The Americas Flow Measurement Conference
26-27 April 2012

Performance Results from the Cryogenic Flow Facility at NEL

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1 INTRODUCTION

The LNG industry is a fast growing and very valuable industry throughout the world. During various stages of the LNG supply chain, measurement of LNG quantity stored, distributed or consumed constitutes an essential part the supply chain.

Currently LNG is traded on the basis of long-term contracts based on measurement of the volume of ship's tanks using level gauges [1]. Inline flow measurement of LNG is already taking place and with the move to spot trading, ship to ship transfers and use of small scale LNG plants incorporated into FPSO (floating, production, storage and offloading) vessels, the demand for inline flow measurement technology will increase. Therefore the demand for traceable calibration facilities to serve the LNG industry will also increase [2]. However, it is recognised that building an industrial scale LNG calibration facility will be technically challenging and care must be taken to address both safety aspects and the accuracy required for custody transfer applications.

To facilitate for the above requirements, NEL have designed and built a small scale cryogenic test facility capable of running and controlling the flow and the condition of cryogenic fluid. The design and build of this facility was funded by the UK National Measurement Office (NMO) though NEL's Engineering and Flow Research Programme. This facility will help to develop the required experience to deal with the safety aspects and allow functionality and reliability tests of instruments. The information and experience gathered from this work will contribute to the potential development of an industrial scale cryogenic calibration facility in the future, which, if built, would be the first of its kind and scale in the world.

Following the completion of the small scale facility build, further funding was secured through the three years (2010-2013) European Metrology Research Programme (EMRP) for LNG to allow completion of facility commissioning and test programme. The EMRP project is jointly funded by the European commission and the UK (NMO). The overall objective of the EMRP project is to improve the uncertainty of custody transfer measurements in the LNG industry by developing new techniques and methods. This will be achieved by looking at the complete custody transfer process including volume and composition measurements along with density and gross calorific value calculations.

This paper describes the test facility briefly and presents results from functionality testing to verify that the rig meets its design specifications. Performance results from temperature and pressure instruments are presented including stability of measurements. In addition the performance of the Coriolis flow meter used in this facility is compared with and without its insulation jacket. This includes comparing the measured mass flowrate, density and wall temperature.

2 DESIGN AND CONSTRUCTION OF FACILITY

The design and build of the small-scale test facility were carried out over three stages. The first stage considered three design options depending on location of the facility within NEL with the objectives of; providing approximate cost estimates for each design, undertake HAZOP studies, and then recommend the most appropriate design [3]. This has resulted in selecting the most appropriate design taking in consideration available space and overall cost. In this design option it was recommended to integrate the test rig onto the existing liquid nitrogen storage and vaporisation facility at NEL.

The second stage focused on taking the selected concept design to full engineering drawing status, preparation of an accurate bill of materials and specification of construction cost. This has resulted in a detailed design specification ready for execution by specialist contractor in the third and final stage.

The final design of the NEL cryogenic rig is shown in Figure 1. The main elements of the facility and existing supply liquid nitrogen tank and vaporisers are described briefly in the next section.

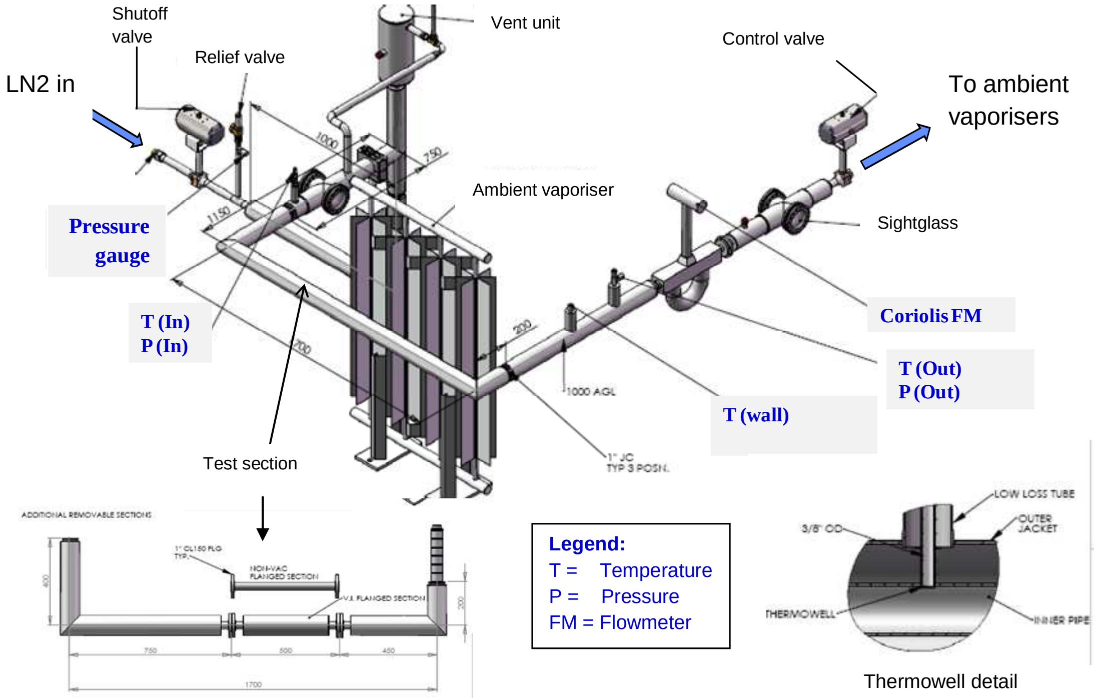


Figure 1 - Final design of cryogenic facility

2.1 Main Components of Test Facility

The liquid nitrogen (LN2) storage tank used for the multiphase test facility at NEL was modified so that it could also be used to supply the cryogenic rig. The tank is a 20 tonne vessel which is constructed with a double skin. The inner vessel contains the liquid nitrogen and is enclosed by the outer vessel with a vacuum insulated space between the two layers. Once the vacuum has been created between the two skins the space is filled with special insulating material and the combination of this vacuum and insulation ensures that the heat gain to the liquid nitrogen is minimised. When the tank is filled about 10% of the inner volume is left for gas space which allows for liquid expansion and can also be vented to lower the pressure within the tank. The pressure within the storage tank was controlled by a pressure regulation system to stabilise the operation pressure in the tank and allow pressure regulation between ambient and 14 barg.

Once the liquid nitrogen has passed through the rig it is vented to atmosphere through two ambient vaporisers. These vaporisers function by taking heat from surrounding air and transferring it to the liquid nitrogen as it travels through the coils. The vapour is heated to near ambient conditions to prevent freezing water vapour in the air and causing the formation of fog in the area. This could be a safety hazard in particular to traffic in the nearby road. Two stainless steel vent silencers were installed immediately after the two ambient vaporisers to reduce the noise level from vented nitrogen gas both during tank pressure reduction and operation of the cryogenic test facility. A low temperature control system was fitted in order to monitor the temperature of the nitrogen gas leaving the ambient vaporisers and ensure that the fluid leaving the ambient vaporisers is in full gaseous phase.

Within the working pressure range of the rig the saturation temperature of liquid nitrogen is between -170℃ and -180℃. The large temperature d ifference between ambient temperature and saturation temperature means that the liquid nitrogen will boil very quickly when exposed to ambient temperature. This means that any trapped liquid in the pipework will boil and expand to approximately 695 times causing significant pressure rise within a section of pipework. It is therefore vitally important that every section of pipework that can be isolated with valves is fitted with a safety relief valve. It is also important that the pipework in the rig is insulated very efficiently to keep the temperature at or below the saturation temperature to minimise or, if possible, prevent liquid boiling.

It was decided that vacuum insulation would provide the level of insulation needed to meet this requirement. It is estimated that vacuum jacketed piping is significantly more effective than foam insulated pipe in reducing heat leak. The vacuum insulated pipework is manufactured from two layers of stainless steel with a gap between them. A vacuum pump is used to create a vacuum within this gap to ensure very efficient insulation within each section of pipework. There were some sections of pipework which could not be vacuum insulated for example the connection pipe from the tank to the rig and sections next to the flanges. The supply pipe between the tank and the test rig was lagged with high density insulation and it was thought that the other small flanged sections would not introduce significant heat gain to cause boiling.

A gradual reduction in vacuum level is expected with time and therefore the manufacturer recommends re-evacuation every two years. Vacuum degradation can be identified by the appearance of extended areas of condensation or icing on the outer jacket of the pipework.

Since the supply pipe from the storage tank to the cryogenic rig was lagged with conventional insulation, this would be insufficient to prevent some boiling of the liquid nitrogen. It was therefore decided to include a vent unit within the cryogenic rig to remove the nitrogen gas from the liquid nitrogen before it entered the test rig. The vented gas is heated to near ambient conditions by a small ambient vaporiser as shown in Fig. 1. The venting unit significantly reduces bubbles entering the cryogenic rig which may affect the performance of the flowmeter.

A removable pipe section of 0.5m long is used as a test section (Figure 1) and two spools were manufactured, one with no insulation and the other with vacuum insulation in order to study the condition of LN2 with and without insulation. In this project no attempt was made to replace this pipe section with a flow meter or any other instrument and all testing was carried out with only the insulated pipe section.

Although design considerations were made to minimise heat gain into the liquid nitrogen the only way to visually check that it remained in the liquid phase with no bubbles was to design viewing sections (sightglasses) within the rig. The viewing section would provide reliable information on the flow condition compared to any other way such as comparing the actual fluid temperature with its saturation temperature.

The design of the sightglass was one of the main design challenges because conventional sightglasses for test rigs would not be able to withstand the low temperatures experienced within the cryogenic rig. The sightglass was designed to have two layers with a vacuum insulated gap between them. The material chosen for the transparent section was Kodial glass which has a very low coefficient of thermal expansion. This means it is highly resistant to thermal shock and can deal with the high temperature gradients experienced within the cryogenic rig. Two sightglasses were installed as shown in Figure 1, the first immediately after the venting unit and the second after the Coriolis flowmeter. The first sightglass allows checking the performance of the venting unit and time required to vent all nitrogen gas and the second shows whether LN2 leaving flowmeter contains gas bubbles or not. Figure 2 shows the design of sightglass.

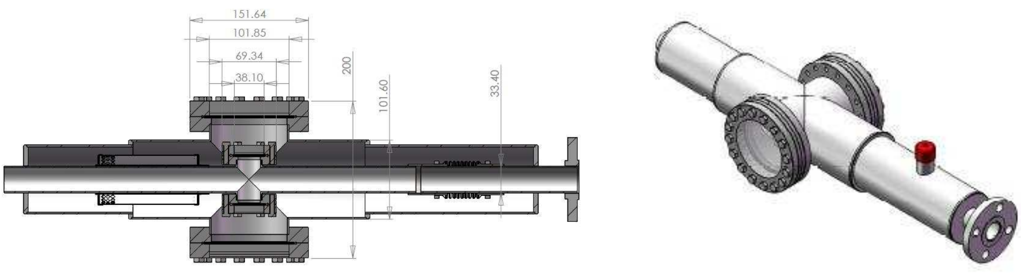


Figure 2 - Sightglass design

In order to control the flowrate within the rig an air-actuated control valve was fitted after the second sightglass (Fig. 1). The valve can be controlled remotely from the control room and allows fine control over the valve position and hence fine control over the flowrate. The flowrate can also be controlled by adjusting the manual inlet valve.

2.2 Instrumentation

Referring to Figure 1, the following table gives detailed list of the instruments used in the facility.

TABLE 1 - LIST OF MEASUREMENT AND INDICATION INSTRUMENTS

Instrument	Quantity	Manufacturer/ details	Function	Range
Pressure Transducer	2	Kulite, CT-375 (M) Series. ± 0.5% FSO (Max)	Upstream Pressure (P_{in})	0 to 35 barg
			Downstream Pressure (P_{out})	0 to 35 barg
PRT	3	TC, platinum resistance thermometer. Class 1/10 to IEC 6071, ± 0.1^{o}C	Upstream Temperature (T_{in})	-200 to 50℃
			Downstream Temperature (T_{out})	-200 to 50℃
			Wall Temperature (T_{wall})	-200 to 50℃
Pressure Gauge	1	Rototherm, DMC100	Upstream LN2 pressure	0 to 30 barg
Coriolis flowmeter	1	Krohne, Optimass 800K S25.	Measurement of mass flowrate, temperature and density	0 to 2.5 kg/s

The secondary instruments such as pressure and temperature transmitters are required to give information about the condition of the fluid within the rig. These can be used to monitor the stability of the temperature and pressure over time, the amount of subcooling which can be achieved in the rig and the difference between wall and bulk fluid temperature. Readings from instruments are also used for further analysis and calculations. Due to the large temperature gradients within the rig special instrumentation had to be sourced which could handle the low temperatures.

The two pressure transmitters are located upstream and downstream of the removable test section and they are mainly used to obtain the LN2 saturation temperature. They may also give an indication of pressure drop within the test section. There are three temperature probes within the system. Two PRT's are located upstream and downstream of the test section measuring the bulk fluid temperature at the centre of the pipe and the third PRT sits in a thermowell arrangement specially designed to measure the temperature of pipe wall (Figure 3). The PRT is dipped in a cryogenic gel to ensure good thermal bonding with the tube wall. By comparing the wall and bulk temperatures, a temperature gradient across the pipe can be determined. However, due to the small diameter of the pipe of 1 inch and the vacuum insulated piping, temperature gradients may be very small. There are also two pressure gauges in the upstream section of the rig. These are used primarily to get visual indication of LN2 supply pressure.

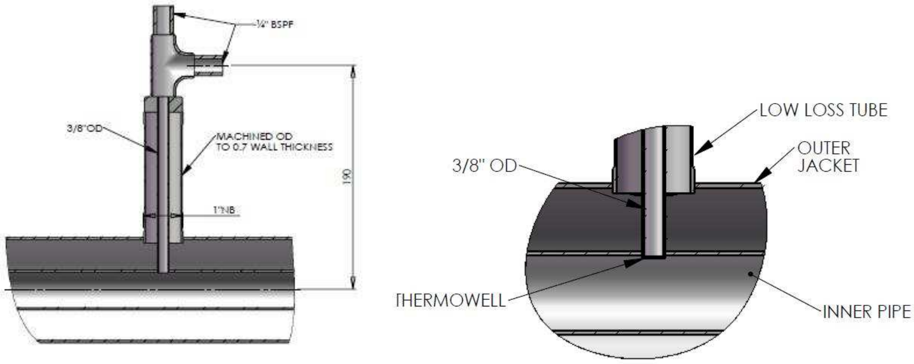


Figure 3 - Pressure and temperature tapping detail

A Coriolis flowmeter was chosen for the measurement of mass flowrate. The flowmeter also give measurement of density and wall temperature. The wall temperature is used to correct for the stainless steel behaviour at cryogenic conditions. The flowmeter has an insulation jacket which can be removed so that the flowmeter could be tested with and without insulation.

3 TESTING PLAN

The test plan covered safety tests to ensure that the rig conformed to safety legislation and sound engineering practice and ensure that the performance of the rig met the functional specification. The performance of the instruments was also investigated at cryogenic conditions.

The safety tests carried out were as follows:-

- Pressure test of the cryogenic rig pipework to 11 Bar,
- Pressure test on all other pipework to 27.5 Bar,
- Leak tests on all pipework,
- Blockage tests on all relief valve lines.

Several tests were carried out to ensure that the rig met the functional specification required for the cryogenic test programme as follows:-

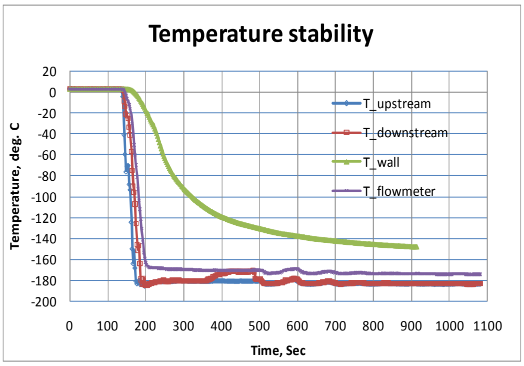
- Check if the rig could keep the liquid nitrogen in the liquid phase using the two viewing sight glasses and information from temperature and pressure measurements.
- Determine the maximum achievable flowrate through the rig. This was determined by fully opening the main inlet valve and the control valve at the exit of the test rig.
- Check whether the flowrate could be controlled using the control valve. Starting from fully open, the control valve was closed gradually and the flowrate was logged to ensure that there was acceptable control of flowrate.
- The final test was to take a series of test points at different flow rates. During these test points all data was logged over a five minute period for pressure, temperature, flowrate and density. Stability of each instrument was also logged at each test point (about 100 readings within the five minutes test point). The data acquisition software also performed calculations to determine the saturation temperature based on the measured pressure and the subcooling temperature which is the temperature difference between the saturation temperature and the bulk fluid temperature. The ambient temperature and tank level were manually recorded during every test point.

The insulation was then removed from the flowmeter and the measurements above were repeated to study the effects of insulation on flowmeter performance.

4 FACILITY FUNCTIONALITY TESTS

The first functional test carried out was to run liquid nitrogen through the test rig and monitor its condition in the sightglasses and instruments. Initially boiling took place due to the ambient temperature in the pipework and nitrogen gas flowed through the rig. After a short period of time the temperature decreased enough to allow liquid nitrogen to flow through the rig albeit with some boiling still taking place. As the temperature dropped, the amount of boiling reduced and after 10 to 15 minutes the boiling ceased altogether. In this case both inlet and outlet sight glasses showed clear single phase liquid flow.

Figure 4 shows the temperature and pressure stability during start up. It can be seen from temperature stability graph that after about 2 minutes liquid nitrogen starts to flow through the rig and the temperature starts to drop rapidly. After about 2 minutes of liquid flow, the bulk temperature stabilises at around -180℃ and remains at that low temperature ensuring that the LN_2 remains in the liquid phase. The pressure takes about 10 minutes to stabilise at 6.2 barg.



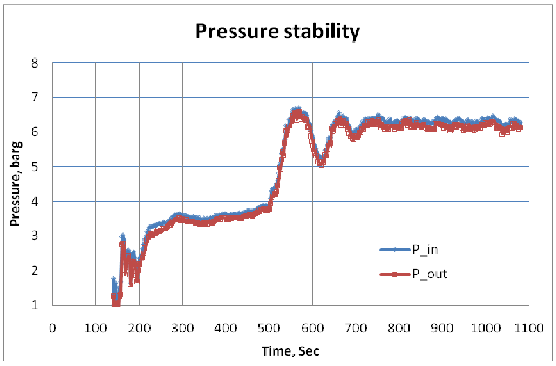
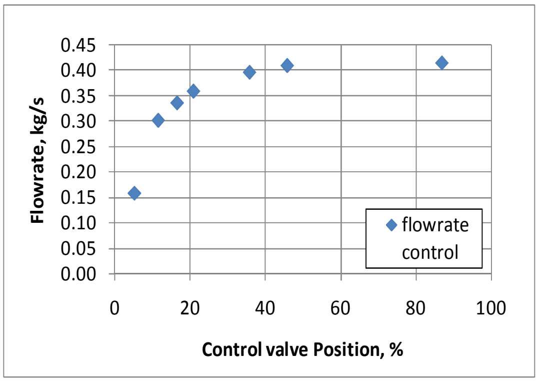


Figure 4 - Temperature and pressure stability during startup

The next test was to check the control of flowrate by the motorised control valve. The valve opening can be changed between 0% (fully closed) and 100% (fully open) in steps of 1% through a manual dial on the control panel. It was found that the flowrate stayed relatively constant between 0.45 kg/s – 0.40 kg/s when the control valve position was reduced from 100% open to 50% open. As can be seen in Figure 5 (left) the flowrate starts to reduce when the valve is less than 50% open and reduces fairly linearly between 25% and 0% open. This therefore shows that the greatest amount of flowrate control is achieved when the control valve is between 0% and 50% open. Figure 5 (right) shows the flowrate over a five minute test point with LN2 supply valve fully open and the control valve 90% open. It can be seen that there is a large amount of fluctuation in the flowrate but the average flowrate is about 0.4 kg/s.



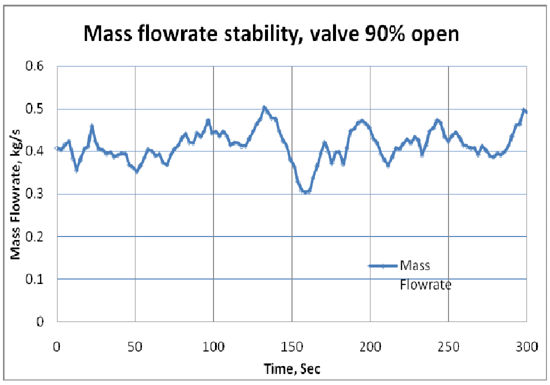


Figure 5 - Flowrate control and maximum achievable flowrate

Having established confidence in temperature and pressure measurements, it was possible to check if it is possible to maintain the fluid in subcooled condition. Subcooling is defined as the temperature of the liquid nitrogen measured at the centre of the pipe minus the saturation temperature at the working pressure. If the liquid nitrogen is below the saturation temperature then it is said to be subcooled and no boiling will take place. Therefore the liquid nitrogen will stay in liquid phase. If the liquid nitrogen is above the saturation temperature then boiling will take place and it will be in the liquid and gas phase.

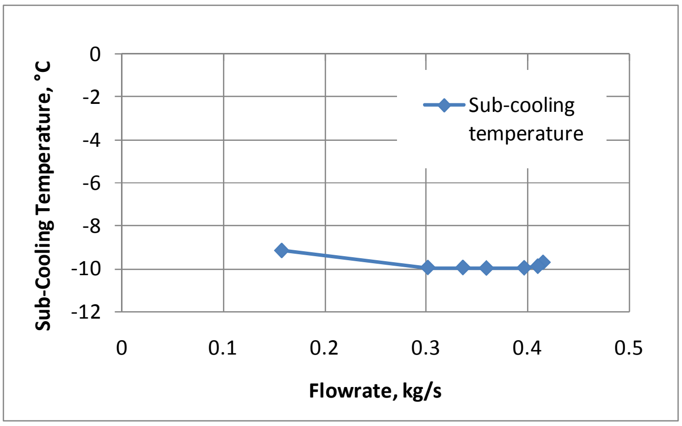


Figure 6- Subcool temperature

From Figure 6 it can be seen that the liquid nitrogen was subcooled between 9℃ and 10℃ during the current programme of testing. This level of subcooling will minimise the chance of boiling in particular near the pipe wall which may effect the performance of instruments in particular the Coriolis flowmeter.

A closer look at the performance of pressure and temperature instruments and the Coriolis flow meter readings with and without its insulation jacket are descibed in the next section.

5 INSTRUMENTS PERFORMANCE

5.1 Temperature Instruments

The stability of temperature measured by the PRT's was logged over a period of five minutes in a number of different test points. Figure 7 shows the temperature upstream and downstream at two different valve positions. It can be seen that the temperature at the upstream PRT was an average of about 0.5℃ lower than the downstream PRT. This is as expected due to ambient heat gain into the system and is likely to have taken place mainly in the flanged connections which have no insulation. It can also be seen that both PRT's are following the same pattern, ie when the temperature rises and falls it is shown by both PRT's. The fact that the PRT's are showing a heat gain in the system and showing small rises and falls in temperature increases confidence that the PRT's are operating well at cryogenic conditions

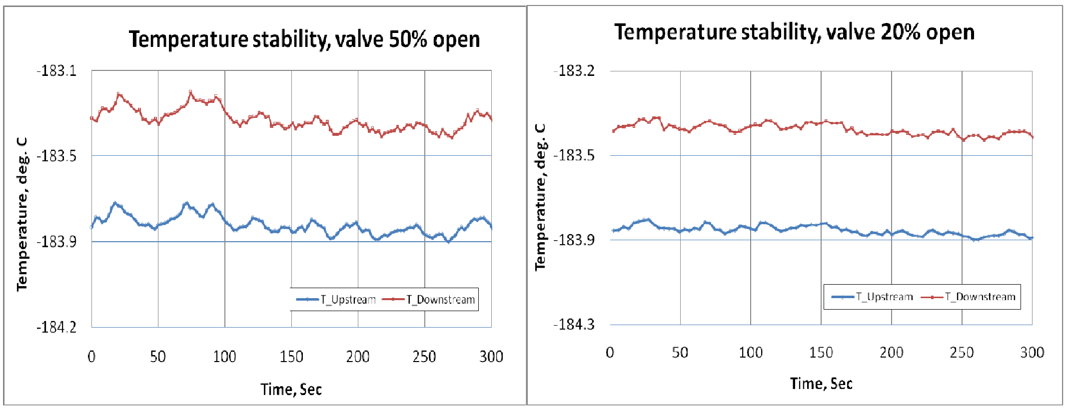


Figure 7 - Bulk temperature at different control valve positions

The stability of temperature at different valve positions (10% to 100% open) was also monitored. It was flound that the temperature is very stable with the maximum deviation from the mean being about 0.4%. It is thought that these fluctuations are genuine and are related to the fluctuations in flowrate. This is backed up by the fact that the fluctuations in temperature increase as the fluctuations in flowrate increase when the control valve is fully open.

The measurement of pipe wall temeprature by wall PRT described in section 2.2 was found to be about 28℃ higher than the temperature of fluid at the centre of the pipe. It is thought that although there would be a temperature gradient across the pipe it is unlikely to be as high as 28℃ especially in a 1" diameter pipe. In addition, the Coriolis flow meter also measures the wall temperature and from Figure 4 it can be seen that "T_flowmeter" is very close to the bulk temperature. There are two possible reasons for this. Firstly, the PRT is not in good contact with the inner pipe wall. Secondly, the cryogenic gel filling the thermowell housing is effected by ambient conditons surrounding the thermowell surface causing conduction along the PRT. If the PRT is bonded to the inner pipe wall carefully then using efficent insulation around the PRT instead of using the thermal gel may results in a more representative measurement of wall temperature.

5.2 Pressure Instruments

The pressure stability was measured over the different test points by the upstream and downstream pressure transmitters. The maximum deviation from the mean was around 2.8% for both the upstream and downstream pressure transmitters when the control valve was 90% open. These fluctuations are considered genuine variation in pressure rather than large instabilities in the transmitters because during testing the tank pressure control system was set to vary the pressure between 8 and 9 bar in the storage tank. This will lead to pressure fluctuations in the rig itself which are picked up by the pressure transmitters as can be seen in Figure 8. The fluctuation in pressure reading decreases as the control valve is closed. This is consistent with the stability in flow.

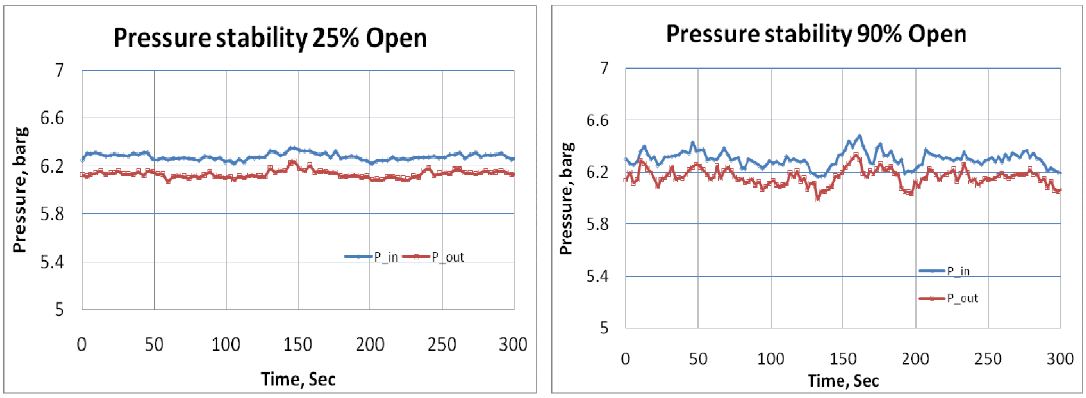


Figure 8 - Pressure stability at two control valve positions

Also it can be seen in Figure 8 that the pressure downstream of the test section (P_Downstream) is lower than the pressure upstream (P_Upstream) by about 0.14 bar. This is caused by pressure drop throughout the test section. The fact that these pressure transmitters show a pressure drop and both follow the same pattern indicate that they are operating well at cryogenic conditions.

5.3 Coriolis Flowmeter

The Coriolis flowmeter is capable of measuring three parameters; the mass flowrate, wall temperature and fluid density.

The stability of the mass flowrate measured by the Coriolis flowmeter was logged at a series of 7 different flowrates ranging from 0.15 kg/s to 0.40 kg/s. It was found that there was significant fluctuations in the flowrate and at high flowrates for example there was deviations from mean value up to 27% when the control valve was 90% open. Another trend that can be noted from Figure 9 is that the flowrate was significantly more stable at low flowrates than at high flowrates. For example the maximum deviation was only 2.7% when the control valve was 9% open. It appears that closing the control valve dampens these flucuations due to the resistance imposed to the flow. Therefore it can be said that these fluctuations are genuine fluctuations rather than inaccuracies in the flowmeter. These fluctuations are consistent with the pressure fluctuations discussed earlier.

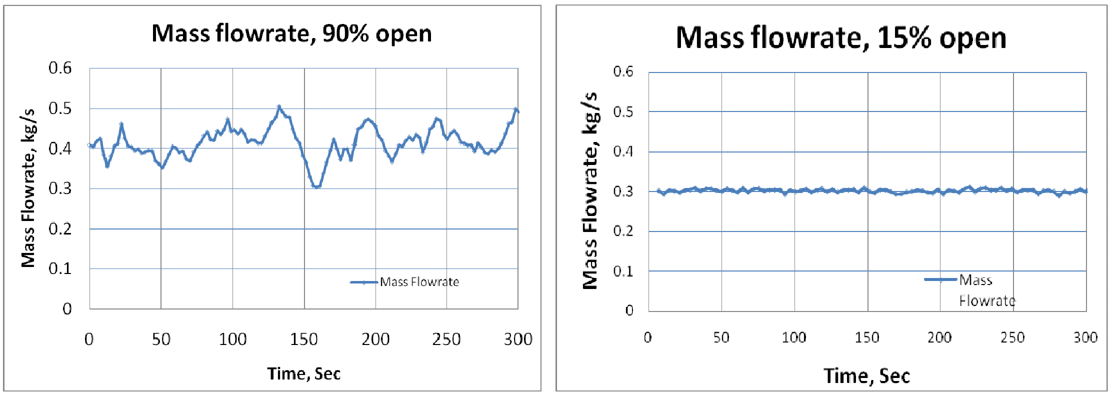


Figure 9 - Flowrate stability at two different control valve positions

The stability of density measured by the Coriolis meter over two test points is shown in Figure 10. In general the density was very stable with the maximum deviation from the mean being just 0.2%. Again these are thought to be genuine fluctuations.

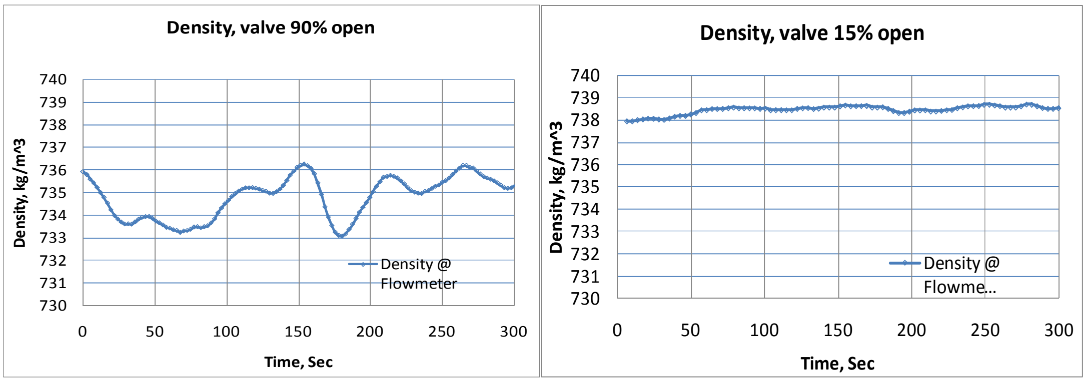


Figure 10- Density stability at different valve positions

The measured density by the flowmeter was compared with calculations from NEL physical property package (PPDS). The downstream bulk temperature and pressure were used as inputs in the PPDS calculations. The results of this are shown in Figure 11. It can be seen that the measured density was between 1% and 1.4% lower than the PPDS calculated density. This is considered to be good agreement.

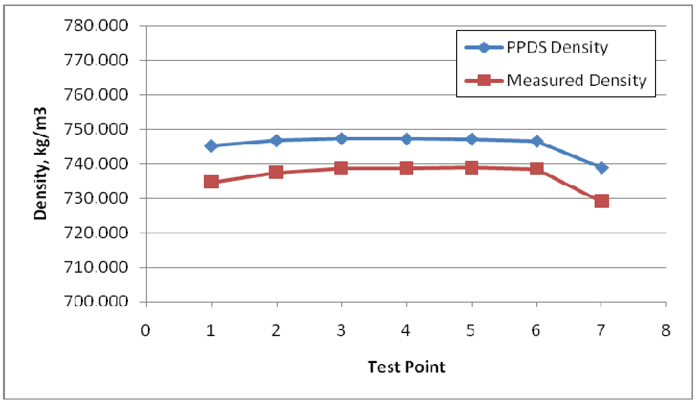


Figure 11- Measured and calculated densities

As indicated above, the flowmeter incorporates a temperature measurement of the measuring tube to allow for correction of measured mass flow rate. Testing experience with cryogenic fluids showed that the Young's modulus of elasticity of stainless steel used in the meter tubes has a non-linear dependence on temperature, causing a calibration shift. It is claimed that, when the temperature-dependent calibration shift is allowed for, standard factory calibrations at ambient conditions can be transferred to operation at cryogenic temperatures [4]. To achieve accurate correction, it is important to measure this temperature accurately.

Figure 12 shows the maximum deviation of measuring tube temperature from the mean value. It can be seen that the maximum deviation is close to 0.4% which is similar to that of the bulk temperature measurement. Again the stability improves as the flowrate reduces which suggests that the fluctuations in temperature at high flowrates are genuine fluctuations caused by fluctuations in the flowrate. The flowmeter temperature was found to take longer to stabilise than the bulk temperature and stabilises about 5℃ above the bulk temperature. This is reasonable because the flowmeter measures the temperature at the flowmeter tube wall and not in the bulk of the flow so the temperature was expected to be slightly higher.

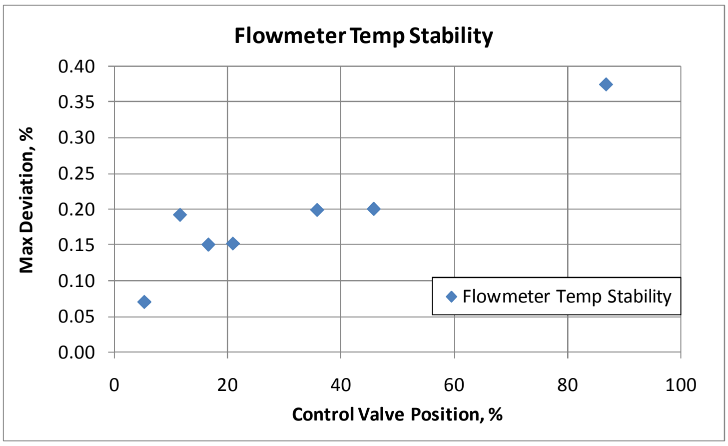


Figure 12 - Stability of flowmeter measured wall temperature

Tests were also performed on the flowmeter with and without the insulation jacket to assess the importance of insulation in cryogenic applications. Figure 13 shows the flowrate at different valve positions. It can be seen that the flowmeter reading and measurement stability are generally unaffected by the removal of insulation in this case. This is because the fluid was sub-cooled by 10.75℃ for insulated test and an d 9.77℃ for uninsulated test. The test without insulation jacket was conducted two days after the test with insulation jacket and therefore has resulted in about 1°C loss in subcooling in the main supply tank.

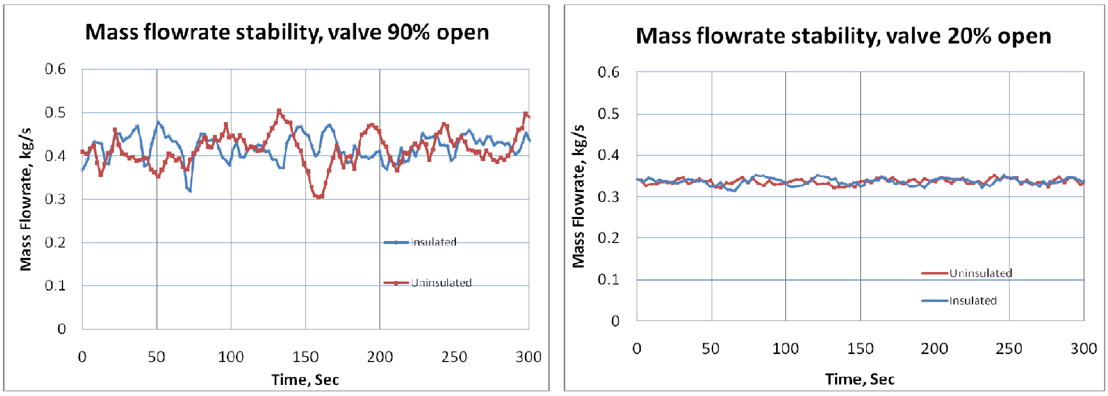


Figure 13 - Flowrate stability with and without flowmeter insulation

Figure 14 shows the difference between the flowmeter metal temperature and the saturation temperature (i.e. subcooling at flowmeter wall) for the insulated and uninsulated flowmeter tests. In both cases the flowmeter temperature was below the saturation temperature and indicates that no boiling is taking place at the tube walls. As expected the subcooling at flowmeter wall is higher when the flowmeter is insulated. Although Figure 14 shows an average difference of about 3°C in subcooling, part of this difference is due to the 1°C loss in sub-cooling indicated above. The actual difference in subcooling at flowmeter wall is therefore about 2°C. This suggests that the insulation reduces heat gain into the system and would reduce the chance of boiling.

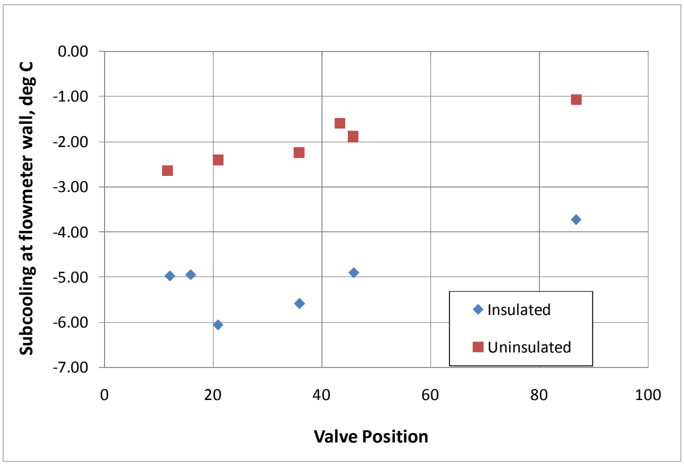


Figure 14 - Subcooling at flowmeter wall

6 CONCLUSIONS

From the tests carried out at the NEL cryogenic flow facility many conclusions can be drawn.

It was found that the facility performed well and met the specification required for the cryogenic test programme. Liquid Nitrogen was flowed safely through the facility and was maintained as a single phase liquid. This was due to the sub-cooling of 10°C which was achieved by ensuring that the LN2 in the supply tank was under sub-cooled condition in addition to the use of vacuum insulated piping. The tank is normally supplied with liquid nitrogen under sub-cooled condition but the sub-cooling decreases with time due to ambient heat gain. This project has shown that the testing must be completed within 2 to 5 days after a tank fill depending on ambient temperature.

Within the test rig, there was a temperature rise of 0.5°C from the upstream to the downstream PRT which is likely to have been caused mainly by un insulated flanged connections. In the design of a larger re-circulation facility it is important that vacuum insulation is used wherever possible to minimise heat gain and a separate sub-cooling system will be needed to prevent boiling. If there are sections of pipework which cannot be vacuum jacketed then high density foam insulation can be used but this will be less effective. There was no facility to monitor the vacuum level of the insulation jacket and therefore it is recommended to have a pressure indication to show this. A gradual reduction in vacuum level is expected over time as air gets into the vacuum. If there are extended areas of condensation or icing on the outer layer of the vacuum jacket then this indicates a loss of vacuum and the pipework should be re-evacuated. The manufacturer of the vacuum jacketed pipework used in this project recommends a check in vacuum level every two years.

It was shown that the flowrate could be controlled effectively using the downstream control valve. The most effective control was achieved when the valve is 9% to 50% open and the flow could be controlled from 0.15 kg/s to 0.4kg/s. When the control valve was more than 50% open the flow of LN2 fluctuates significantly with no increase in average flowrate.

The PRTs were stable and showed deviations from mean value within 0.4% across the working range of the facility. The upstream, downstream and flowmeter PRT's gave consistent readings. The upstream PRT generally measured higher LN2 temperature than the downstream PRT by about 0.5℃ due to the heat gain into the pipe work between them. The flowmeter temperature measurement was around 5℃ higher than the downstream PRT. This was considered reasonable as the flowmeter measures its wall temperature. However, the wall PRT in the rig indicated a much higher temperature of 28℃ than the bulk temperature which is thought to be unlikely in a 1" pipe. This is attributed to the poor contact of the PRT with the tube wall and the use of cryogenic gel in the PRT thermowell which has resulted in increased conduction error along the PRT. If wall PRTs are required for a larger scale facility then it is recommended that they are embedded into the pipe wall, very close to the inner surface of the pipe, rather than placed in a thermowell with a cryogenic gel or paste. Measures must also be taken to reduce conduction error along the PRT.

The pressure transmitters within the rig were stable to within 3% across the working range of the facility. These were considered to be genuine pressure fluctuations caused by the bottom pressure control system in the liquid nitrogen storage tank. Pressure fluctuations will affect calibrations due to lack of flow stability and it is therefore recommended that within a traceable facility more effort is put into pressure control. In a closed loop system where a circulation pump is carefully designed with a sub-cooling system, better stability can be achieved. The pressure drop between the upstream and downstream transmitters was measured at around 0.13 to 0.15 bar depending on the flowrate. It was noted that both pressure transmitters showed the same trend which indicates that they are operating well at cryogenic conditions.

The Coriolis flowmeter in the facility showed fluctuations in flowrate of up to 30% when the control valve was 90% open. However the stability improved to less than 3% when the control valve was only 9% open due to the resistance imposed to the flow by the control valve. These fluctuations are consistent with those shown by pressure transmitters reflecting genuine fluctuations in the flow. The flowmeter measured density was also consistent throughout the flow range and fluid conditions. The measured density was only 1.4% lower than the calculated density from NEL's PPDS software using the downstream bulk temperature and pressure measurements as input. This is considered to be good agreement.

Another important aspect of the test programme was to investigate the effect of insulation on flowmeter performance. It was found that the stability of the flowmeter was largely unaffected by the removal of insulation. This was due to the fact that the flowmeter wall temperature was below the fluid saturation temperature by about 9℃ resulting in no boiling at the wall. However, in practice, it is unlikely to have any significant subcooling, in particular in LNG custody transfer applications, and therfore the flowmeter must be operated with insulation jacket. It was shown that the effect of the insulation in these series of tests was to reduce heat gain to the flowmeter by around 2℃. This illustrates the importance of insulation for cryogenic flowmeters because a lack of insulation could lead to boiling within the flowmeter. Boiling within the flow meter should be avoided as it will increase errors in the flowmeter measurements

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