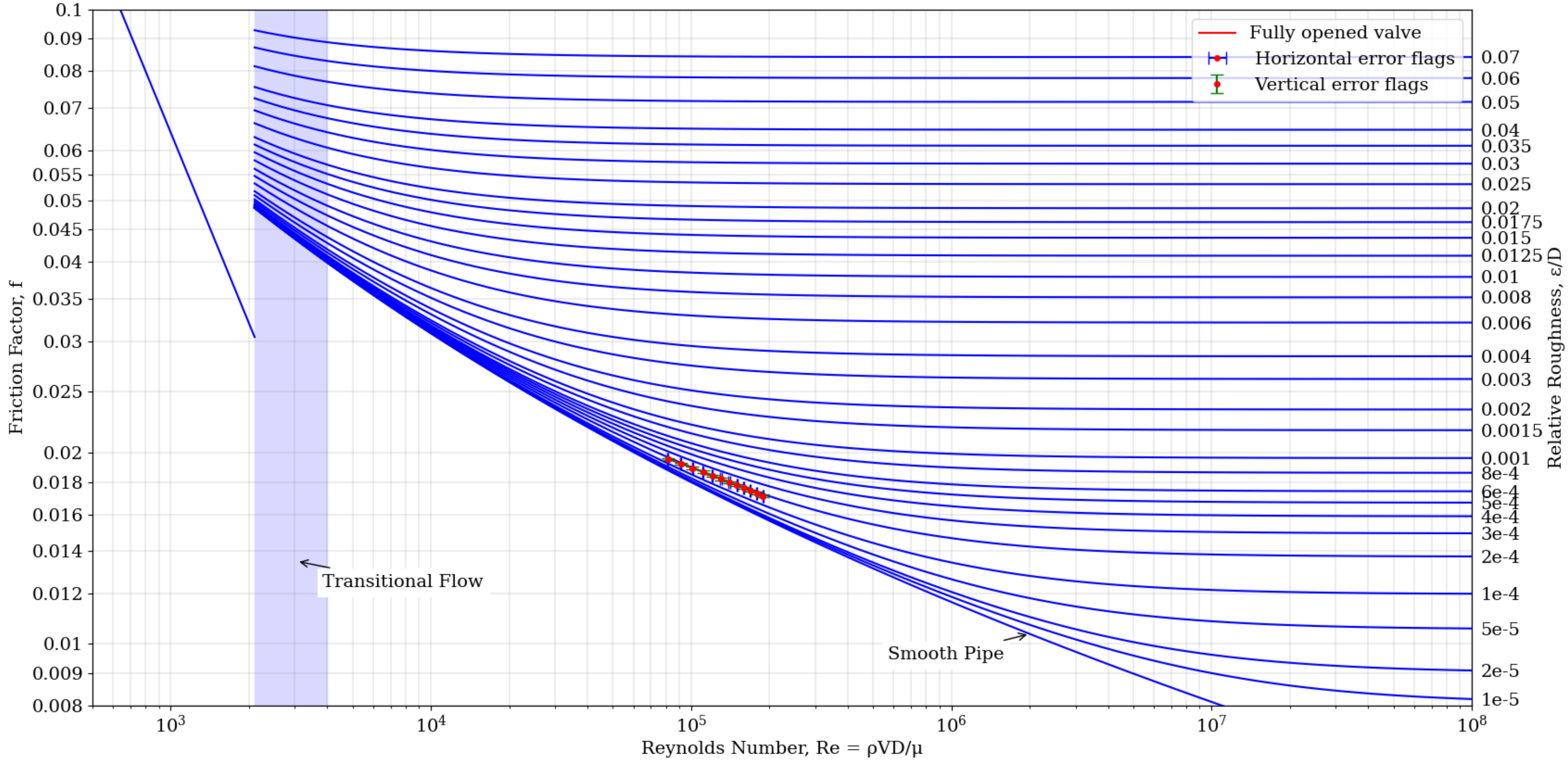
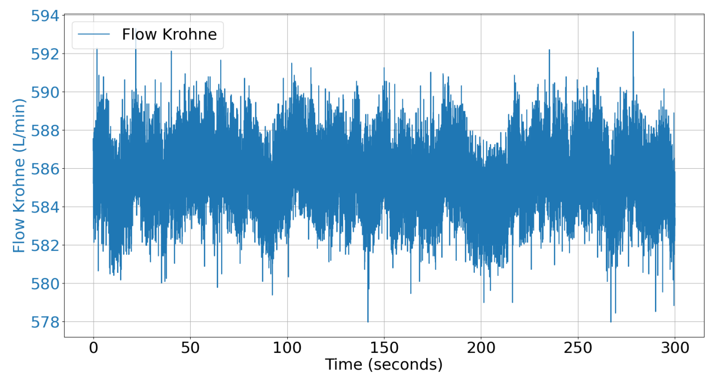


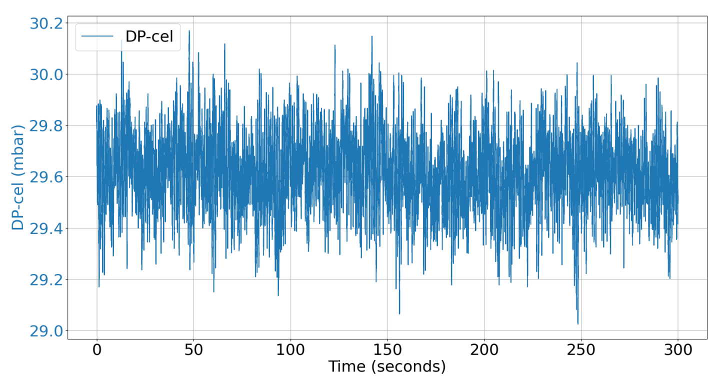
Figure 28: Moody plot with Beta loop friction factors for experimental setup-1

5.2.2 For experimental setup-2

The friction factor measured the experimental setup-2 was plotted against the Reynold's number at which they were measured. This is given in Figure 30. The error factors measured, remains the same as in Table 36. An example of the flow and differential pressure sensor signals considered for the moody plot calculation is given in Figure 29. The moody plot obtained for a sample length (21.07 m) lies between a relative roughness of 1e-4 and 2e-4. This corresponds to a roughness value of 0.01 mm and 0.02 mm. This is approximately 0.6 - 1.3 times larger roughness than roughness of a new PVC pipe. The difference in roughness measured in this measurement matches the results obtained for friction factor of experimental setup-1.



(a) Krohne flowmeter signal (Flow krohne) signal for the measurement W0_L0_F3_C1



(b) Differential pressure sensor (DP-cel) signal for the measurement W0_L0_F3_C1

Figure 29: Signals recorded for the measurement W0_L0_F3_C1 for experimental setup-2

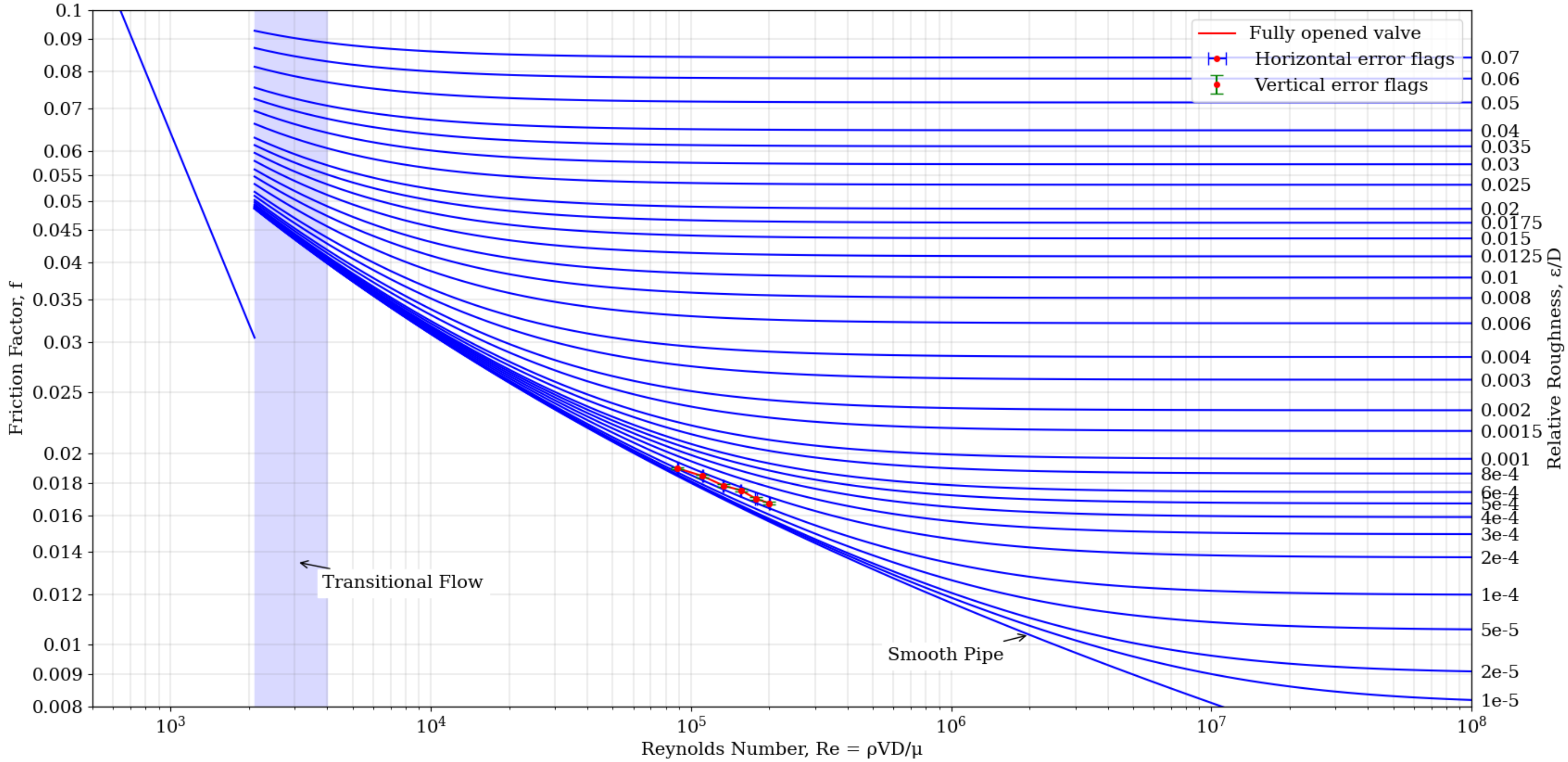


Figure 30: Moody plot with Beta loop friction factors for experimental setup-2

5.3 Tap 2 flow rate per rotation or tap 2 operating profile

The profile of operation of tap 2, measured as per subsection 3.4 is given in Figure 31. Tap 2 operates on a screw-down mechanism, which lifts up a plunger (that usually closes the flow path when fully down), when the cap is revolved to allow flow through the tap. It can be observed that between 2 revolutions and 4 revolutions of the cap of tap 2, the flow rate through the tap increases almost linearly. The flow rate reaches a maximum with 5.5 revolutions at 30 m^3/h. The flow rate increases slightly at 7.5 revolutions to 0.32 m^3/h.

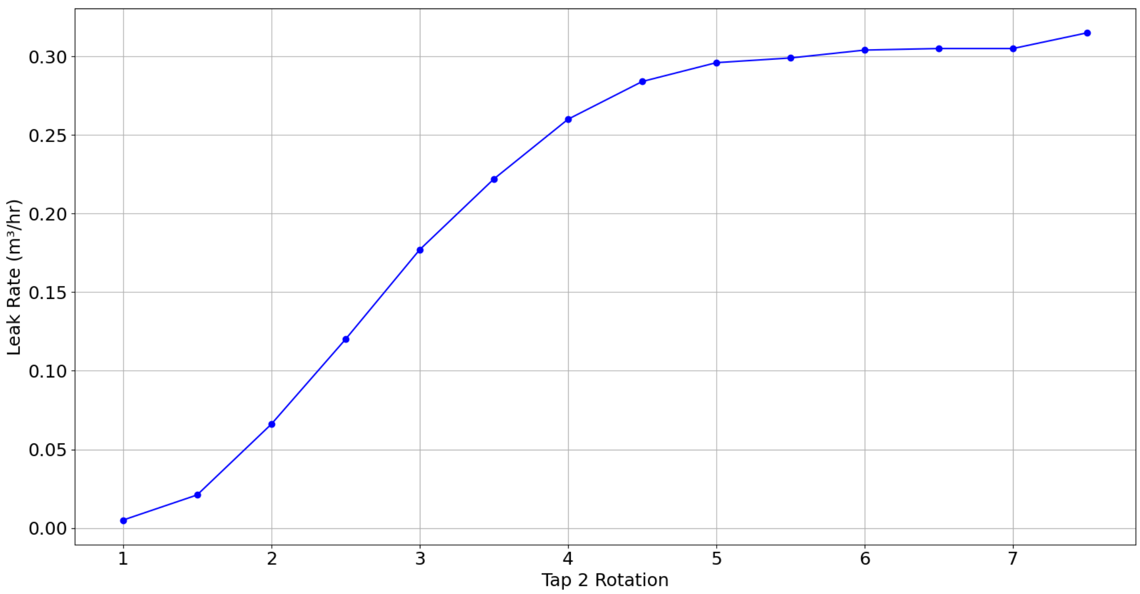


Figure 31: Tap 2 characteristics

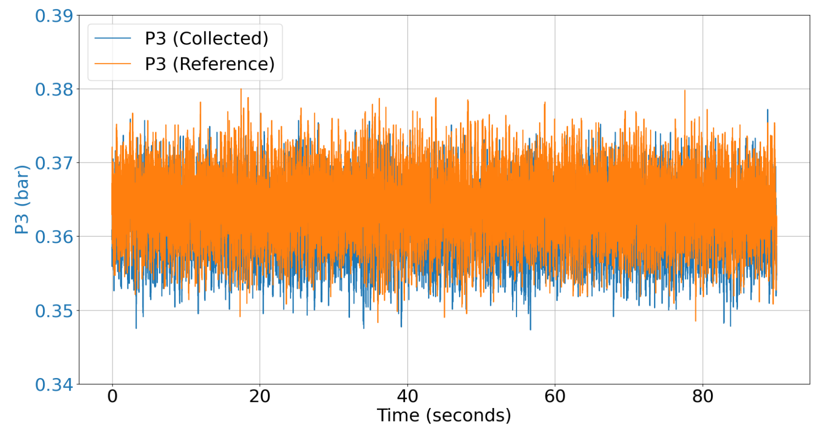
5.4 Leak measurement data

5.4.1 For experimental setup-1

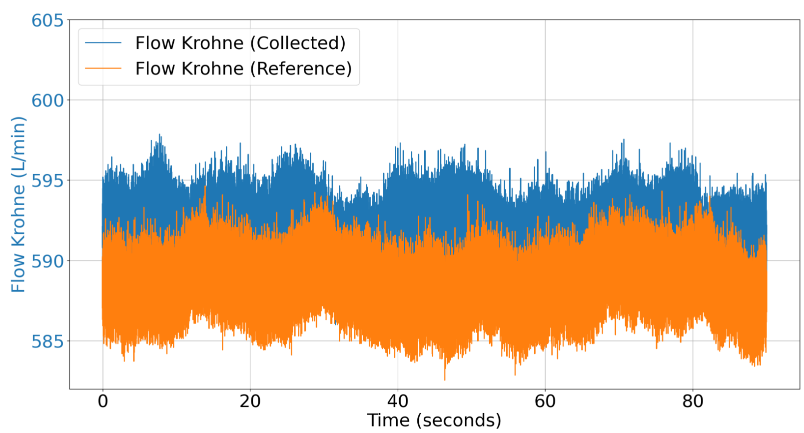
The leak measurement data is measured for the purpose of measuring the impact of the tap 1 and tap 2 individually and collectively. The measurement is done in continuously open tap and impulsively open tap conditions and reference measurements with no leak as mentioned in subsubsection 3.5.1 and for the purpose being used to measure K_v value as mentioned in subsection 3.6. The data measured is represented in Figure 32 for continuously open tap measurements and Figure 33 for impulsively open tap measurements. Both the measurements are compared against a reference condition where no taps are opened. The data measured for the continuously open tap measurements were done for the measurement named "3.5V_L1_FO", where tap 1 is the only tap being opened, with the MCV being under fully open position and the pump is run at a constant voltage of 3.5 V. The data measured for the impulsively open tap measurements were done for the measurement named "3.5V_L1_HO_T3", where tap 1 is the only tap being opened, with the MCV being under half-way open position and the pump is run at a constant voltage of 3.5V. The impulsively open tap measurement is also the third iteration of the same measurement as marked by the suffix "T3".

For the continuously open tap measurements, it can be observed in Figure 32a that the pressure sensor upstream of tap 1 (P3) measures a drop in pressure compared to the corresponding reference (no-leak) condition. Due the presence of the open tap, the flow through the Beta loop is also increased as seen in Figure 32b. The collected discharge is measured using the wave height meter in collecting vessel, which is plotted in Figure 32c.

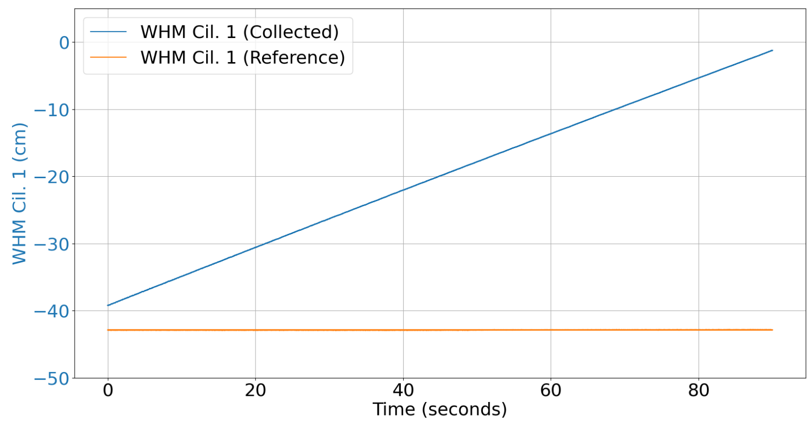
For the impulsively open tap measurements, it can be seen in Figure 33a, that the pressure sensor upstream to tap 1 (P3) produces a sharp depression in the pressure when the tap is opened. The average pressure seems to be slightly lower than the value of the P3 sensor measured for the no-leak condition (reference). There is also a pressure peak that appears on closing the tap, during measurement. Figure 33b shows the increase in flow rate through the Beta loop between the period of the tap 1 being opened and closed, as compared to the no-leak (reference) condition. The wave heght meter also measures the amount of leak collected in the collecting vessel, while the tap is impulsively opened, as shown in Figure 33c.



(a) Pressure sensor upstream of tap 1 (P3): continuously open tap vs no tap opened (reference) condition

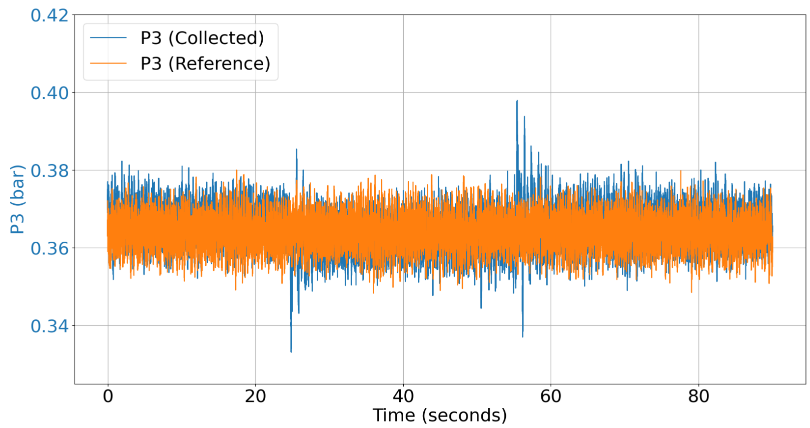


(b) Krohne flow meter: continuously open tap vs no tap opened (reference) condition

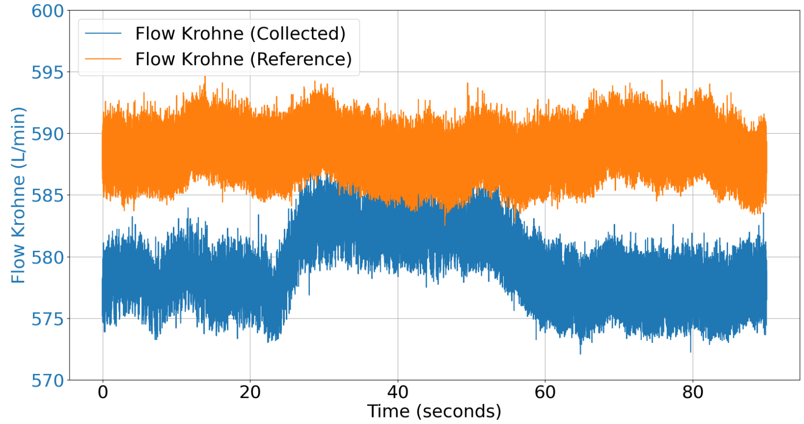


(c) Wave height meter 1 in collecting vessel: continuously open tap vs no tap opened (reference) condition

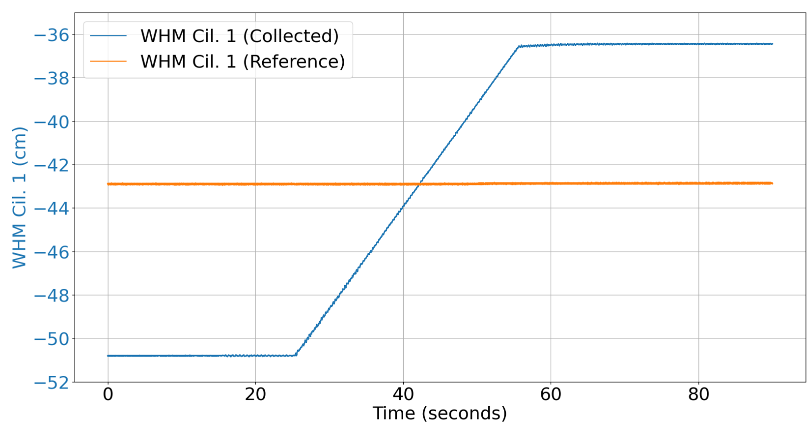
Figure 32: Signals recorded in measurement 3.5V_L1_FO - Continuously open tap measurement for experimental setup-1



(a) Pressure sensor upstream of tap 1 (P3): Impulsively open tap vs no tap opened (reference) condition



(b) Krohne flow meter: Impulsively open tap vs no tap opened (reference) condition

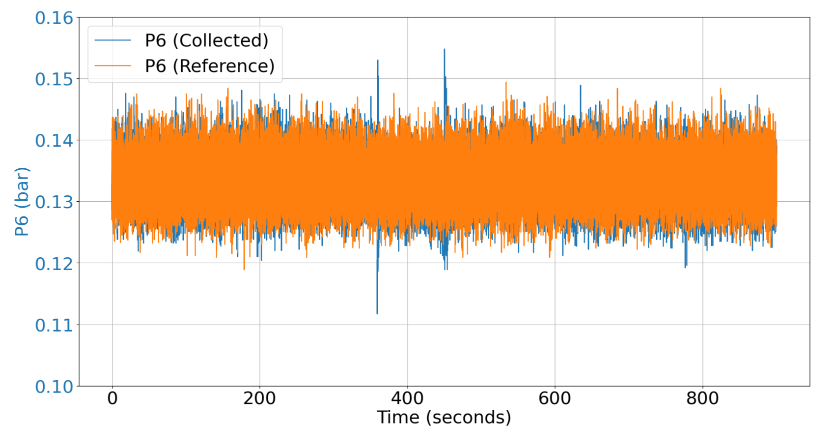


(c) Wave height meter 1 in collecting vessel: Impulsively open tap vs no tap opened (reference) condition

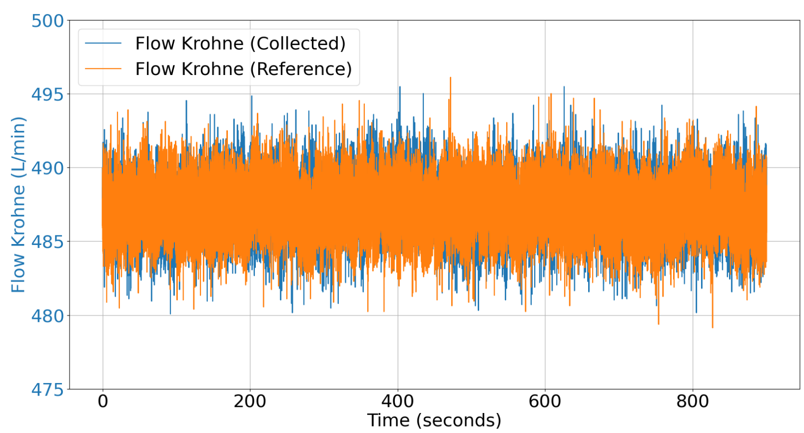
Figure 33: Signals recorded in sample 3.5V_L1_HO_T3 - Impulsively open tap measurement for experimental setup-1

5.4.2 For experimental setup-2

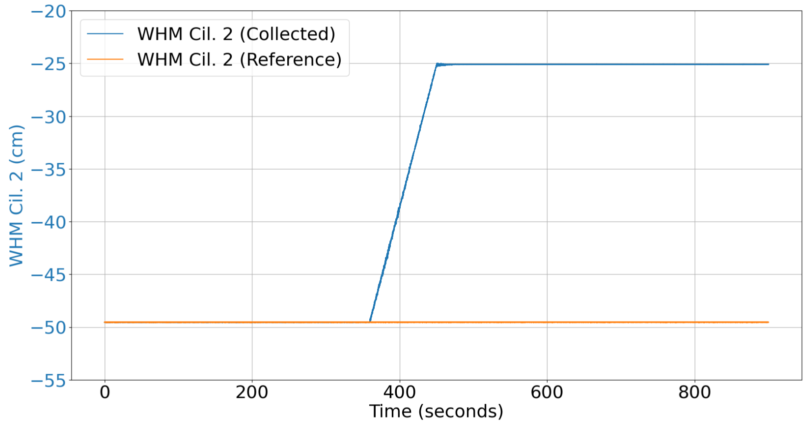
The impulsively open tap leak measurement data for experimental setup-2 was measured using the method stated in subsubsection 3.5.2. These measurements are also used to determine the K_v value of the solenoid + Tap 1 and solenoid + Tap 2 combination. An example of an impulsively open tap measurement, done for Tap 2 at a bulk velocity of 0.8 m/s is represented in Figure 34 (measurement W0_L2_F2_M1). This measurement is compared against a reference measurement at same bulk velocity (measurement W0_L0_F2_M1), where no taps where opened in the same figure. It consists of the pressure sensor data of the down stream pressure sensor to tap 2 (here P6), the flow meter measurement and the wave height meter measurement in collecting vessel gathering the discharge from tap 2. It can be observed in Figure 34a, a pressure pulse is seen on switching on and switching off the solenoid connected to the tap 2. The peaks in pressure are separated by 90 s, same as the duration of the tap 2 being open. The flow meter also registers an increased flow rate during the time when tap 2 is opened, which is seen in Figure 34b. Finally, the amount of leak collected in the collecting vessel during the time when the tap 2 was kept open is seen in Figure 34c.



(a) Pressure sensor upstream of tap 2 (P6): Impulsively open tap vs no tap opened (reference) condition



(b) Krohne flow meter: Impulsively open tap vs no tap opened (reference) condition



(c) Wave height meter21 in collecting vessel: Impulsively open tap vs no tap opened (reference) condition

Figure 34: Signals recorded in sample W0_L2_F2_M1 and W0_L0_F2_M1- Impulsively open tap measurement in experimental setup-2

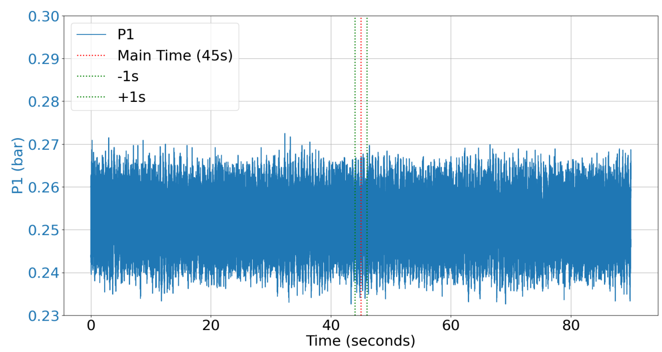
5.5 K_v value of the taps

5.5.1 For experimental setup-1

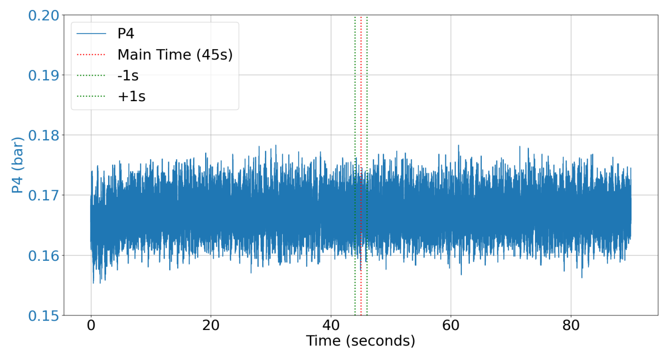
The signals recorded during K_v measurement, as given in subsection 3.6 are represented in Figure 35. Here, Figure 35a, represents an example of the measurement taken for calculation of K_v of tap 1 using pressure measured upstream of tap 1 (P1), where the pump input voltage if 3V , with the MCV fully open. Similarly, Figure 35b represents an example of the measurement taken for calculation of K_v of tap 2 being half-way open, using pressure measured upstream of tap 2 (P4), where the pump input voltage if 2.5V , with the MCV fully open. As per the measurements and calculations done on the basis of subsection 3.6 the K_v of the taps were measured are given in Table 37. The 45th second was chosen for finding the average of parameters required for calculation of K_v, as stated in subsection 3.6, with a span of ±1 s. This is also represented in Figure 35.

Table 37: K_v of taps used in experimental setup-1

	K_v value of tap
Tap 1 (fully open)	0.75
Tap 2 (fully open)	0.76
Tap 2 (half-way open)	0.44



(a) Pressure sensor upstream of tap 1 (P1): average of measurement 3V_L1_FO for Kv calculation of tap 1.



(b) Pressure sensor upstream of tap 2 (P4): average of measurement 2.5V_L2h_FO for Kv calculation of tap 2 (half-way open).

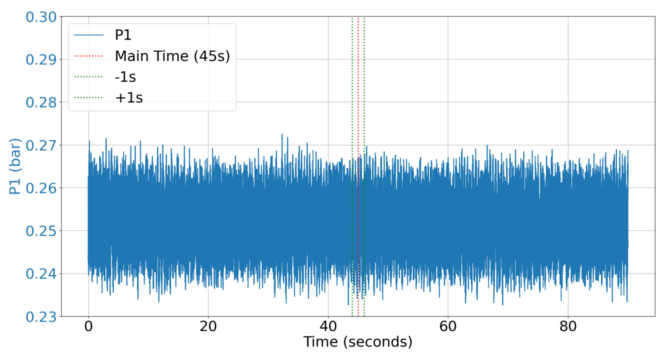
Figure 35: Signals measured for K_v calculation for experimental setup-1

5.5.2 For experimental setup-2

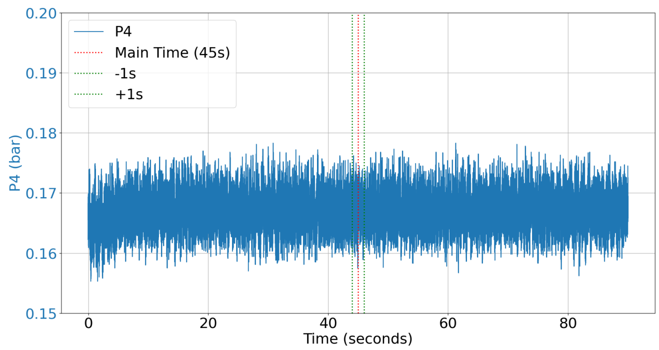
The K_v value of the solenoid+tap setup used in experimental setup-2 were calculated using the measurements done in subsubsection 5.4.2. Here the signals considered are represented in Figure 36. Figure 36a, represents an example of the measurement taken for calculation of K_v of solenoid + tap 1 using pressure measured upstream of tap 1 (P1), where bulk velocity is 0.8 m/s. Similarly, Figure 36b represents an example of the measurement taken for calculation of K_v of solenoid + tap 2 , using pressure measured upstream of tap 2 (P4), where bulk velocity is 0.8 m/s. As per the measurements and calculations done on the basis of subsection 3.6 the K_v of the taps were measured are given in Table 38. The 400th second was chosen for finding the average of parameters required for calculation of K_v, as stated in subsection 3.6, with a span of ± 10 s. This is also represented in Figure 36.

Table 38: K_v of taps used in experimental setup-2

	K_v **value of tap**
Tap 1 (fully open)	0.86
Tap 2 (fully open)	0.0.85



(a) Pressure sensor upstream of tap 1 (P1): average of measurement W0_L1_F1_M1 for Kv calculation of solenoid + tap 1 of experimental setup-2



(b) Pressure sensor upstream of tap 2 (P4): average of measurement W0_L2_F1_M1 for Kv calculation of solenoid + tap 2 of experimental setup-2.

Figure 36: Signals measured for K_v calculation for experimental setup-2

6 Verification of data by WANDA

WANDA is a 1D simulation software, developed in Deltares, which is used in hydraulic design, control and optimization of pipeline systems. It is use to analyze changes of parameters in a 1D pipeline system, which include the steady state characteristics of the system as well as the dynamic and multi-phase (transient) behaviour of different media. WANDA can be used extensively during the lifetime of a pipeline system, starting from its initial design, component optimization, control procedure evaluation, till commissioning and operator training.

6.1 For experimental setup-1

The data collected from the measurements done on the experimental setup-1 was decided to be compared with simulation results from WANDA to understand the gaps of data obtained. For this, a 1D simplification of the Beta loop was created in 3 parts.

1. Part 1: has Beta loop with no leaks introduced.
2. Part 2: has Beta loop with leak/tap 1 introduced to the model.
3. Part 3: has Beta loop with leak/tap 2 introduced to the model.

6.1.1 WANDA model created and components used

The WANDA model used were created as a one dimensional simplification of the actual Beta loop. A schematic representation of the WANDA model created for a Beta loop with no leaks, is shown in Figure 37. The components used in the model are defined in Table 39.

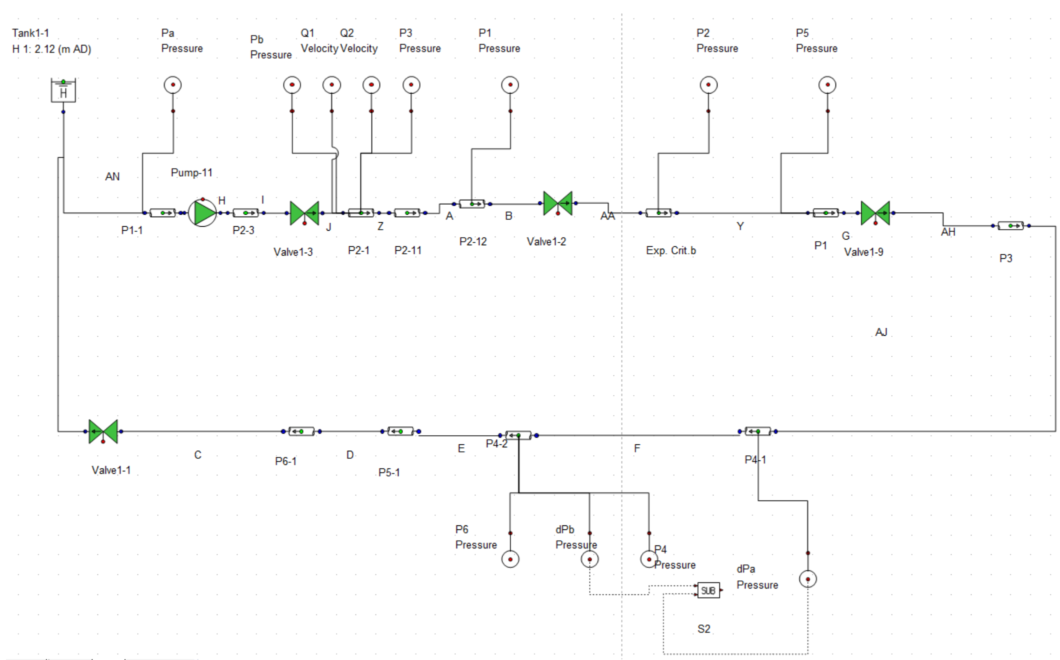
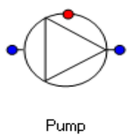
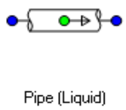
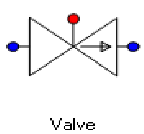
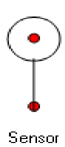
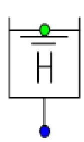


Figure 37: WANDA model created for Beta loop: with no leaks

Table 39: Components used in WANDA model

Symbol of components used	Name of components	Component detail
	Centrifugal Pump	Defined by • QHE table (Flow-head-efficiency table) • Initial discharge (Q) • Rated speed (rpm) • Polar moment of inertia (m^3/h)
	Pipe	PVC pipe to carry liquids, defined by • Cross section (circle) • Calculation mode (Rigid column) • Diameter (D) • Friction model and wall roughness used • Additional losses (Xi) • Geometry profile (length vs height)
	Valve/tap	Defined by • Characteristic (Standard) • Standard type (Butterfly) • Inner diameter (D) • Initial setting (position) • Initial position (100%)
	Sensor	Defined by • Type (Sensor) • Quantity (Pressure, velocity) • Meas location (Location along pipe)
	Reservoir with limited area	Used to define the tank and collecting vessel, • Area type (constant) • Area (m^2) • Head (m)

The models used were created by including the roughness of the pipes obtained through the moody plot measurement done initially, including loss coefficients due to bends in pipes, presence of valves etc. Figure 38 and Figure 39, represents the WANDA model with tap 1 and tap 2 attached to it respectively.

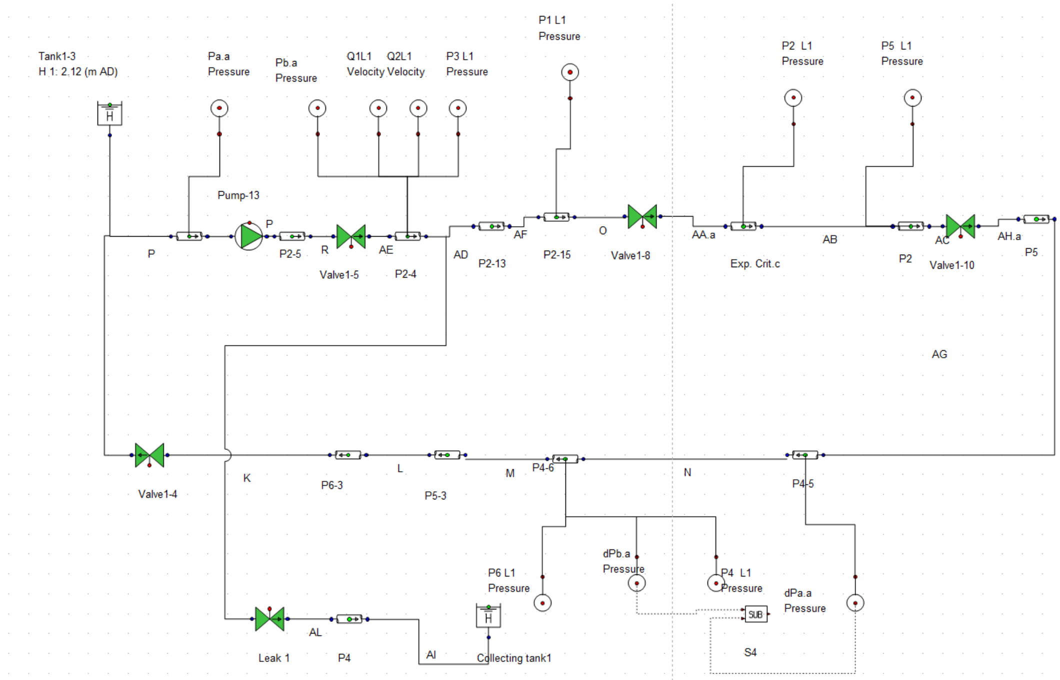


Figure 38: WANDA model created for Beta loop: with tap 1

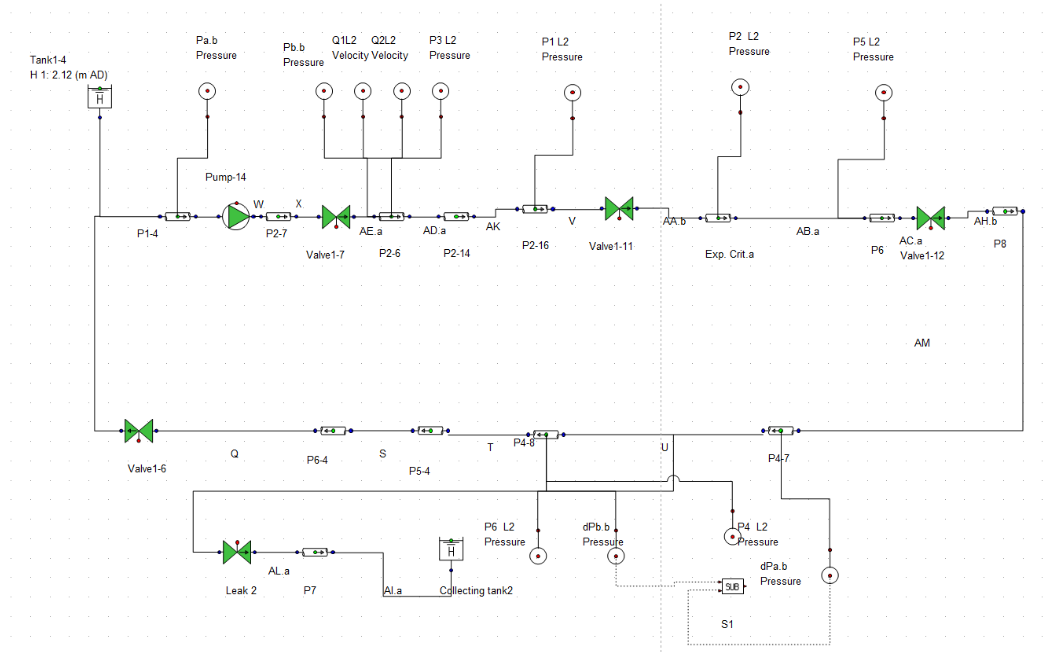


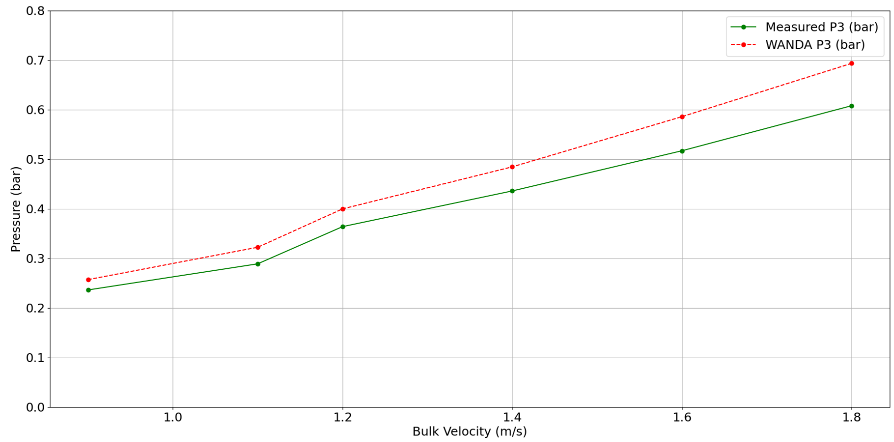
Figure 39: WANDA model created for Beta loop: with tap 2

6.1.2 Method of running simulation and comparison with measured data

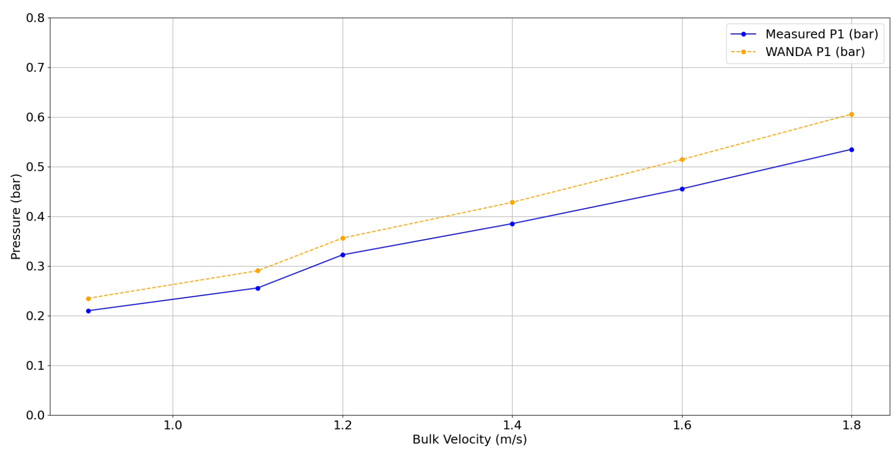
The simulations were run in the steady-state mode. This was done to avoid the impact of the slight non-linear height increase registered in the wave height meter, collecting the discharge rate from the leaks. A blue tube as mentioned in subsection 2.3, was provided to avoid any splashing. Consequently, the presence of a rising water column at the exit of this hose (in the collecting tank) ensured a counter pressure to be formed. This rate of pressure increase from this water column impacted the leak outflow rate.

For the sake of comparison to a steady state simulation, a random point in time was selected in the 90 s recording time of the continuously open tap measurements, and small sample size of 1 s forwards and backwards in time were selected to average the values of sensor readings to model a steady state situation. This method is the same as what was done in subsection 5.5. These averaged sensor readings, were used for the static components like water level in the tank upstream, the water column level in the collecting vessel and the pump discharge rate, in the WANDA model to resemble the actual measuring conditions during this steady state simulation.

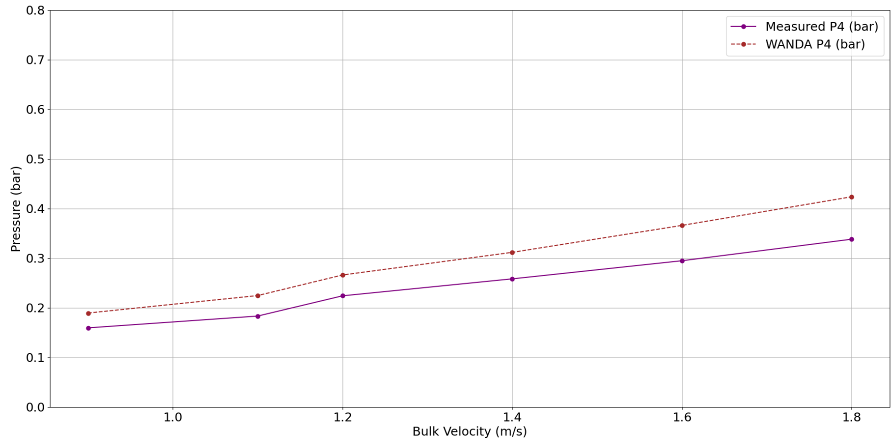
The main points of interest on the comparison of the actual measurement data and simulated data was the pressure drop across the tap and leak discharge rate. Initially the pressure drop measurements were compared between the reference data (no leak condition) for all Reynold's number regimes, which is given as in Figure 40. Then, pressure drop and leak discharge rate measurements for leak 1 and leak 2 were compared separately as represented in Figure 41 and Figure 42. It is to be noted that the comparison were done only for fully opened leak/tap conditions for both cases.



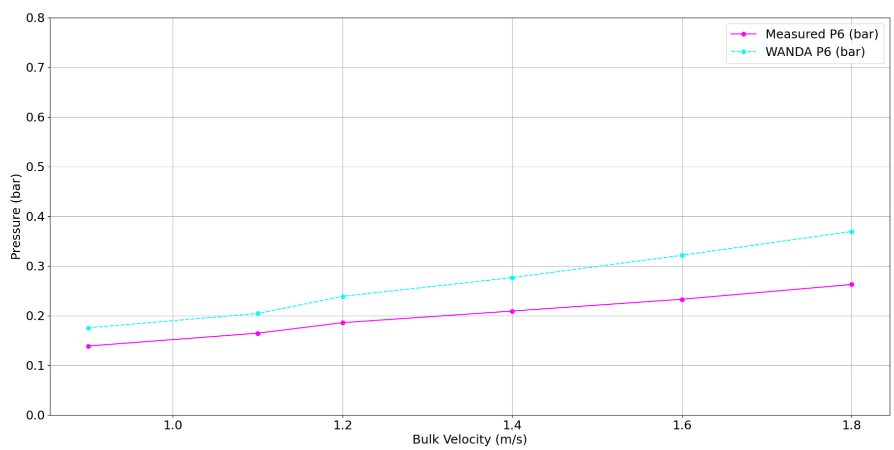
(a) Measured data Vs WANDA simulation result of pressure at sensor P3 when no taps are opened



(b) Measured data Vs WANDA simulation result of pressure at sensor P1 when no taps are opened

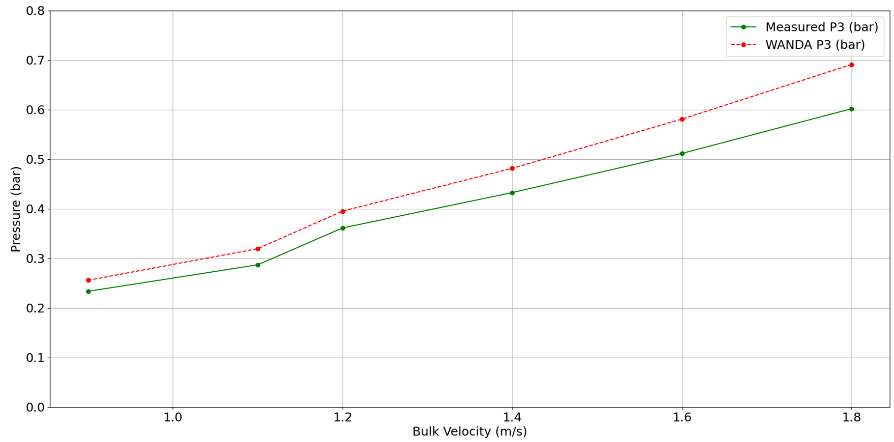


(c) Measured data Vs WANDA simulation result of pressure at sensor P4 when no taps are opened

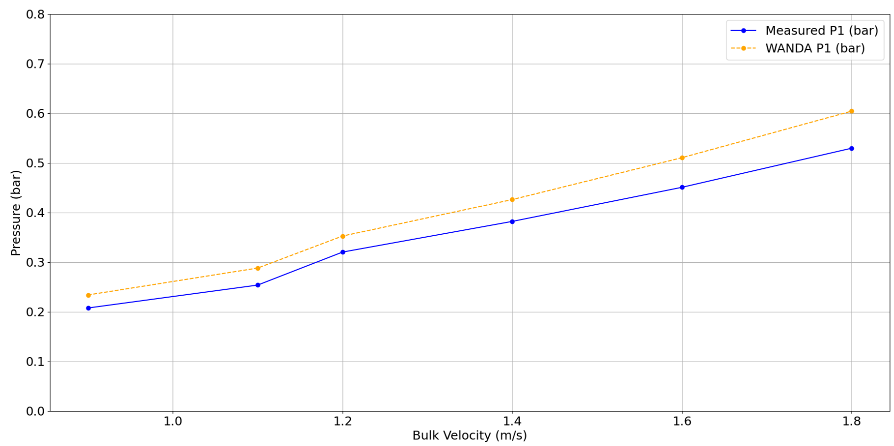


(d) Measured data Vs WANDA simulation result of pressure at sensor P6 when no taps are opened

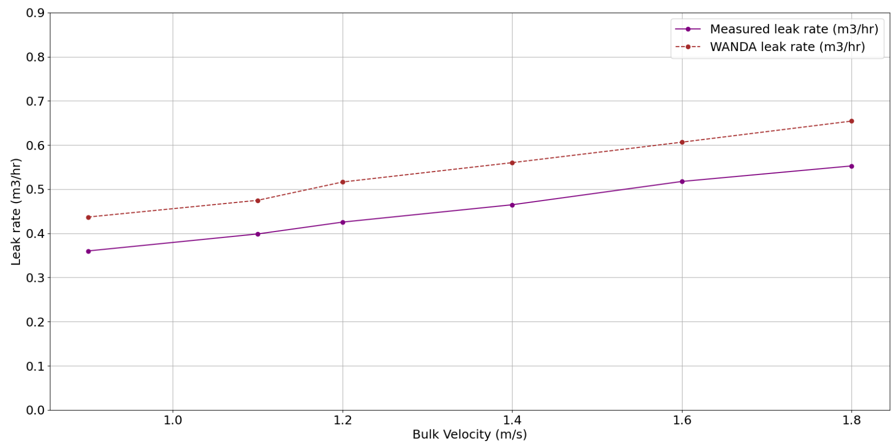
Figure 40: Measured data VS WANDA simulation result for no taps opened



(a) Measured data Vs WANDA simulation result of pressure at sensor P3 when Tap 1 is opened

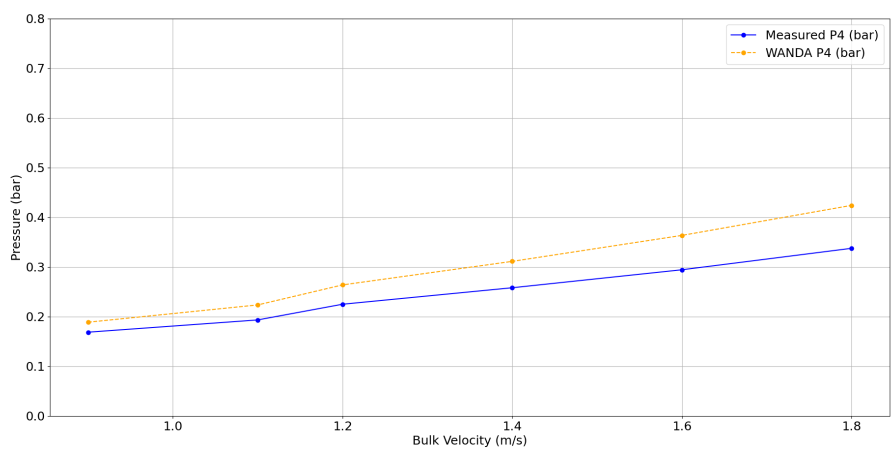


(b) Measured data Vs WANDA simulation result of pressure at sensor P1 when Tap 1 is opened

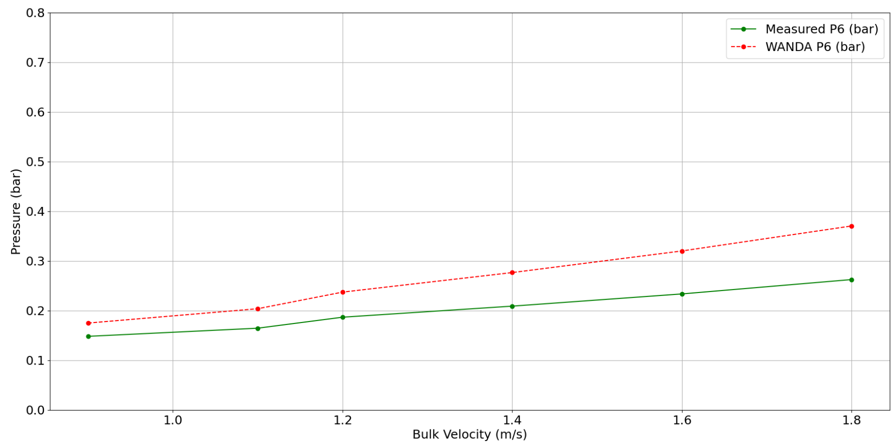


(c) Measured data Vs WANDA simulation result of discharge through the tap 1

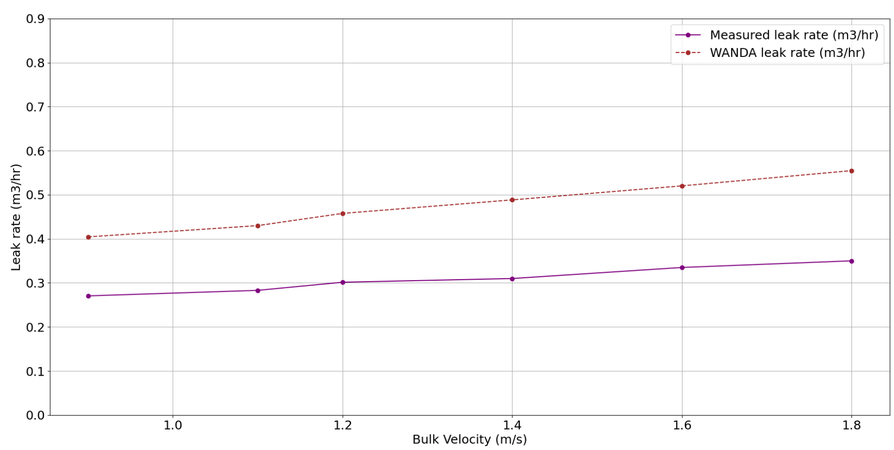
Figure 41: Measured data VS WANDA simulation result for only Tap 1



(a) Measured data Vs WANDA simulation result of pressure at sensor P4 when Tap 2 is opened



(b) Measured data Vs WANDA simulation result of pressure at sensor P6 when Tap 2 is opened



(c) Measured data Vs WANDA simulation result of discharge through the tap 2

Figure 42: Measured data VS WANDA simulation result for only Tap 2

6.1.3 Results and observations

There appears to be a diverging offset between the measured values and the WANDA results obtained for the reference as well as the tap 1 and tap 2 opened cases. The deviation between the measured data and the results from WANDA lie between the range of 8%-26% for the pressure sensors considered for reference as well as open tap measurements. The leak rate comparison shows a larger deviation. The leak rate of tap 1 shows a deviation between 18%-21%, while that of tap 2 shows a deviation between 41%-58%. These deviations could be due to the following factors:

1. Deviation between losses entered into the WANDA model and actual losses posed by the components in the experimental setup-2.
2. Error in the K_v value calculated and entered in the WANDA model.

7 Conclusions, learning's and recommendations

7.1 Conclusions

1. The components and features (Operating range, friction factor, K_v of taps) of experimental setup-1 and experimental setup-2 of the Beta loop were studied.
2. The leak measurements with continuously open and impulsively open taps were done and the data was stored in different formats for experimental setup-1.
3. The leak measurements with impulsively open taps were done and the data was stored in different formats for experimental setup-2.
4. The impact of leaks being spontaneously created and those leaks which were already existing were compared to a no-leak flow conditions and the difference between them were studied.
5. The measurements done in experimental setup-1 to define features of the components of the Beta loop were used to build a WANDA model. The results obtained from the continuously open tap measurements and reference measurements were compared with results from the WANDA model.

7.2 Learning's

Through this internship at Deltares, I was able to experience working in a research institute and gain a good understanding on the scientific research done in the field of hydraulic systems. I was able to understand the impact of leaks on hydraulic pipe lines and the negative impact they pose to the economy and society.

I was also fortunate to participate (although for a brief period of 3 months) in the research done on leak detection. Through this, I was able to understand on how leaks in a pipe system of large scale could be scaled down to an experimental setup and how the presence of a leak affects flow parameters like pressure and flow velocity in the pipeline. The impact of the size of the leak and the nature of the leak (spontaneously occurring or pre-existing) were also studied.

This internship also gave a good understanding on how to design and conduct experiments, and to collect data to be further analyzed according to the problem being investigated. This includes on analysis of the setup, detailed investigation into the components used and their properties (which includes various sensors) and proper measurement techniques. I also gained insight into methods for determining the duration of data collected along with acquisition rates chosen. Finally, I learned proper data measurement, naming conventions and storage to create a FAIR data set.

Over the span of 3 months working as an intern at Deltares, I was also able to take part in various knowledge sharing sessions, which introduced me to various topics being currently researched, both experimentally and numerically. This improved my current theoretical and practical knowledge. This includes introduction to measurement software like Delft measure and numerical simulation tools like WANDA.

7.3 Recommendations

1. The WANDA model needs to be better calibrated to identify the current gap between it and the experimental setup.
2. Impact of multiple leaks at varying elevations could be studied in a future iteration of the Beta loop setup.
3. The addition of a flow meter on the return line of the Beta loop after the taps, could give a better look into the impact of the leaks on the bulk flow.

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8 Annexure

8.1 Alternate method for K_v measurement

In this method, the leaks are collected into an open collecting vessel, ensuring the exit pressure at the taps being atmospheric, instead of having the impact of the height of the water column collected on top of the blue tube trailing from the exit of the taps to the bottom of the collecting vessel. The leak rates were measured based on the height of water collected in the collecting vessel at the end of each trial, without the use of wave height meters installed in the collecting tanks, and was done visually using a standard meter tape.

Step 1: The operating voltage of the pump was fixed at a constant value, while the main control valve (MCV), between the operating range of 3 - 5 V to get the corresponding Reynold's number regimes as mentioned in Table 34, with an intial value of 3 V to get a corresponding Reynold's number of 11.4 $\times 10^4$. The operating range voltage was controlled by the pump control GUI, where the voltage starts from 0 V, remains there for 2 s , and rises to the corresponding voltage at a rate of 7 s/V. The required voltage is held constant for 100 s and is ramped down to 0 V at the same rate of 7 s/V.

Step 2: The data is recorded at a 1000 Hz, where the main parameters of interest recorded were the absolute pressure sensor readings across the tap 1 (P3 and P1 in Figure 1) and tap 2 (P4 and P6 in Figure 1).

Step 3: The taps are opened once the steady voltage range has been achieved, for a period of 30 s. Once the 30 s marks are reached, the taps are turned off and the amount of water in the collecting vessel were measured to measure the flow rate through the tap in m^3/hr i.e. Q'. The values of P3, P1, P4, P6 as well as the flow rate, were all averaged over a period of 30s.

Step 4: The above steps were repeated for the same voltage 2 more times (a total of 3 measurements per voltage chosen). The pressure on the supply side of the taps were then found using (2), by interpolating from the value of P3 for tap 1 and P4 for tap 2. Using the exit pressure condition as atmospheric pressure (outside the tap), ΔP is calculated as the difference .

Step 5: Steps 1-4 are repeated, by increasing the voltage by a step of 1 V.

Step 6: The average K_v value for each tap was calculated as an average obtained for 3, 4 and 5 V.

8.2 File nomenclature used for method 1 of K_v measurement

The data is recorded with a sample length of 147 s, 161 s and 175 s, which corresponds to the operating voltage 3 V, 4 V and 5 V respectively of the pump, as mentioned in **??**, at 1000 Hz. The following nomenclature was used in naming the trials.

Table 40: File naming convention for method 1 of K_v measurement

File format	`[voltage chosen]_[KvTap#]_[FO]_[Measurement#]`
Voltage chosen	3V, 4V or 5V
KvTap#	KvTap1/KvTap2
MCV position	FO
Measurement#	M1, M2 or M3
eg	`3V_KvTap1_FO_M2`
	`5V_KvTap2_FO_M1`

Here the data is recorded in the format which starts with the bulk velocities in the Beta loop are represented by the values of the corresponding voltages used to control the pump, as shown in Table 34. These could be 3V, 4V or 5V as mentioned in subsection 8.1. This is then followed by an indicator which indicates which tap is under consideration for measurement by the KvTap#, which could be Tap 1 or Tap 2 indicated as KvTap1 and KvTap2 respectively. The file name then has a part which indicates the MCV position used during measurement, which is FO (fully open). The nomenclature concludes with the trial number of the measurement done for each voltage (which is 3 as mentioned in subsection 8.1), which could be M1, M2 or M3 indicating measurement 1, measurement 2 and measurement 3 respectively.

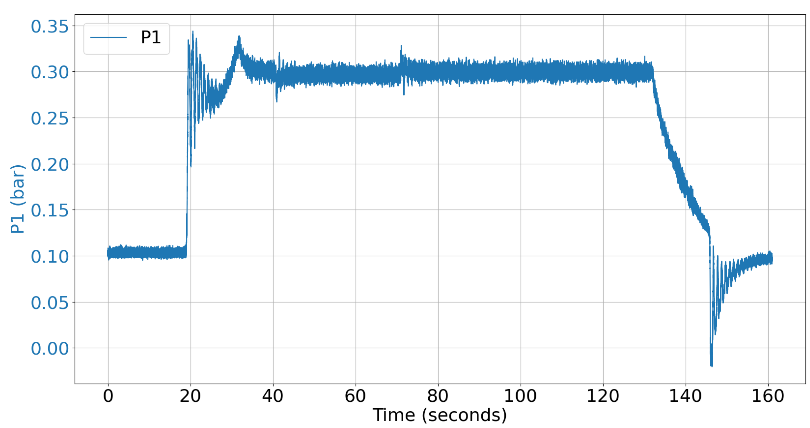
8.3 K_v value measured using alternate method

The signals measured during the alternate K_v measurement is shown in Figure 43. After the rampup ends, the steady voltage input in the signals can be seen in the signals measured as regions of almost steady values. In this region of steady signal, the initial and final pressure pulse of opening and closing the taps can be observed in the signal across a time span of 30s. The positions of the pressure peaks are noted and the pressure sensor value of P1 and P4 are averaged between the pressure pulse positions for K_v measurements done for Tap 1 and Tap 2 respectively. As per the measurements and calculations done on the basis of subsection 3.6 the K_v of the taps were measured are given in Table 41.

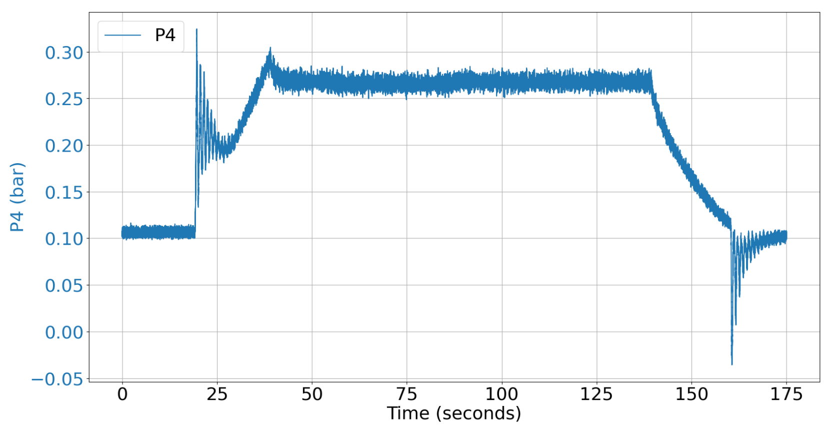
The K_v values measured using the alternate method is not accurate due to visual measurement method of the discharge through the taps in the collecting vessels as well as due to the presence of splashing of water discharged from the tap, while collected into the collecting vessel. The alternate method also has varying signal lengths and the pressure pulse positions were observed manually too.

Table 41: K_v of taps measured in using alternate method

	K_v **value of tap**
Tap 1 (fully open)	0.76
Tap 2 (fully open)	0.72



(a) Pressure sensor upstream of tap 1 (P1): average of measurement 4V_Kvtap1_FO_M2 for Kv calculation of tap 1.



(b) Pressure sensor upstream of tap 2 (P4): average of measurement 5V_Kvtap2_FO_M3 for Kv calculation of tap 2 (fully open).

Figure 43: Signals measured for alternate method of K_v calculation