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Paper 4.3

A Novel Infrared Absorption Technique for Measuring Flare Gas Flow

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1 INTRODUCTION

An infrared (IR) cross-correlation flow meter that had previously been applied in combustion stacks was modified for testing at NEL as a potential flare gas meter. The work was part-funded by the DTI National Measurement System under the Measurement for Innovators (MFI) initiative and by BP. The MFI scheme is designed to help UK small and medium sized enterprises (SMEs) to develop new and innovative technologies.

The tests were carried out using ambient air with a small amount of atomised water injected into it to act as a tracer. The purpose of the tests was to assess how the modified IR meter (IR4MKII) responded over a wider range of velocity than in previous applications and to then draw conclusions as to its potential for operation in an actual flare line.

The tests showed that the meter was capable of measuring a velocity range of 0.4 – 67 m/s (a turndown of 167:1 on flow), although tests at higher velocity may have revealed an extended meter range. The repeatability of the meter was moderately good, but it was found that it could be further improved through subtle modifications to the system electronics.

From the test data presented, and an assumed mass fraction of 80% methane, it was calculated that a 0.1% variation in the flow (arising from turbulent fluctuations etc.) should be enough to enable a signal to be obtained from the meter in a flare gas line, which is an encouraging result. However, it is recognised that the IR4MKII meter would have to be tested on methane gas to increase confidence in its use for flare gas applications. The current technology would also have to be modified to respond to changes in methane, rather than water, but this is a relatively straightforward modification.

2 BACKGROUND

Gas flaring constitutes about one-fifth of the total CO_2 emissions produced by the UK oil & gas industry (UKOOA [1]). The CO_2 released by flaring contributes to global warming and, thus, the amount of gas flared must be reported to the regulator on an annual basis. Offshore flaring in the UK sector is currently regulated by the DTI Licensing and Consents Unit (LCU), based in Aberdeen. The law requires that operators must apply for flare consents on an annual basis (and more regularly during start up of a well).

The EU Emissions Trading Scheme (EU ETS), phase 1 of which commenced in January 2005, is the world's first mandatory carbon trading scheme. The EU ETS spans a number of industry sectors, including oil and gas (EU directive 2003/87/EU [2]). The EU ETS is a Kyoto initiative with the goal to reduce collective carbon emissions from the EU by 8% below baseline levels by 2012. Phase 2 of the EU ETS (2008 – 2012), due to commence in 2008, has been extended to cover additional CO_2 emissions from additional industry sectors including flaring from offshore oil and gas production.

The Measurement and Reporting Guidelines (M&RG) [3] accompanying EU directive 2003/87/EC set out the method of calculating CO_2 emissions for various activities that produce CO_2, such as chemical processes, combustion facilities and flaring. Section 2.1.2 of Annex II of the M&RG refers to routine and operational flaring under the sub-heading "Sources of CO_2 emissions from combustion installations and processes".

The M&RG stipulate various uncertainty tiers with the mandate that an operator must meet the lowest uncertainty tier, unless there is an economic or technical reason why it cannot be achieved. For volumetric flow rate, these are currently: Tier 1: ±12.5%, Tier 2: ±7.5% Tier 3: ± 2.5%.

2.1 Issues with flare gas measurement

Ideally, flare-gas flow rate should be measured by a flow meter to give the lowest uncertainty. However, there are very few flow meter technologies suitable for accurate flare-gas measurement. Estimation techniques can be an acceptable alternative where metering technologies will struggle to give an accurate reading (i.e. during emergency blow-downs) where a high proportion of the gas produced is flared-off for safety purposes. Pressure drop must be minimised in the flare line to enable gas to be expelled as quickly as possible, meaning that any technology that is installed must be non-intrusive.

Metering flare is not generally an easy proposition: a wide flow measurement range (typically 0.1 and 100 m/s), coupled with large line sizes, and the potential for liquids and solids to be present in the gas stream are just some of the aspects that a meter must be able to cope with. Another key issue is that it is not normally possible to calibrate the meter over the entire flow rate range. Often meters are installed hot-tapped onto existing flare lines and, thus, a calibration of the meter is not forthcoming.

Many technologies have been tried in the past and have failed - either due to complete structural failure, fouling or an inability to cover the wide range of velocities that can exist in the flare stack. The stipulation that any installed technology must be non-intrusive and cover a wide turndown rules out many of the more traditional technologies - such as full-bore turbines and orifice plates. Any installed technology must be intrinsically safe for explosive environments and should be installed using hot-tapping processes, since the cost of stopping production is very high.

The two technologies commonly used in flare lines are ultrasonic meters and thermal mass probes. Similar to other metering technologies, thermal mass meters need to be in contact with the fluid, as they use convective heat transfer to infer a mass flow rate. They are sensitive to changes in gas composition and also suffer from the effects of dirt deposition, which tends to insulate the sensing probes – in the worst case leading to loss of signal. Liquid droplets will cause sudden spikes in meter output as the liquid phase boils off the heated probes.

The current state-of-the-art for flare gas measurement is widely viewed as the ultrasonic transit-time meter. The main advantages of this technology over others is that it is non-intrusive and has wide enough turndown (> 1000:1) to enable it to be used in emergency flares offshore.

One drawback with ultrasonic meters is that they are particularly expensive to buy and install. Installation costs can often dwarf the cost of the meter itself because of the precision welding required to retrofit to existing flare lines. For example, a flare gas ultrasonic meter might cost around £50,000, whilst the total installed cost may be closer to £300,000 [4].

3 OPTICAL FLOW METERING TECHNOLOGIES

Whilst Laser Doppler Velocimetry (LDV) has been used to map out velocity profiles in pipes and ducts for many years now, the use of optics as a flow meter is relatively new. Several manufacturers have already recognised the potential of using optical methods as a means of measuring flow rate through pipes and ducts. These include: Perception Sensing & Instrumentation™, based in the UK, Canadian company Photon Control™ Inc. and Optical Scientific™ Inc. (OSI), based in California.

When an infrared or laser light beam is shone across a pipe or duct, temporal fluctuations in the gas flow (due turbulence etc.) can be detected as changes in received light energy in order to determine a velocity, and hence volumetric flow rate. There is no interaction between the fluid and the light beams, analogous to a passive observer watching a train pass between two markers. The observer has no interaction with the train or the environment surrounding it. The ability of an optical system to observe movement in flare stacks, or other flow systems irrespective of pressure, velocity or temperature has distinct advantages. However, in order for optical techniques to work there must be an "observable" feature that can be tracked.

To understand the way in which optical techniques work, the interaction of the measurement with the target medium needs to be understood. Coriolis, vortex and differential pressure meters (Fig. 1) all rely to some degree on mechanical forces being exerted by the measurement medium. This means both intimate contact with the measurement medium, giving rise to reliability problems in dirty or aggressive gas applications, and the necessity to extract energy from the flow stream. The latter is particularly difficult at low velocities and low pressures.

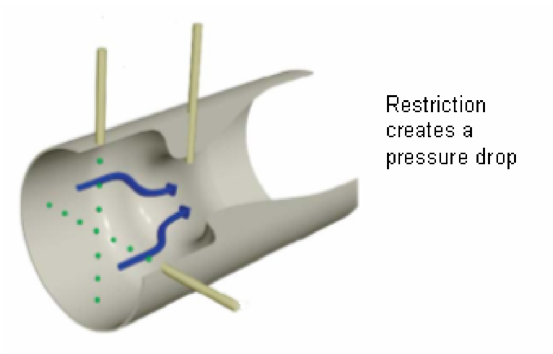


Fig. 1 – Schematic of a differential pressure device

Whilst ultrasonic meters do not extract energy from the measurement medium, they do transmit energy through it. The level of intimate contact may be less than other methods, but the measurement is still essentially the mechanical process of molecules pushing against each other to transmit the ultrasonic energy from one side of the duct to the other.

However, ultrasonic pulses are not easily propagated through low-pressures gases and, at high velocity, the ultrasonic beams may be deflected by the flowing gas leading to insufficient energy reaching the receivers. In extreme cases, these could lead to a complete loss of signal.

In addition, ultrasonic noise can be generated during emergency depressurisation processes, reducing the signal-to-noise ratio; in extreme cases the noise could completely swamp the signal. Dual- or multi-phase flows also present problems to ultrasonics, owing to the large difference in the speed of sound between the liquids/solids and the gas.

Optical meters are not as susceptible to the aforementioned effects as there is no signal propagation through the fluid. However, obscuration of the optical path due to build-up of dirt on the windows could be a problem in especially dirty gas flows.

Up to now, optical flow meters have found application in hot or particle-laden gases where other technologies, such as ultrasonic meters and Pitot tubes, fail because of damage to the sensors, fouling or a loss of signal. Successful applications for optical techniques include gasification and incineration plants, dual-phase flows (especially where water droplets form), and in high vacuums.

In relation to flare stacks, the anticipated advantages of optical-based techniques over other technologies are:

- A wide turndown on velocity
- Non-intrusive sensors (near-zero pressure drop)
- High velocity upper limit (some designs reportedly cope with sonic conditions)
- Output independent of gas composition
- Applicable to a wide range of line sizes
- Can operate at both low or high pressure
- Can operate at high temperature
- Low power input - intrinsically safe for explosion proof environments

There are three types of optical flow meter: Optical scintillation, twin laser and absorption cross correlation meter.

- Optical scintillation meter

These meters utilise the phenomenon that small changes in gas density give rise to variations in apparent brightness or colour of a luminous object when viewed through a gaseous medium (this is analogous to the twinkling of stars viewed through the earth's atmosphere). The gas velocity is measured by sensing the speed of movement of the "scintillations" produced by time-dependent fluctuations in density arising from temperature differentials or turbulence. The sensors operate in the infrared wavelength. The technique was developed for high-temperature gases, but has been modified for use at ambient temperature. The optics are placed in bosses located at either side of the pipe such that the single, infrared beam crosses the pipe diameter. This meter has been commercialised by Optical Scientific™ Inc. [5], with a model specifically targeted at flare gas applications being recently introduced. It is claimed that this meter can operate over the range 0.1 to 100 m/s to an uncertainty of 5% over the range 5 – 100 m/s.

- Twin laser meter

A twin laser time-of-flight (TOF) velocity meter for flue-gas applications, developed by J. Hyde in 1999 [6], is one of the few successful implementations of the technology for industrial applications. Small particles of dirt inherent in the gas stream will produce "visible" specks of light that are picked up by a set of photo-detectors (this is analogous to observing dust particles crossing sunlight beams on a sunny morning). Two lasers placed a fixed distance apart illuminate and detect the passage of the particulates in order to derive a TOF measurement.

The detectors may be located on the same side of the pipe as the transmitters, with the light being reflected back onto the detectors, or they may be located on the opposite side, with the light being refracted onto the receiving optics. The light is focused onto the detectors using a series of lenses. Canadian company Photon Control™ Inc. have developed a similar technique for measuring flow in gas pipelines that they refer to as Laser-Two-Focus (L2F) [7]. It is claimed that the L2F can operate in flare lines over the range 0.1 to 160 m/s to an uncertainty of between 3 and 10%, depending on velocity.

- Infrared absorption cross correlation meter

This is the meter-type that is the focus of this paper. The infrared (IR) absorption cross-correlation meter uses the phenomenon that certain gases, such as CO_2, CH_4 and H_2O, absorb infrared light at discrete wavelengths which can then be sensed by an optical detection system.

The absorbance of the light energy is defined as the log of the light intensity entering a sample (i.e. a gas), divided by the light intensity leaving the sample

$$A = \log_{10} (P_0 / P) \tag{1}$$

where P_0 is the light intensity incident on a sample, whilst P is the intensity of the light leaving the sample. The absorbance can be calculated using Beer-Lambert's law

$$A = \varepsilon bc \tag{2}$$

where ε is the molar absorbtivity of the gas (m^3/mol-m), b is the path length through the gas (m) and c is the molar density of the gas (mol/m^3). Thus, if the absorptivity and molar density of the gas are constant, the light intensity reduces logarithmically with path length through the gas.

In addition, temporal variations in light intensity caused by turbulence etc. will provide a characteristic signal pattern that can be tracked in order to determine a time-of-flight measurement of the gas through the meter.

4 DEVELOPMENT OF IR TECHNOLOGY FOR TESTS AT NEL

Figure 2 details a schematic of the IR time of flight (TOF) meter installed in a pipe spool. Two light beams (labelled A and B) separated by a known distance in the axial direction, L, detect temporal fluctuations in gas density. The velocity of the gas is then given by dividing the distance between the beam centres, L, by the time difference, Δt (i.e. v = L/Δt).

Fluctuations in pressure, temperature, turbulence, or in the movement of particulates carried within the gas, will generate a unique digital waveform at the two beam positions separated in time (as shown on Fig 2b). A technique called cross-correlation is employed to determine Δt accurately. The basis of cross-correlation is that the two waveforms are cross-multiplied whilst progressively sliding them together until a spike occurs indicating that a good match has been achieved (Fig. 2c).

The time taken to do the correlation calculations is important as it affects the response time of the instrument. The current processing method allows 500,000 samples from each channel to be processed in real time (i.e. the correlator outputs a new correlation result, correlating 2 data streams, each with 500,000 16-bit samples, every 20 µs). This includes performing the correlation to generate the correlation output array, performing "peak picking" and outputting the array coordinate of the peak result. In practice, these results are averaged and a final output given every few hundred milliseconds. The high-speed correlation algorithm is key to the success of the IR meter.

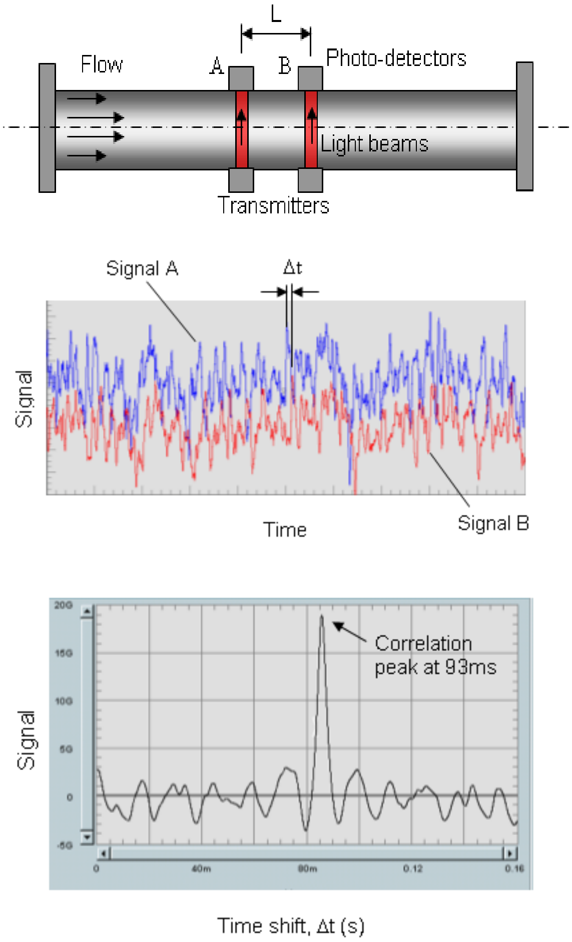


Fig. 2 – TOF method using the cross-correlation method

In flare-gas lines there will be an abundance of methane and other higher-hydrocarbons, such as ethane, propane and butane, generally in progressively smaller quantities as molecular weight increases.

Figure 3 shows the infrared absorption lines for H_2O, CO_2, CO and CH_4. These gases produce strong absorption lines at wavelengths of between 2 µm and 5 µm. The range of absorption wavelengths for alkanes is around 3 – 30 µm, although hydrocarbons with spectra at the shorter wavelengths produce a weaker response. Thus, the absorption technique can be used to determine the composition of a hydrocarbon gas mixture as well as method with which to measure gas flow rate.

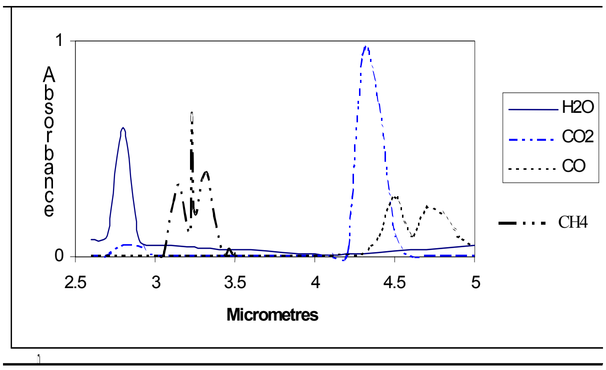


Fig. 3 – Absorption spectra for various gases

4.1 Development of the IR4MKII Meter for Flare Gas Application

4.1.1 System electronics

Figure 4 shows a schematic of the IR4MKII meter electronics (note: the IR4MKII is a modified version of the IR4 infra-red cross-correlation meter used previously in stacks and ducts with hot or particle-laden gases).

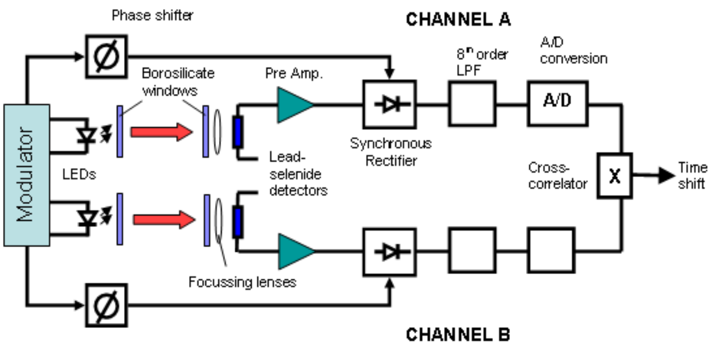


Fig. 4 – Schematic of the electronics of the IR4MKII meter

The meter consists of the optics and associated signal processing electronics. The measuring optics comprises two infrared light sources (LEDs) and two lead-selenide (PbSe) detectors. These are located behind borosilicate glass windows to shield the optics from the prevailing flow. The LEDs are modulated at a frequency of 150 kHz. The detectors can sense at a frequency of 200 kHz, but the frequency of the final processed signal, after rectification, an 8th-order Low Pass Filter (LPF) and A/D conversion, is 50 kHz.

The output from the IR4MKII meter was connected to a PC that allowed graphical information from the meter to be displayed and logged during testing. In field applications, the PC would be replaced by a dedicated flow transmitter.

The LED light sources provide a 1mW output, about 25% of which falls on the lead-selenide detectors through the optical focussing system, assuming zero absorption in a line size of about 200mm. The total energy used by the source and detector is therefore very low and is therefore suitable for applications in explosive atmospheres, such as found on offshore platforms.

4.1.2 Signal analysis

Up to now the IR meter had only been used in ducts where the gas velocity ranged from about 3 to 30m/s. In the original system, only changes in the amplitude of the received infrared signal were resolved using the cross-correlator

In flare-gas applications, the dynamic range is generally considered to be in the region of 0.1 to 100m/s. Hence, to extend the dynamic range of the meter, the system was changed to respond to absolute concentrations in the gas make-up by removal of the DC component of the signal (Fig. 5).

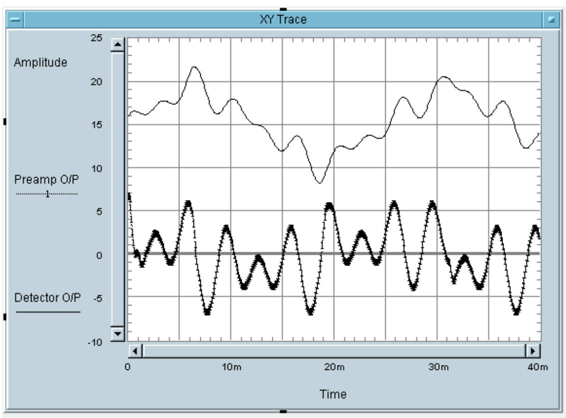
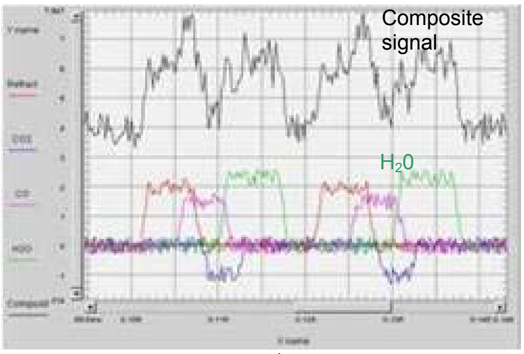


Fig. 5 – Short-term meter signals

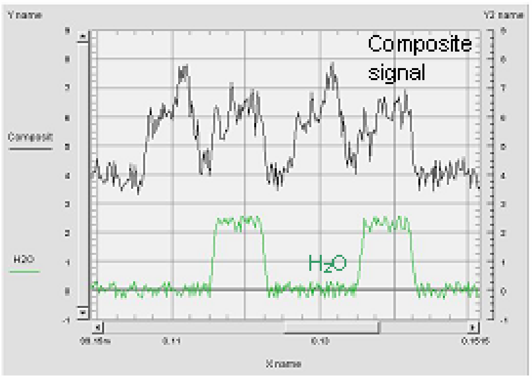
Thus, the steady-state infrared signal, along with its low frequency components, was removed and the instrument was configured to respond only to high frequency changes in the gas make-up [8].

4.1.3 Simplifying the signal

A second innovation aimed at improving resolution of the lower velocities was in moving from measuring infrared in the 2 to 5 μm region (i.e. the dynamic range of the lead-selenide detectors), to a single absorption wavelength of about 1.45 μm. The reason for this was primarily because of the complex way in which the gas travels along the duct. Gas travelling along the central region of the pipe travels faster than the outer regions, owing to frictional losses and turbulence. This process tends to increase mixing creating a more homogeneous fluid, thus making it difficult for the IR meter to track specific features.



a)



b)

Fig. 6 – Analysis of a complex combustion mixture: a) Multi-component signal, b) H_2O signal isolated for clarity.

The original system effectively added the signals from all of the gases with infrared spectrums resulting in a complex modulated signal. Figure 6 shows an example of such a signal obtained for combustion gases in a smoke stack. A similarly complex signal would result from analysing a flare-gas stream where methane, higher hydrocarbons and CO_2 will all absorb infrared at different frequencies.

The received signal from the mixture is produced by the addition of the individual signal components (labelled composite signal on Fig. 6a). This signal is not problematic if significant changes in gas composition occur, or if the response time of the correlator is set to a long sample period. However, in flare-gas applications, the response must be fast enough to capture transient events; in addition, the gas may not have significant changes present within a sample period to provide enough signal. The IR4MKII was set up to concentrate on a single species (Fig. 6b) which greatly simplifies the signal pattern, thus improving the level of correlation.

In its current configuration, the IR4MKII meter can be set up to detect one of two species: either water or methane, depending on the application. The detectors can measure variations in concentration at approximately 50,000 times per second (i.e. 50 kHz).

4.1.4 Sensitivity considerations

A typical flare-gas stream might contain 80% methane, 5% ethane, with the remaining 15% being made up of higher hydrocarbons, inert gases (CO_2, N_2) and H_2S etc.). During blow-down episodes, a greater amount of higher hydrocarbons, liquids and even solids may be carried through from the separator and the molecular weight of the gas can increase significantly, albeit for short time periods.

All of the aforementioned gases (apart from N_2) absorb infrared radiation and can, therefore, be used to measure gas flow rate. However, it was not possible to test the IR4MKII meter at NEL on hydrocarbon gas. Instead, the IR4MKII meter was tested on ambient air with a small amount of atomised water liquid injected into it to provide a “tracer” for the IR4MKII to detect. The system was therefore set up to measure absorption of water. For use in a flare line, the detectors would simply be changed to allow the meter to be used on hydrocarbon gas.

The level of water in the tests was low compared with the typical methane content of a flare-gas line and, in this respect, represented quite a challenge for the IR4MKII meter technology. The amount of water vapour used in the tests was generally less than 0.4% by mass, whilst the methane content in a flare-gas line would likely be closer to 80 - 90% by mass. Therefore the purpose of the tests was to determine at what level of variation in the flow and over what velocity range the meter could function.

As optical absorption instruments respond to the number of molecules in the path of the instrument, the response to gas concentrations can be roughly calculated from given parameters. Using the LED manufacturer's specification of an 80% absorption of light per kg of water per m^3 at a wavelength of 1.45 μm, it was calculated that the detection limit would be in the region of 0.01 to 0.1% change in water content. The purpose of the tests at NEL was to explore and characterise these operational limits further.

4.2 Prototype IR4MKII Meter Spool

Figure 7 shows photographs of the IR4MKII meter spool on the bench. The spool was made of rolled sheet and riveted along the seam to form a nominal bore of 207mm to match 8-inch, Sch. 20 pipework. The flanges were tack-welded to the pipe at either end of the spool and sealed with silicon.

The spool was initially made to allow the beam spacing to be adjusted. This was achieved by cutting two slots into either side of the spool, allowing the bosses to be slid apart in the axial direction (Fig 7b). However, preliminary tests showed that the meter was in fact seen to perform satisfactorily with the beams set in just one position [9]. Thus, it was decided that he meter would be tested with the beams set in one position (i.e. 71 mm apart) – the meter body being sealed-up with an outer shroud.

a)

b)

Fig. 7 – IR4MKII meter spool and internal view

4.3 Test Method and Instrumentation

A schematic of the IR4MKII meter installed in NEL's atmospheric fanline is given in Fig. 8 (flow is from right-to-left); Fig. 9 shows a photograph of the test line.

Air is drawn into the test line, under a slight vacuum by a 70 kW, centrifugal fan. The fan runs at a constant speed, whilst the flow rate in the test section is adjusted by opening and closing a "pepper pot" intake section (basically a perforated drum surrounded by a sliding cover) and a set of guide vanes located downstream of the reference meters. The guide vanes change the angle of attack of the flow entering the fan, giving further adjustment to the test line velocity by varying the momentum change across the fan.

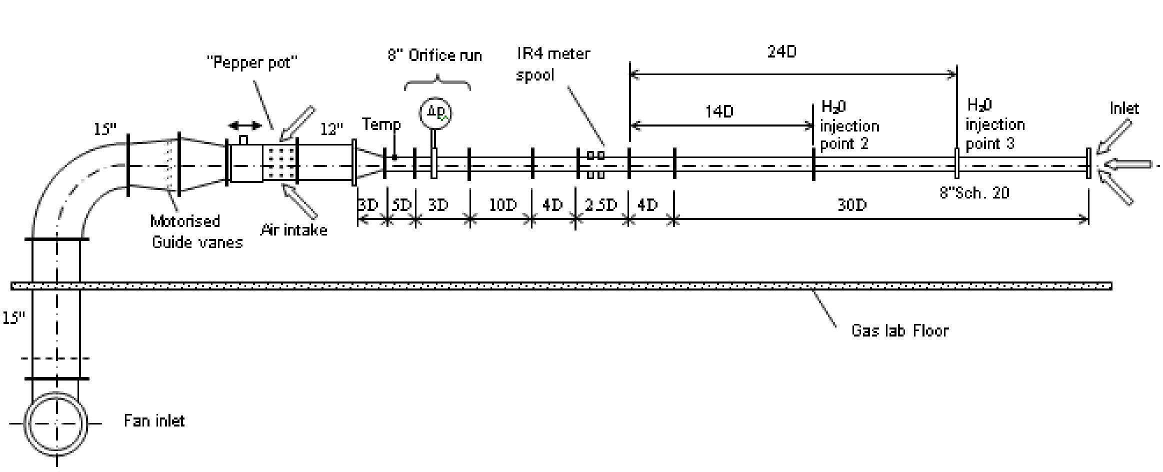


Figure 8 - Installation of the IR4MKII meter in NEL's atmospheric fanline
(note: flow is from right-to-left)

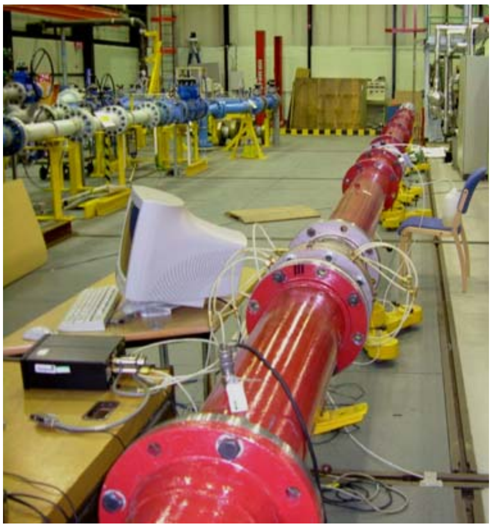


Fig. 9 – Photo of IR4MKII meter installed in NEL's fanline facility

The reference flow rate over the range tested was measured using two, 8-inch orifice plates (of β = 0.3 and 0.8) which were connected into NEL's fully traceable pressure and temperature measurement system. The maximum achievable flow rate in the fanline is 16,000 m^3/hr, depending on the overall pressure drop and the diameter of the test line.

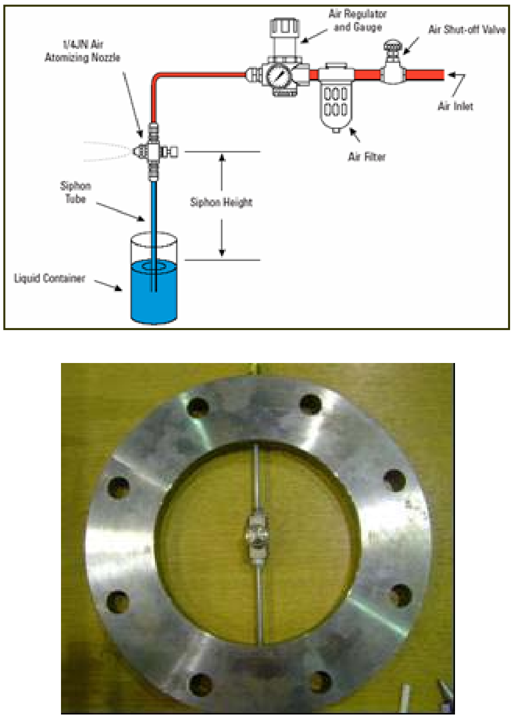


Fig. 10 – Water injection system and photo of nozzle mounted in carrier ring

4.4 Water Injection System

The water-injection nozzle was placed within a mounting ring designed to be captured between the flanges of the test line firstly 14D, then 24D upstream of the inlet to the IR4MKII meter spool to examine the effect of moving the injection point on meter performance.

Figure 10 shows a schematic of the water injection system and photograph of the nozzle as installed in its mounting ring. The system comprises the water storage vessel, injection nozzle, pressure regulator and interconnecting tubing. The water was siphoned upwards from a 5-litre storage vessel (with a fixed siphon height of 30 cm) and into the nozzle by the action of compressed air, generally supplied at between 0.8 and 2 bar g. The injector nozzle, supplied by the Spraying Systems Company™ (Illinois, USA), supplies a fine mist of atomised water droplets. The average size of these droplets was of the order of 15 - 20 microns, based on manufacturer's information.

The mass flow of water into the pipeline is determined by the air pressure, which could also be used to roughly determine the mass flow rate of water injected using charts in the manufacturer's literature. The range of water-to-air mass fraction (m_f) during the tests was generally limited to $m_f \leq 0.4\%$ for the preliminary and subsequent tests, although a few points were taken with m_f of up to 1.5%. The mass flow rate of air injected into the system was small in comparison with the mainstream air, but was in any case passed through both test and reference meters.

Inspection of the test line after periods of testing revealed no major build-ups of water except for a few small puddles near the injector – indicating that the nozzle was dripping slightly.

4.5 Results of Tests on the Modified IR4MKII Meter

This section summarises the test results undertaken with the water-injector spool located 14 and 24D upstream of the inlet to the IR4MKII meter spool. It was of interest to determine what effect changing the water content and moving the injection point had on the meter performance.

As the tests during this project were of a development nature, the IR4MKII meter was connected to a PC so that graphical data could be produced. The data acquisition (DAQ) software used was HPEE (now VPRO) from Agilent™ Technologies. Figure 11 shows a screenshot from the IR4MKII meter's DAQ software at a reference velocity of about 5 m/s at a water-to-air mass fraction of 0.14%. The screen contains plots relating to the cross-correlation of the received waveforms and the resulting output of velocity. Anticlockwise from bottom-right are the waveforms received at the two beam locations (which are the digitised signal received by the lead selenide detectors), the correlation window and the velocity obtained from the correlation.

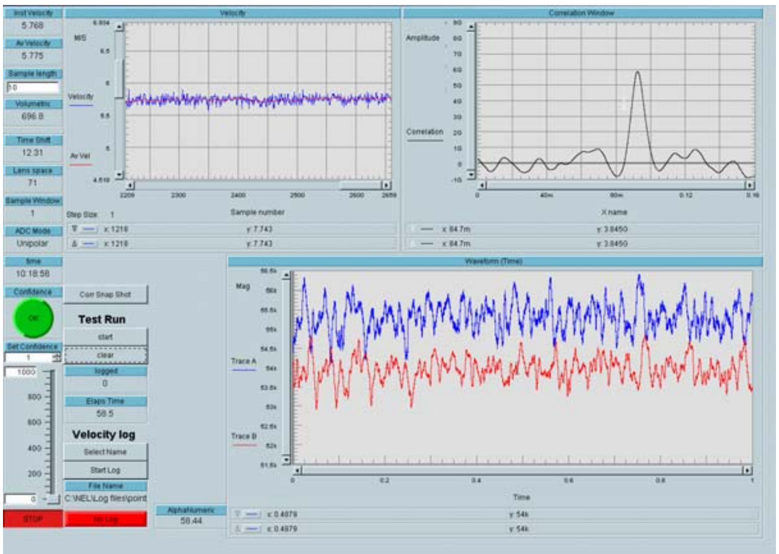


Fig. 11 – Screenshot of IR4MKII logging screen during a test at 5.8 m/s (697 m^3/hr).

The correlation window indicates the level of pattern matching that has occurred between the waveform signals (the similarities in the two waveforms can be clearly seen). The numbers on the y-axis of the correlation plots relate to the result of the multiplications undertaken during cross-correlation. The magnitude of the correlation peak tends to be very large when the meter is obtaining a reading (i.e. of the order of 10^6 to 10^9 bits). In general, the larger the peak in relation to the noise, the better the correlation.

The position of the spike indicates the time-of-flight. The time shift figure, Δt (in ms) is also given on the top left-hand side of the windows. For the example of 5.8 m/s shown, Δt = 12.31 ms, this time shift being linearly proportional to the velocity of the water droplets and, by inference, the bulk air-stream.

The variation in the flow is a measure of the stability of the signal. The detectors operate at a frequency of 200 kHz, with the processed signal at 50 kHz. The meter is therefore capable of picking up time-dependent variations in flow due to turbulence. A first-order filter is used to obtain average velocity from a number of logged samples.

4.6 Comparison of Meter Response to Changes in Water Injection Rates

It was of interest to observe the level of influence from injector position on meter performance. Figure 12 shows the change in meter output (error) with increase m_f for the tests with the injector at 14 and 24D upstream of the meter inlet. These points were taken at fixed line velocity, whilst the injection pressure was gradually increased.

It was not possible to cover the same range in m_f for all velocities as there was a limit on the minimum and maximum air pressure on the injection system (i.e. the maximum supply pressure was about 4 bar g, the minimum to obtain a stable, atomised jet was about 0.5 – 0.8 bar g).

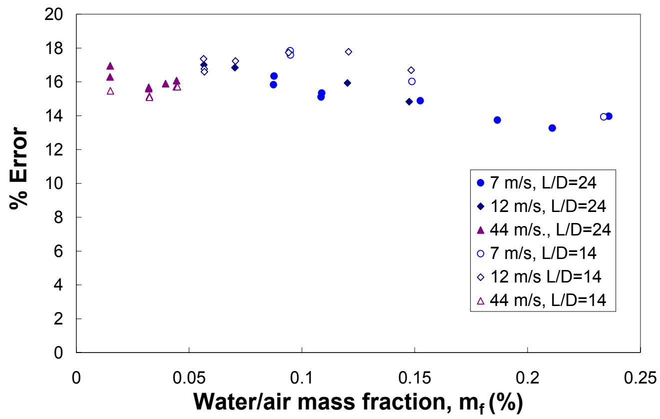


Fig. 12 – Meter error vs. water-to-air mass fraction, m_f, at three discrete velocities

From the data collected there is no obvious relationship between meter output and m_f, although the output appears to reduce slightly with increasing mass fraction (Fig. 12). The meter trends obtained with the jet at the 14D and 24D positions do not lie exactly on top of one-another, indicating that there is still an influence from the water jet on the meter performance, at least for the 14D position.

4.7 Meter Response to Velocity

Figure 13 details the meter performance across the velocity range 0.4 – 67 m/s, with the water injector located at 14D and 24D upstream of the IR4MKII meter spool respectively. It appears that the meter can read velocities as low as 0.4 m/s provided there is enough variation in the flow.

Over the range 7 – 67 m/s, the meter output is not strongly affected by the relative position of the injection nozzle. The two error curves are within about 1 to 2% of one another which, given the nature of the tests, can be considered to be within the expected uncertainty of the rig.

Where the meter was responding properly, the magnitude of the measurement error is seen to be quite large - varying from around 9 to 18% across the velocity range. Fitting a curve through the data would reduce the uncertainty significantly.

In general, the repeatability does not appear to be as good as the injection point is moved upstream of the meter spool and this could either be down to a reduction in variation in the flow as distance from the injected point is increased or a tendency for the water to drop out at lower velocities (the liquid jet having a longer length over which to settle out).

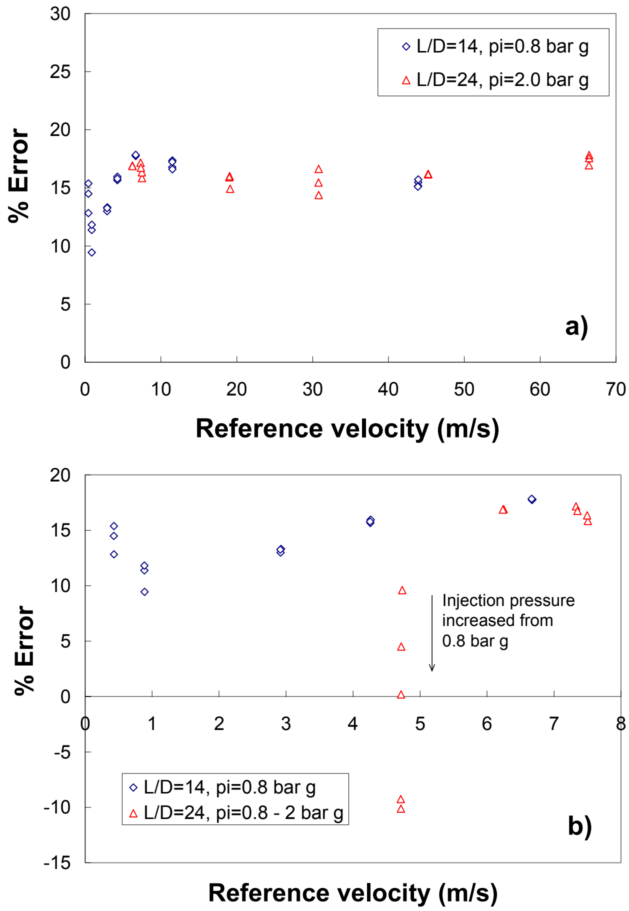


Fig. 13 – Comparison of IR4MKII data for injector at two locations: a) high-velocity end b) low-velocity end.

It can be seen from Fig 13b that the meter stopped responding properly at just under 5 m/s with the injector at the 24D position. Increasing the jet pressure pushed the data still further away from that obtained at the 14D position. The breakdown in response of the meter is therefore an artefact of the test set-up.

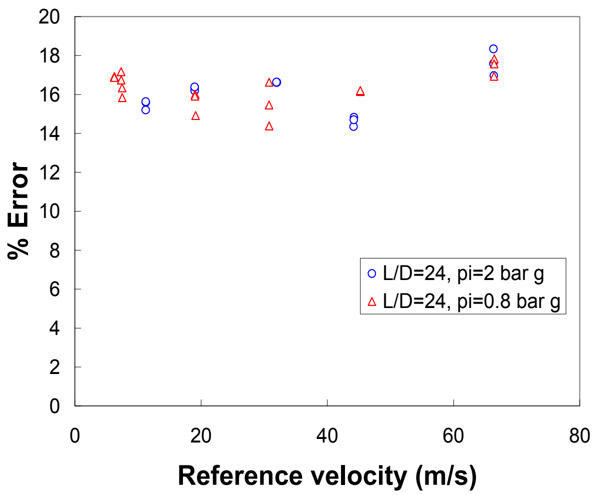


Fig. 14 – IR4MKII meter performance at the L/D=24 injection position at pi = 0.8 bar g and 2 bar g

Figure 14 shows that the repeatability improves with increased water content; it is 0.77% with a 2 bar g injection (increasing water content by a factor of about 2), as opposed to 1.2% for the 0.8 bar injection over the comparable velocity range.

Flow profile considerations

The behaviour of the meter is complicated by the fact that there will be an inherent error offset, even in fully developed flow. Changes in flow profile will affect any flow meter where measurement is based on a point or line measurement, but there is a greater effect on the IR4MKII because it does not take an average of the velocity in the same way as an ultrasonic meter†.

The IR4MKII meter correlates a range of velocities across the pipe, but tends to favour velocities from the dominant flow region. Unlike an ultrasonic meter the IR4MKII meter does not take an average along its line of sight.

However, if the flow profile is relatively predictable, it can be compensated for to some degree through type-testing. The procedure normally used is to perform a flow profile test with Pitot tubes taken at low, mid and high velocity and then program correction factors into the instrument. Reasonably long straight lengths are not uncommon in flare gas lines, although installation on the flare stack itself (where there can be 100 diameters or more of straight pipe available) is uncommon owing to issues of safety and access.

4.8 Determining the Variation in Flow During a Test

It was of interest to be able to calculate the level of variability in the flow that facilitated a reading from the meter during the measurements. From this it is possible to imply what level of variation in density might be required to get a reading in an actual flare gas stream. Before the tests were performed it was calculated that the variation in the flow would have to be about 0.01% - 0.1% in order to get an acceptable signal.

To obtain this information, the data acquisition software was adjusted to display both the magnitude and the RMS noise component of the received signal of the upstream detector channel. This, combined with the signal strength, was used to determine the variation in water content that occurred during a test.

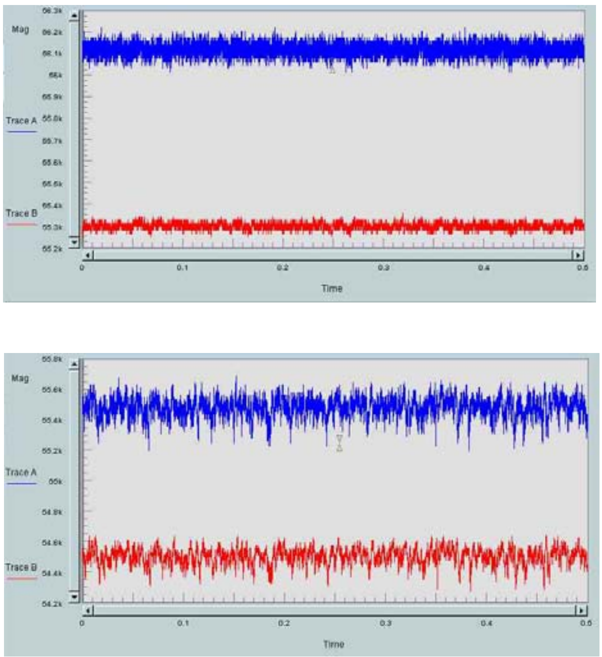


Fig. 15 - Received waveforms at 44 m/s: a) zero water flow, b) mf=0.013% (injector at 14D)

Figure 15 below shows the waveforms received at the upstream (upper waveforms) and downstream (lower waveforms) detector channels at an average line velocity of 44 m/s with zero water flow (Fig. 15a) and with a water injection rate, m_f = 0.013% (Fig. 15b). The magnitude of the DC component for the two channels is around 55,000 to 56,000 bits; they do not lie on top of one another due to subtle differences in the manufacture and set-up of the optics for the two channels.

There are two points of note:

1) The signal strengths reduce when the water is injected

2) The noise on the signals increases when water is injected

The DC component of the signals reduces slightly because the water in the flow is absorbing some of the light energy (i.e. obscuration). The noise on the two signals is an indication of the variation in the flow, which occurs due to turbulence fluctuations and/or changes in pressure or temperature.

†Flare-gas ultrasonic meters tend to have only a single path and are also very sensitive to flow profile. An output of average velocity along a 45° chord is obtained which must be corrected using a k-factor. Multipath ultrasonic meters, used in fiscal and custody transfer applications, can reduce the sensitivity to flow profile significantly.

There are clearly features that are common to both waveforms enabling cross-correlation to take place.

The variation in the flow is given by the equation

$$\% \text{ Variation in flow} = \frac{N}{S_0 - S} \times \%m_f \qquad (3)$$

where N is the RMS noise component of the signal, S_0 is the baseline average signal strength (i.e. with no water flow and the meter giving a null output of flow) and S is the average signal strength with water injected into the flow (i.e. when the meter is actively reading a velocity).

For this particular example the various parameters were[1]:

N	=	53
S_0	=	55,300
S	=	54,500
$\%m_f$	=	0.013%

Therefore, the percentage variation in water content is calculated to be 0.001% (or 10 ppm), during which the meter was outputting a satisfactory measurement of velocity. This is a very small variation indeed and was a somewhat surprising result given that it was expected that the meter would stop responding at around the 0.01% (i.e. a tenfold improvement in sensitivity).

Figure 16 shows the percentage variation in the flow plotted against m_f for some of the lower velocities with the injector in the 24D position and also provides a comparison with data obtained when injecting at the 14D position. The variation in water content increases with m_f and average air velocity.

There is clearly more variation on the signal for the L/D=14 position than the L/D=24 position. For example, with m_f = 0.09%, the signal is about 6 times stronger at 6m/s for the L/D=14 position than at for the L/D=24 position at a comparable 7.5 m/s.

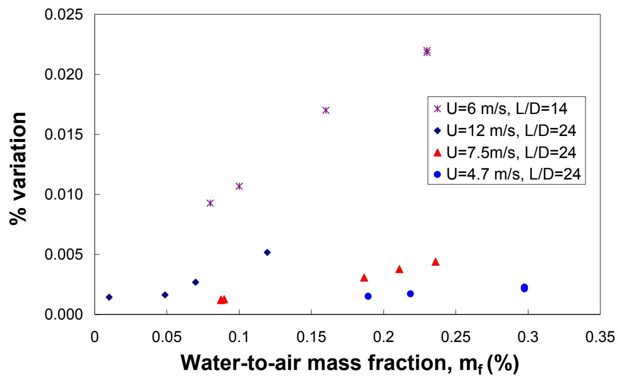


Fig. 16 – Percentage variation in water content with increase in m_f for various velocities

After some further in-house testing the manufacturer concluded that the increased response of the meter was down to the water being in droplet form as opposed to vapour form; this was not anticipated at the start of the tests. There are, in fact, three mechanisms by which the IR4MKII meter can sense:

1) Absorption
2) Lensing (refraction)
3) Reflection

Of the above, 2) and 3) will only occur when liquid droplets are present.

It is concluded that the system is therefore much more sensitive to water in droplet form than in vapour form. This also helps explain the reduction in signal as the injection point was moved further upstream to the L/D=24 position.

[1] Note: values were only taken from channel B.

However, the results of the current air/water tests are useful as they give some indication as to the IR4MKII meter's performance at low signal levels. In the current tests, the IR4MKII meter was set up to sense changes in water content which made up, by necessity, a small proportion of the flowing air (i.e. < 0.4%). Therefore, the meter was looking for changes in a very small amount of water.

In flare lines, there is typically about 80% methane by mass in gaseous form. This would result in an 80% light loss (from transmitter to detector) in a 200 mm test line using a combination of the specification of the LEDs and application of Beer-Lambert's law (equations 1 and 2 detailed earlier). Using the raw data from the meter, it was calculated that a 0.1% variation in flare gas density would give the same level of signal from the IR4MKII meter as seen in the current tests. This figure can be viewed as relatively small and likely well within the normal fluctuations seen in turbulent gas flow.

4.9 Carrier Breakthrough

A further limitation on the IR4MKII meter performance was revealed upon examination of the logfile data after the tests were completed. This was due to a phenomenon known as "Carrier Breakthrough" that contaminated the cross-correlation plot. This issue could have been easily rectified if the problem had been identified before testing was complete.

Figure 17 shows plots of the instantaneous and average velocity obtained from the IR4MKII meter at velocities of 7 m/s (Fig. 17a) and 67 m/s (Fig. 17b) respectively. Both velocities were logged with the injector at 24D from the inlet of the IR4MKII meter spool, but similar behaviour was prevalent for the 14D position.

What is immediately striking is that the instantaneous velocity is jumping between two (and occasionally three) discrete values and the spread in the points is appreciable. However, the filtered average result obtained from the meter (labelled IR avg.) is clearly more continuous, with its spread about the mean also being significantly reduced compared with the instantaneous trace (IR Inst.). It should be noted that the IR4MKII meter reading, as used to determine the meter error, is also based on the average data logged during the 60-second sample.

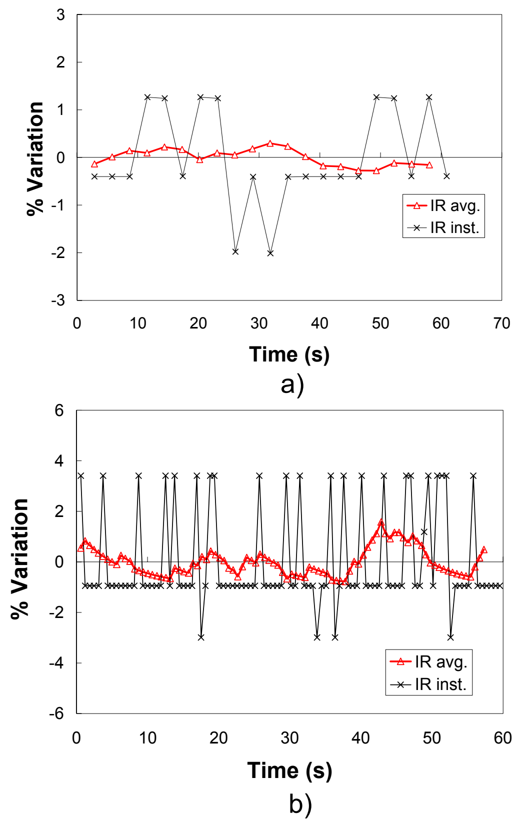
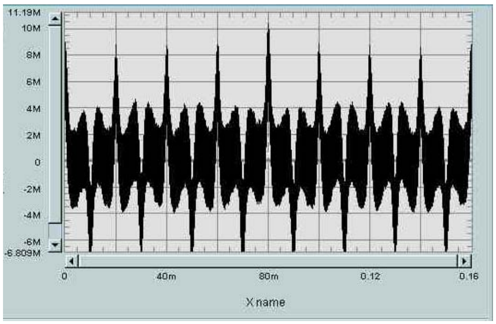


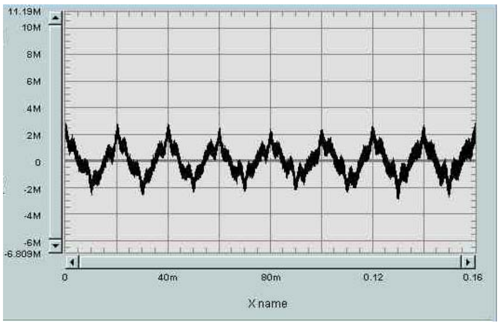
Fig. 17 – Instantaneous and average velocities logged at: a) 7 m/s, b) 67 m/s

Referring back to the electronics diagram given in Fig. 4, infrared light is pulsed across the pipe by two LEDs. In an attempt to extend the velocity range of the IR4MKII meter, the LED pulsing frequency was increased from 50 and 100 kHz, for channels A and B respectively, to 150 kHz on both channels for the current tests. The final processed signal that the cross-correlator sees is 50 kHz. Unfortunately it was discovered only after the tests were completed that this introduced a limitation on the resolution of the meter signal.

Figure 18 shows the correlation plots at zero flow. The correlation plot is made up of a 50 kHz signal and some modulated electronic noise (Fig. 18a). The electronic noise can be removed by applying a filter to the signal (Fig. 18b), leaving the 50 kHz signal, which in this case has an amplitude of about ± 2 ×10^6 bits.



a)



b)

Fig. 18 – Zero flow correlation plots:
a) without noise filter, b) with noise filter

Figure 19 is a schematic representation of a highly magnified view of a correlation peak that might be prevalent during a flow point. The target signal is the dotted line, but the meter has also correlated the carrier signals and thus a 50 kHz ripple is superimposed onto the target signal to produce a rippled profile (solid line). The noise ripple is stationary as the carrier signals are in phase with one another, and the true peak value of the target signal is not found. Instead, the system hops between the peaks which return the same value each time. This noise is always present and superimposed on the signal across the entire range of velocities.

One way of getting rid of this problem, whilst still maintaining a high enough frequency signal to resolve the high velocities, would be to operate the two carriers at slightly different frequencies of, say, 145 and 150 kHz. If two different frequencies had been used then the ripple would have not been stationary. As a result, the average of several results would locate the true peak.

However, even with this embellishment, it is inevitable that there would come a point at low velocity where there is not enough signal for the meter to read properly. This point was not determined by the tests due to complications with the meter performance and the test set-up.

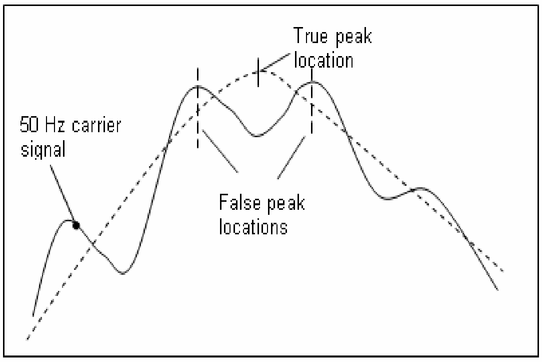


Fig. 19 – Schematic of the correlation peak as modulated by the carrier signal

5 CONCLUSIONS

- The modified IR4MKII meter was tested on air over the range 0.4 – 67 m/s with an atomised water jet located at 14D and 24D upstream of its inlet proving a traceable feature. This extended the limit of previous applications of 10:1, to about 165:1.
- The meter error varied from about 9% to 18% across the velocity range tested. A moderate level of repeatability was achieved over the velocity range. The error is positive because the IR4MKII meter takes its signal from the dominant flow region close to the pipe axis. These biases can be removed by further calibration and type testing over a range of line sizes and velocities
- The behaviour of the meter was similar with the injector at 14D and 24D upstream of the meter, although there did appear to be a fairly weak influence from m_f on meter reading.

- The IR4MKII meter was seen to work with variations in flow of only 0.001% by mass, which was much lower than the calculated detection limit. Additional testing showed that the reason for this was probably due to the reflection and refraction of the infrared by the water droplets, whereas it was anticipated prior to testing that absorption would be the dominant measurable feature.

- It was calculated that only a 0.1% variation in flare gas density would be required to get a similar level of signal from the meter as seen in the current tests.

- It appears that the IR4MKII meter can operate at velocities as low as 0.4 m/s, provided there is enough variation in the signal due to turbulence etc. It is anticipated that the meter could not operate at much below 0.4 m/s in an 8-inch line as the flow would be tending to be laminar in nature. The low velocity cut-off point would increase with line size for a given gas mixture, flow rate and line conditions.

- Even if it was found that there is not enough variation in a flare-gas line at normal, quiescent velocities (e.g. 0.1 – 0.5 m/s), the IR4MKII meter could be still be used to measure the moderate-to-high velocity range that occurs during depressurisation processes where other technologies are known to struggle.

6 FURTHER IMPROVEMENTS TO THE IR TECHNIQUE FOR USE AS A FLARE-GAS METER

There were clearly issues related to both the IR4MKII meter set up and the test procedure that cast doubts on the meter's applicability for measuring flare gas flow. However, with further development, it is possible that the technique could be applied in flare-gas streams.

6.1 Improvements to Sensitivity

The meter manufacturer discovered that it would be possible to use an optical system with longer wavelengths of between 3.2 μm and 3.4 μm. This would provide, potentially, 100 times the sensitivity of the detectors used in the current IR4MKII meter tests, allowing operation at the 0.1% variation level in methane with a strong signal.

6.2 Resolving the Carrier Signal Breakthrough Problem

It was discussed that a relatively simple solution to the problem of carrier breakthrough would be to operate the channels at slightly different frequencies (for example: 150 kHz for channel A, and 145 kHz for channel B). An improvement in repeatability would be expected.

6.3 Further Testing

The results of the current tests were inconclusive with respect to how the meter would perform on dry hydrocarbon gas. There are few test facilities in the world that can deliver flow rate ranges comparable to flare gas lines in natural gas, especially at atmospheric pressures. Natural gas is a difficult medium because of the safety aspects involved and the expense of either venting or flaring off the gas used or recompressing it back to sales pressure.

The only sure way of finding out whether the IR4MKII meter would work in flare gas applications would be to install it on an actual flare line (with any modifications deemed necessary to improve its performance). Given the complexities of installing a meter offshore, it is likely that a better location would be within an onshore refinery flare. The IR4MKII meter performance could be compared with an installed ultrasonic meter and with estimations based on other process measurements.

7 ACKNOWLEDGEMENT

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8 REFERENCES

[1] UKOOA Environmental report 1999 (www.ukooa.co.uk).

[2] DIRECTIVE 2003/87/EC of the European parliament and of the council 13 Establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC October 2003.

(http://www.europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_275/l_27520031025en00320046.pdf)

[3] Establishing guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council

(http://europa.eu.int/comm/environment/climat/pdf/c2004_130_en.pdf)

[4] BP and Flaring – Presentation to the Flare Gas Club meeting, BP Dyce, Aberdeen, Sept. 2005 (unpublished).

[5] Wang, Ting-I & Williams, D. Optical flow sensing for flare stack and process control applications, ISA Expo paper, 2004 (www.opticalscientific.com)

[6] Hyde, J. Patent No. GB 2349946, 09/11/1999

[7] Melnyk, I. Novel technique for flare gas measurement – optical L2F gas flow meters, NEL Flare Gas Measurement and Reporting Seminar, Aberdeen, 15 June 2005.

[8] Hyde, J. Patent No. US1 2004 113081

[9] Gibson, J. Evaluation of an IR4MKII Infrared meter for the measurement of flare gas emissions, NEL Report 2006/147, May 2006.