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Technical Paper

Experimental Research into the Measurement of Temperature in Natural Gas Transmission Metering Systems

Bob Ingram, DNV GL
Sarah Kimpton, DNV GL

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1 INTRODUCTION

High-pressure offtake metering installations at National Grid Gas Distribution are audited for conformance with the Uniform Network Code Offtake Arrangements Document (OAD) Appendix D [1]; the auditors are Ofgem, independent auditors and the Measurement Assurance Group of National Grid Gas Transmission. The auditors repeatedly report that there is no thermal lagging on meter tubes; this is quoted as a category 1 finding based on the presumptions that thermowells should exclusively be the temperature measurement method for custody transfer metering applications and that the tip should be sited in the centre third of the pipe diameter.

Lagging, however, obscures meter tube corrosion and inspection can be expensive due to the need to remove and then re-install the lagging. If National Grid Gas Distribution is required to lag its meter tubes then the financial impact is in the region of £2M plus ongoing additional maintenance costs.

The aim of this experimental work was to demonstrate that lagging was not necessary for National Grid Gas thermowell installations. It was also intended to demonstrate that an alternative method of temperature measurement for custody transfer metering purposes using surface mounted sensors may be acceptable. Due to the non-intrusive nature of the surface mounted method, this would be an advantage for metering installations.

Recent computational fluid dynamics (CFD) [2] calculations carried out by DNV GL and Loughborough University show that existing National Grid Gas meter tubes installed with National Grid Gas CT4 type thermowells do not require lagging. Furthermore, CFD calculations indicate that the temperature at the bottom of the standard T/SP/S/21 thermowell [3] is the same as the gas temperature. The CFD calculations also showed that locally lagged surface-mounted sensors could be used to measure the gas temperature with acceptable accuracy. It was decided to test the CFD calculations by experimental measurements. This paper documents the tests carried out at the DNV GL Flow Centre at Bishop Auckland and the subsequent results. The CT4-type thermowells are not considered appropriate for small diameter metering pipes and alternative methods of temperature measurement with acceptable levels of uncertainty were investigated.

The work in this paper considers the uncertainties in temperature measurement that can be achieved using surface and National Grid Gas CT4 thermowell temperature measurement methods over a wide range of gas velocities and temperatures, with and without insulation.

All temperature sensors used in the temperature tests were calibrated to ISO 17025 (UKAS) standards and had a measurement uncertainty of 0.1 °C or less.

2 AUDIT FINDINGS

Typical findings from recent audits are:

- The orifice fittings, meter tube upstream and downstream straight lengths and temperature fittings are not thermally insulated and are open to the elements in an exposed location

- In an exposed site location, an even heat transfer throughout the metering tube lengths cannot be guaranteed and it is possible to introduce temperature gradients within a flowing stream. There may be a big difference between the flowing gas temperature and the ambient temperature depending on the time of the year

- The exposed position of the meter run and the lack of lagging on the pipe work and the temperature probe and fitting means that the temperature used to calculate gas density is unlikely to reflect the true flowing gas temperature.

ISO 5167 [4] does not provide clear guidance on the measurement of temperature and whether thermowells are a requirement. For example, section 5.4.1 of ISO 5167-1:2003 states:

Any method of determining reliable values of the density, static pressure and temperature of the fluid is acceptable if it does not interfere with the distribution of the flow in any way at the cross-section where measurement is made.

3 TEMPERATURE MEASUREMENT REQUIREMENTS FOR OFFTAKE METERING

Existing metering contracts at Ofgem-directed offtakes normally state a minimum flow of 10% of maximum flow rate unless there is no alternative route to delivering gas into the network. The uncertainty requirements for the existing offtake meters are set at:

- ±2.0% for volume measurement and ±3.2% on energy over the flow range 30% to 100%

- ±3.5% for volume measurement and ±4.3% on energy over the flow range 10% to 30%

For National Transmission System (NTS) offtakes not under Ofgem direction, each metering system has its own Network Exit Agreement (NExA). The uncertainty limits vary by site although the following limits are consistent for many of the NExAs. Under the generic NExA the site must operate at:

- ±1.0% and ±1.1% uncertainty on standard volume and energy flow rates respectively over the range 30% to 100% of maximum contractual flow rate

- ±2.0% and ±2.2% uncertainty on standard volume and energy flow rates respectively over the range 20% to 30% of maximum contractual flow rate

National Grid Gas validation procedure T/PR/ME/2 [5] also forms part of the contractual requirements for metering systems. Each part of the metering system is individually tested against a pass/fail tolerance. For temperature measurement there are up to three tests that need to be carried out:

- Resistance thermometer detector test with a pass/fail tolerance of ±0.5 ºC
- Temperature transmitter test with a pass/fail tolerance of 0.2% of span (normally equivalent to 0.1 ºC for a span of 50 ºC)
- ADC calibration with a pass/fail tolerance of 0.03% of span

The experiments in this project were carried out at gas velocities varying between about 0.1 to 14 m/s. For a typical 12-inch orifice-plate metering system, a gas velocity of 0.1 m/s corresponds to about 1% of the maximum contractual flow rate with a differential pressure of 0.1 mbar or less. A gas velocity of 14 m/s corresponds to at least 45% of maximum contractual flow at minimum operating pressures of about 40 barg. At the minimum allowed flow rate of 10% of maximum contractual flow, the gas velocity is typically between 1 and 3 m/s depending on the pressure and beta ratio. Examples of uncertainty (quoted with a confidence of 95%) related to velocity are shown in figures 1 and 2 below.

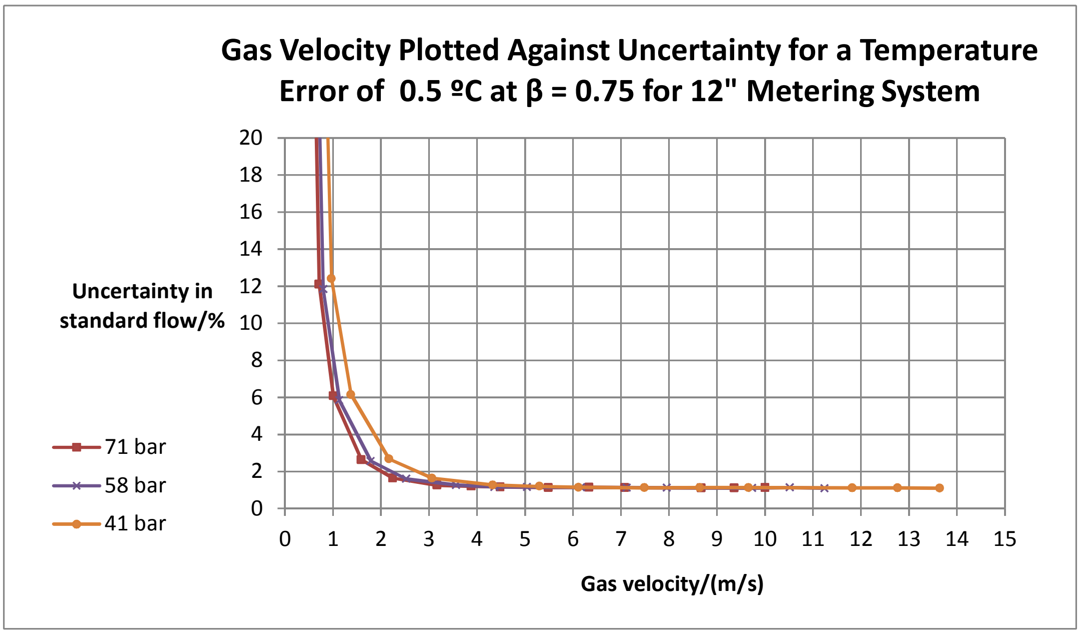


Fig. 1 – Effect of temperature errors of 0.5 ºC on the overall uncertainty in volume and energy flow for typical 12-inch orifice-plate offtake metering systems.

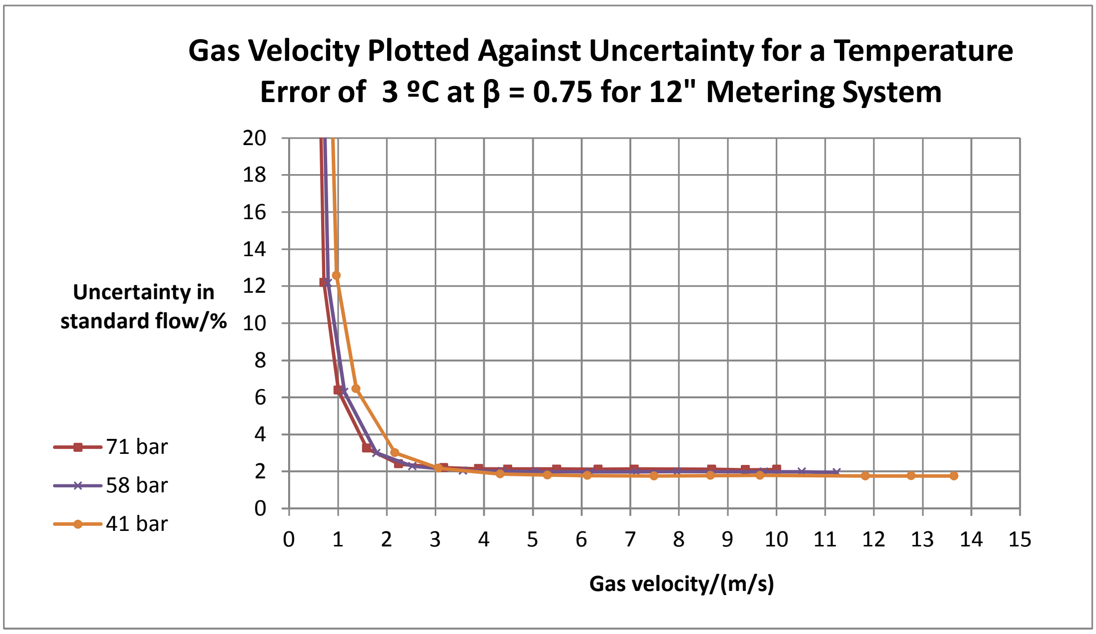


Fig. 2 – Effect of temperature errors of 3 ºC on the overall uncertainty in volume and energy flow for typical 12-inch orifice-plate offtake metering systems.

4 DESIGN OF THERMOWELLS

In the early days of what was originally British Gas, a number of thermowell failures occurred on the National Transmission System (NTS). The failures were investigated by the British Gas Engineering Research Station (ERS) and found to be due to high cycle stress fatigue. The stress fatigue was caused by vortex shedding exciting the resonant frequency of the long thermowell stems installed. A programme of work was initiated to determine the best engineering solution to the problem.

The outcome was a recommendation in 1972 to install a shorter design thermowell made from a single 316 stainless steel forging. Key features of the shorter design are:

- A tapered stem for strength and reduction in vortex shedding forces
- No welds that might fail due to stress fatigue
- A large root radius and smooth finish to minimise the initiation of stress fatigue cracking
- A 14 mm bore to enable mercury in steel temperature sensors to be inserted, designated 'Type A'
- A 6 mm end bore option to enable the use of platinum resistance elements to be fitted, designated 'Type B'.

In practice, only the 14 mm 'Type A' thermowell was installed and an aluminium bore reducing insert was used to enable 6 mm diameter PRT sensors to be fitted.

Also, the thin wall of the S21/CT4 thermowell stem reduces the thermal conduction path to the mounting flange exposed to atmospheric temperatures, compared to a narrow bore full thickness conventional thermowell.

An up to date drawing of the CT4 thermowell design is shown in Figure 3. This design of thermowell was the preferred method of temperature measurement in all transmission and distribution pipework when the NTS was constructed.

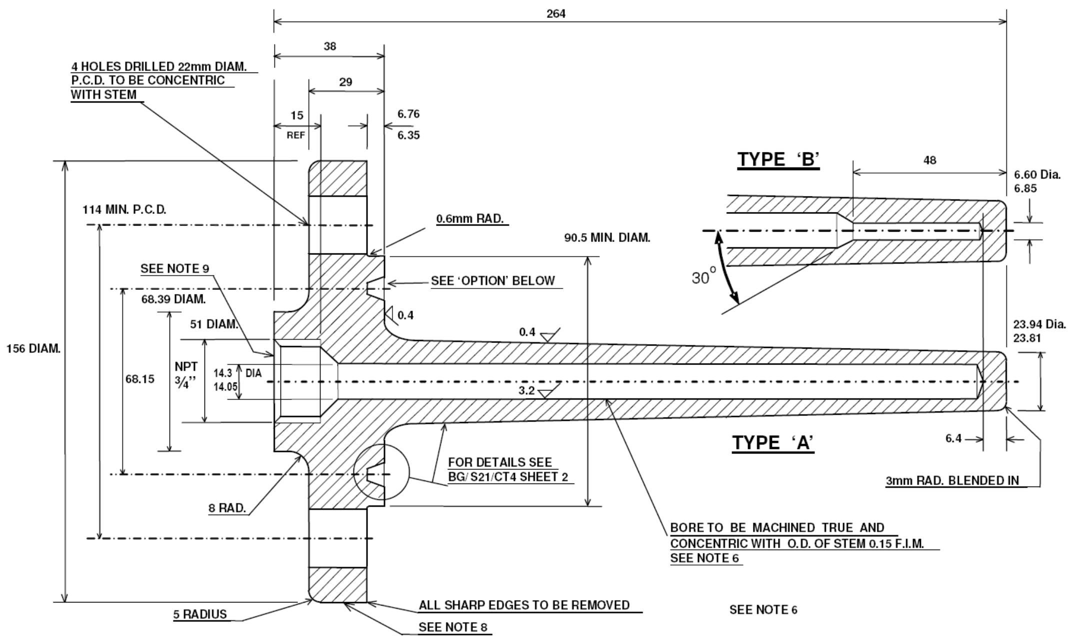
With regards to mechanical integrity, the CT4 and screw type thermowells employed in the DNV GL Flow Centre tests conform to the latest *ASME PTC19.3 TW-2010 Thermowells* [6] code of practice. ASME PTC19.3 TW incorporates recent advances in the understanding of thermowell fatigue failure. From our knowledge of process plant designs, it is likely that a significant number of existing thermowells installed in the gas industry will not comply with this code and will have a high risk of failure.

Soon after 2000 it was decided that due to a number of pressure fitting failures, the number of flange type fittings would be minimised on the NTS to reduce the risk of stress fatigue failure. The current National Grid Gas guidance states that non-invasive surface temperature measurement shall be used unless there is a compelling reason to fit thermowells. Thermowells are now only fitted where a fast response is required or where flow metering installations require the use of thermowells. Welded or fabricated thermowells are not permitted for use on the National Grid Gas Transmission System. Due to the use of the relatively short CT4 design thermowell, questions are continually raised by inspectors in relation to the accuracy of temperature measurement on custody transfer metering. The nominal insertion length beyond the pipe wall is 90 mm.

There is also concern about whether thermowells should be insulated or not. The guidance in current international engineering standards is that temperature measurement should be implemented by using thermowells inserted into the gas stream between 30% and 50% of the pipe bore. For example, BS ISO 15970:2008 [7] states that:

To ensure good temperature measurement, Thermowells shall protrude into the pipework to approximately 1/3 of the nominal inside diameter measured from the inner wall. However, for pipes larger than 300 mm where the resonant vibrations of the Thermowell are known to be a problem, the design of the Thermowell can restrict the depth of insertion. Resonant-vibration problems can be avoided by the application of conical instead of parallel Thermowells. For larger pipes, insertion depths of 75 mm to 100 mm are conservative. For smaller pipes where the insertion depth becomes larger than ¾ of the nominal inside diameter of the pipe, Thermowells shall be installed in a pipe bend or obliquely at 45° to the flow direction.'

CT/4 SHEET 1



GENERAL NOTES

1. ALL DIMENSIONS IN MILLIMETRES.
2. TOLERANCES, UNLESS OTHERWISE STATED, ± 0.4mm
3. SURFACE FINISH 1.6
4. FORGING TO BE MANUFACTURED IN ACCORDANCE WITH BS EN 10222 Part 1:1998 MICRONS, UNLESS OTHERWISE STATED
5. MATERIAL. BS EN 10222 Pt.5, GRADE 1.4401 (Formerly BS 1503-316 S31) OR BS EN 10222 Pt.5, GRADE 1.4436 (Formerly BS 1503-316 S33)
6. BORE SURFACE FINISH AND CONCENTRICITY TOLERANCES HAVE BEEN RELAXED. THEY ARE NOW AT THEIR MAXIMUM PERMISSIBLE VALUES. THERMOWELLS FALLING OUTSIDE THESE TOLERANCES SHOULD BE REJECTED AND NOT CONSIDERED FOR CONCESSION.
7. AFTER FINAL MACHINING, THERMOWELLS ARE TO BE SUITABLY PROTECTED BEFORE HANDLING.
8. EACH FORGING PRODUCED SHOULD BE STAMPED IN ACCORDANCE WITH BS EN 1759-1:2004, CLAUSE 5.10, MARKING. IN ADDITION STAMP THE TYPE DESIGNATION (i.e. TYPE 'A' or 'B') AND PROJECT NAME. e.g. 1½" CL600, STEEL F316 S31 x x x TYPE 'A' (OR 'B'), 'ST. FERGUS TERMINAL'. (x x x = maker's name.) THE ABOVE INFORMATION IS TO BE STAMPED ON THE FLANGE PERIPHERY & RE-STAMPED AFTER REMOVAL DURING ANY PROCESS. MINIMUM LETTER SIZE 5mm.
9. A COUNTERBORE IS TO BE PROVIDED AS SHOWN, TO ENSURE EASY ENTRANCE WHEN MAKING A JOINT. THE THREAD SHALL BE CHAMFERED TO AN ANGLE OF APPROXIMATELY 45° TO THE BOTTOM OF THE COUNTERBORE
10. THERMOWELLS ARE TO BE TESTED IN ACCORDANCE WITH BRITISH GAS GENERAL INSTRUMENTATION STANDARD S21. (Pressure Test To 150bar And Dye Penetrant Test) .
11. THE THERMOWELL IS BASED ON A STEEL 1½" CLASS 600 FLANGE.

DESIGN NOTE

THE NATURAL FREQUENCY OF A TYPE 'B' THERMOWELL FITTED WITH A RESISTANCE THERMOMETER SYSTEM IS HIGHER THAN THE NATURAL FREQUENCY OF A TYPE 'A' THERMOWELL FITTED WITH A MERCURY IN STEEL SYSTEM HAVING A 102mm ACTIVE LENGTH

OPTION

AT THE OPTION OF NATIONAL GRID GAS, INSTEAD OF THE RING TYPE JOINT SHOWN, A RAISED FACE FLANGE FACING TO BS EN 1759 Part 1 (FORMERLY BS 1560 SECTION 3.1) MAY BE USED

Standard Specification		FORGED THERMOWELL	Standard No. BG / S21 / CT4 SHEET 1
			Issue No. 5 / Date 3 - 4- 2007
nationalgrid	STANDARD DRAWING	Section:- COMMUNICATONS & INSTRUMENTATION	Drawing No. BG / DO / ST / 74 SHEET 1

Fig. 3 – National Grid Gas CT4 thermowell

Another example of guidance that conflicts with National Grid Gas installations is from the API Manual of Petroleum Measurement Standards 1985 [8]:

7.2.6.2 MOUNTING

The thermowell should be selected to conform to code and user mounting practices. Thermowells are typically threaded, welded, or flanged mounting.

The immersion length of the thermowell should be sufficient to put the sensor element within the center third of the pipe's diameter or as nearly so as possible limited only by practical thermowell design. When mounting thermowells, consideration should be given to the effects of thermal conductivity (see 7.2.6.4).

7.2.6.3 MATERIAL

The thermowell's material of construction should be compatible with the liquid media and provide a degree of corrosion resistance for all surfaces. Usually Type 304 or 316 stainless steel is specified.

7.2.6.4 THERMAL CONDUCTIVITY

In cases where the temperature sensor does not come into contact with the thermowell walls, the space between the sensor and the thermowell wall should be filled with an appropriate heat-conducting media. This will improve heat conduction between the well and the sensor and improve the temperature sensor's response time.

Although long thermowells will limit the effects of thermal conduction error, they increase the risk of vortex shedding and stress fatigue failure. The statement 'Thermowells are typically threaded, welded or flanged mounting' is also of concern. Long, threaded or welded thermowells would not be recommended for use on the National Grid Gas NTS. However, short threaded thermowells can provide a suitable compact method of temperature measurement.

A typical National Grid Gas historical installation is shown in Figure 4 with a weldolet pressure fitting. The current recommended installation is to use a weldoflange type pressure fitting, which has greater resistance to vibration related fatigue.

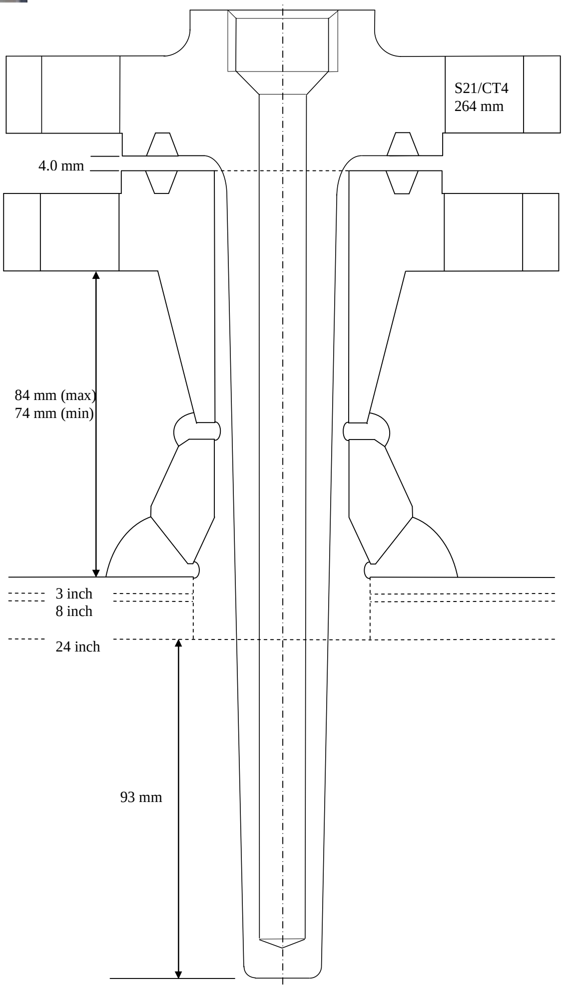


Fig. 4 – Typical CT4 thermowell installation with a weldolet pressure fitting

5 CFD ANALYSIS

Previous CFD analysis [2] indicated that there was no temperature gradient with an uninsulated CT4 thermowell design. An example of CFD analysis on a CT4 thermowell installation is shown in Figure 5. The aim of the experimental work was to confirm the findings modelled previously using CFD.

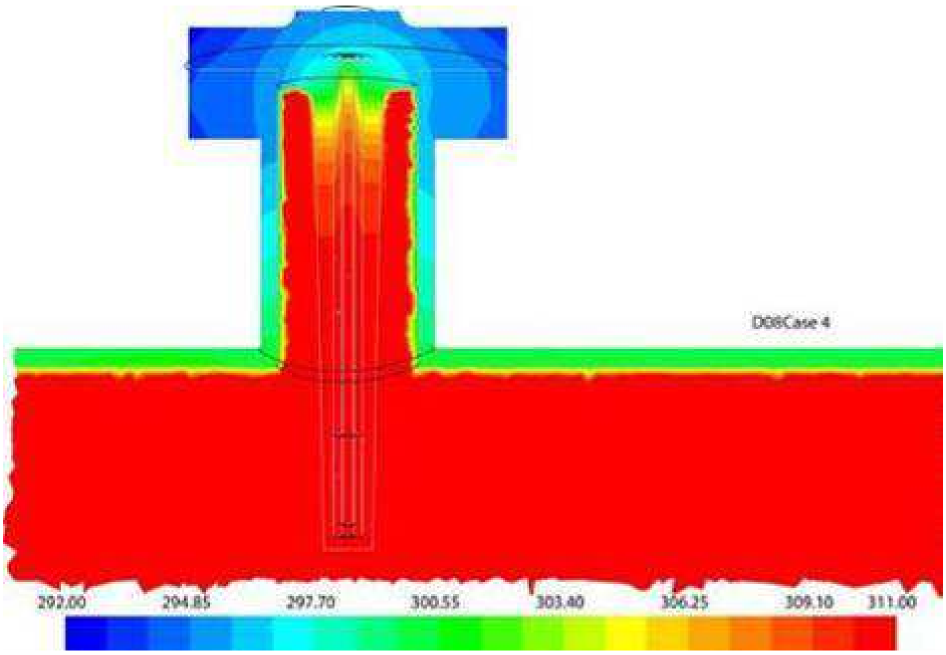


Fig. 5 – CFD analysis of a CT4 thermowell as reported previously [2]

6 DESIGN OF EXPERIMENTAL TESTS

6.1 Design of Temperature Sensors

To investigate the best ways to measure the mean temperature of gas in a pipeline, a number of special temperature sensors were designed. *Sensing Devices Ltd* were used to manufacture the special temperature sensors as they have the skills and flexibility to carry out this type of work and they are UKAS accredited. National Grid Gas required that temperature measurement should be investigated on a range of representative metering pipe sizes:

- 3-inch nominal bore (Figure 6)
- 8-inch nominal bore (Figure 7)
- 24-inch nominal bore (Figure 8)

In addition to temperature sensors used to measure gas temperature, a number of surface sensors were used to measure thermowell flange and pipe flange temperatures.

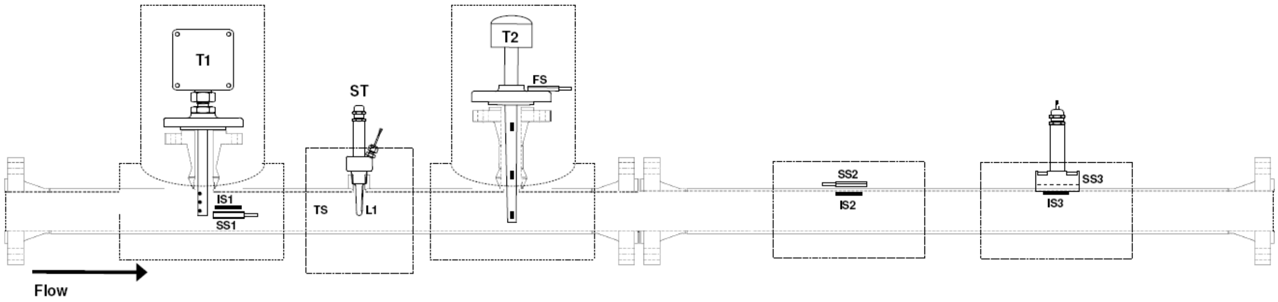


Fig. 6 – Three inch test spool assembly

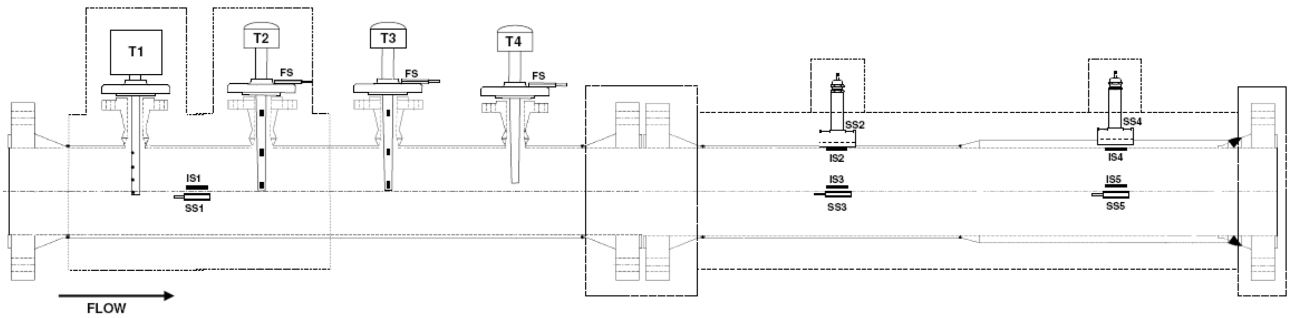


Fig. 7 - Eight inch spool assembly

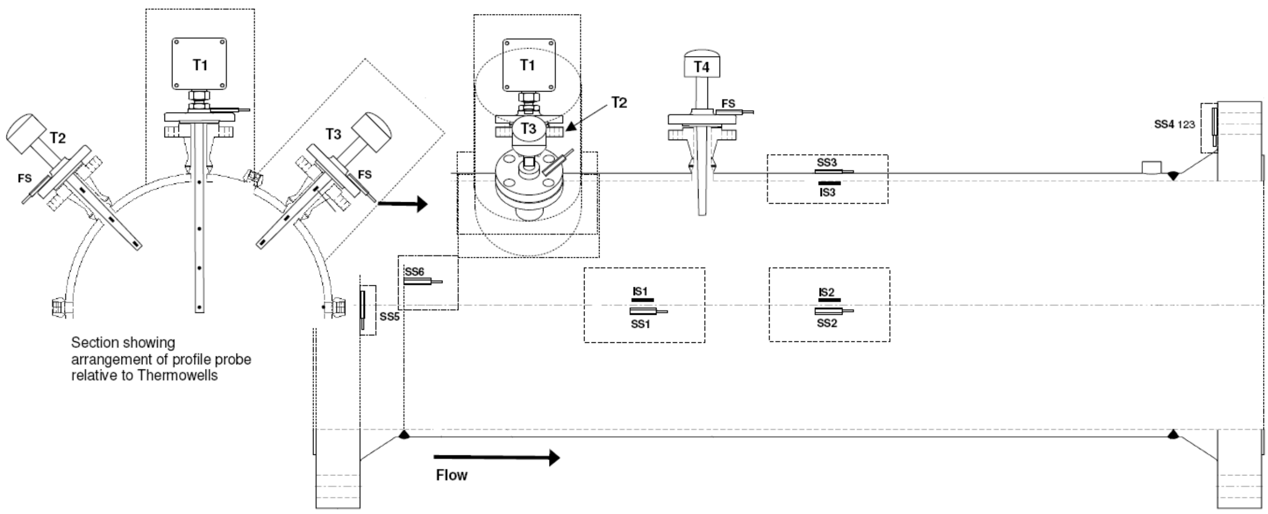


Fig. 8 – Twenty four inch spool assembly

6.2 Temperature Sensor Construction and Configuration

The following sensors were used in the tests:

- Surface sensors for the outer pipe walls – the design of these sensors is detailed in the National Grid Gas T/SP/S/21 Instrument Engineering Document [11] and they are four wire 1/10 DIN specification

- Surface sensors for inner pipe walls – the temperature sensors required for the internal wall of the pipe were four wire 1/10 DIN. These sensors measure the inside surface temperature of the pipe to compare with outside sensors and gas temperature

- CT4 Thermowells with additional surface sensors to measure temperatures on the stem in the gas stream

- Temperature profile probes designed for each of the three pipe sizes, 3-inch, 8-inch and 24-inch pipe

- One screw type thermowell for mounting in small diameter pipes

- Prototype vertical surface mounting sensors that can be removed for maintenance and calibration to comply with National Grid Gas flow validation requirements

- Ambient air temperature sensors mounted internal and external to the test housing

- Water temperature for rain simulation tests.

A number of sensors were installed on the surface of the thermowells to measure the interface temperature between the gas and the thermowell material; this is illustrated in Figure 9.

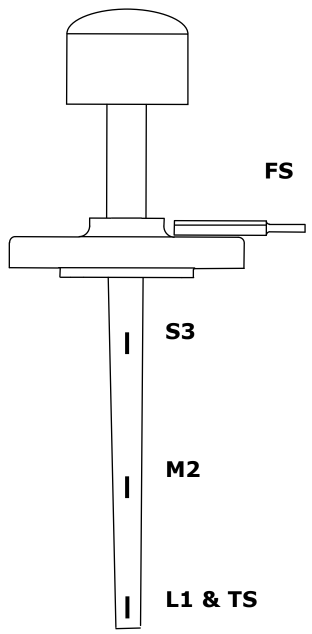


Fig. 9 – Location of sensors on CT4 thermowells

6.3 Temperature Profile Probes

Measuring the internal gas temperature profile accurately was given a great deal of consideration during the design stage. The main difficulty was to limit the thermal conduction paths between the sensor mounting and the carrier stem in a manner that is robust enough to withstand gas turbulence and gas pressure. The design of the temperature sensor, mounting arrangement and gas flow path is shown in Figure 10 and the longest profile probe for the 24 inch pipe is shown in Figure 11. The profile probe assembly calibrations were also checked at 50 bar to confirm that there was no change under pressure.

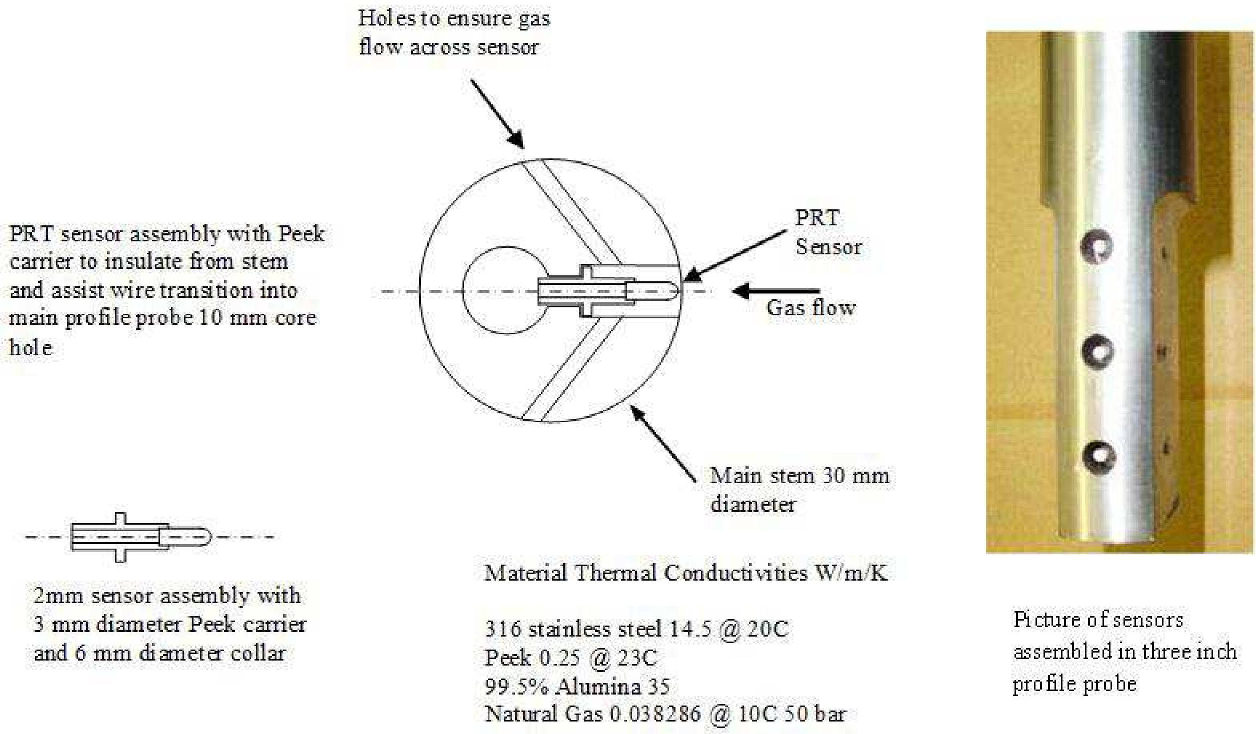


Fig. 10 – Profile probe sensor mounting design

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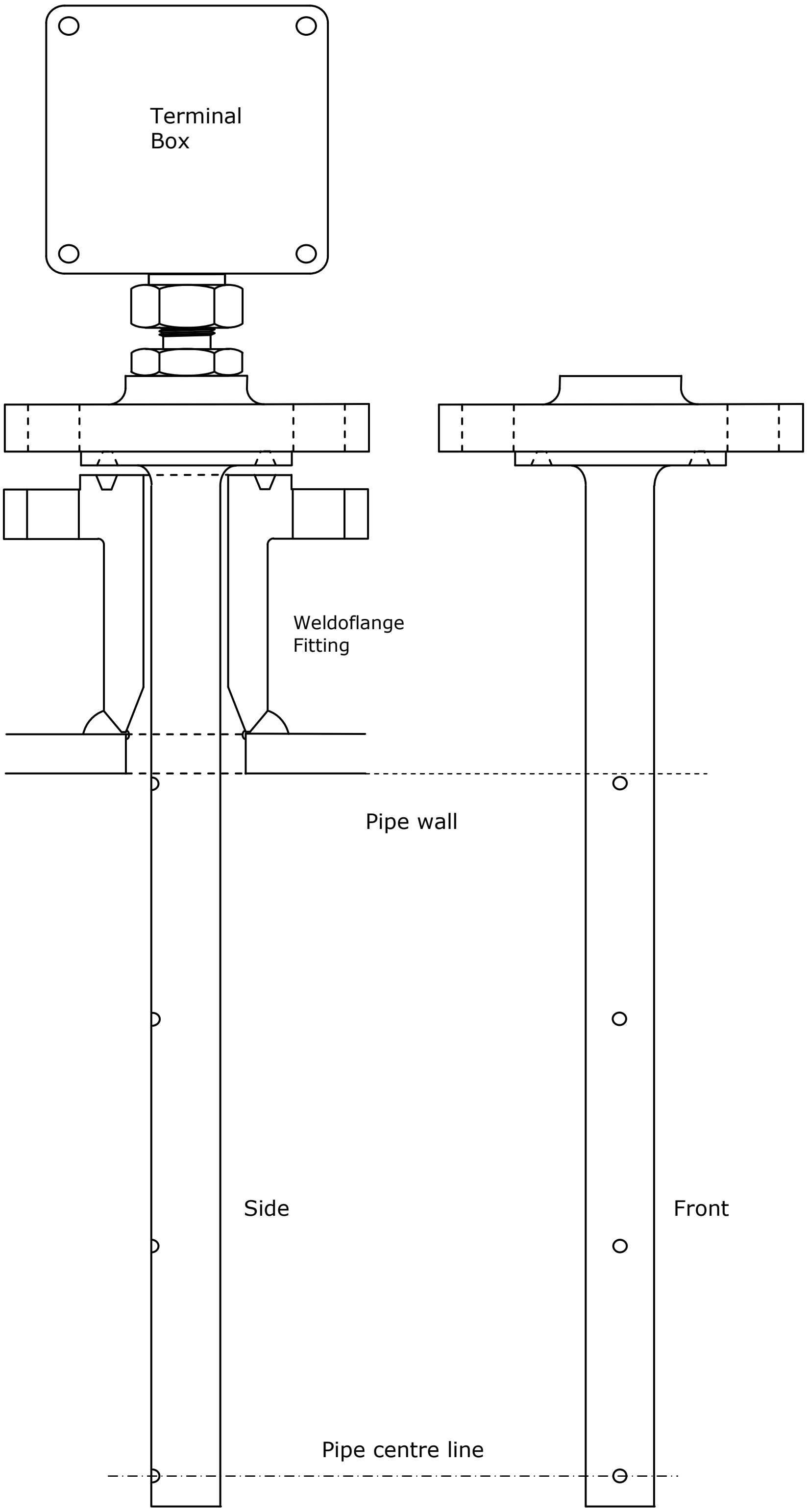


Fig. 11 – Example of 24 inch pipe profile probe

6.4 CT4 Thermowell Probes

Three CT4 thermowell probes were constructed with additional 2 mm mineral insulated PRT's installed on the surface to measure external stem temperatures and the flange temperature was also measured. The design is shown in Figures 12 to 14.

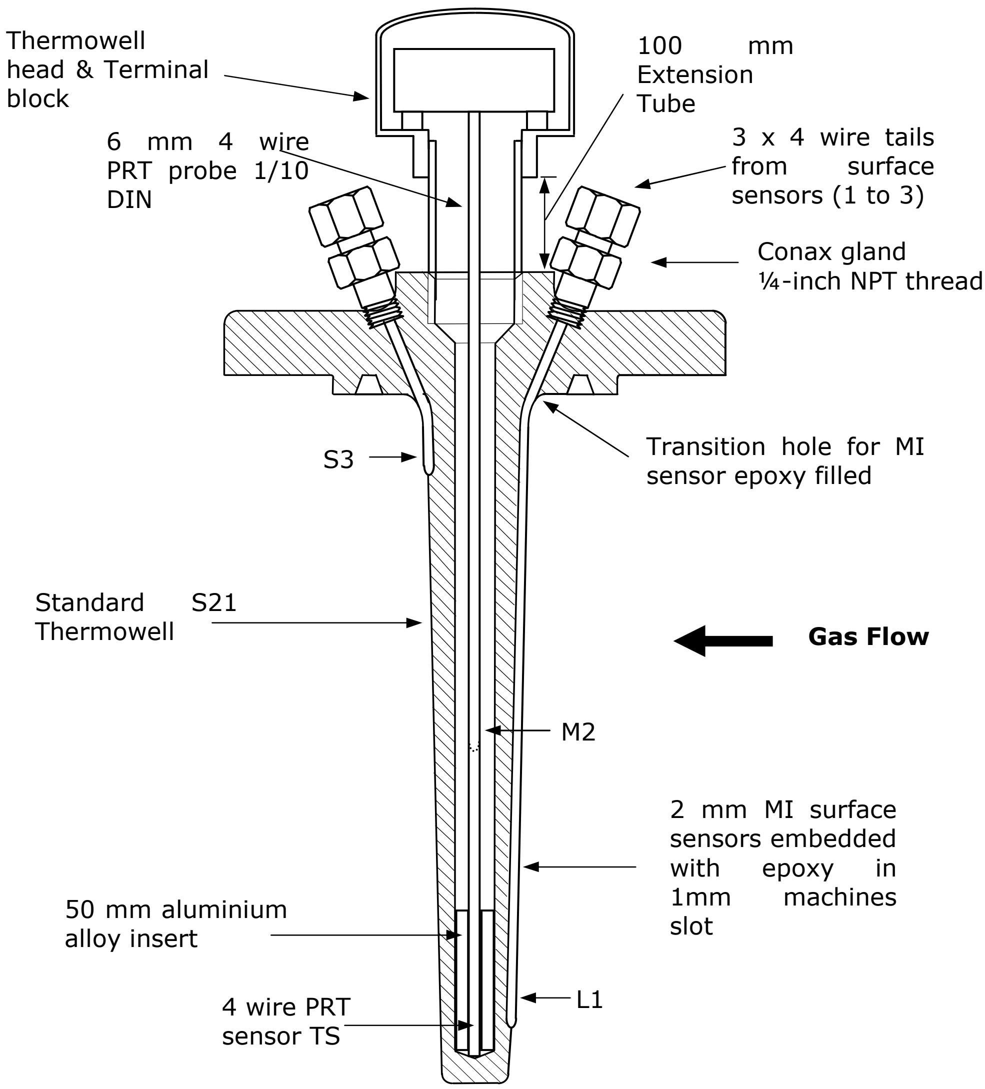


Fig. 12 – CT4 thermowell with additional sensors installed

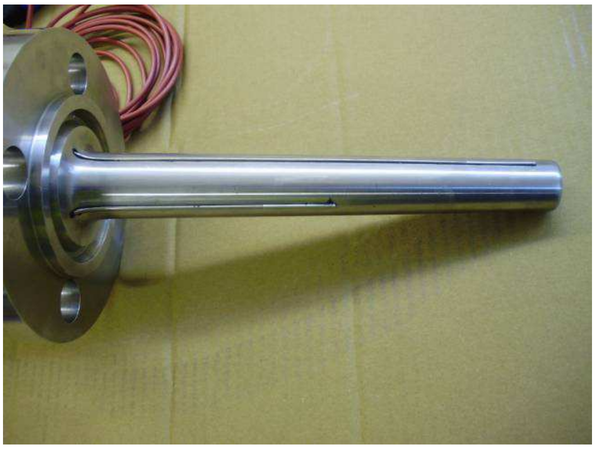


Fig. 13 – Pictures of actual thermowells installed for tests

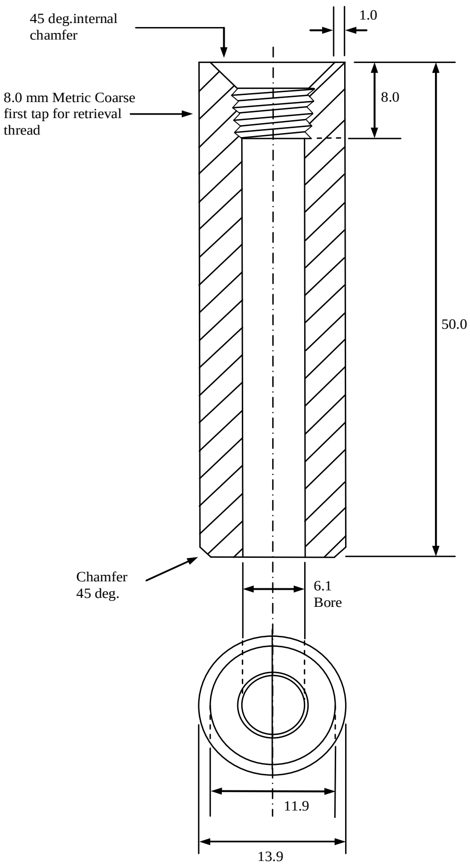


Fig. 14 – CT4 Aluminium alloy insert for 6 mm probes

6.5 Screw-Type Thermowell

A screw-type thermowell was also manufactured with an external temperature sensor to measure the stem temperature during tests. The complete assembly and photograph of the thermowell is shown in Figure 15. The screw mounting gives close thermal coupling to the pipe minimising thermal gradient errors.

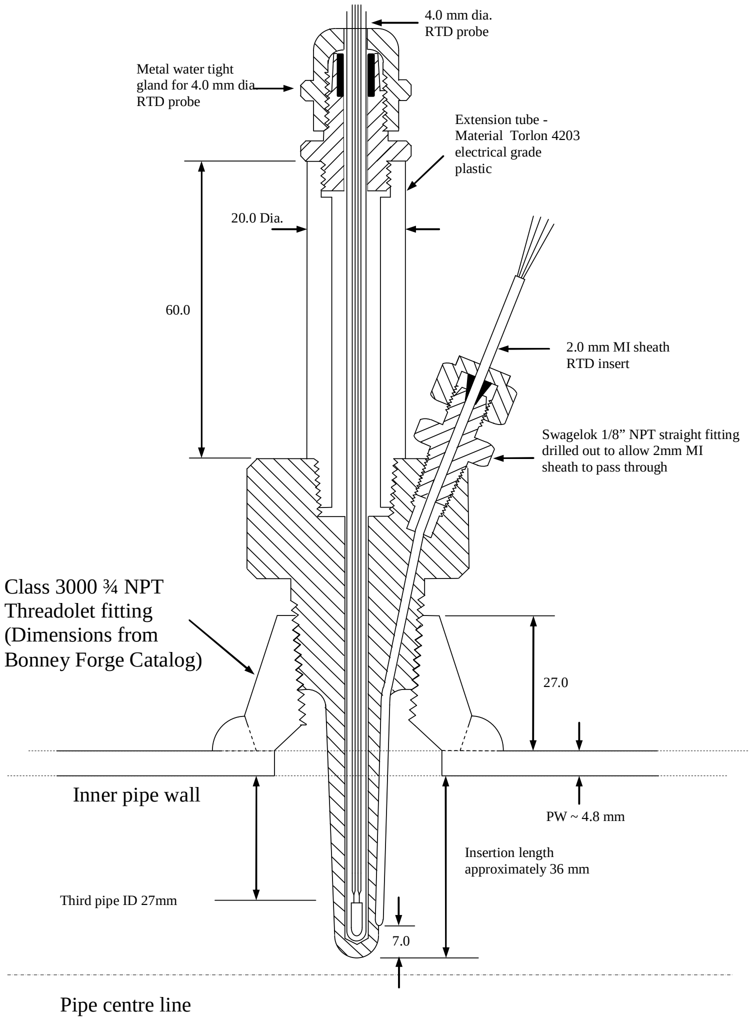


Fig. 15 – Screw thermowell design for small bore pipes

6.6 Surface Temperature Measurement

The same design of mineral insulated 2 mm RTD sensors used on the CT4 thermowells were used to measure internal pipe temperatures. For external surface temperatures, a standard longitudinal sensor was used along with a prototype vertical temperature sensor design. The longitudinal sensor is shown in Figure 16 and the prototype vertical design is shown in Figure 17.

Fig. 16 – Standard National Grid Gas longitudinal surface sensor installed on a three inch pipe before applying insulation

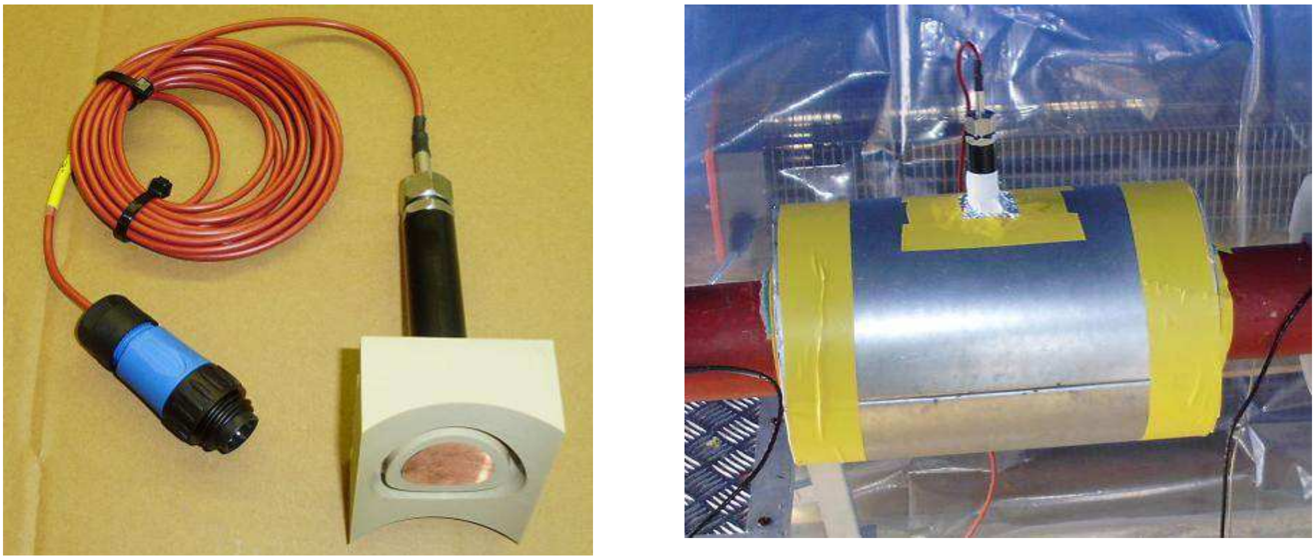


Fig. 17 – New prototype design surface sensors

The vertical sensor design enables maintenance and calibration to be carried out more easily than the longitudinal installation. However, the vertical sensor needs to be machined to fit the curvature of the pipe and more care must be taken with the installation to ensure good surface contact. This design is now being used successfully on metering installations.

6.7 Test Enclosure

A test enclosure was constructed as an environmental chamber that could be installed around test pipes at the DNV GL Flow Centre to enable different weather conditions to be simulated. The test enclosure was fitted with the following equipment for environmental testing:

- 5 kW chiller (cold weather)
- 9 kW of electric heaters (hot weather)
- Tungsten halogen lamps totalling 900 W (solar radiation simulation)
- Chilled water drench system (cold rain)
- Three 3100 m^3/h airflow fans (wind)

Details of the enclosure design are shown in Figures 18 to 21.

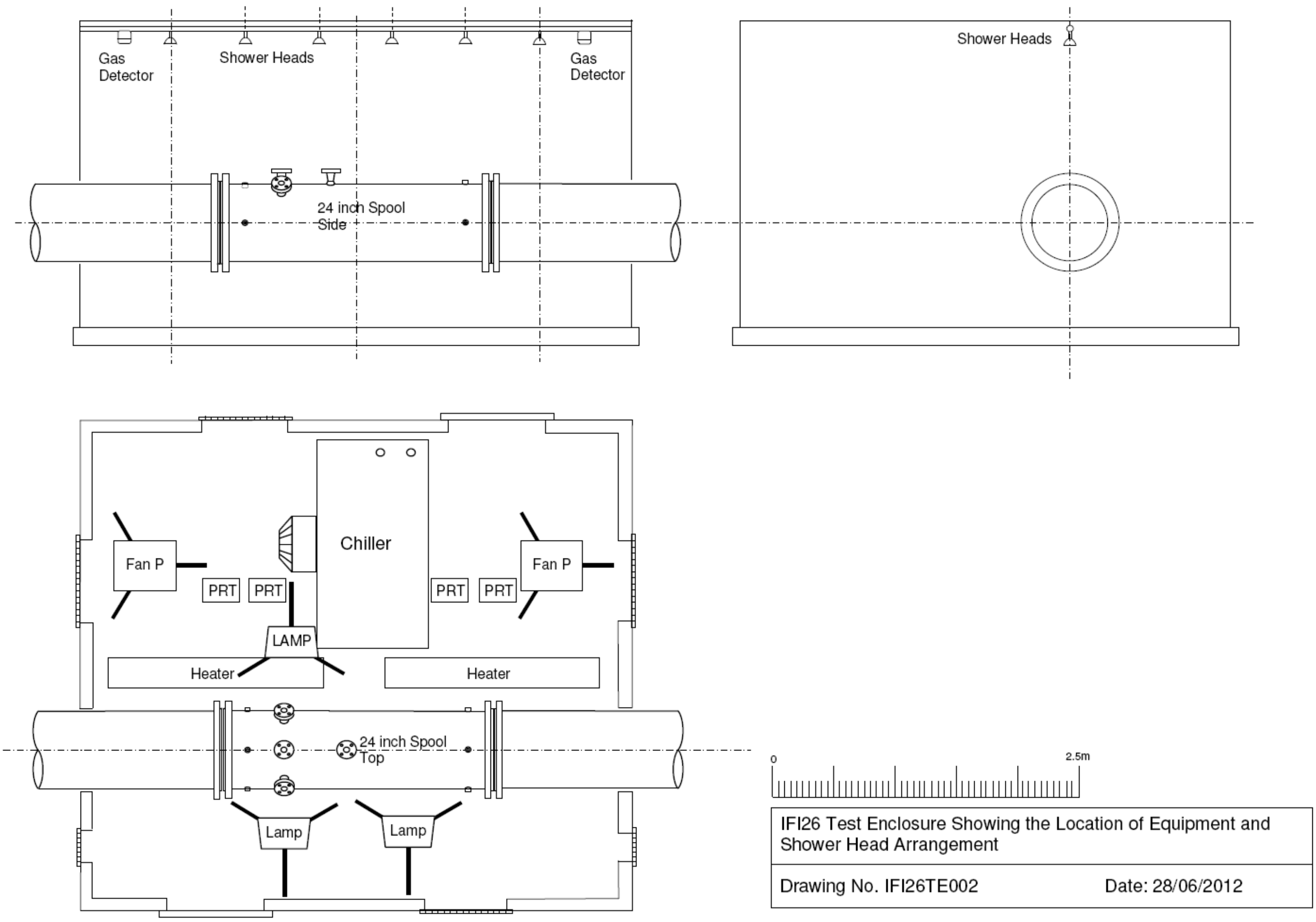


Fig. 18 – Design of the environmental enclosure and location of equipment

Fig. 19 – Environmental test enclosure installed on the 24 inch test pipe at a DNV GL Flow Centre

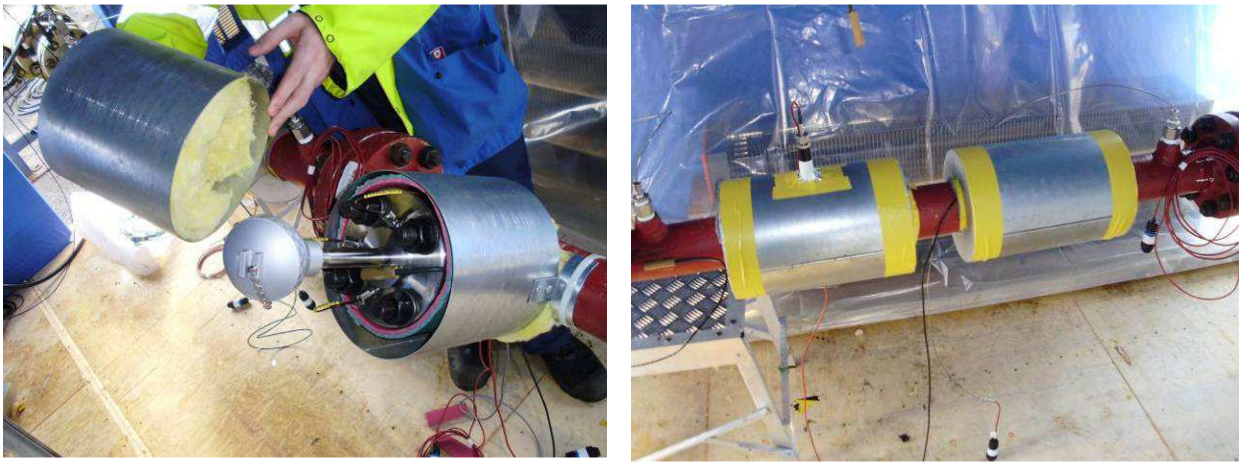


Fig. 20 – Three inch spool test installation inside enclosure

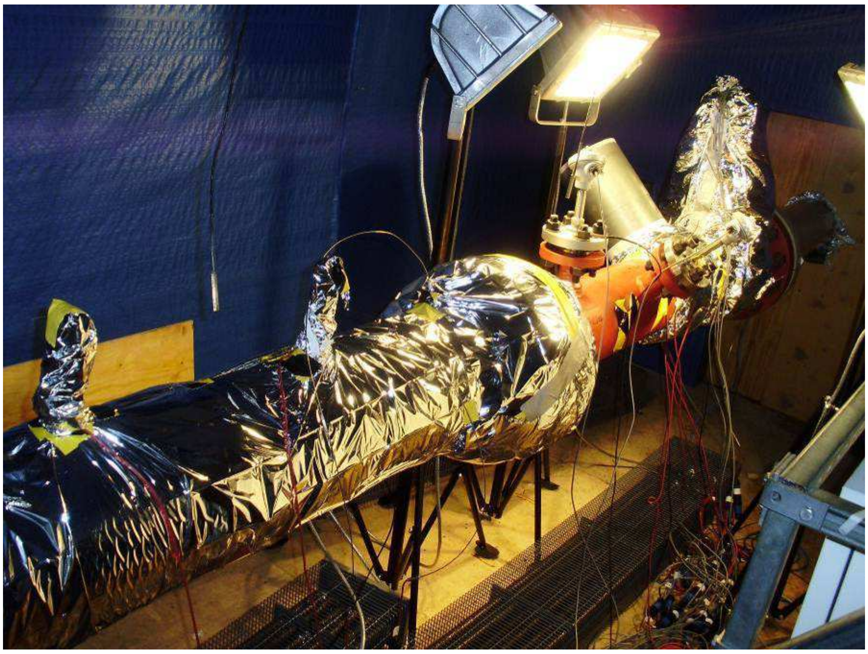


Fig. 21 – High ambient temperature eight-inch spool tests with simulated sunlight

7 RESULTS

7.1 Infrared Photographs

Examples of infrared photographs of the test spools during the temperature tests are shown in Figures 22 to 24. The temperature scale is shown on the right hand side of the photographs in °C.

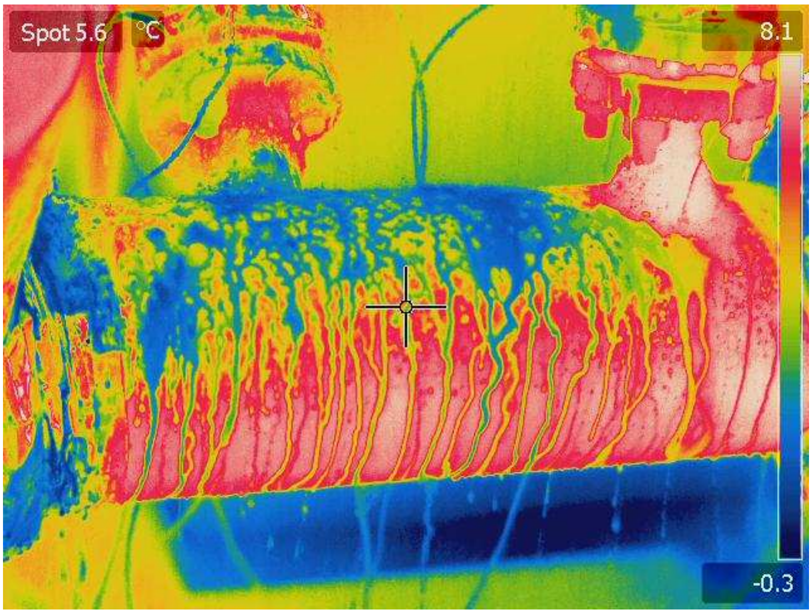


Fig. 22 – Infrared photograph of thermowells on 8-inch spool during rain tests

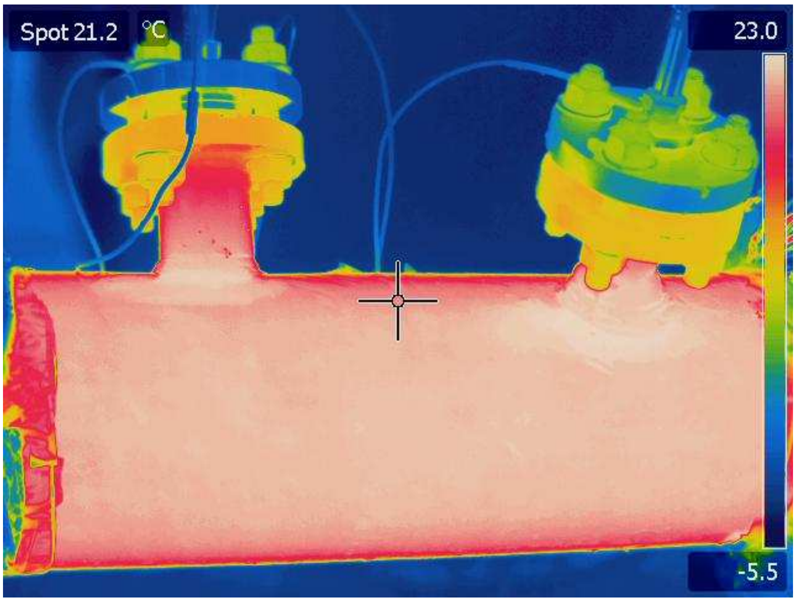


Fig. 23 – Infrared photograph of thermowells on 8-inch spool during low temperature tests

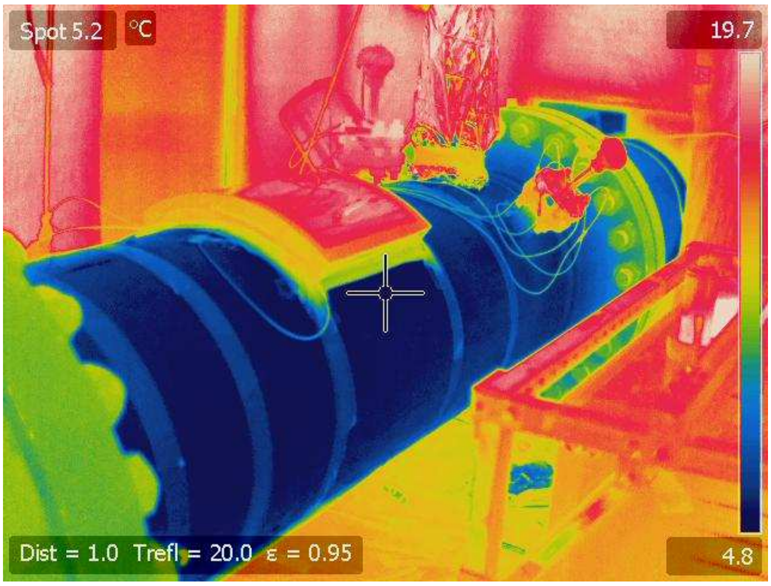


Fig. 24 – 24-inch spool during high temperature tests

7.2 Measurement Response Times

The response times for the sensors in a thermowell to reach the gas temperature are shown in Figure 25. The thermowell was fitted with a close-fitting aluminium insert and poly dimethyl siloxane (PDMS) was used as a heat conduction fluid. Response times for surface sensors are shown in Figure 26.

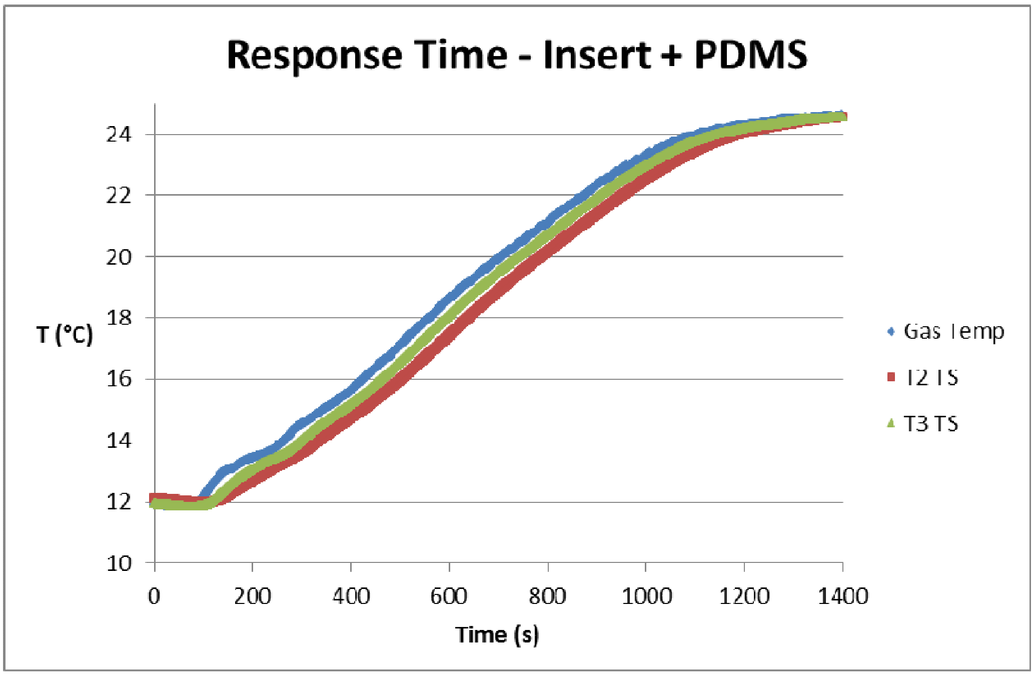


Fig. 25 – Response time for insulated and non-insulated 264 mm CT4 thermowells with insert and poly dimethyl siloxane (PDMS)

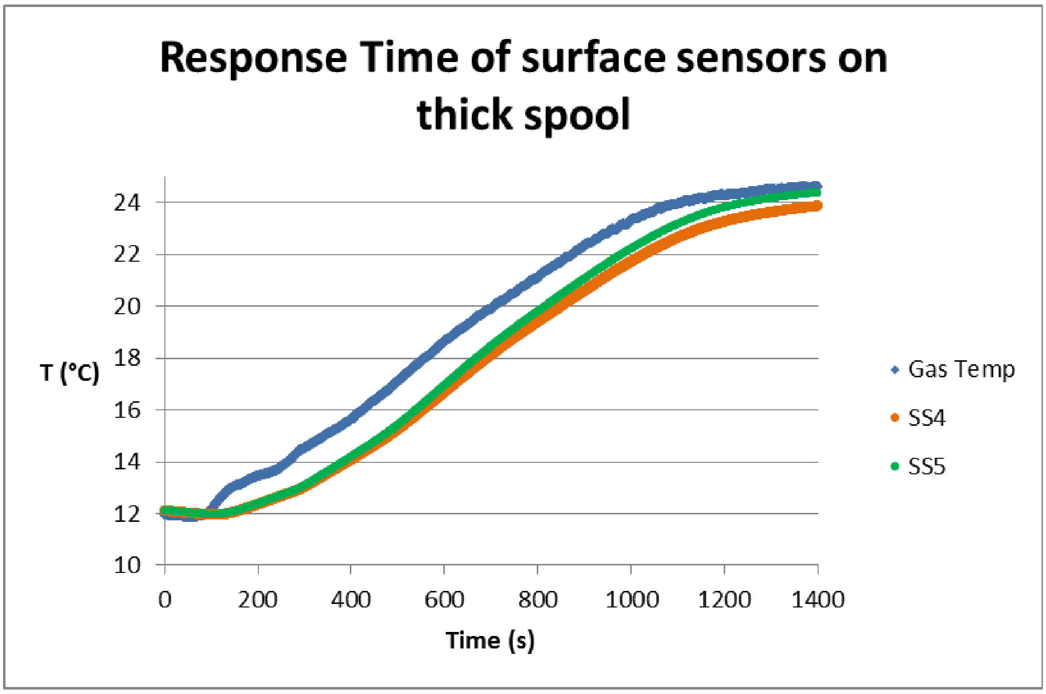
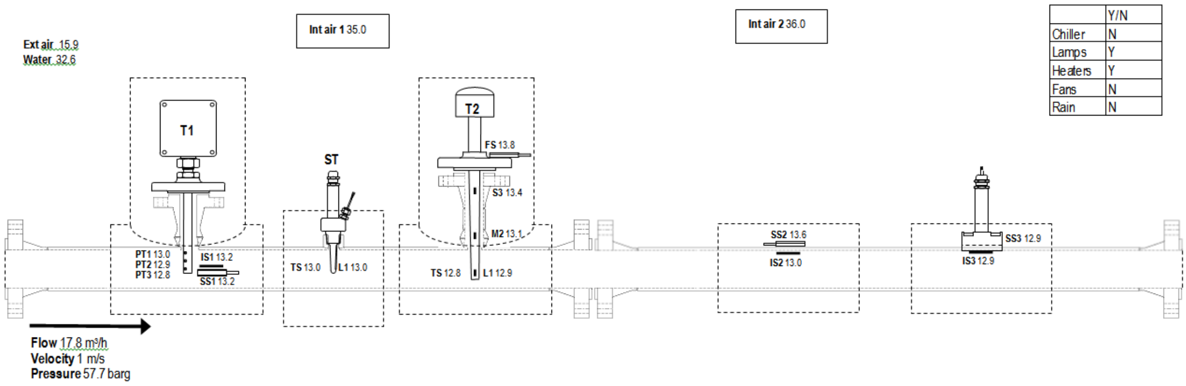


Fig. 26 – Response time of surface sensors on thicker pipe

7.4 Summary of three inch spool tests at a gas velocity of 1 m/s

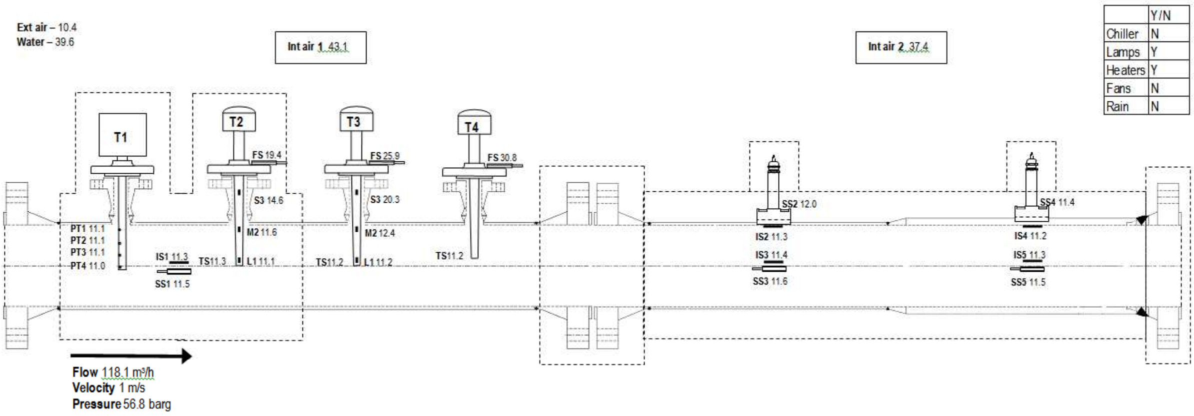


Date	19/10/2012		Time	14:54	Test conditions	Heat + no insulation, 1 m/s														
T1			IS1/SS1			ST			T2			IS2/SS2			IS3/SS3			Air & Water		
3 inch Profile Probe			surface sensors			Screw type thermowell			CT4/264/1 thermowell			surface sensors			surface sensors			PRT sensors		
Insulated			Insulated			Insulated			Insulated			Insulated			Insulated					
Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.
	°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C
PT1	12.96	0.15	IS1	13.18	0.37	L1	13.00	0.19	FS	13.8	0.99	SS2	13.60	0.79	SS3	12.90	0.09	Air 1	35.00	22.19
PT2	12.87	0.06	SS1	13.21	0.4	TS	12.95	0.14	S3	13.41	0.6	IS2	13.00	0.19	IS3	12.90	0.09	Air 2	36.00	23.19
PT3	12.81	0							M2	13.07	0.26							Ext.	15.90	3.09
									L1	12.89	0.08							Water	32.60	19.79
									TS	12.84	0.03									

Three inch spool tests at 1 m/s:

- Gas to air temperature difference 23 °C
- Temperature profile less than 0.15 °C
- Screw thermowell error 0.26 °C
- CT4 thermowell error 0.25 °C
- Vertical surface sensor error 0.09 °C

7.5 Summary of eight inch spool tests at a gas velocity of 1 m/s

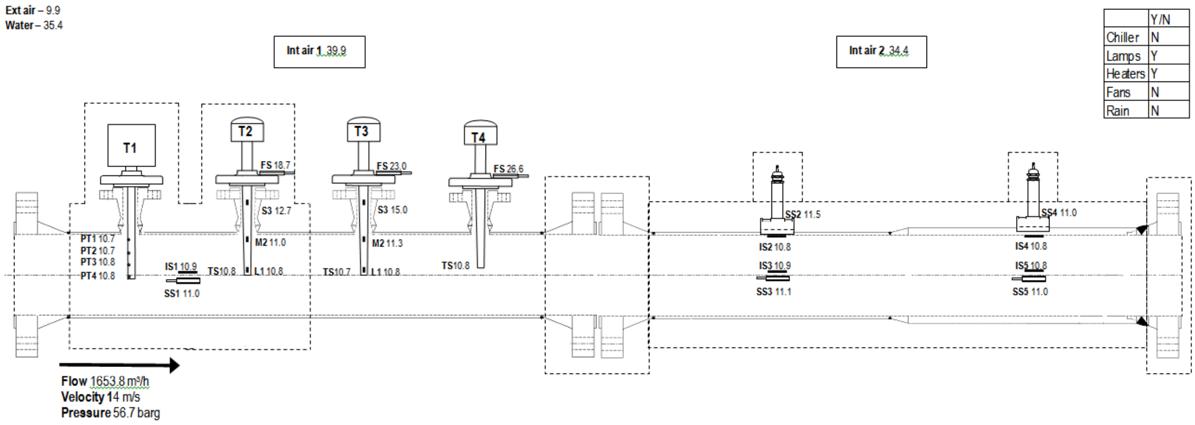


Date	24/10/2012	Time	20:36	Test conditions		Insert + 5 cc PDMS, 1 m/s																	
T1			IS1/SS1			T2			T3			T4			SS2/SS3			SS4/SS5			Air & Water		
8 inch Profile Probe			Surface Sensors			CT4/264/1 thermowell			CT4/264/2 thermowell			CT4/243 thermowell			Surface sensors			Surface sensors			PRT sensors		
Insulated			Insulated			Insulated			Not Insulated			Not Insulated			Insulated			Insulated					
Pipe wall: 6.35 mm																		Pipe wall: 18 mm					
Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C
PT1	11.12	0.08	IS1	11.32	0.28	FS	19.4	8.36	FS	25.86	14.82	FS	30.77	19.73	SS2	11.98	0.94	SS4	11.44	0.4	Air 1	43.14	32.1
PT2	11.05	0.01	SS1	11.47	0.43	S3	14.57	3.53	S3	20.27	9.23	TS	11.16	0.12	IS2	11.26	0.22	IS4	11.21	0.17	Air 2	37.38	26.34
PT3	11.07	0.03				M2	11.58	0.54	M2	12.37	1.33				IS3	11.40	0.36	IS5	11.31	0.27	Ext.	10.37	-0.67
PT4	11.04	0				L1	11.14	0.1	L1	11.19	0.15				SS3	11.60	0.56	SS5	11.45	0.41	Water	39.59	28.55
						TS	11.32	0.28	TS	11.24	0.2												

Eight inch spool at 1 m/s:

- No measurable temperature profile; less than 0.1 °C
- Thermowell gas to air temperature difference 32 °C around thermowells
- Insulated and non-insulated thermowells low error
- Surface sensors low error except thin wall vertical surface sensor
- The vertical surface sensor error was due to poor surface contact

7.6 Summary of eight inch spool tests at 14 m/s

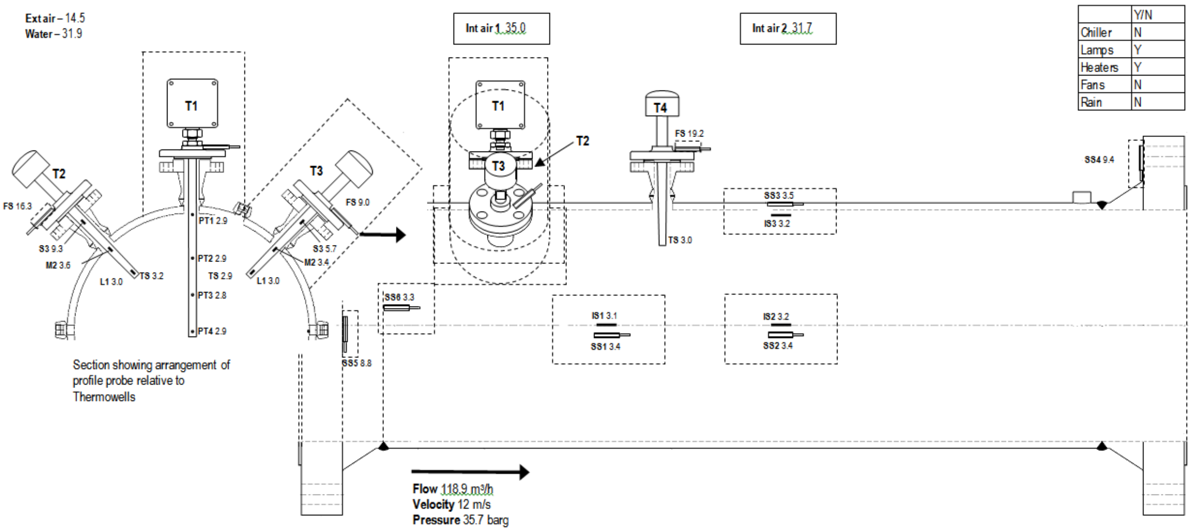


Date	24/10/2012		Time	19:09	Test conditions	Insert + 5 cc PDMS, 14 m/s																	
T1			IS1/SS1			T2			T3			T4			SS2/SS3			SS4/SS5			Air & Water		
8 inch Profile Probe			Surface Sensors			CT4/264/1 thermowell			CT4/264/2 thermowell			CT4/243 thermowell			Surface sensors			Surface sensors			PRT sensors		
Insulated			Insulated			Insulated			Not Insulated			Not Insulated			Insulated			Insulated					
Pipe wall: 6.35 mm																		Pipe wall: 18 mm					
Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.
	°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C
PT1	10.76	0.01	IS1	10.85	0.1	FS	18.7	7.95	FS	22.99	12.24	FS	26.61	15.86	SS2	11.54	0.79	SS4	10.99	0.24	Air 1	39.91	29.16
PT2	10.76	0.01	SS1	11.04	0.29	S3	12.74	1.99	S3	15.03	4.28	TS	10.79	0.04	IS2	10.83	0.08	IS4	10.76	0.01	Air 2	34.43	23.68
PT3	10.79	0.04				M2	10.96	0.21	M2	11.31	0.56				IS3	10.89	0.14	IS5	10.83	0.08	Ext.	9.92	-0.83
PT4	10.75	0				L1	10.78	0.03	L1	10.8	0.05				SS3	11.12	0.37	SS5	10.97	0.22	Water	35.37	24.62
						TS	10.83	0.08	TS	10.71	-0.04												

Eight inch spool at 14 m/s:

- Profile probe maximum difference 0.04 °C
- Thermowell gas to air temperature difference 29 °C around thermowells
- All thermowell errors less than 0.08 °C with or without insulation

7.7 Summary of 24 inch spool tests at 12 m/s

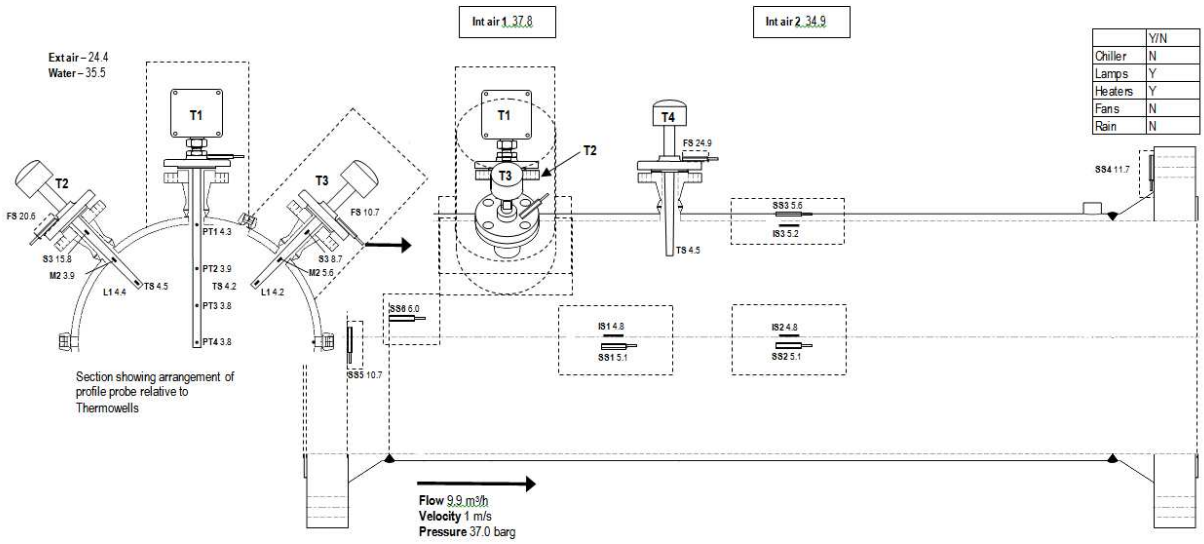


Date	15/11/2012		Time	12:26	Test conditions	heat, 12 m/s																	
SS5/SS6			T1			T2			T3			IS1/SS1			T4			IS2/3 & SS2/3/4			Air & Water		
surface sensors			24 inch profile probe			CT4/264/1 thermowell			CT4/264/2 thermowell			surface sensors			CT4/243 thermowell			surface sensors			PRT sensors		
Insulated			Insulated			Not Insulated			Insulated			Insulated			Not Insulated			Insulated					
Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.	Sensor	Temp.	Diff.
	°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C		°C	°C
SS6	3.34	0.47	PT1	2.88	0.01	FS	16.28	13.41	FS	9.03	6.16	IS1	3.10	0.23	FS	19.18	16.31	SS3	3.49	0.62	Air 1	35.03	32.16
SS5	8.77	5.90	PT2	2.88	0.01	S3	9.27	6.40	S3	5.74	2.87	SS1	3.39	0.52	TS	3.03	0.16	IS3	3.16	0.29	Air 2	31.73	28.86
			PT3	2.84	-0.03	M2	3.55	0.68	M2	3.39	0.52							IS2	3.18	0.31	Ext.	14.49	11.62
			PT4	2.87	0	L1	2.97	0.10	L1	2.97	0.10							SS2	3.40	0.53	Water	31.85	28.98
						TS	3.16	0.29	TS	2.93	0.06							SS4	9.44	6.57			

Twenty four inch 12 m/s:

- Gas air temperature difference at thermowells 32 °C
- Profile temperature difference less than 0.03 °C
- Non-insulated CT4 error 0.29 °C
- Insulated CT4 error 0.06 °C
- Surface sensor errors, 0.52 °C, 0.62 °C, 0.53 °C

7.8 Summary of 24 inch spool tests at 1 m/s

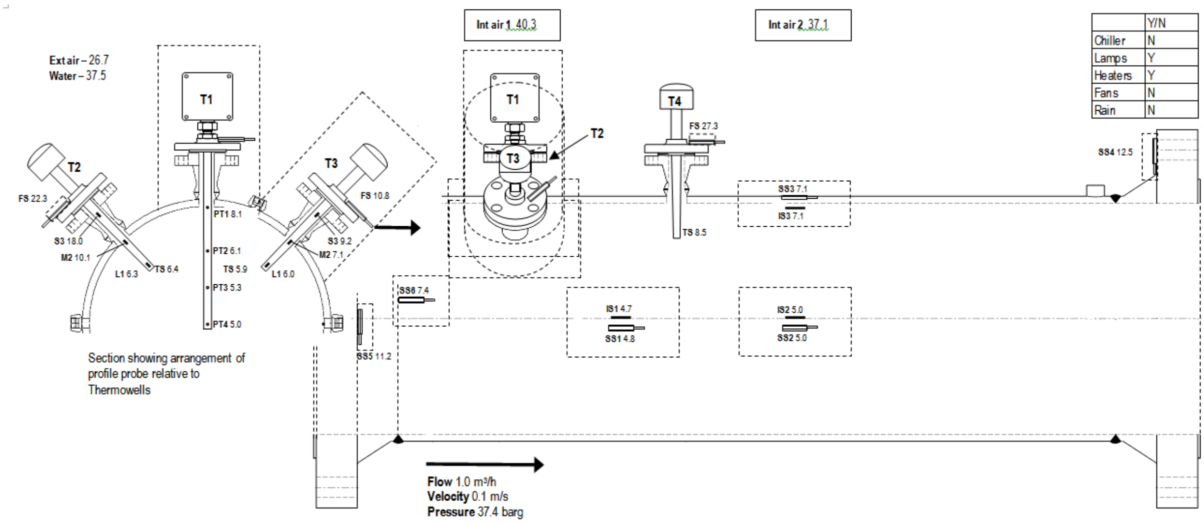


Date	15/11/2012		Time	13:42	Test conditions	heat, 1 m/s																	
SS5/SS6			T1			T2			T3			IS1/SS1			T4			IS2/3 & SS2/3/4			Air & Water		
surface sensors			24 inch profile probe			CT4/264/1 thermowell			CT4/264/2 thermowell			surface sensors			CT4/243 thermowell			surface sensors			PRT sensors		
Insulated			Insulated			Not Insulated			Insulated			Insulated			Not Insulated			Insulated					
Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C
SS6	6.01	2.26	PT1	4.27	0.52	FS	20.56	16.81	FS	10.73	6.98	IS1	4.84	1.09	FS	24.87	21.12	SS3	5.60	1.85	Air 1	37.8	34.05
SS5	10.72	6.97	PT2	3.88	0.13	S3	15.80	12.05	S3	8.71	4.96	SS1	5.14	1.39	TS	4.46	0.71	IS3	5.20	1.45	Air 2	34.92	31.17
			PT3	3.75	0	M2	3.86	0.11	M2	5.57	1.82							IS2	4.83	1.08	Ext.	24.41	20.66
			PT4	3.75	0	L1	4.39	0.64	L1	4.17	0.42							SS2	5.05	1.30	Water	35.54	31.79
						TS	4.50	0.75	TS	4.15	0.40							SS4	11.65	7.90			

Twenty four inch spool piece 1 m/s:

- Gas air temperature difference at thermowells 34 °C
- Profile temperature difference 0.52 °C near pipe wall
- Non-insulated CT4 error 0.75 °C
- Insulated CT4 error 0.4 °C
- Surface sensor errors, 1.39 °C, 1.85 °C, 1.3 °C

7.9 Summary of 24 inch spool tests at 0.1 m/s



Date	15/11/2012		Time	14:27	Test conditions	heat, 0.1 m/s																	
SS5/SS6			T1			T2			T3			IS1/SS1			T4			IS2/3 & SS2/3/4			Air & Water		
surface sensors			24 inch profile probe			CT4/264/1 thermowell			CT4/264/2 thermowell			surface sensors			CT4/243 thermowell			surface sensors			PRT sensors		
Insulated			Insulated			Not Insulated			Insulated			Insulated			Not Insulated			Insulated					
Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C	Sensor	Temp. °C	Diff. °C
SS6	7.39	2.4	PT1	8.05	3.06	FS	22.26	17.27	FS	10.84	5.85	IS1	5.21	0.22	FS	27.29	22.3	SS3	7.08	2.09	Air 1	40.28	35.29
SS5	11.24	6.25	PT2	6.13	1.14	S3	18.01	13.02	S3	9.23	4.24	SS1	5.32	0.33	TS	8.53	3.54	IS3	7.06	2.07	Air 2	37.14	32.15
			PT3	5.26	0.27	M2	10.08	5.09	M2	7.14	2.15							IS2	5.02	0.03	Ext.	26.74	21.75
			PT4	4.99	0	L1	6.32	1.33	L1	5.98	0.99							SS2	5.04	0.05	Water	37.5	32.51
						TS	6.37	1.38	TS	5.89	0.9							SS4	12.49	7.50			

Twenty four inch spool piece 0.1 m/s:

- Gas air temperature difference at thermowells 35 °C
- Thermal conduction errors starting to dominate
- Profile temperature difference 3.06 °C near pipe wall
- Non-insulated CT4 error 1.38 °C
- Insulated CT4 error 0.9 °C
- Surface sensor errors, 0.33 °C, 2.09 °C, 0.05 °C
- Surface sensor temperatures close to inner pipe wall temperatures

7.10 Solar Radiation

The impact of solar radiation on a CT4 thermowell is shown in figure 27.

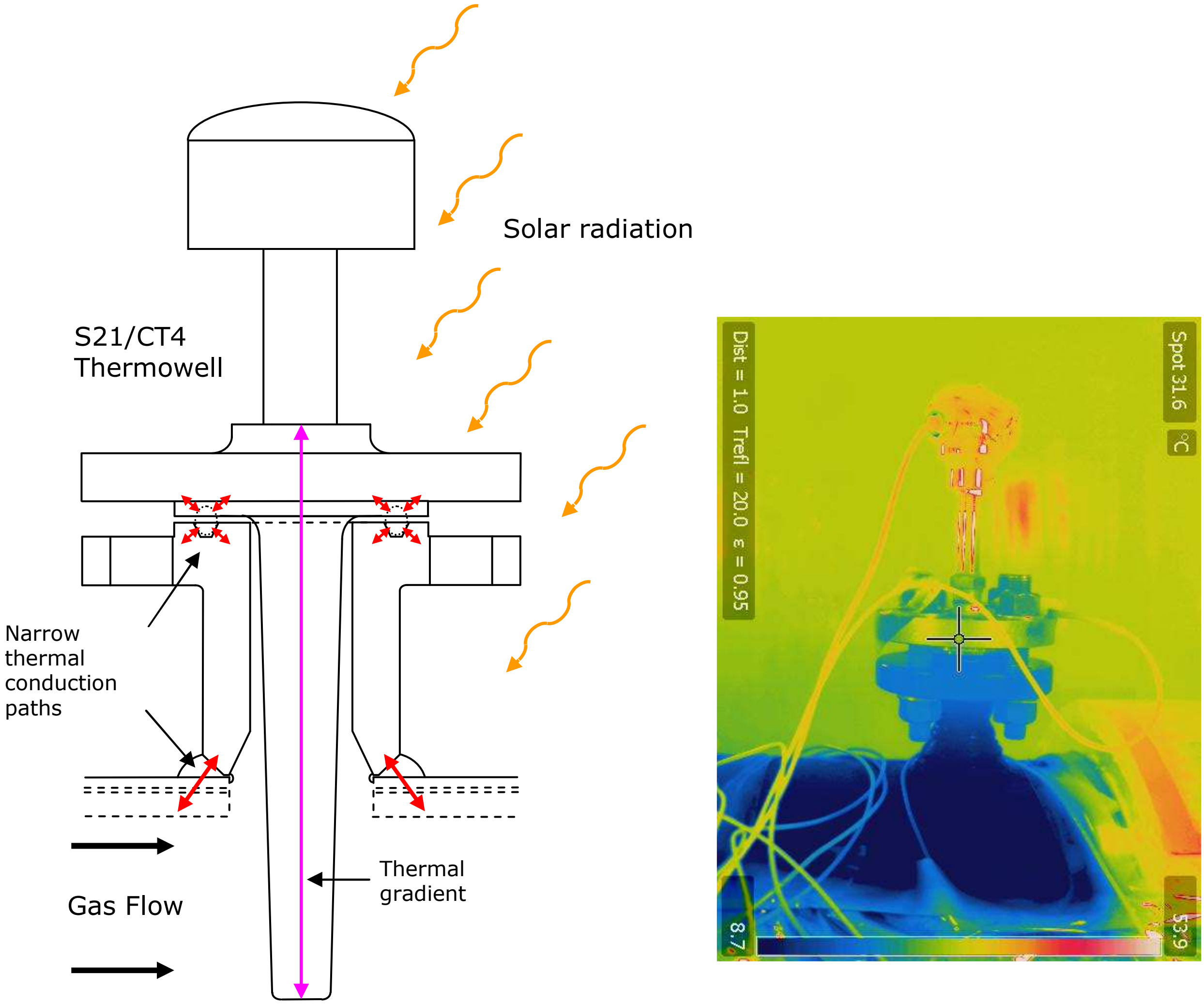


Fig. 27 – CT4 thermowell thermal conduction paths and solar radiation with a thermal image illustrating a hot thermowell with cool pipe and fitting

Ring type joints have a very small thermal conduction path area – the thermal image shows that solar radiation affects the top of the thermowell to a much greater extent than the lower part which remains close to the pipe temperature.

Raised-faced flanges, however, give a better thermal coupling to the thermowell to minimise thermal gradients and potential errors at low flows.

8 CONCLUSIONS

1) For gas velocities between 2 m/s and 10 m/s no temperature profile was measured across the gas stream on any pipe size (no greater than 0.2 °C of gas temperature). Apparent temperature profiles at very low velocities and high differential temperatures are due to thermal conduction in the profile probe.

2) It is not necessary to insert thermowells of the CT4 type of design to a depth greater than approximately 90 mm to measure gas temperature with an uncertainty of 0.5 °C for gas velocities over 2 m/s for pressures of greater than 30 bar.

3) For all CT4 thermowells at gas velocities above 1 m/s, with or without insulation, the measured temperature was within ±0.5 °C, within ±20 °C of ambient temperature.

4) Surface sensors had reasonable transient response, about half that of a CT4 thermowell.

5) Insulation can reduce measurement errors in conditions where air temperature is less than gas temperature.

6) Insulation may not significantly reduce measurement error where air temperature is greater than gas temperature and where solar heating effects are present – the insulated area is subject to an oven effect.

7) The short screw type thermowell design used on the 3-inch spool had a measurement error less than 0.5 °C under all operating conditions.

8) Surface temperature measurements at velocities over 1 m/s using the National Grid Gas T/SP/S/21 installation guidance, within ±20 °C of ambient temperature, generally had measurement errors less than 0.5 °C under stable operating conditions.

9) Errors in some of the prototype vertical surface sensors were found to be due to surface contact in one case and the sensor not being fully inserted in the other case. Manufacturing tolerances and installation procedures have since been improved.

10) The recommendations for surface temperature installation and thermal insulation are:

    a) The minimum width and breadth of insulation should be 60 times the wall thickness of the pipe to minimise environmental effects of thermal conduction along the pipe wall.

    b) Surface mounting sensors should not be installed closer than 60 times the pipe wall thickness from a pipe clamp, flange, pipe fitting, ground entry or any situation that may influence measurement accuracy.

    c) Minimum insulation thickness should be 80 mm.

9 ACKNOWLEDGEMENTS

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