WET GAS FLOW MEASUREMENT BY MEANS OF A VENTURI METER AND A TRACER TECHNIQUE.

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SUMMARY

Experiments in wet gas flow have demonstrated that venturi flow meter readings can be corrected to give the actual gas rate, provided the entrained liquid flow rate or wetness is known. A technique has been developed to measure the liquid flow rate in a wet gas stream, which is based on the tracer dilution technique using fluorescent dyes. Laboratory experiments and field tests under various operating conditions have demonstrated that the liquid flow rate can be determined within the target accuracy of 10%. Hence the gas flow rate measurement can be corrected to within approximately 2% to 4% accuracy. The new technique makes it possible to develop satellite gas fields without (test-)separators and manifolds, thereby offering substantial capital savings and enhancing the economics of marginal fields.

1 INTRODUCTION

To make the development of small gas fields economically viable, costs have to be reduced significantly. If the flow measurement of the produced gas can be made before, rather than after any entrained liquids have been removed, then satellite field developments could be set up without conventional separation facilities. The production streams from a number of small fields can then be simply commingled prior to transportation and processing by shared facilities. Evidently, the gas flow meters should handle some liquid in the flow. Also, as the gas price and ownership of each field is often different, these meters should have a sufficiently high accuracy to allow commercial custody transfer[1].

Previous tests at a NAM location in the Netherlands demonstrated that both venturi meters and orifice meters can be used to accurately measure the flow of wet gas, provided the liquid fraction is known[2]. The over-reading of those meters, compared to the actual dry gas measurement, at pressures around 90 bar and with liquid fractions up to 4% by volume closely followed the relationships developed by Chisholm[3] and Murdock[4]. However, recent venturi meter tests at a Norwegian test site performed at different line pressures and with liquid fractions up to 10% by volume, showed that for other pressures than around 90 bar above relationships do not predict the correct over-reading. The recent experimental data enable a more accurate wet gas correlation to be developed. This is, however, beyond the scope of this paper.

Correction of the venturi meter readings using a wet gas correlation, requires the total liquid fraction of the gas stream to be measured. This measurement needs to be neither very accurate, ±10% will be sufficient, nor continuous as the wetness only gradually changes with time.

A technique has been developed to measure the liquid fraction of a wet gas stream, which is based on the tracer dilution technique. Fluorescent dyes have been identified as suitable tracers. The tracer dilution technique and the fluorescent tracer dyes have been successfully tested at both the laboratory and a NAM field location.

2 VENTURI METER PERFORMANCE IN WET GAS FLOW

Empirical correlations currently in use with venturi meters in wet gas are limited in their experimental range. The well-known relationships published by Murdock and by Chisholm for example have been established in steam/water flow at low to moderate pressures, and formally apply to orifice plates only. Previous experiments at Coevorden[2], a NAM location in the Netherlands, have shown that the over-reading of venturi and orifice meters measuring natural gas at pressures around 90 bar and with liquid fractions up to 4% by volume closely followed the coinciding predictions by Chisholm and Murdock.

However, extrapolation of the above correlations show that they only coincide for pressures around 90 bar. For all other pressures each correlation gives a different predicted over-reading. This can be explained by the fact that the correlations are based on different physical models. To examine the physics behind the behaviour of a venturi in wet gas flow, flow conditions have to be expressed by their gas and liquid Froude numbers instead of the corresponding gas and liquid velocities. The gas and liquid Froude numbers are given by:

$$Fr_g = \frac{v_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{(\rho_l - \rho_g)}} \qquad (1) \qquad\qquad Fr_l = \frac{v_{sl}}{\sqrt{gD}} \sqrt{\frac{\rho_l}{(\rho_l - \rho_g)}} \qquad (2)$$

According to theory, flow conditions which have identical Froude numbers are located in approximately the same position in the two-phase flow map. The liquid to gas ratio expressed in Froude numbers is the Lockhart-Martinelli parameter (X):

$$X = \frac{Q_l}{Q_g} \sqrt{\frac{\rho_l}{\rho_g}} \qquad (= \frac{Fr_l}{Fr_g}) \qquad (3)$$

With the equations of Murdock and Chisholm expressed in terms of the Lockhart-Martinelli parameter, it shows that the over-reading predicted by Murdock is independent of the line pressure and flow regime. The over-reading predicted by Chisholm is independent of flow regime, but dependent on the line pressure.

The experiments at Coevorden were conducted within a narrow range of pressure and flow regimes. The line pressure could only be varied slightly. The flow conditions were all located in only a small part of the flow map. Stratified wavy with almost no entrainment.

Therefore, it was recognised that additional experiments, covering different line pressures and flow regimes, were required to address the problem. Recently, such experiments were performed at the SINTEF multiphase flow laboratory, located near Trondheim, Norway. Tests were performed at line pressures of 90, 45, 30 and 15 bar, with liquid fractions up to respectively 10%, 8%, 6% and 4%. In total, about 100 different flow conditions were covered.

To indicate the difference between the experimental range at Trondheim for 90 bar and the experimental range at Coevorden, both ranges are indicated in a two-phase flow map, as shown in figure 1. As can be seen, the tests at Trondheim cover a much larger range than the previous experiments at Coevorden. Flow conditions at Trondheim were both in the stratified and annular dispersed flow regime.

The experimental ranges at Trondheim for the other three pressures (45, 30 and 15 bar) were selected by taking identical gas and liquid Froude numbers as for the 90 bar tests.

Some typical results from the venturi tests at Trondheim are shown in figure 2, in which the results of the Coevorden tests are also shown. The over-reading of the venturi meter is plotted against the Lockhart-Martinelli parameter. As can be seen from the data in figure 2, there is a clear line pressure dependency. From more Trondheim results, which are not presented, it can be seen that there is also a Froude number i.e. flow regime dependency.

It can be concluded from the Trondheim experiments that the correlations of Murdock and Chisholm do not predict the venturi meter over-reading correctly, and that their apparent similarity at approximately 90 bar stratified wavy flow is a coincidence. However, the extensive data set gathered at Trondheim will enable a more accurate correlation to be developed. Which is, however, beyond the scope of this paper.

3 PRINCIPLES OF THE TRACER METHOD

Measuring flow by means of the tracer dilution technique, which is a well-established method in single phase flow applications, is simple. A suitably chosen tracer is injected into a flowing stream at a precisely metered rate. Downstream of the injection point, where the tracer has mixed thoroughly with the fluid, a sample is taken. The sample is analysed to determine the concentration of the tracer, whereupon the flow rate (Q) can be calculated from the following relationship:

$$Q = \frac{(C_0 - C_s)}{(C_s - C_b)} \cdot q \qquad (4)$$

in which C_0 is the concentration of tracer in the solution injected into stream Q, C_s the plateau of the concentration-time curve as measured in the downstream sample, C_b the background tracer concentration of the stream, and q the injection flow rate of the tracer solution.

The liquid flow rate to be measured is in practice much larger than the tracer injection flow rate. This means that the initial tracer concentration C_0 is much larger than the sample concentration C_s. If it is further assumed that the background concentration is zero, then the above formula can be reduced to:

$$Q = \frac{C_0}{C_s} \cdot q \tag{5}$$

From this equation it can be seen that no absolute concentration, but in fact a dilution measurement is required, which is much more precise and repeatable. The accuracy of the tracer dilution method is therefore only dependent on the following factors: (a) the accuracy of the injection flow rate; and (b) the accuracy of determining the dilution ratio of injection and sample concentration. With the tracer dilution method neither pressure, nor temperature, nor gas or liquid velocity has any influence on the results.

The tracer dilution technique as described above, has been used to measure the liquid flow rate in a wet gas stream. See the schematic overview in figure 3. As the liquid phase can contain water as well as condensate, two tracers are required. One selective for the water phase and one selective for the condensate phase. Note that the liquid samples taken from the flow line do not have to be representative as the tracers will distribute themselves selectively into the phase of interest. The only requirement is that the samples should contain enough water and condensate for analysis.

Tracer dilution measurements require that the flowing section, between the injection point and the sample point, should be of sufficient length for the tracer to mix fully with the phase of interest. There should not be any inflow or outflow of liquid within the section. The minimum measuring section for single phase flows is listed in ISO 2975/I[5]. To achieve an allowable variation in tracer concentration at the sample point of less than 1%, approximately 150 diameters of straight pipe are required. For multiphase flow, however, no data is available. For wet gas flow, where the liquid is only occupying a small portion of the pipe area, lateral mixing will obviously require less effort. Therefore, by specifying a measurement section that is at least as long as that for single phase flow and includes at least one component that introduces additional mixing like a bend or valve, one will probably be on the safe side.

The liquid samples taken from the flowing stream are flashed to atmospheric conditions before analysis. This means that the tracer method determines the liquid flow rate at ambient conditions. To determine the venturi meter correction factor, however, the liquid flow rate under actual conditions needs to be known. Therefore, the shrinkage factor of both the water and the condensate phase have to be taken into account.

4 FLUORESCENT TRACERS

4.1 Fluorescent dyes

The best tracers are those which mix well with the fluid and which are easily detected at the sample point. Tracer loss in the measurement section, for example due to absorption on the pipe wall or chemical degradation should be minimum. A tracer should preferably be readily available, cheap and safe to use. Due to the presence of two different liquid phases, i.e. water and condensate, suitable tracers should have a

good partitioning between those phases. They should also be non-volatile because of the presence of the gas phase.

Fluorescent dyes were identified as the most suitable tracers for our application. Particularly because of the following advantages:

- the detection limits for fluorescence are extremely low, allowing that only very small quantities of tracer need to be used. This is of particular importance with respect to tracer handling, cost and environmental considerations.
- suitable fluorescent tracers are available for the water and condensate phase. This makes it possible to use a single detection technique for both phases.
- portable fluorometers for field use are available. These instruments are simple to use, not too expensive, and combine the accuracy of a research instrument with rugged simplicity.

Initially, four fluorescent tracer dyes were selected. Two for the water phase and two for the condensate phase. Suitable water tracers were selected from a large set of fluorescent dyes commonly used in hydrology. The suitability of a large number of these dyes was investigated by Smart and Laidlaw[6] (1977) and Viriot and André[7] (1989). Suitable condensate tracers were selected from the dye product ranges of various chemical companies. These dyes are sold to colour fuels and greases.

In contrast to above mentioned applications, the amount of tracer that will be required for a flow measurement is very low: typically 0.1 gram of tracer per measurement. These relatively low quantities involved, in combination with their low environmental and health impact make the use of these tracers fully acceptable.

4.2 Concentration measurement

Fluorescence occurs when a dye absorbs light at a certain wavelength range and emits light at a longer range. Fluorescence is measured by means of a fluorometer. A laboratory spectrofluorometer has been used for all measurements up till now, but it's cost, complexity and delicacy make it unsuitable for general application in the field. For field measurements a filter fluorometer should be used. This instrument combines the accuracy, sensitivity and stability of a research instrument with rugged simplicity.

The optimum dye concentration in the sample lies in the range of 50 to 500 ppb (parts per billion). The upper value originates from the fact that for larger concentrations the relationship between the measured fluorescence intensity and dye concentration becomes non-linear. Although a concentration of 1ppb can easily be measured, the lower value is arbitrarily set at 50 ppb as very dilute solutions ($\leq$1 ppb) are relatively unstable. Also, a somewhat larger concentration makes additional dilution of the samples with a clear liquid possible in case of turbid or opaque solutions.

The reference dilutions, against which the samples are compared, should be prepared using actual produced water and condensate. This will eliminate systematic errors, made in both the sample and reference measurements, as the calculation of the liquid flow rate is essentially determined from a dilution ratio. For all four tracers, a plot of fluorescence intensity against reference dilution ratio is shown in figure 4.

5 TRACER EXPERIMENTS

The tracer dilution method and the selected dyes have been tested at the laboratory and at a NAM field location. Both experiments have shown that the tracer technique is capable of determining liquid flow rates in a wet gas stream. The results of the laboratory tests showed that an accuracy of about ±2% is achievable. The results of the field test showed an accuracy of ±8%. The difference between these results is mainly due to the fact that the reference measurements in the field had larger uncertainties than those at the laboratory.

5.1 Laboratory experiments

5.1.1 Test set up

Laboratory tests in a 3" line were performed with water as the liquid phase. Experiments with condensate were not possible since recirculation of the condensate would lead to its gradual pollution with tracer.

Tracer solutions were injected by means of a calibrated metering pump. The injection rates were varied between 1 ml/min and 5 ml/min, with an uncertainty of approximately 0.3%. The initial concentrations were around 1500 ppm for tracer W1 and 1000 ppm for tracer W2.

The air flow rates ranged from 4800 m^3/d to 17000 m^3/d, equivalent to superficial gas velocities of respectively 9 m/s and 40 m/s in the 3" line. The water flow rates were in the range of 12 m^3/d to 24 m^3/d. The flow regimes were observed to be stratified wavy for all conditions tested. At the larger air flow rates some wall wetting was observed. The experiments were conducted at atmospheric pressure.

5.1.2 Discussion of the results

The results for tracer W1 are shown in figure 5. The error in the calculated water flow rate is plotted against the air flow rate. It can be seen that the errors are within ±2% for all conditions tested. The measuring section in this case consisted of 250 pipe diameters including three bends.

The results for tracer W2 are shown in figure 6. The mixing distance for these tests consisted of 150 pipe diameters including only a single bend. The errors in the calculated water flow rate are within ±2%, which is comparable to the previous results.

It was concluded from the laboratory tests that the tracer method is capable of determining the water flow rate in an air/water stream far better than the required accuracy of ±10%. A field test with both the water and condensate tracers was required to demonstrate the method also works under field conditions.

5.2 Field experiments

5.2.1 Test set up

Field tests were carried out in July 1993 at De Wijk 16, a NAM field location in the Netherlands (figure 7).

A movable well test unit was connected to the well to provide the means of setting the gas flow, measure the gas and liquid flow rates, and the flow line in which to install the tracer injection nozzle and the liquid sample nozzle. The distance between the two nozzles was 150 pipe diameters including four bends. This meant that the mixing was expected to better than in the laboratory tests.

An additional liquid injection nozzle, installed upstream of the tracer injection nozzle, made it possible to adjust the water and condensate fraction of the well stream. Water and/or condensate was injected using two, high pressure, positive displacement pumps. The liquid reference flow rates were determined by measuring the amount of liquid pumped into the flow line. To determine the total flow of liquid in the flow line, the background water and condensate flow rates had to be taken into account. The background water flow was found to be negligible. The background condensate production was approximately 1.5 m^3 of condensate per million normal m^3 of gas. These background flow rates were determined by using the test separator.

No gas production was lost during the tests. The test facilities were set up in such a way that the gas from the separator was injected back into the regular production system.

The gas flow rate was varied between 120,000 normal m^3/d to 240,000 normal m^3/d, corresponding to superficial gas velocities in the 3" flow line of 5 m/s and 11 m/s respectively. The pressure at the test section was around 73 bar for all experiments.

The liquid flow rate ranged from approximately 2.4 m^3/d to 90 m^3/d, which corresponds to liquid to gas ratios between 20 and 420 m^3 of liquid per million normal m^3 of gas. The availability of two liquid injection pumps made it possible to vary the watercut of the liquid phase. The watercut was arbitrarily varied between 0%, 40% and approximately 99%. A watercut of 100% was not possible as the well was producing some background condensate.

The tracer solutions were injected by means of a high pressure metering pump, connected to the flow line by a high pressure flexible hose, as shown in figure 8. The injection rates lay between 10 ml/min and 12.5 ml/min. The concentration of the dye in the injection solution was around 100 ppm for all four tracers.

5.2.2 Discussion of the results

Samples at the sample point were taken every 5 minutes, after the start of the injection, for a period of 30 minutes. The results for a number of tests are shown in figure 9. It can be seen that a sufficiently stable tracer concentration at the sample point already exists after 5 minutes.

The overall test results are shown in figure 10, in which the deviation between the calculated and injected liquid flow rates is plotted against the liquid to gas ratio. Each

data point is the average of all samples taken at that particular flow condition. It can be seen from this figure that the results for tracer W1 and C1 are within the target accuracy of ±10%. The other two tracers, W2 and C2, show disappointing results. The results for tracer C2 are not even on the graph as the deviations involved were too large. The explanation for the poor performance of these tracers has been found to lie in the fact that their fluorescent capability had been degraded by the influence of sun light. The capillary tubing at the suction side of the injection pump was made of transparent plastic, allowing sun light to pass and damage the tracer dyes. Therefore, it is expected that the tracers W2 and C2 can be used successfully as well, provided the injection solution and the samples are not exposed to sun light.

It can also be seen from figure 10 that the liquid flow rates as measured by the test separator are approximately 10% low. Apparently, 10% of the liquid injected disappeared with the gas stream. The separator measurements at the low liquid to gas ratios are considered unreliable as relatively low flow rates were involved.

6 CONCLUSIONS

Laboratory and field trials have demonstrated that the tracer dilution technique is capable of determining the water and condensate flow rates in a wet gas stream within a 10% accuracy. These flow rates are required to correct the venturi meter readings in order to determine the actual gas rate.

Suitable fluorescent tracer dyes for both the water and condensate phase are available, as well as portable fluorometers for field use.

Recent venturi meter experiments have shown that existing wet gas correlations, such as developed by Chisholm and Murdock, do not predict the correct over-reading. Further work is required to develop a more accurate relationship.

7 REFERENCES

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[7] M.L. Viriot, J.C. André, Fluorescent dyes: a search for new tracers for hydrology. Analysis, v.17, no. 3, 1989.

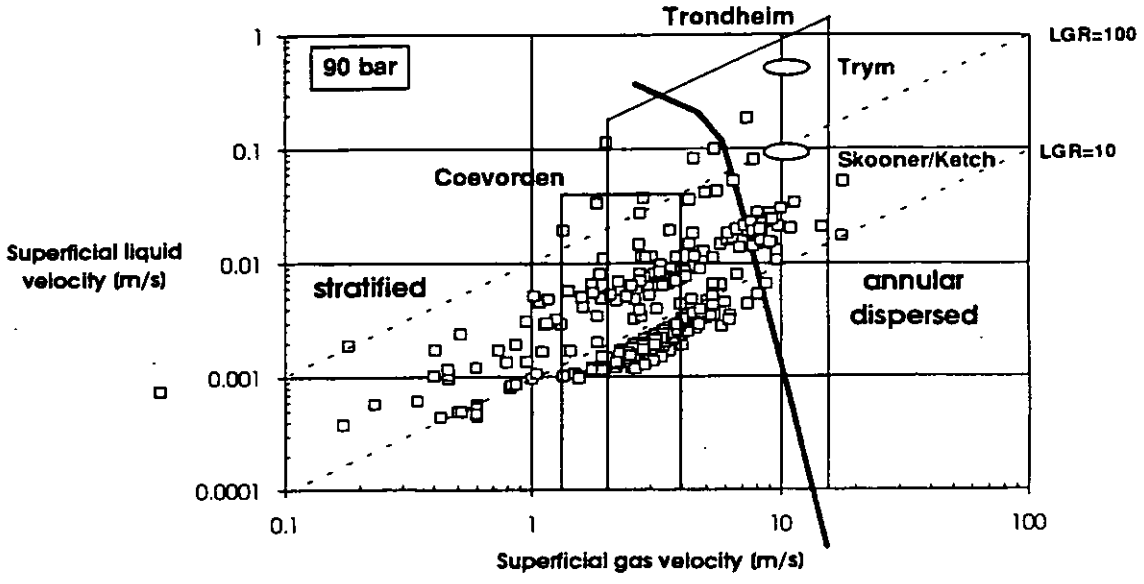

Figure 1. Experimental test range at Trondheim at 90 bar, compared to the Coevorden test range, a distribution of NAM wells and two recent developments of Shell Expro and Norske Shell.

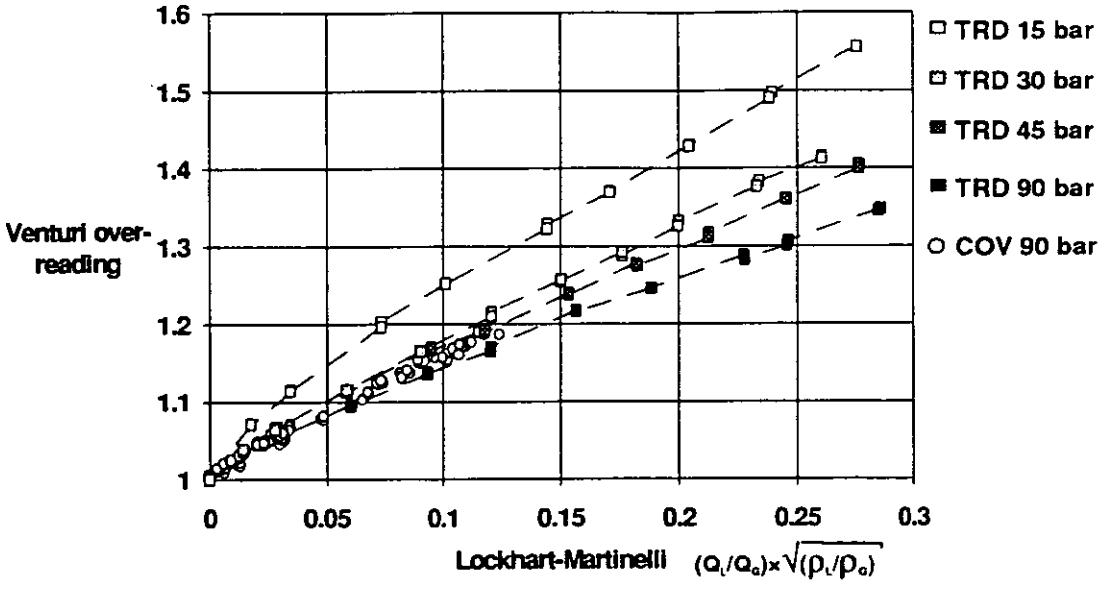

Figure 2. Typical test results from Trondheim and Coevorden indicating a line pressure dependency. The gas Froude number is the same for all data.

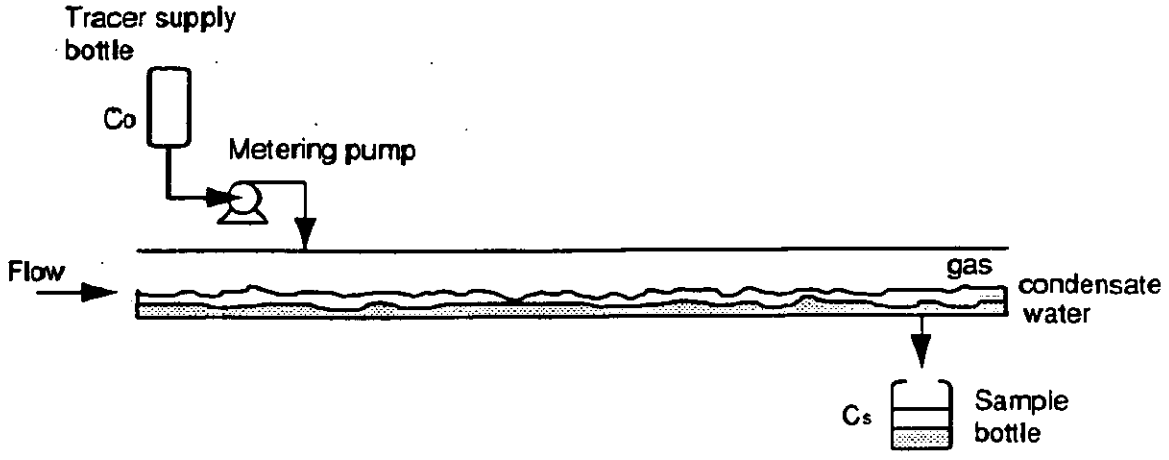

Figure 3. The tracer dilution technique for measuring the water and condensate flow rates in a wet gas stream.

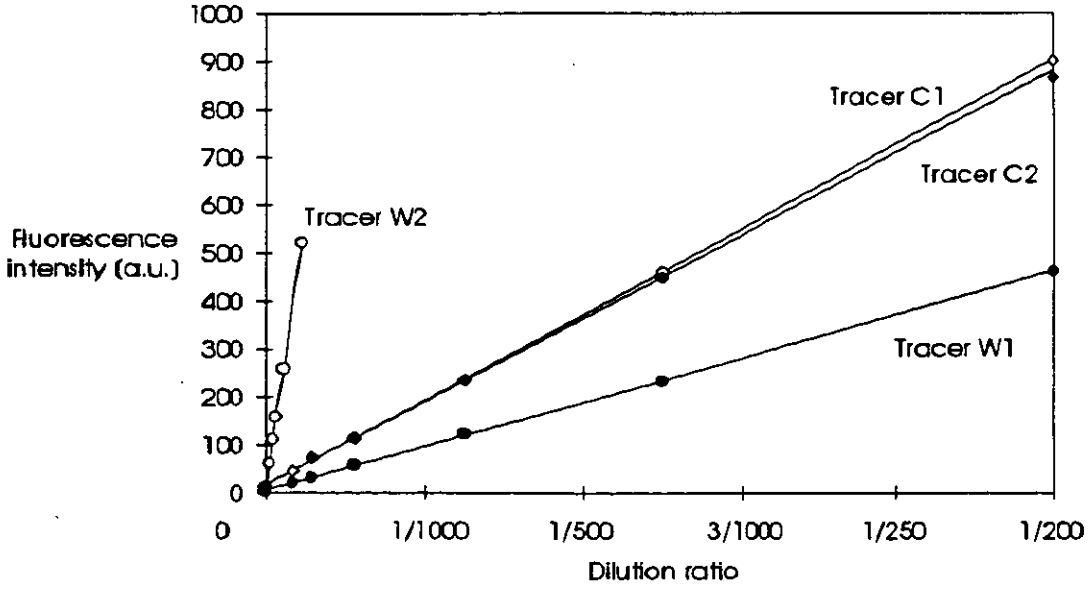

Figure 4. Plots of fluorescence intensity against tracer dilution ratio.

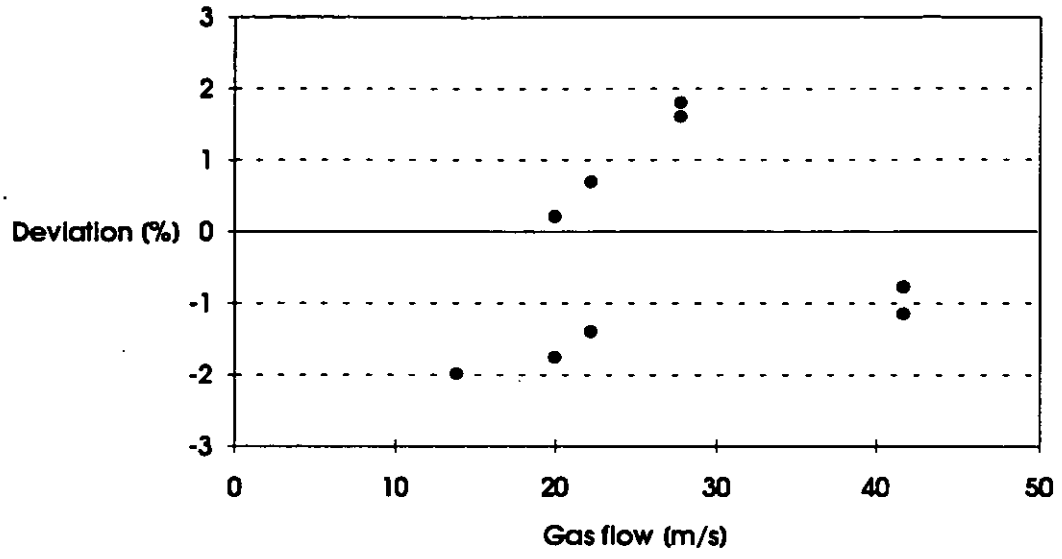

Figure 5. Laboratory test results for water tracer W1. The measuring section consisted of 250 diameters of pipe including three bends.

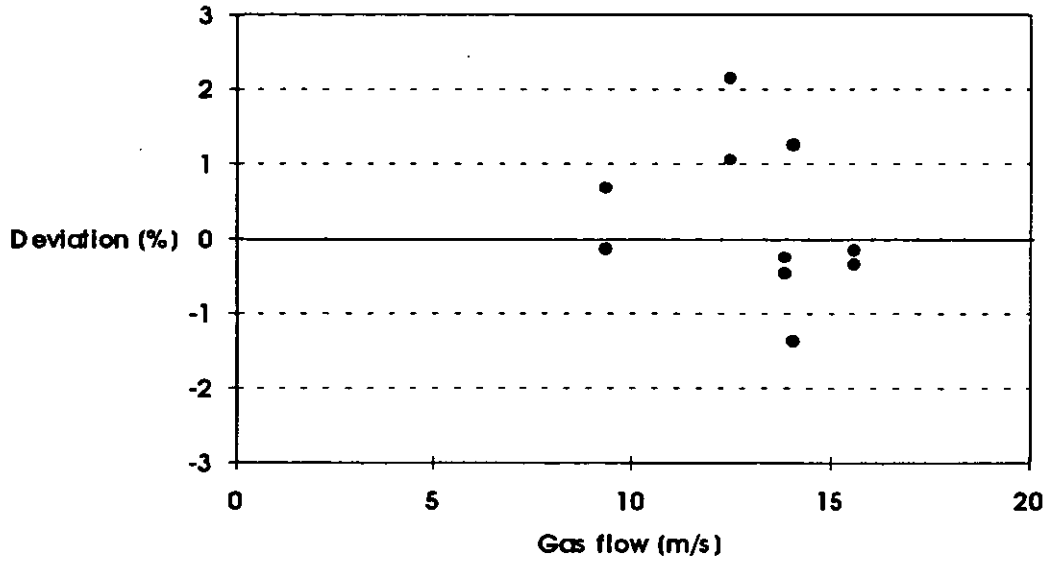

Figure 6. Laboratory test results for water tracer W2. The measuring section consisted of 150 diameters of pipe including a single bend.

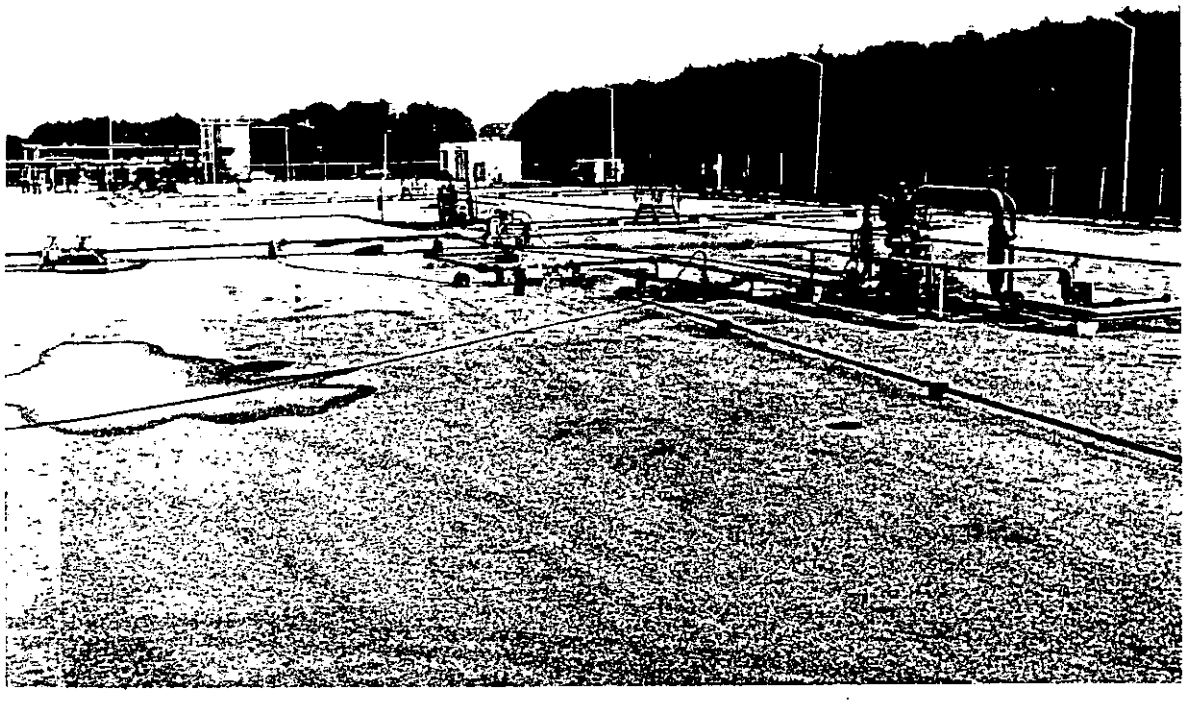

Figure 7. Overview of the field test location De Wijk 16, NAM, the Netherlands.

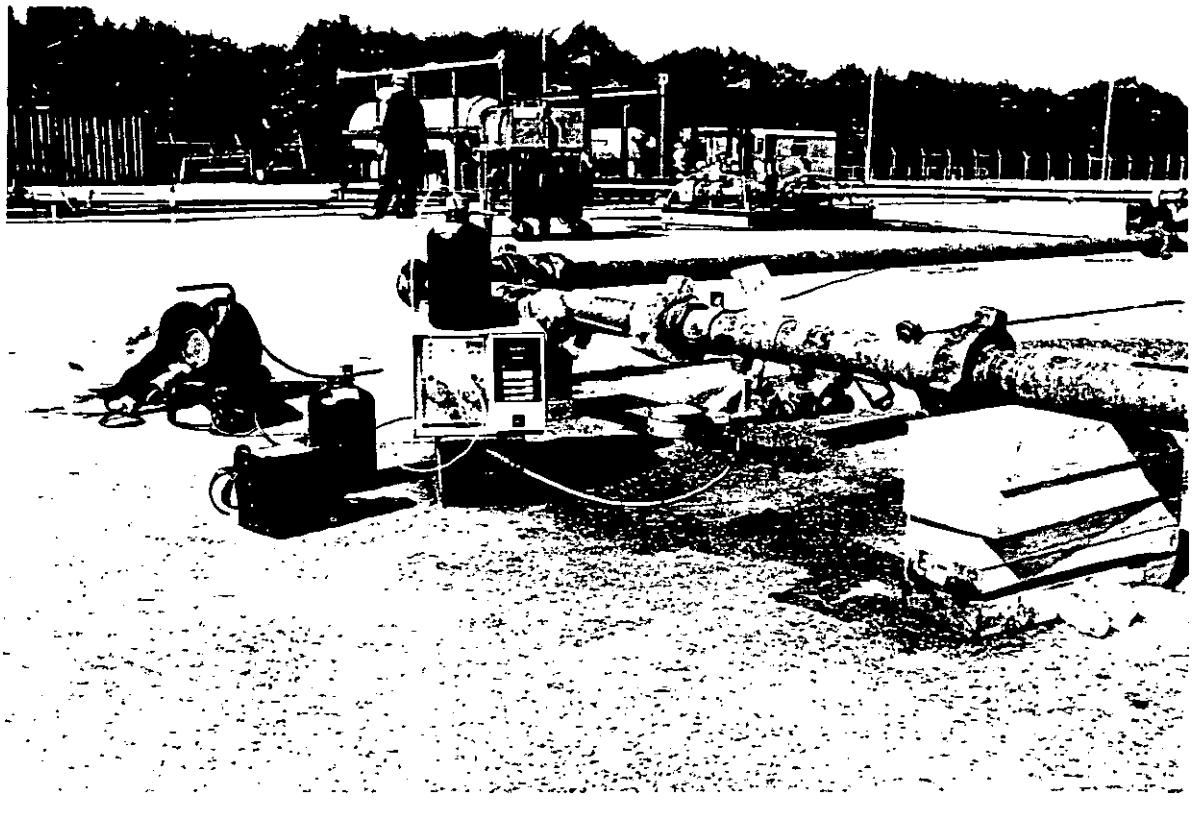

Figure 8. Tracer injection pump connected to the flow line by means of a high pressure flexible hose.

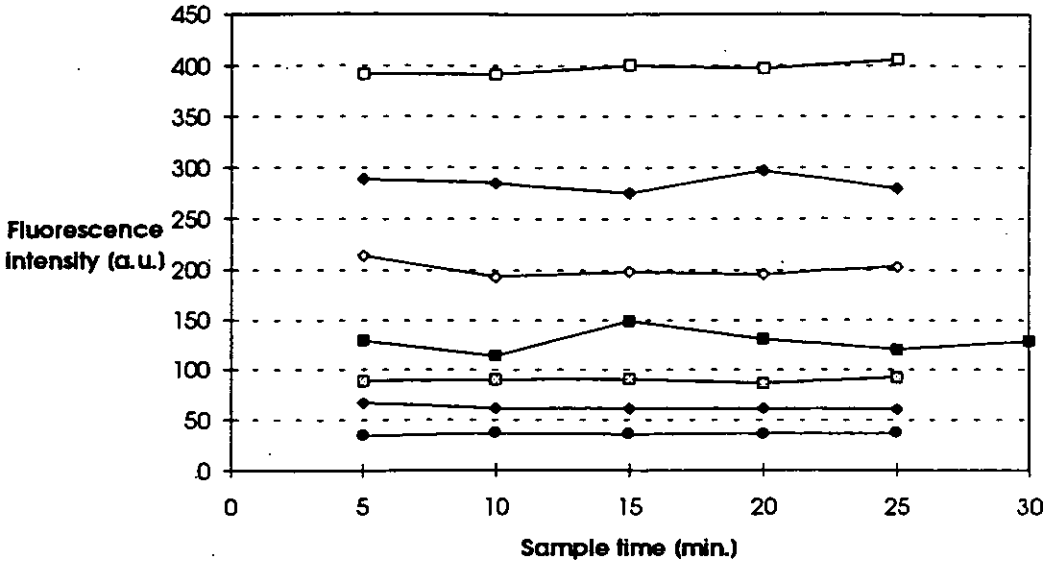

Figure 9. Variation of the tracer concentration at the sample point for a number of tests. Samples were taken at 5 minute intervals after the start of the injection.

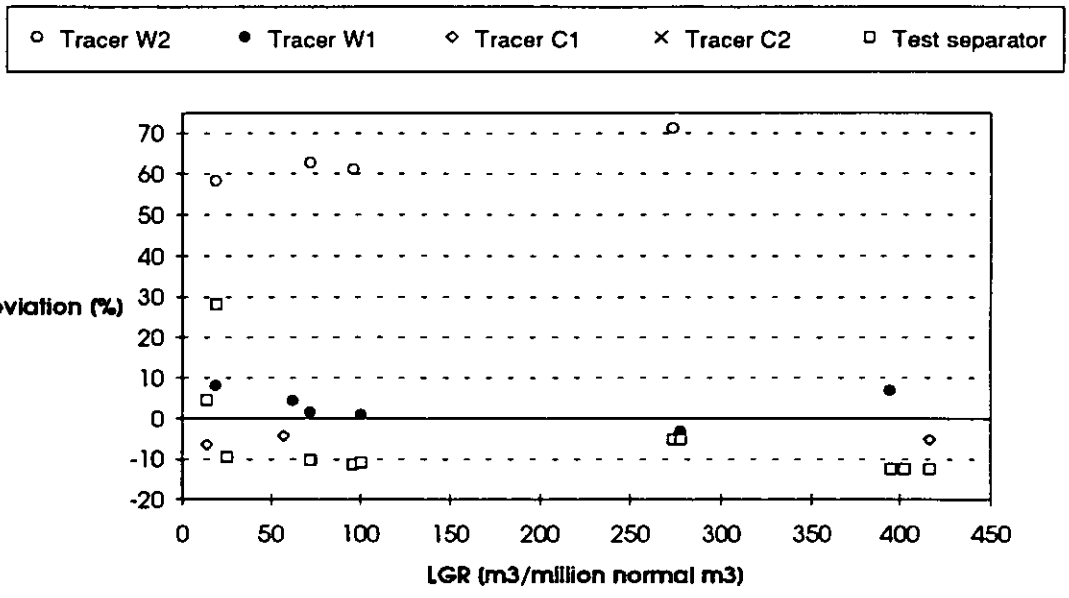

Figure 10. Overview of the field test results. The results for tracer W1 and C1 are within the target accuracy of 10%. Each data point represents the average result of all samples taken at that particular test condition.