Experimental investigation of valve driven transient effect in liquid nitrogen pipeline

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Abstract. Liquefied cryogenic fluids like Liquid oxygen, nitrogen, and hydrogen have various industrial applications. The cryogenic fluid transfer lines are generally fitted with valves to regulate, and control flow. The sudden operations of these valves lead to transient effects characterized by pressure fluctuations. The severity of pressure oscillations depends on various parameters including the valve parameters and the fluid properties. The fluid properties of cryogenic fluid in turn vary rapidly during such valve transients. In this work, a Cryogenic test facility is developed to investigate the valve-driven transients in a liquid nitrogen pipeline. The effect of the transient in the system is evaluated for two different cases of tank pressure and flow rate. The behavior of the transient is detected with the help of dynamic pressure sensors and RTD sensors. Further, the results are interpreted to understand the effect of the transient in the cryogenic fluid transfer system.

1. Introduction

Cryogenic Fluid Transfer system is one of the major subsystems of cryogenic installations which focuses on directing and controlling the flow for efficient transfer [1]. The system transfers cryogens from storage units to meet the demand of various applications like space transportations, industrial supply lines, production plants, etc [2]. Fluid transfer systems are generally liable to different transient effects, which causes the fluid properties to vary unconditionally over time and affect the performance and reliability of the overall system. Transient effects are instigated mainly by the sudden valve operations, starting and shutting off pumps, a sudden change in pump rotational speed, the presence of non-condensable gases, phase change, the switchover of flow from one element to another, sudden shut down of valves or motor due to power failure, etc.

In this work, the transient effects occurring due to the valve operation are considered, since the fluid transfer systems are generally equipped with valves to control, adjust and regulate the flow and pressure. Furthermore, cryogenic systems use pressure relief valves and safety valves like vapor vents to eliminate excess pressure in the system. In certain circumstances, these valves are operated very frequently or suddenly creating sudden flow restrictions in the pipeline, which increases the fluid pressure and results in pressure wave formation. The operation of these valves may happen in a very short time but the effect produced in the system sustains for a long time.

Different designs and types of valves are being developed to meet specific requirements and minimize the transient effect created due to valve operation [3]. But the effect of transients produced in cryogenic systems is quite difficult to understand due to the distinctive behavior of cryogenic fluids.
The interaction of fluid transient pulse with vapor bubbles present in the pipeline is experimentally investigated by Alexander et al [4]. The pressure wave generated by rapid opening and closing of solenoid valve and the transmission of the pressure wave with and without vapor bubbles is investigated. The results show that the peak pressure is smaller when vapor bubbles are present. This work suggests that a controlled test facility is required to distinguish the effect of vapor bubbles on fluid transients.

Lema [5] and Gouriet et al [6] performed experiments in non-cryogenic fluids like water, ethanol, and acetaldehyde to understand the multiphase physics occurring during the operation of Fast-Opening Valve in the system. The multiphase behavior during the transient is explained with the help of unsteady pressure and temperature measurements along with flow visualizations. The effect of fluid property on the pressure rise of three different fluids is explained using the Joukowsky equation [7]. A new experimental facility was also developed for investigating fluid hammer in Liquid Nitrogen (LN$_2$) system which was placed inside the vacuum chamber to control the heat–in-leak from outside. Different tests were performed in the LN$_2$ facility [8] by varying line pressure and reservoir temperature. The obtained results concluded that the high vaporization of the liquid phase drives the fluid transient. The results were also compared with the non-cryogenic fluids and it was concluded that LN$_2$ has faster attenuation than non-cryogenic fluids due to the presence of vapor.

Peveroni et al [9] performed experiments in a LN$_2$ facility to predict the transients during valve closure in different regimes of single-phase flow, cavitation, and flashing regimes. The measurements of pressure and flow rate along with flow visualization are used to interpret the behavior of the system during transients.

Atwell et al [10] performed fluid transient experiments in a reaction control system with liquid oxygen and liquid methane propellants. The important findings explain that in the cryogenic system, multiphase front advances during fluid transient towards the dead end. The pressure transients in the cryogenic system can easily lead to cavitation and column separation which even increases if heat transfer exists from surroundings. Further, the predicted peak pressure was higher during valve opening than valve closing and higher in subcooled liquid than two-phase flow.

In literature experiments to predict the transient effects in two-phase water pipelines are abundantly reported. The results with water cannot be directly implemented for cryogenic fluids due to the difference in the behavior of cryogenic fluid at similar conditions. The experimentation with cryogenic fluid is quite complex due to the additional cost requirements and risk factors. Few literature explaining the transient effect in the cryogenic fluid are addressed. However, more detailed experimental results are required to understand the effects of valve-driven transients in cryogenic transfer lines which has potential applications in various fields. The objective of this paper is to develop a cryogenic test facility suitable for capturing the valve driven transients. Further to investigate the effect of transient occurring in LN$_2$ transfer lines due to sudden valve opening and closing.

2. Experimental setup
A Cryogenic experimental facility with a simple tank – pipe and control valve configuration and measuring instruments is developed as shown in figure 1. Liquid nitrogen is selected as the working fluid as it is easily available and involves low hazards. Also, its behavior during transient can be easily applied to some of the other cryogenic fluids.

2.1. Setup
A double-walled vacuum insulated self-pressurizing tank of capacity 220 litres and vertical orientation is used for storing the LN$_2$. Self-pressurizing tank is used to maintain the tank pressure to a constant value with pressure build-up system [11]. The tank pressure is monitored using a pressure gauge mounted on it. The liquid withdrawal line of the tank is connected to the main pipeline using a stainless steel corrugated pipe. The flexible transfer line minimizes the amplitude of transient pressure than rigid pipe [12] hence flexible pipe is used near the tank to reduce the possibility of transient affecting the tank. The flexible line is followed by a vacuum insulated pipe of 15 mm diameter.
The pipeline consists of various measuring instruments installed in between the system as mentioned in table 1. The RTD and piezoelectric sensors are placed before and after the Control valve since the impact of valve-driven transient is more prominent at this location.

Table 1. Distance of different components of the experimental setup from the tank.

| Distance from tank                     | Value (m) |
|----------------------------------------|-----------|
| Coriolis Mass flowmeter                | 6.5       |
| Piezoelectric and RTD sensor 1         | 8.1       |
| Control valve                          | 8.4       |
| Piezoelectric and RTD sensor 2         | 9.2       |
| Exit                                   | 11.5      |

A normally open globe control valve with spring and diaphragm type actuator and equal percentage characteristic is used with flow coefficient of 13.2 USGPM/sqrt.(psi). Equal percentage characteristic minimizes the pressure amplitude during transient effect than linear and quick opening valve characteristic [13]. The operations of the control valve are activated by a smart electro – pneumatic positioner which is supplied with compressed air and a current signal of 4-20 mA. A value of 4 mA causes the valve to OPEN, whereas 20 mA causes the valve to reach CLOSE position. The various pipe connections in the setup are provided with foam insulation and the exit is open to a collecting Dewar.

2.2. Measuring instruments

The major challenge of any experimental test facility requires proper selection and installation of the measuring instruments. In this setup, the flow rate is measured using the Coriolis mass flowmeter which works on the principle of Coriolis force. When fluid passes through the tubes of the flowmeter, the tube vibrates and results in phase shift or twist which is measured with the help of sensors attached to tube.

The RTD sensor produces a change in resistance corresponding to the temperature change of the fluid. A constant current is supplied to the RTD from the analog output module (A109) of the Data Acquisition (DAQ) system. The voltage readings generated from the RTD during temperature change are supplied to the input module (A108) of the DAQ, which is then scaled to temperature readings. The RTD sensors are calibrated with known input values in the laboratory.
Table 2. Details of various equipment and measuring instrument used in the experimental setup.

| Component          | Type                        | Operating Range          |
|--------------------|-----------------------------|--------------------------|
| Coriolis mass flowmeter | NAGMASS 40                  | Upto 24000 kg/h          |
| RTD sensor         | CRZ 1632 R-100              | -200 °C to 400 °C        |
| Piezoelectric sensor | KISTLER 603CAA              | 0 bar to 1000 bar        |
| Charge Amplifier   | KISTLER 5073A211            | -10 V to 10 V            |
| Control valve      | FISHER/EZ-C                 |                          |
| Actuator and Positioner | FISHER/657 and DVC 6200-HC | 0 bar to 4 bar           |
| DAQ                | QBRIXX A108 and A109        | -10 V to 10 V            |

The piezoelectric pressure sensor consists of a quartz sensing element that produces a charge when pressure acts on it. The charge reading is converted into voltage by a Charge amplifier and the voltage readings are scaled to pressure values. The sensor has an operating temperature range of 77 K to 473 K with sensitivity of -5 pC/bar and rise time < 0.4 µs. The piezoelectric sensor and the Coriolis mass flowmeter are industry calibrated.

The readings of the measuring instruments are configured using DAQ system which consists of separate input and output modules. The different configurations are performed with Test Commander Software while visualization and analysis of the acquired data are performed with Test Viewer software.

2.3. Measurement modules
The design of pipeline modules for holding the piezoelectric and RTD sensors in a fixed position under all conditions is mandatory for accurate measurement. The sensors are installed in the pipeline with flush type mounting system ensuring that the sensing element is in direct contact with the liquid. Flush mountings are suitable for best accuracy and minimal rise time. Also, it avoids cavity and turbulence.

The mounting of piezoelectric sensor constitutes various components as shown in figure 2 to prevent throwing off the sensor at high pressure. Seals are used to prevent leaks through fittings. Similar to the piezoelectric sensor, the RTD is mounted in an adapter which is then inserted into the pipeline module.

![Figure 2. Pipeline module mounted with RTD and piezoelectric sensor.](image)

![Figure 3. Coriolis mass flowmeter installed in the setup.](image)

The installation of the Coriolis mass flowmeter requires free hanging of the measuring tube for accurate measurement and to avoid external disturbances. Hence, the pipeline connecting the flowmeter is clamped to a stand on both sides as shown in figure 3. The entire setup is shown in figure 4.
3. Test procedure
Initially, the tank pressure is set to the desired value and the valves mounted in the system are kept in the OPEN position and the pipeline is allowed to chill down. Once a steady flow condition is achieved the control valve operation is performed. Repeatability of the measurement represents the closeness of the results of successive experiment performed under the same condition [14]. The repeatability test is performed by repeating the experiment with tank pressure 2 bar and flow rate of 173 kg/s twice under same operating conditions and the transient pressure results are shown in figure 5 and figure 6.

The errors in experimental results are predicted by performing uncertainty analysis [15] for the repeated readings taken under similar operating conditions using the standard deviation method of ASTM E691-99 [16]. It is found that the uncertainty in pressure readings is ± 1.16%, mass flow rate is ± 0.28%  and the temperature readings is ± 0.32%.

4. Results and discussions
4.1. Chill down
The first and important step in the cryogenic fluid transfer is to chill down the transfer lines from atmospheric temperature to cryogenic fluid temperature. The chill down of this system is ensured from the temperature profile of the RTD sensors shown in figure 7. Understanding the chill down time is essential to avoid additional energy loss and to determine the quantity of fluid consumed [17] for efficient transfer. The chill down is started at 150 s and completed at 750 s with duration of 10 minutes.
4.2. Valve driven transient

The valve transient is performed for two different cases with parameters shown in table 3. The response time of the control valve used is 1.5 s i.e it takes 1.5 s to reach from open to close position or vice versa.

| Parameters     | Case 1       | Case 2       |
|----------------|--------------|--------------|
| Tank pressure  | 2.2 bar abs  | 2 bar abs    |
| Flow rate      | 213 g/s      | 173 g/s      |

4.2.1. Case 1. The transient is generated by closing the control valve at 8.5 s and opening at 23 s.

The results in figures 8 and 9 show that the pressure varies contrasting to temperature before and after the valve during valve closure. When the control valve is closed, the cryogenic fluid coming from the tank gets compressed and vaporizes before the valve. This produces a large vapor which continues to accumulate before the control valve forming regions of the vapor phase, followed by two-phase and single-phase LN$_2$. But the pressure wave traveling in the pipeline forces the liquid to move with high velocity reducing the static pressure. Hence the pressure of the fluid before the valve decreases while the valve is closed [18]. The two-phase nature of LN$_2$ is identified from the pressure and temperature results using the NIST property table interpreted by REFPROP [19] as mentioned in table 4.
### Table 4. Properties of LN$_2$ [19] during different conditions of the experiment

| Temperature | Pressure | Liquid density | Vapor density |
|-------------|----------|----------------|---------------|
| 80 K        | 1.9 bar  | 794.09 kg/m$^3$| Subcooled     |
| 82 K        | 2 bar    | 784.65 kg/m$^3$| Subcooled     |
| 92 K        | 1 bar    | Superheated    | 3.75 kg/m$^3$ |

In the downstream region the fluid remains in liquid phase during valve closure hence the pressure increases. But as the valve is opened, the vapor phase and two phase flow accumulated before the valve is ejected quickly causing the pressure drop after the valve. After this, the liquid phase proceeds leading to pressure rise before and after the control valve. This is further evident from the Joukowsky equation [7] that the pressure variation due to transient is directly proportional to the density of the fluid.

#### 4.2.2. Case 2.

The control valve is closed from 12 s to 13.5 s and opened from 25.5 s to 27 s.

![Figure 10. Pressure vs time profile during valve-driven transient (Case 2).](image)

![Figure 11. Temperature vs time profile during valve-driven transient (Case 2).](image)

The results obtained are similar to case 1 as shown in figure 10 and figure 11 but the amplitude of peak pressure is lower than in case 1. This is observed due to the low flow rate of case 2 than case 1.

The experimental facility developed is a unique setup and the one on one comparison of results with other facilities may not be possible due to the geometrical constraints. However the pressure profile is compared with a similar problem [18] and a match in pattern is observed. Similarly the temperature profile is compared with the liquid nitrogen test facility [8] and close match is observed. In future attempts will be made to perform more experiments to confirm the accuracy.

### 5. Conclusions

A cryogenic experimental test facility is developed to predict the valve-driven transients in the LN$_2$ transfer line. The major findings are

- Sudden closure of valve in cryogenic system induces phase change in pipeline upstream of the control valve accompanied by pressure drop.
- In Cryogenic fluids, the sudden transition from single phase to two-phase region and vice versa is probable during valve transient. The pressure variation during valve transient highly depends on the properties of the cryogenic fluids. In the subcooled region, the pressure increases during valve closure whereas in the superheated region the pressure decreases.
The amplitude of pressure drop higher than the pressure rise has been observed due to valve closing in the LN$_2$ system. Hence the possibility of cavitation before the valve is prominent.

6. References

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