

MANUAL

**FLOW RATE MEASUREMENT IN WET GAS
ENVIRONMENTS BY MEANS OF VENTURI TUBES AND
TRACER DILUTION TECHNOLOGY**

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DESIGN AND ENGINEERING PRACTICE



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1. INTRODUCTION

1.1 SCOPE

The application of Venturis in wet-gas flows requires stricter guidelines than for single-phase (gas or liquid) flows. In this DEP, these guidelines and their background are described and discussed in order to achieve the best possible wet-gas measurements by means of Venturis, based on current knowledge.

The tracer dilution technique can be used for the determination of liquid flow rates in pipe lines. It can be used as a part of the wet-gas measurement technique when combined with the over-reading algorithm for the Venturi flow meter, but also for the calibration of the liquid readings of a multi-phase flow meter or a direct oil measurement in a high water-cut well stream, provided the liquid flow rate is sufficiently stable. The technique has some specific requirements for its correct and optimized implementation. This DEP describes the current best practices for the implementation of the tracer dilution technique, based on experiences with this technique so far. It includes selection of solvents for the tracers, injection of the tracer solutions, mixing, sampling, determination of the shrinkages and laboratory practices.

This DEP replaces the report EP 2000-5564 (ref. 13). It explains the implementation of the Venturi as a wet-gas meter.

1.2 DISTRIBUTION, INTENDED USE AND REGULATORY CONSIDERATIONS

Unless otherwise authorised by Shell GSI, the distribution of this DEP is confined to Shell companies and, where necessary, to Contractors and Manufacturers/Suppliers nominated by them.

This DEP is intended for use in exploration and production facilities and sales allocation systems mainly but is also applicable to the wider field of measurement science. The target audience of this DEP are instrumentation and metering engineers and well engineers,

When DEPs are applied, a Management of Change (MOC) process should be implemented; this is of particular importance when existing facilities are to be modified.

If national and/or local regulations exist in which some of the requirements may be more stringent than in this DEP, the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be acceptable with regard to the safety, environmental, economic and legal aspects. In all cases the Contractor shall inform the Principal of any deviation from the requirements of this DEP which is considered to be necessary in order to comply with national and/or local regulations. The Principal may then negotiate with the Authorities concerned, the objective being to obtain agreement to follow this DEP as closely as possible.

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The **Contractor** is the party that carries out all or part of the design, engineering, procurement, construction, commissioning or management of a project or operation of a facility. The Principal may undertake all or part of the duties of the Contractor.

The **Manufacturer/Supplier** is the party that manufactures or supplies coating materials, equipment and services to perform the duties specified by the Contractor.

The **Principal** is the party that initiates the project and ultimately pays for its design and construction. The Principal will generally specify the technical requirements. The Principal may also include an agent or consultant authorised to act for, and on behalf of, the Principal.

The word **shall** indicates a requirement.

The word **should** indicates a recommendation.

1.4 SPECIFIC DEFINITIONS

adjustment		Operation of bringing a measuring instrument into a state of performance suitable for its use.
background fluorescence		The fluorescence at a specified (optical) wavelength of the target fluid without contamination of fluorescent tracer.
calibration		Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or certified reference material, and the corresponding values realised by standards.
diameter ratio (β)		The ratio of the throat diameter and the diameter of the cylindrical entrance section of the Venturi at the plane of the upstream pressure tapings (provided that the pipe and the cylindrical entrance section are identical in diameter) .
differential pressure (inlet throat)		Difference between the (static) pressures measured at the wall pressure tapings, one of which is on the upstream side and the other of which is in the throat of the Venturi tube, inserted in a straight pipe through which flow occurs, when any difference in height between the upstream and downstream tapings has been taken into account.
discharge coefficient		The coefficient, defined for an incompressible fluid flow, which relates the actual flow rate to the theoretical flow rate through a device, and is given by the formula for incompressible fluids.
flow conditioners		A device that creates a fully developed turbulent flow profile that would have developed otherwise over a straight pipe length of minimal 50 internal diameters.
Froude numbers	Fr	The ratio of inertial force and gravitational force for a particular phase. NOTE: This is the ratio of kinetic to potential energy of the gas or the liquid.
gas volume fraction	GVF	The gas volume flow rate, relative to the multiphase volume flow rate, at the pressure and temperature prevailing in that section. The GVF is normally expressed as a fraction or percentage.
liquid hold-up		The ratio of the cross-sectional area in a conduit occupied by the liquid phase and the cross-sectional area of the conduit.
Lockhart-Martinelli parameter	LM	The ratio of the liquid Froude number and the gas Froude number.
mixing distance		The length of piping over which, by the virtue of flow turbulence, fluids of different constituents upon their delivery are sufficiently mixed for the purpose of measurement. NOTE: Sufficient mixing in the context of this DEP is achieved if the concentration variation is less than 1% at millilitre scale. The minimum mixing distance under optimal conditions is estimated to be minimal 150 internal pipe diameters, which should not be confused with equivalent pipe lengths that are used for friction calculations. Certain piping designs may efficiently achieve adequate mixing with a relatively short mixing distance.
multi phase		Fluids which are present in different states of aggregation.

multi phase flow		Two or more phases flowing simultaneously in a closed conduit.
		NOTE: This DEP deals in particular with multiphase flows of oil, water and gas in a specific region of > 90% GVF.
(pressure differential) primary device		A device introduced into a pipe (that creates pressure differential) in order to facilitate (flow) measurement.
pressure tapping		Annular slot or circular hole drilled in the wall of a conduit in such a way that the edge of the hole is flush with the internal surface of the conduit.
shrinkage		The reduction of volume of a fluid that results from thermodynamical effects.
		NOTE: The thermodynamic effects that play a role in the context of this DEP are thermal expansion, phase exchange and molecular packing.
target fluid		The fluid phase to which a specified tracer will adhere.
total fluorescence		The fluorescence at a specified wavelength of the target fluid upon complete mixing with the fluorescent tracer.
total pressure loss		Difference between the (static) pressures measured at the wall pressure tapplings, one of which is at the upstream side and the other of which is 5 internal pipe diameters downstream of the divergent section of the Venturi tube, inserted in a straight pipe through which flow occurs, after any difference in height between the upstream and downstream tapplings has been taken into account.
tracer dilution		The reduction of tracer concentration due to mixing with one of the phases in the flow line.
tracer induced fluorescence		The fluorescence at a specified wavelength of the target fluid upon complete mixing with the fluorescent tracer minus the background fluorescence.
Venturi		Device which consists of a convergent inlet, which is conical, connected to a cylindrical part called the "throat" and an expanding section called the "divergent" which is conical.
water cut	WC	The water volume flow rate, relative to the total liquid volume flow rate (oil and water), both converted to volumes at standard pressure and temperature. The WC is normally expressed as a percentage.
wedge meter		A (pressure differential) primary device which consists of a wedge type obstruction that is placed in a circular pipe, all to specified dimensions and geometry.
wet gas		A flowing multiphase fluid that contains gas to an amount equivalent to GVF > 90% and that satisfies the criterion of LM < 0.35.

1.5 CROSS-REFERENCES

Where cross-references to other parts of this DEP are made, the referenced section number is shown in brackets {}. Other documents referenced by this DEP are listed in {5}. The papers (other than standards) listed in {5} are referred to as "ref.".

1.6 SUMMARY OF MAIN CHANGES

This DEP is the first one on the subject of in-line measurement and calibration of wet-gas flows in well flows. New updates will be made available as appropriate, e.g. with widening experience and as new technology emerges.

1.7 COMMENTS ON THIS DEP

Comments on this DEP may be sent to the DEP Administrator at standards@shell.com. Shell staff may also post comments on this DEP on the Surface Global Network (SGN) under the Standards folder.

2. PHILOSOPHY AND BACKGROUND

Wet-gas well flows can be measured by means of Venturis but only if corrected for additional differential pressure, which is caused by the presence of liquids (refs. 1 to 4).

NOTE: In general, condensed water and condensate (heavier hydrocarbons) are present in such flows. Also, formation water can be produced.

NOTE: Orifice plates and V-cone meters are also used in wet gas flow measurements by applying the Murdock correlation. However, no best practices have developed due to the lack of insight in the physical mechanism, which describes the over-reading in three-phase flows.

The application of a Venturi as a wet-gas flow meter requires additional information, which is complicated to obtain (ref. 5). Instead, in-line calibration of the Venturi should be performed by means of the tracer dilution technique (refs. 6 to 12).

The tracer dilution technique can also be applied as a direct oil measurement in a high water-cut well stream (ref. 9).

3. FLOW METER DESIGN REQUIREMENTS

A wet gas flow meter designed in accordance with this DEP shall consist of a Venturi flow meter with a wedge flow meter downstream of it. The wedge flow meter provides the necessary isolation of ΔP_2 from downstream effects. Moreover, this two-meter configuration provides redundant information, which allows liquid load monitoring.

The unit should be periodically calibrated by means of the tracer dilution technique.

3.1 VENTURI FLOW METER

The Venturi shall be constructed according to ISO 5167 with the divergent section declining at an angle of 7° (refs. 4 and 15).

NOTE: The differential pressure inlet-throat, often referred to as Δp_1 , is insufficient to determine both gas and liquid flow rates. To obtain two unknowns, at least two equations are required. To that end, it is possible to use the total pressure loss (inlet-outlet) differential pressure, often referred to as Δp_2 , as the liquid loading of the flow also influences this differential pressure. In order to achieve this, it is essential that both Δp_1 and Δp_2 can be predicted accurately as a function of the flow rates and the physical properties of the fluids. This has been achieved for Δp_1 (ref. 3), but only to a lesser extent for Δp_2 (ref. 14). Because the geometry of the Venturi plays a role as well, the design of the Venturi should follow rules stricter than those described in ISO 5167.

Fluid properties play a likely role in Δp_2 . Due to the incompleteness of the current theoretical model for the total pressure loss, experimental data is still to be relied on, which dictates the angle of the divergent section. Larger angles result also in larger fluctuations of Δp_2 , probably because of boundary layer separation. This has been shown in the divergent section of a Venturi with a 15° angle (refs. 4, 15, 16 and 17). Venturis with a 7° angle of the divergent section have shown only small variances in the Δp_2 readings (refs. 18 and 19).

The downstream pressure tap that facilitates the total differential pressure measurement Δp_2 shall be mounted 5 internal pipe diameters (5D) downstream of the end of the divergent section of the Venturi. The Δp_2 pressure tap shall have the same properties (internal diameter, angle to pipe surface, surface finishing, etc.) as the pressure tap at the inlet of the Venturi as described in ISO 5167. The internal diameter of the pipe section on which the Δp_2 tap is mounted shall have the same internal diameter as the inlet of the Venturi (ref. 18).

The upstream length of the Venturi shall comply with ISO 5167.

The Venturi and its upstream and downstream lengths shall be mounted horizontally {4.3.2}.

NOTE: In order to reduce uncertainty the upstream length should be maximised.

The Venturi shall be installed at the highest part of the installation and be self-draining.

"Flow conditioners" shall not be used.

NOTE: The Δp_2 is in most cases smaller than ΔP_1 and it is sensitive to the installation. Important aspects are:

- The internal diameter of the pipe to which the Δp_2 tapping is mounted.
- The hold-up of liquid near the Δp_2 pressure tap.

The first aspect can easily be understood: if the internal diameter of the pipe is different, the fluid velocity will be different and because of Bernoulli's law, the pressure will be different. This was reported during the K-lab tests in 2004 (ref. 18).

The second effect leads to two contributions: the liquid hold-up will change the gas velocity (ref. 15) and thus to a different pressure, similar to the first item, but it will also create a different gas-liquid interface, which will lead to a different pressure gradient. As the Δp_2 tap is mounted 5 D downstream of the end of the divergent section, there is a noticeable pressure drop between the end of the divergent section and the Δp_2 pressure tap.

Under laboratory conditions, the outflow of the fluids is well defined, steady and stable. This is not necessarily the case in practical implementations, which may affect Δp_2 especially.

3.2 WEDGE FLOW METER

A wedge flow meter shall be installed 12 D downstream of the end of the divergent section of the Venturi (and thus 7 D downstream of the Δp_2 pressure tap) so as to isolate the Δp_2 measurement from the influences of disturbances downstream of the meter run.

The wedge flow meter shall be installed in the horizontal metering section.

The wedge shall be placed at the top of the pipe, pointing downwards as is shown in Appendix 2.

The differential pressure across the wedge flow meter should be minimal 10 kPa at the lowest specified flow rate and should be estimated from the "homogeneous model", which assumes the fluid in the flow line to be a homogeneous mixture, with the liquids distributed as small droplets in the gas with a flow rate weighted density.

NOTE: in this configuration, the liquids, which flow mainly at the bottom of the pipe, will tend to acquire their natural hold-up level, thus minimising effects on the Δp_2 measurement. It is possible to measure the differential pressure across the wedge meter as well for the purpose of monitoring. The β -ratio of the wedge meter has to be chosen so that the wedge meter can act as isolator. There is a trade-off: the smaller the β -ratio, the better it acts as isolator, but the higher the permanent pressure loss over the meter.

$$Q_t = Q_g + Q_c + Q_w \quad (1)$$

$$\rho_t = \frac{Q_g \rho_g + Q_c \rho_c + Q_w \rho_w}{Q_t} \quad (2)$$

in which:

Q_t	=	Total volumetric flow rate under line conditions	m^3/s
Q_g	=	Volumetric flow rate of gas under line conditions	m^3/s
Q_c	=	Volumetric flow rate of condensate under line conditions	m^3/s
Q_w	=	Volumetric flow rate of water under line conditions	m^3/s
ρ_t	=	Weighted average density of fluid in the flow line	kg/m^3
ρ_g	=	Density of gas at line conditions	kg/m^3
ρ_c	=	Density of condensate at line conditions	kg/m^3
ρ_w	=	Density of water at line conditions	kg/m^3

$$\Delta p = \frac{Q_t^2 (1 - \beta^4) \rho_t}{2 C_d^2 \beta^4 A_D^2}$$

The discharge coefficient of a wedge meter should be taken as approximately 0.65 and ε as 1. From above equation, the β -ratio can be derived:

$$\beta = \left[\frac{Q_t^2 \rho_t}{2 \Delta p C_d^2 A_D^2 + Q_t^2 \rho_t} \right]^{\frac{1}{4}} \quad (3)$$

in which:

Δp	=	Differential pressure	Pa
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β	=	Beta-ratio of wedge meter	
C_d	=	Discharge coefficient	
A_D	=	Cross sectional area of pipe	m^2

The β -ratio of a wedge flow meter is given as:

$$\beta = \left[\frac{1}{\pi} \left[\frac{\pi}{2} + (1-g)\sqrt{2g-g^2} + \text{TAN}^{-1} \left(\frac{1-g}{\sqrt{2g-g^2}} \right) \right] \right]^{\frac{1}{2}} \quad (4)$$

from equations (3) and (4) the ratio $g = h / r$, (wedge height over internal pipe radius) can be resolved and is shown in Appendix 2.

NOTE: In e.g. Venturis, the β -ratio is defined as the ratio of the throat diameter and the pipe diameter. In order to get comparable figures for the β -ratio of a Δp flow meter with a different geometry, the β -ratio is defined as the square root of the ratio of the area, available for the flow at the restriction and the pipe cross sectional area A_D . This definition would result in the same β -ratio for Venturis. By using $g = h / r$, β can be derived in accordance with the above, see Appendix 2.

Table 1: β -ratio of a wedge meter as a function of the depth of the wedge

$g (= h / r)$	β -ratio
0.700	0.8295
0.800	0.7915
0.900	0.7507
1.000	0.7071
1.100	0.6606
1.200	0.6112
1.300	0.5585
1.400	0.5023
1.500	0.4422
1.600	0.3773

3.3 SIZING OF PRESSURE TAPPINGS

The diameter of the impulse lines shall be in compliance with ISO 5167 and therefore be limited to 10 mm maximum.

NOTE: If the (*throat diameter*) d is greater than or equal to 33.3 mm, the diameter of these tappings shall be between 4 mm and 10 mm and moreover shall never be greater than 0.1 (*times the internal pipe diameter*) D for the upstream tappings and 0.13d for the throat pressure tappings.

If d is less than 33.3 mm, the diameter of the throat pressure tappings shall be between 0.1d and 0.13d and the diameter of the upstream pressure tappings shall be between 0.1d and 0.1D.

Pressure tappings should be as small as is compatible with the fluid to be used (for example, with its viscosity and cleanness)."

4. THE TRACER DILUTION TECHNIQUE

(ref. 6 to 13)

4.1 PRINCIPLE OF OPERATION

Two solutions of fluorescent tracers, one hydrocarbon based and the other water based, are injected into the flow line. The condensate tracer is hydrophobic and thus stays in the condensate, the water tracer is hydrophilic and stays in the water phase. After sufficient mixing of the solutions with their target phase, a sample is taken and from the dilution ratio between the injected tracer solution and the sample, the liquid flow rates can be determined:

$$Q_c = \frac{c_i}{c_c} \cdot Q_i - Q_i \approx \frac{c_i}{c_c} \cdot Q_i \quad c_c \ll c_i \quad (5)$$

$$c_c = c_s \cdot Sh \quad (6)$$

in which:

$$Sh = \frac{Volume_{ac}}{Volume_{lc}}$$

Q_c	=	Volume flow rate of condensate (or water)	m^3/s
Q_t	=	Injection flow rate of condensate (or water) tracer	m^3/s
c_i	=	Concentration of tracer in injection solution	mol/m^3
c_c	=	Concentration of tracer in condensate under line conditions	mol/m^3
c_s	=	Concentration of tracer in the sample at ambient conditions	mol/m^3
Sh	=	Shrinkage factor (for condensate < 1, for water close to 1)	
$Volume_{ac}$	=	Volume of condensate sample at atmospheric conditions	m^3
$Volume_{lc}$	=	Volume of condensate sample at line conditions	m^3

However, although basically straightforward, the technique has some specific requirements for correct implementation. These are related to the following aspects:

- Choice of solvent for the tracers.
- Ratio between background and tracer fluorescence.
- Homogeneity of the tracer solutions.
- Injection flow rate accuracy and stability.
- Simultaneous injection of the tracer solutions.
- Mixing with the target liquids in the flow line.
- Stability of the target liquid flow rate.
- Configuration of the flow line.
- Mixing using short distances or limited available space.
- Sampling of condensate and water.
- Determination of shrinkage of the condensate samples.
- Transportation of the samples to the laboratory.
- Laboratory practices.

The implementation of the tracer dilution technique consists of several main stages, starting with the tracer solutions and their injection into the flow line (the upstream part), followed by the transportation and mixing in the flow line (the middle part), the sampling of the liquids (the downstream part) and finally the processing in the laboratory.

4.2 TRACER PREPARATION AND INJECTION

4.2.1 Choice of solvent for the tracers

The solvent, which is used to dissolve the condensate tracer, shall be miscible with the condensate (or oil) in the flow line and should be a hydrocarbon (mixture) with a density similar to the condensate, both at line conditions.

NOTE: As especially the condensates can be significantly less dense at line conditions than after stabilisation (due to the loss of light components), the density of the condensate should first be calculated at line conditions by means of a PVT package. In order to get realistic results, the composition of the well fluids up to at least C₂₀ needs to be known (refs. 10 and 11), {4.4.2}. If there is a significant difference in density between the tracer solution and the target liquid, stratification might occur and additional turbulence (and mixing length) is then required to overcome the density difference.

The obvious choice for the solvent of the condensate tracer is stabilised condensate from the well. However, the density of the stabilised condensate is significantly higher than the density of the condensate in the line, because the latter contains many lighter hydrocarbons. Also, the viscosity can be relatively high, which will enhance stratification. Density and viscosity should therefore be determined before the final decision to use stabilised condensate as solvent is made. Because of its wide range of constituents, the vapour pressure can be relatively high, which can lead to noticeable evaporation when being pumped in a hot environment (e.g. deserts). Another complicating factor can be that stabilised condensate has not been processed, which means that it may contain (small) solid particles, which could give rise to problems with the injection skid. A good alternative in many cases is the use of diesel fuel, which is solids-free, has both a moderate viscosity and density and hardly evaporates. Other fuels can be used as well, but with e.g. gasoline, the evaporation can easily lead to problems (change in tracer concentration, vapour lock, etc.).

If viscous oil is to be measured, the viscosity could cause a problem with mixing. Use should then be made of a low-viscous solvent and a configuration which generates additional turbulence in order to obtain sufficient mixing {4.3.2, 4.3.3}.

Although the problems with the density difference are most pronounced with condensate (or oil), water can be a problem when minerals are dissolved in high concentrations, as this increases the density significantly. This can cause similar problems due to stratification, enhanced by the fact that the water layer is usually at the bottom of the pipe and can thus experience little turbulence at the lower flow rates.

4.2.2 Ratio between background and tracer fluorescence

In order to reduce the errors introduced by the background fluorescence, the fluorescence generated by the tracer should be at least as high as the background fluorescence. The reason is that the subtraction of the background introduces additional uncertainty and the variability of the shrinkage enhances the uncertainty of the net, tracer induced, fluorescence:

$$\frac{\Delta fl_{tr}}{fl_{tr}} = \frac{fl_{tt}}{fl_{tr}} \frac{\Delta Sh}{Sh} = \frac{fl_{tt}}{fl_{tt} - fl_{bg}} \frac{\Delta Sh}{Sh} \quad (7)$$

in which:

fl_{tr}	=	Tracer induced fluorescence	applicable units
fl_{tt}	=	Total fluorescence	applicable units
fl_{bg}	=	Background fluorescence	applicable units
Sh	=	Shrinkage	

NOTE: This is caused by the low (virtually absent) evaporation of the fluorescent molecules. A numerical example might further clarify this: imagine that the fluorescence reading is 100 with the correct shrinkage and that the background contributes 50 units and the tracer also 50 units. When the volume of the flashed condensate is 1% less than estimated, the total fluorescence *increases* by 1%, as the fluorescent components are more concentrated. Still using the same value for the background fluorescence of 50 units, the determined tracer fluorescence is 51 units, an *increase* of 2%! This leads to a *decrease* of the measured condensate flow rate of 2%. As this figure rapidly deteriorates when the fraction of the background fluorescence increases, the tracer-induced fluorescence should at least be as high as the background fluorescence. See also the problems described in ref. 12.

4.2.3 Homogeneity of the tracer solutions

Tracer solutions, which are to be injected into the flow line, shall be completely homogeneous.

NOTE: As the water tracer is usually available as a solid, the prepared solution should be filtered shortly before injection or given ample time (12 to 24 hours) to ensure that all solids have been dissolved, followed by thorough mixing. Alternatively, a concentrated solution of the water tracer can be prepared, filtered and subsequently used for the preparation of the injection solution.

The condensate tracer is usually available as a viscous liquid, which can be dissolved by thorough mixing with the solvent. If stabilised condensate is used as solvent, it should be shaken vigorously and stored for 24 hours in a container where volatiles can escape before being used to reduce the amount of volatiles in the condensate.

4.2.4 Injection flow rate accuracy and stability

The determined liquid flow rate is linearly related to the injection flow rate, as has been shown in {4.1}. Hence, the injection flow rate shall be constant and known with a high precision. This can be achieved by using a pump which delivers a close to constant flow by itself in combination with the use of a Coriolis meter to measure the flow rate and a control loop (refs. 10 to 12).

The Coriolis meter readings should be continuously recorded so as to ensure traceability of the amount of injected tracer.

NOTE: Piston pumps produce pulsation and because of the delay in the flow line it is impossible to determine exactly the injection flow rate. Additionally, sampling requires time, which introduces a weighted averaging. Hence, the only viable option is to keep the injection rate constant.

4.2.5 Simultaneous injection of the tracer solutions

Both tracers, the hydrophobic one and the hydrophilic one, should be injected simultaneously (ref. 12) by the use of a dual injection probe as shown in Appendix 3.

NOTE: Emulsion might be formed when both tracers are delivered through a single probe. Emulsion will counteract mixing as both tracers first need to demulsify before thorough mixing can take place.

Sequential injection results in lengthening of the testing period, which complicates the process because the process conditions need to be kept constant within agreed margins.

The small holes in the probe force the tracer solutions into small droplets, which mix more easily with the target liquid. The vertical positioning of the holes attempts to bring the solutions in direct contact with the target liquid, thus reducing the chances of stratification. The counter-current injection of the condensate tracer creates additional turbulence around the droplets to enhance the mixing.

4.3 TRANSPORTATION AND MIXING IN THE FLOW LINE

4.3.1 Mixing with the target liquids in the flow line

The mixing needs to be done by turbulence, for the very simple reason that no other mechanism is able to achieve this in the short time and distance available. Hence, the flow conditions are important for the quality of the mixing. The following conditions shall be avoided:

- stratification
- stagnant zones

The minimum distance between tracer injection and extraction shall be 150 D (physical length and NOT the equivalent length), unless it can be proven that mixing will be complete within a shorter, specified distance.

NOTE: Stratification will always occur to some extent in a horizontal flow line due to gravity. In general, the water layer is the lowest and the condensate layer floats on top of the water layer. At higher gas flow rates the flow condition will become more annular. The amount of turbulence in the condensate layer will be low at the lower flow rates as the water layer largely isolates the condensate layer from the wall and the gas-condensate interface is smooth. Under such conditions 150 D is often insufficient as a mixing length and additional turbulence should be generated by the hardware.

4.3.2 Configuration of the flow line

In order to improve the mixing, the stratified liquid layers should be broken up. This can be achieved by valves, sharp bends, upward and downward sections etc. or specially designed static mixers, in combination with some length of pipe to let the generated turbulence do the mixing. The addition of a wedge flow meter, 12 D downstream of the Venturi, also helps to increase the mixing.

Use should not be made of any configuration enhancing stratification such as upward bends at the end of the flow line (ref. 12).

The piping section in between the tracer injection point and the tracer extraction point shall be horizontal and:

- shall include neither a riser nor a pocket unless it comprises the in line mixer {4.3.3},
- may slightly and continuously decline toward the sample extraction point at a maximum of 5°.

NOTE: Upward slopes may cause liquid pools, which complicates mixing. Expansion loops, if installed in the piping section concerned, shall therefore be mounted horizontally instead of vertically, in which case they generate additional turbulence.

Any other configuration shall not be used.

4.3.3 Mixing using short distances or limited available space

Errors due to incomplete mixing are difficult to predict and might vary greatly (ref. 12). If the distance is too short or if there are other doubts about the flow regime in order to achieve appropriate mixing {4.3.1, 4.3.2}, a mixing line as shown in Appendix 4 should be used. The mixer should be mounted as a spool piece with a length of 6 D and might be sufficient for achieving complete mixing on its own. It should be added to installations where insufficient mixing length is available or when insufficient mixing might be expected for other reasons.

4.3.4 Limitations to the flow regime

The tracer technique shall only be selected for "steady" flow regimes like stratified and annular flows and not for unsteady flow regimes like slug flows (ref. Appendix 5). Hence, one has to estimate the stability of the liquid flow rate before the tracer testing is done.

If stratified flow is encountered, additional measures should be taken to break up the stratification by appropriate mixing as outlined in {4.3.2, 4.3.3}.

4.4 SAMPLING AND TRANSPORTATION OF THE LIQUID SAMPLES

4.4.1 Sampling of condensate and water

Before the tracer test is started, background samples of both the water and condensate phases shall be taken in order to:

- determine the background fluorescence,
- provide control samples.

A minimum of 500 cm³ of each fluid phase shall be taken for the above purpose.

A sample of each of the injected tracer solutions shall be taken for the preparation of the control samples. The amount shall be 500 cm³ minimum for each tracer.

Sampling shall start not earlier than 10 minutes after commencement of tracer injection.

Prior to use, the sample bottles for collecting the flashed liquids and / or the mini separator shall be cleansed and the sample bottles shall be labelled.

A minimum of 8 to 10 samples shall be taken at 5 to 10 minute intervals.

The temperature of each sample shall be recorded immediately upon collection.

NOTE: It is usually not a problem to obtain the water samples during the indicated times; the condensate samples can take longer when the amount of condensate in the flow from the sample point is small. This depends on the conditions. In a field trial, 10 to 15 minutes was common. This is long, compared to the axial dispersion and even the transit time from injection to sampling point, which means that the injection flow rate should remain constant during the time required for sampling. It also means that the sample is affected by large-scale condensate flow rate variations {4.3.4}.

The first collected sample shall be discarded, regardless of whether the mini-separator (Appendix 6) or the sample container (Appendix 7) is used for flashing.

NOTE: The first sample should be taken with the same care as all other samples, i.e. subject to the same procedure as explained below.

The sampling of the water and condensate does not need to be done in the same ratio, as these liquids are present in the flow line, i.e. flow proportionality is not a requirement.

Samples shall be extracted by means of a retractable and adjustable probe, which shall either be positioned on top of the pipe at strict 12 o'clock position, which is preferred, or at the bottom of the pipe at strict 6 o'clock position.

The probe shall be able to sample the bottom section of the pipe. If positioned at the bottom of the pipe, it shall be possible to flush the piping connection in order to cleanse it of solid particles.

In view of the high process pressures that are likely in this application, due care shall be taken when designing and operating a retractable probe.

NOTE: Due to the stratification, a sampling point at the bottom of the flow line will enhance the collection of water, relative to the condensate. As long as the water production is low (merely condensed water vapour from the reservoir), this does not pose a real problem, but as soon as water is produced from an aquifer, too little condensate might be collected from a sampling point at the bottom. The use of an injectable probe is then recommended (ref. 11).

The use of an injectable probe has also the advantage that solids, deposited by the flow, do not hinder the sampling. Solids can e.g. be sand, but also proppant, back produced after a fracking job. These solids tend to collect in the "dead" volume between the flow line and the valve of the sampling point at the bottom, thereby hampering the sampling and often damaging the valve(s). Cleaning the sampling points means deferred production, depressurisation of the flow line, and man-hours spent, but still no guarantee can be given that the sampling point will be free of solids, as the well will have to flow for at least 24 hours before it will be stable enough for a reliable tracer measurement to be performed. During that time again solids can collect in such spots.

4.4.2 Determination of shrinkage of the condensate samples

The composition and density of the condensate at line conditions are in general quite different from those of stabilised condensate (at ambient conditions). The reason is that due to the high pressure in the flow line, significant amounts of light hydrocarbons are dissolved in the condensate. At ambient conditions, these evaporate almost completely and as a result, the volume of the condensate is smaller than at line conditions. Also, in general, the line temperature is higher than ambient and thus the cooling of the condensate to ambient temperature further reduces the volume. This reduction of volume is expressed in the so-called "shrinkage factor". Also, both the density and the average molecular weight at ambient conditions are higher than at line conditions. As the tracer is not volatile, this shrinkage increases the fluorescence of the sample inversely proportional to the shrinkage and therefore the shrinkage has to be incorporated into the calculation of the condensate flow rate {4.1}.

There are three ways to determine the shrinkage.

1. PVT calculations

PVT software packages like STFlash are able to predict the composition of the gas and condensate when the composition of the well fluid is known. So basically the shrinkage can be calculated when samples are analyzed. However, there are some problems with this approach:

- The conditions at the flow line are often far from ambient ($P \approx 9.5$ MPa, $T \approx 85$ °C, which means that the extrapolation is over a very wide range of conditions.
- Previous experiences have shown that the composition needs to be known to at least C_{20} before reliable predictions of the shrinkage can be obtained (refs. 9 and 10).
- The flashing process into an "open container" to ambient conditions is not very well defined. It is neither isothermal nor adiabatic, which makes the prediction somewhat doubtful and dependent on the actual weather conditions.

2. The use of a pressurised sample container

The use of a pressurised sample container has the advantage that the flashing process is better defined than in the case of an open container; see Appendix 7. It also enables the shrinkage to be determined experimentally (ref. 12) when it is filled at line pressure.

The reproducibility of the shrinkage factor depends amongst other things on ambient conditions, which may vary, and on the pressure build up during filling of the sample container.

3. The use of a mini-separator

The best way to determine the shrinkage factor is to use a mini-separator as shown in Appendix 6 (ref. 5). This mini-separator should be placed in a wind-tight, insulated cabinet with temperature control to maintain the line temperature. With such a system, the gas-liquid system will stay in equilibrium at the line conditions during the sampling process. The flashing to ambient conditions is well defined and reproducible. So the shrinkage can be determined experimentally for all the samples taken and thus a reliable estimate can be made.

4.4.3 Transportation of the samples to the laboratory

The samples should be stored in sample bottles, which shall be closed to avoid further evaporation of the lighter components or loss of sample during transportation. To avoid deterioration of the tracer molecules due to UV light, the sample bottles should be kept out of direct sunlight. Good practice is to keep the samples cool until processing these in the laboratory, e.g. storing on ice.

4.5. LABORATORY PROCEDURES.

The laboratory procedures are based on the following starting points:

- The amount of additional errors introduced should be as small as possible.
- A laboratory with temperature control should be used as both the fluorescence and the fluorometer are temperature dependent.
- Only fluorescence should be measured.
- The absorbencies should be small to avoid non-linearities of the fluorometer.

Using these starting points, the following procedure is prescribed:

- Use calibrated pipettes for the determination of small liquid volumes.
- Use calibrated measuring flasks for the determination of larger liquid volumes.
- Filter the samples to eliminate turbidity.

- If the absorbency of the condensate is so high that the samples should be diluted to avoid non-linearity of the fluorometer, a clear solvent should be used with has a low background fluorescence of its own *and* a boiling point > 140 °C (e.g. ShellSol D70) in order to avoid "shrinkage" of the prepared samples due to evaporation of the (light) solvent.

NOTE: The use of a solvent like ShellSol D70 is also attractive because it virtually eliminates evaporation of the condensate once it is diluted with the solvent.

- Switch on the fluorometer at least one hour before the fluorescence measurements are made to let it stabilise.
- The control samples should be made by using the "blank" condensate. A "two-step" dilution should be used, with identical or similar steps, to avoid very small amounts of the injected tracer solution having to be dosed. For example, a dilution of 2500 can best be achieved by two steps of 50 instead of one of 25 and one of 100.
- Three different control samples (different dilution ratios) should be produced to reduce the chances of error with the dilution steps and to determine the most accurate dilution ratio. The net fluorescence of the final control sample should not differ more than 20 % of the net fluorescence of the samples and preferably less than 10 %.

4.5.1 Verification

Sometimes, the samples contain many solids. The tracer molecules can adhere to solids, which reduces the tracer concentration in the liquid, leading to an overestimation of the liquid flow rate (ref. 9). To verify this has not happened to a noticeable extent, the solids, filtrated from the samples, can be washed with small amounts of water (for the water tracer) or ShellSol D70 (for the condensate tracer) and the fluorescence of the thereby obtained liquids measured. The fluorescence should be virtually absent. If not, it will be certain that the liquid flow rate has been overestimated and as it is very difficult to get a proper correction, the results should be discarded, or at least flagged.

4.6 METHOD UNCERTAINTY

For as long as the background fluorescence is relatively small, the uncertainty in the tracer results can be estimated to be less than 5 %, provided that:

- the best practices for the technique are applied.
- the liquid flow rates are "steady", which means that the fluctuations (with time scales > axial dispersion between the injection and sampling points) are "small". Such fluctuations will induce systematic errors, which add to the uncertainty specified above.

The methodology is explained in Appendix 10.

4.7 HSE CONCERNS

Execution of the tracer dilution testing including off-line and / or laboratory analysis shall be covered by local work permit and appertaining safety instruction. The following are the major HSE concerns during the execution of the tracer dilution test.

4.7.1 Construction and manipulation of adjustable probes

Local regulations may prohibit the routine use of adjustable probes.

NOTE: It may require additional procedural coverage to allow tracer dilution testing.

Adjustable probes shall be pressure balanced. The excursion of the probe shall be strictly limited to its adjustment over the required distance only, which is maximum one internal pipe diameter. Probe movement shall be constrained by mechanical means that withstand resulting forces and prevent expulsion of the probe from its lodging position due to the differential pressure between pipe internal and ambient.

Probes shall be removed upon completion of the testing so as to prevent their use outside the testing regime. Insertion and removal shall be by means of double block and bleed valves.

4.7.2 Exposure

The fluorescent materials used for tracer dilution testing are not toxic. The risk of exposure to toxic materials originates predominantly from release of process inventory, of which H₂S, if present, is the most notorious. Appropriate personal protection equipment should be available, e.g. personal gas monitors and breathing apparatus.

The hydrophilic tracer material is harmless. The risks involved in handling hydrophobic tracer depend on the nature of the solvent used. Inert gas is used as a source for gas tracer. Although not toxic, the risk of handling gas tracer lies in the safe handling of industrial gas cylinders. Handling of gas cylinders shall comply with local regulations.

4.7.3 Flammability

Due to the opening of the process, the execution of the tracer dilution test may change the area classification according to IEC 60079-10. Appropriate operational measures shall be taken to mitigate increased risk exposure in such cases; e.g. the zoning of surrounding areas of the test site and the use of portable and personal flammable gas detectors.

4.7.4 Emissions

Spent samples, and vapours and liquids produced during the course of sampling should not be discarded into the environment; i.e. only closed sample disposal systems should be used. Hence, the design should provide for sending produced vapours to flare and capturing liquids in closed bins. Samples should be carried in closed containers.

All precautions shall be taken to minimise release of process inventory to the environment if the above requirement cannot be adhered to. When the process is carried out as specified, such release will be minimal during tracer dilution testing; e.g. flushing of sample lines to the mini separator as described in Appendix 6.

Closed sample disposal systems shall be used for toxic fluids, e.g. H₂S, regardless of the above clauses.

4.7.5 Pressure and temperature

Containment of sample fluids is often at high pressure. Sampling system components such as pressure relief devices, if any, and sample containers shall be designed and certified for use under these conditions.

Piping downstream of the production choke may still be hot. Hence, thermal insulation shall be applied to the piping and sampling components adjacent to the sample handling location if the skin temperature of piping is in excess of 40 °C.

5. REFERENCES

In this DEP, reference is made to the following publications:

- NOTES:
1. Unless specifically designated by date, the latest edition of each publication shall be used, together with any amendments/supplements/revisions thereto.
 2. The DEPs and most referenced external standards are available to Shell staff on the SWW (Shell Wide Web) at <http://sww05.europe.shell.com/standards/>.
 3. Shell research reports are usually confidential and can only be issued to Shell staff and those who have signed a secrecy agreement.

INTERNATIONAL STANDARDS

Electrical apparatus for explosive gas atmospheres – Part 10: IEC 60079-10
Classification of hazardous areas

Issued by:
Central Office of the IEC
3, Rue de Varembe
CH 1211 Geneva 20
Switzerland

Copies can also be obtained from national standards organizations.

Measurement of fluid flow by means of pressure differential devices ISO 5167
inserted in circular cross-section conduits running full

Issued by:
ISO Central Secretariat
1, ch. de la Voie-Creuse
Case postale 56
CH-1211 Genève 20
Switzerland

Copies can also be obtained from national standards organizations.

OTHER PAPERS

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2. H. de Leeuw, "Liquid correction of Venturi Meter Readings in Wet Gas Flow", Proceedings of the North Sea Flow Measurement Workshop, October 1997 (Kristiansand, Norway)
3. Hans R.E. van Maanen and Martin van Werven: A New Two-Phase flow Model, Using an energy balance, to determine the overreading of a Venturi meter in wet-gas flows, SGSI Research Report, January 2002 (code: 02-30230)
4. Richard Steven, "Wet Gas Metering", Ph.D. thesis, University of Strathclyde, Department of Mechanical Engineering, Glasgow, U.K., April 2001.
5. Hans R.E. van Maanen, "Additional Information for the wet-gas meter – The V-Cone flow", OG.02.31017 (2002).
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7. H. de Leeuw, "Fluorescent tracer technique for measuring the wetness of wet gas. Part I: A Laboratory evaluation", RKGR 93.172
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10. H.R.E. van Maanen, "Report on the Tracer Test Measurements at BED-2, well 7 (Egypt) on March 5 - 9 1998", SIEP 98-5147 (March 1998).

11. H.R.E. van Maanen, "Demonstration of the Tracer Dilution Technique for the determination of the liquid flow rates in the wells BED 2-7 and BED 2-8, Egypt", SIEP 99-5554 (September 1999).
12. H.R.E. van Maanen, "Analysis of the results of the tracer dilution tests in Saih Rawl and Barik (Oman) in July and August 2000", EP 2000-5512 (August 2000).
13. H.R.E. van Maanen, "Current best practices for the implementation of the tracer dilution technique for the determination of liquid flow rates in pipe lines", EP 2000-5564
14. Hans R.E. van Maanen and Isaac A. Olalemi, "Modelling of the Total Pressure Loss of a Venturi meter in Wet-Gas flow", SGSI Research Report, November 2002 (code: OG.02.30890)
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16. V.A. Nievaart, "LDA improvement and tailoring for near-wall turbulence measurements in a Venturi", Master's thesis Delft University of Technology, Faculty of Applied Sciences, Department of Applied Physics (Delft, Netherlands), November 30, 2000.
17. Linda Deutz, "Study of the Properties of Turbulent Flow through a Venturi using LDA techniques", Master's thesis Delft University of Technology, Faculty of Applied Sciences, Department of Multi Scale Physics (Delft, Netherlands), December 2003.
18. H.R.E. van Maanen, "Analysis of the wet-gas and "proof-of-concept" tests at K-lab (Norway) in January and February 2004", SGSI Research Report, February 2005 (EP 2007-0080, OG 04-50852)
19. Hans R.E. van Maanen, "Consequences of the tests at K-lab in January and February 2004 for the wet-gas measurement technique", (EP 2007-0081, OG.04.51017)

APPENDIX 1 VENTURI ACCORDING TO ISO 5167

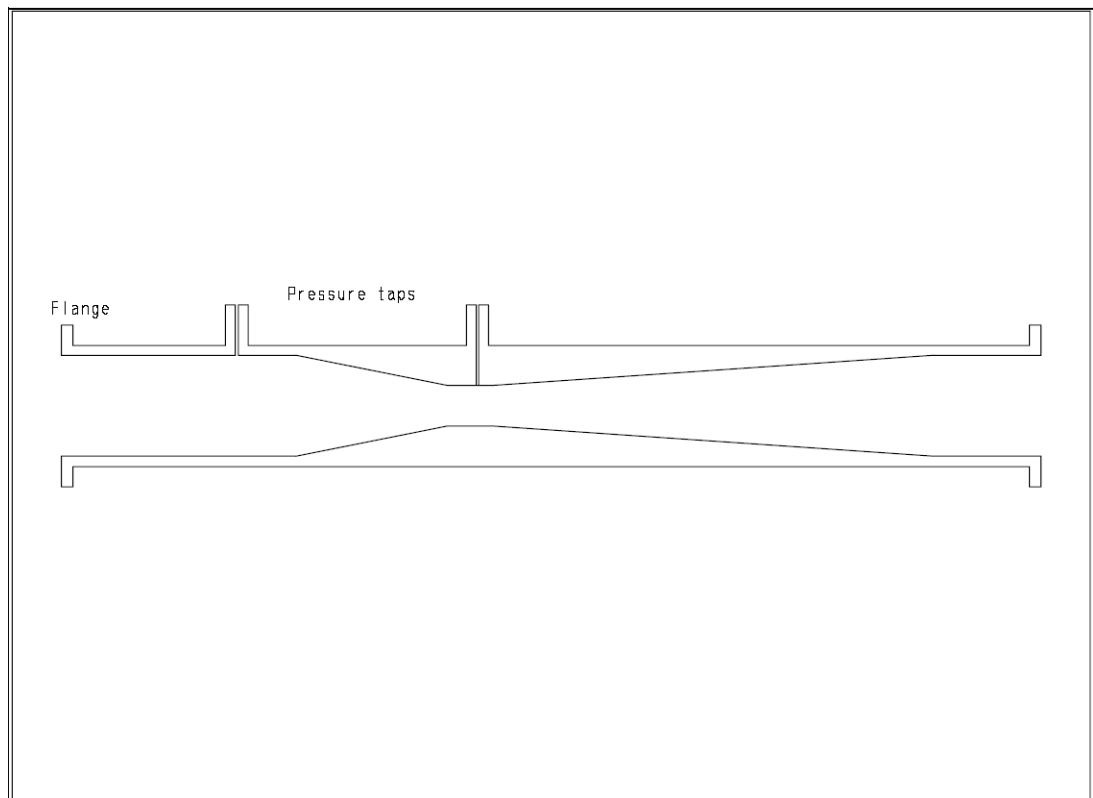


Figure 1 Venturi according to ISO 5167 with an angle of the divergent section of 7°. The β -ratio of this Venturi is 0.4, the flow is from left to right.

APPENDIX 2 WEDGE FLOW METER

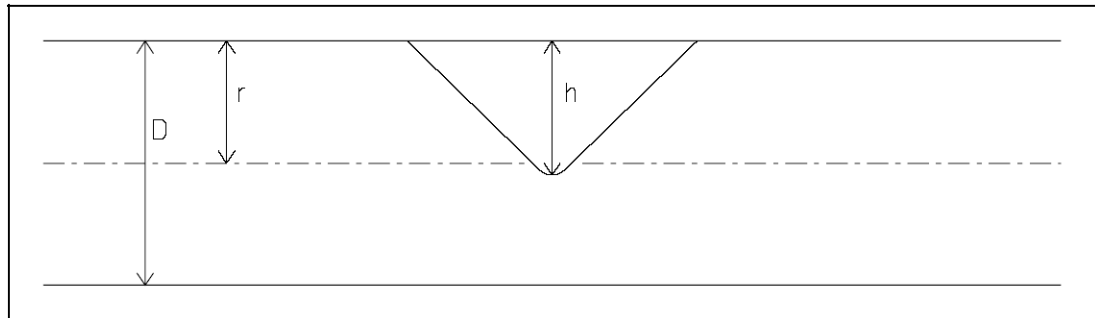
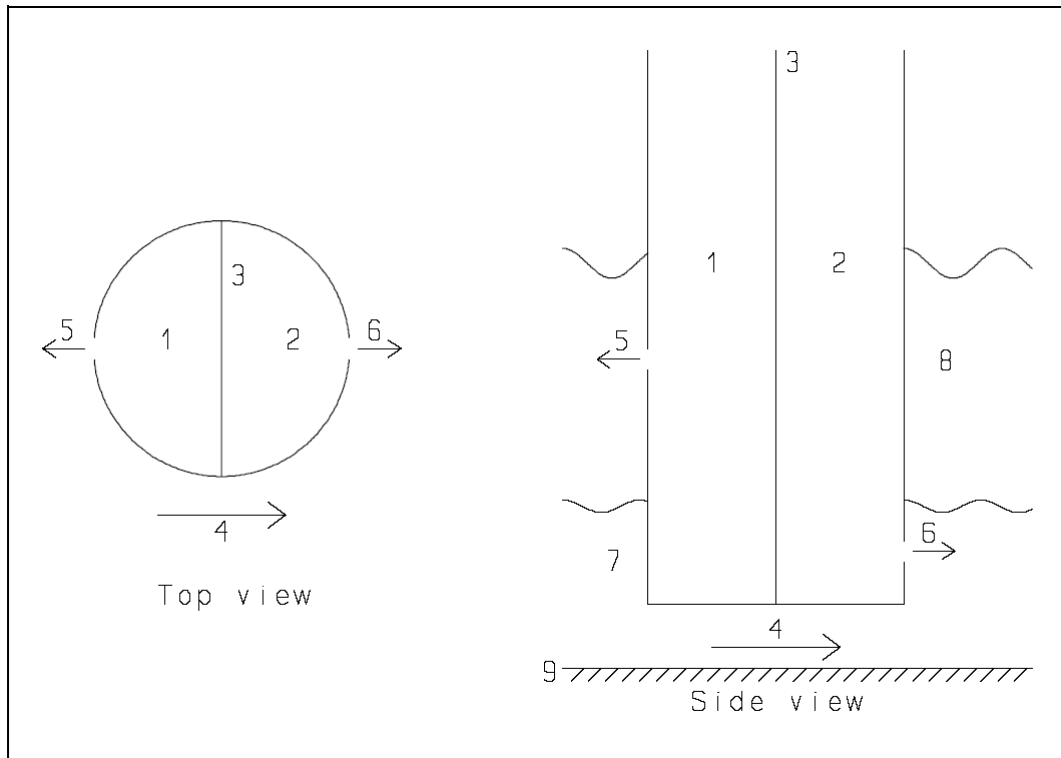


Figure 2 Schematic drawing of a wedge meter with the relevant dimensional definitions

APPENDIX 3 SAMPLE INJECTION PROBE FOR DUAL TRACER DELIVERY



- 1 = Condensate tracer compartment
- 2 = Water tracer compartment
- 3 = Partition
- 4 = Main flow direction
- 5 = Condensate tracer outflow direction
- 6 = Water tracer outflow direction
- 7 = Water layer
- 8 = Condensate layer
- 9 = Inner pipe wall

Figure 3 The proposed injection pipe which keeps the tracer separated and has counter-current injection for the condensate tracer solution

APPENDIX 4 PIPE MIXER

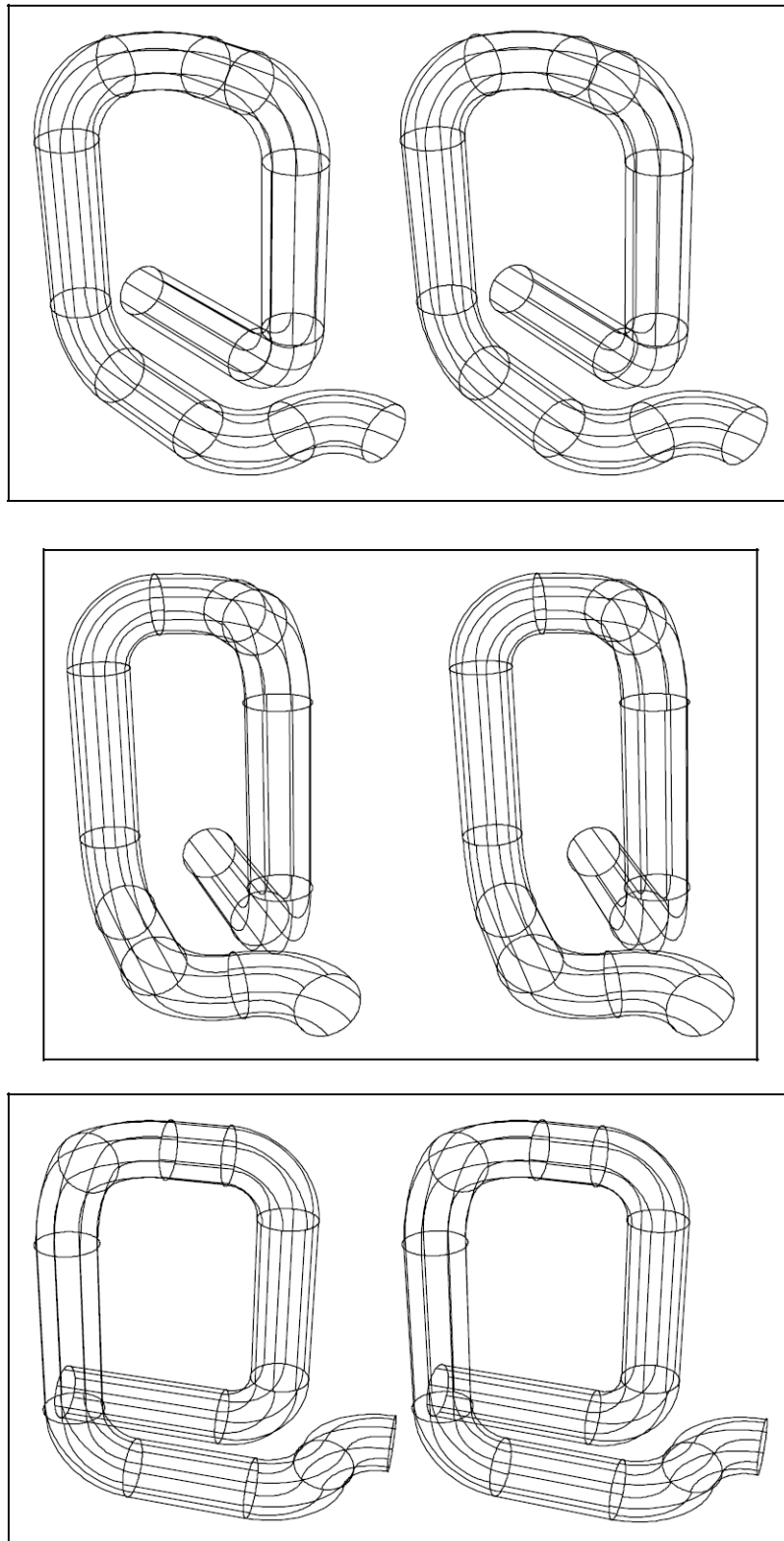


Figure 4 Pipe mixer

The flow enters at the rear side and (following the flow direction) is bent upwards over a straight length of 3 D and is then bent to a horizontal flow in the backward direction.

NOTE: The radius of curvature of all the bends at the axis is equal to D . This is, however, not critical, but too gentle bends should be avoided.

This horizontal part has a length of $1 D$ after which the flow is diverted to the left, immediately followed by a downward bend and a straight vertical pipe with a length of $3 D$. The flow is then again made horizontal over a straight length of pipe of $2 D$, followed by a left-hand bend and a right-hand bend, which brings the flow back to the original flow direction. The whole mixer can therefore be mounted as a spool piece with a length of $6 D$, but its mixing efficacy is enough to replace any length of straight pipe. It can be used in all cases where insufficient mixing length is available or when insufficient mixing might be expected.

APPENDIX 5 ERROR DUE TO VARYING LIQUID FLOW RATE

The flow rates of the liquids are not constant in a turbulent multi-phase flow but vary in time instead, which can range from minor changes to severe fluctuations, like those in the slug flow regime.

In the case of e.g. wet-gas well flows, this effect is enhanced by the variability of the liquid hold-up in the tubing. This, however, has consequences for the tracer dilution technique. The following concerns fluctuations at time scales larger than the time scale of the axial dispersion of the tracer mixing between injection and sampling point. Axial dispersion of the mixing can best be understood by the following thought experiment: imagine that in a very short time a pulse of tracer solution is injected into the flow line. The transportation velocity of this pulse of tracer solution will not be the same for every molecule, so if we were able to determine the tracer concentration at the sampling point, we would see a gradual increase to a maximum value and a gradual decrease until it vanishes. The time scale of this rise-and-fall is a measure for the axial dispersion. Compare e.g. the widening of peaks in chromatography, which is a similar phenomenon. The longer the distance between injection and sampling points, the larger the time scale of the axial dispersion will be. Note that a larger pipe diameter has the opposite effect.

The presence of fluctuations with large time scales means that the instantaneous tracer concentration also fluctuates. But the tracer concentration is inversely proportional to the liquid flow rate and the relation is therefore non-linear. However, the sampling requires a time, which is significantly longer than the time scale of the axial dispersion, which means that the average tracer concentration is not equal to the inverse of the average liquid flow rate. As a result, the liquid flow rate will show a systematic error (a too low value), which rapidly increases with the amplitude of the large-scale liquid flow rate variations. A simulation result is shown below, in which a sinusoidal change in liquid flow rate is assumed. The maximum amplitude, shown in Appendix 5, is 50% of the average value. As can be seen, the error rapidly increases with increasing amplitude. Therefore the tracer technique can only be applied in "steady" flow regimes like stratified and annular flows and not in unsteady flow regimes like slug flow. This is a fundamental limitation of the tracer dilution technique and therefore, one has to estimate the stability of the liquid flow rate before the tracer testing is done. This is not always easy, but e.g. the sounds, produced by the flow line, can give an indication.

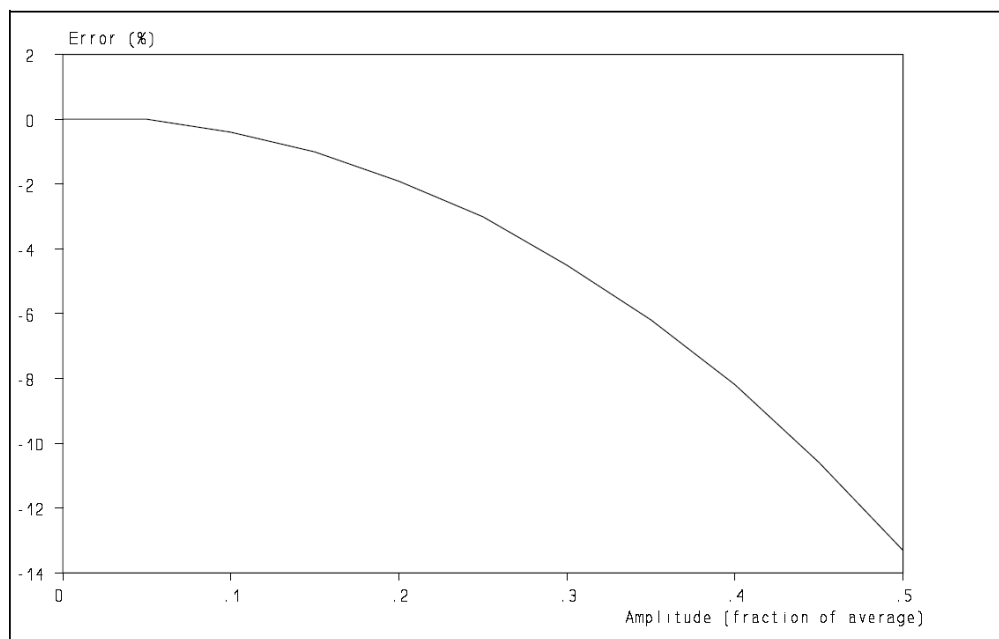
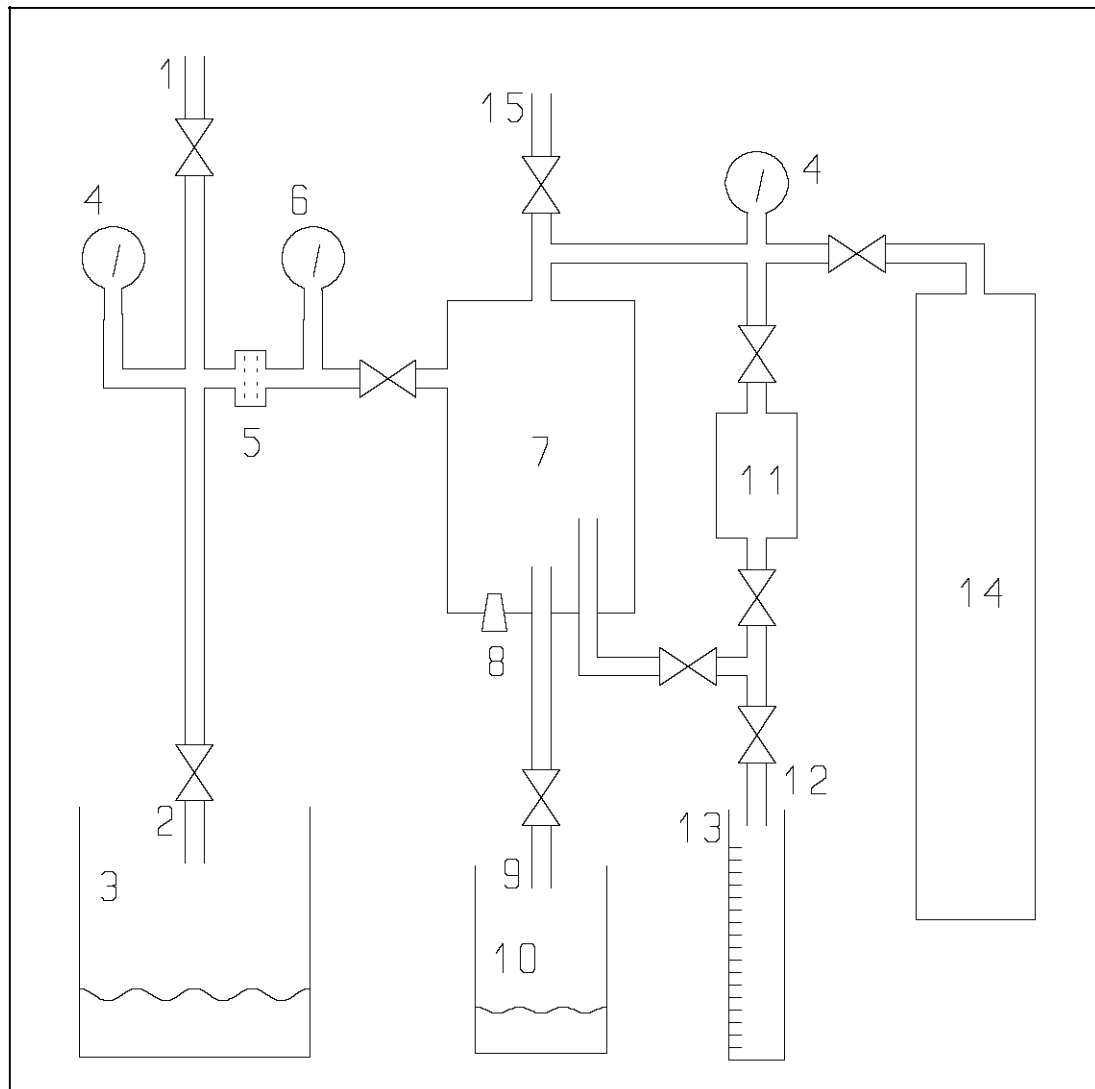


Figure 5 Error of the tracer dilution technique due to varying liquid flow rate

APPENDIX 6 MINI SEPARATOR



- 1 = Connection to flow line / injectable probe
- 2 = Drain to flush line, connecting the mini-separator to the flow line
- 3 = Waste container
- 4 = Pressure gauge
- 5 = Optional proppant / solids filter (easy to clean when connected)
- 6 = Pressure gauge to monitor drawdown over proppant filter (could also be Δp gauge)
- 7 = Mini-separator main vessel
- 8 = Plug to clean out BS&W part (easy to clean when connected)
- 9 = Drain for water to waste container or sample bottle
- 10 = Water waste container or sampling bottle
- 11 = Calibrated pressurised condensate sample container
- 12 = Drain for condensate to measuring flask
- 13 = Measuring flask
- 14 = Dry gas cylinder or dry gas connection to flow line
- 15 = Gas drain to atmosphere

Figure 6 Improved mini-separator for sampling of condensate

The procedure for the use of the mini-separator is as follows:

- Close the valves between 1 and 7 and between 2 and 3.
- Close the valves to 9, 12 and 15 (all connections to the outside world) and 14.
- Open the valves between 7 and 11 and around 11.
- Open the valve between 14 and 7 until the line pressure has been reached. This brings the interior of the mini-separator to the line pressure using dry gas.
- Close the valve between 14 and 7 to avoid unnecessary loss of gas.
- If the mini-separator is used for the first time at the well, vent the gas to remove air or gas from a previous well and fill the mini-separator again with dry gas at line pressure.
- Flush the connecting line and the "dead" volume of the valve and its connection to the flow line by opening the valves between 1 and 2 and 2 and 3. Maintain the pressure within 1% of the line pressure to avoid the loss of light components in the sampling line. After flushing, close the valve at 2.
- Close the valves around 11 to isolate the condensate sample container.
- Open the valves between 1 and 7 to enable the fluids from the pipeline to flow into the mini-separator main vessel (7).
- Open the control valve to the outside atmosphere (between 7 and 15) very slowly so that gas can escape, but the pressure inside the sample container is maintained within 1% of the flow line pressure.
- When condensate starts flowing out of the control valve, close the control valve. The mini-separator main vessel is now filled completely with liquids (water and condensate).
- Close the valve between 5 and 7.
- Open the valve between 14 and 7 in order to maintain the line pressure in the mini-separator. Alternatively, keep the valve between 5 and 7 open to maintain the pressure, which can be monitored using gauge 6.
- Drain the water via 9 to 10 by opening the valve between 7 and 9 gently. As soon as condensate is produced, close the valve again. This is to reduce the amount of water in the mini-separator main vessel.
- Close the valve between 14 and 7 and repeat the steps to fill the mini-separator's main vessel (7) as described above.
- Repeat this procedure until only a little water is produced to make sure that the water level is below the opening of the pipe, which connects the mini-separator's main vessel (7) to the condensate sample container (11). The mini-separator's main vessel is now filled mostly with condensate.
- Close the valve between 5 and 7 to avoid other fluids to come into the mini-separator.
- Flush the line between 7 and 12 by opening the valve between 12 and 13 very slowly and flowing a small amount of condensate through it to remove any water that might have been collected during the filling process. Close this valve when condensate starts flowing.
- Open the valves around 11 to let the condensate from the mini-separator's main vessel into the calibrated pressurized condensate sample container (11).
- Close all valves around 11 and the valve between 7 and 12 to isolate the condensate in the condensate sample container.
- Drain the lines between 7/11 and 12 by opening the valve between 12 and 13 to remove the condensate (this is not taken into account with the calibration!)
- Close the valve between 12 and 13 and place the measuring flask below 12.
- Open the valve between 12 and 13.

- Open the valve between 11 and 12 to drain only the calibrated pressurized condensate sample container and collect the liquid in the measuring flask.
- Determine the volume of the condensate sample.
- Determine the shrinkage by dividing the volume of liquid in the measuring flask with the original volume of the pressurized sample container.

Although this procedure looks rather complex, it is easy to understand by keeping in mind that the flow line pressure needs to be maintained until the condensate is flashed to ambient: liquids push out gas and gas pushes out liquids. As long as this is done at low flow rates, the pressure differential and temperature differential between the flow line and the sampling skid can remain small (less than 1% of the actual pressure and a few Kelvin), thus ensuring that the condensate composition will hardly change.

The dry gas cylinder can easily be filled in the following way:

- Cool the cylinder by placing it in an ice bath.
- Connect it to the flow line by means of a connection at the top of the flow line.
- Open the valves and let the gas stream freely into the cylinder.
- When the gas flow has stopped, close all valves and disconnect the cylinder from the flow line. N.B. Because the cooling of the gas will take time, the gas flow rate could be rather low once the line pressure has been reached. Make sure that the cylinder is connected as long as the gas is still cooling down.
- Bring the cylinder back to line temperature and due to the rise in temperature, the pressure will rise above the line pressure, enough for use in the mini-separator.

The use of a "dry gas" line, directly connected to the flow line, is the easiest and works well. So if this can be arranged, it is the recommended practice. If a cylinder has to be used, as is shown in Appendix 6, a pressure control valve should be used between the cylinder on top of the cylinder to regulate the pressure from the cylinder to the flow line pressure.

The use of the mini-separator will result in shrinkages which are independent of the ambient conditions and which can easily be determined experimentally. Clear proof of the improvement is the determination of the shrinkage. During a field trial in Oman (December 2005), the following results were obtained for well SR-147: difference between maximum and minimum value is 0.55%, average = $0.8531 \pm 0.12\%$

Because the sampling technique as described above removes the water from the samples before it is transferred to the sample container, the condensate samples are water-free. This enhances the accuracy of the shrinkage determination, as the subtraction of the water volume is no longer required:

$$S = \frac{V_t - V_w}{V_s - V_w}$$

in which:

S	=	Shrinkage	
V_t	=	Total volume of liquids (condensate and water) after flashing	ml
V_w	=	Volume of water	ml
V_s	=	Volume of sample container	ml

When the volume of the water becomes a significant fraction of the total volume of the liquids (see e.g. ref. 12), an error in the water volume will reflect as a larger error in the shrinkage.

APPENDIX 7 THE USE OF A PRESSURISED SAMPLE CONTAINER

- Flush the connecting line and the "dead" volume of the valve and its connection to the flow line.
- Close all the valves on the pressurized sample container.
- Open the valve at the bottom of the pressurized sample container to let the fluids from the pipeline flow into the sample container.
- Open the valve to the manometer.
- When the pressure has reached the flow line pressure, open the control valve to the outside atmosphere very slowly so that the gas can escape, but the pressure inside the sample container is maintained within 2% of the flow line pressure.
- When condensate starts flowing out of the control valve, close all valves in the reverse order.
- Disconnect the pressurized sample container and flush the liquids into a measuring flask by only opening the bottom valve.
- Measure the amount of water and the total liquid volume.
- Measure the temperatures of the water and condensate.

The shrinkage can subsequently be determined by comparing the volume of liquids in the measuring flask with the original volume of the pressurized sample container. However, the flashing is still dependent on the actual ambient conditions, because of the change in temperature and the pressure build-up during the filling of the sample container. So it is not ideal yet.

APPENDIX 8 EXAMPLES OF RESULTS

Raw data from the tracer tests of well SR-147 (Saih Rawl, Oman) on 20 December 2005 [ref. 15].

Condensate tracer data:

Name	Water ml	Total ml	Start time	Stop time	Shrinkage	Temperature °C
Blank#1	0	417	11:25	0.8528		82
Blank#1	0	418	11:45	0.8548		82
Tracer#1	0	418	13:55	14:00	0.8548	91
Tracer#2	0	417	14:15	14:21	0.8528	89
Tracer#3	0	417	14:32	14:37	0.8528	88
Tracer#4	0	416	14:50	14:50	0.8507	86
Tracer#5	0	417	15:05	15:05	0.8528	88
Average shrinkage = $0.8531 \pm 0.12\%$						

Name	Fluorescence #1	Fluorescence #2	Injec. flow rate l/h	Flow rate m ³ /day
Tracer#1	450	448	10.5	16.558
Tracer#2	466	468	10.5	15.888
Tracer#3	472	471	10.5	15.729
Tracer#4	455	456	10.55	16.387
Tracer#5	471	469	10.5	15.781
Background	22.3	22.4		
Control	406	404		
Dilution factor = 62.5				
Flow rate = $16.07 \text{ m}^3/\text{d} \pm 2.1 \%$ (variance)				

Water tracer data:

Name	Start time	Stop time	Fluorescence #1	Fluorescence #2	Injec. flow rate l/h	Flow rate m ³ /day
Blank#1	15:30	15:32				
Blank#2	15:35	15:37				
Water#1	16:15	16:17	471	467	5.8	9.264
Water#2	16:20	16:22	478	481	6	9.274
Water#3	16:25	16:27	505	504	6.2	9.102
Water#4	16:30	16:32	500	501	6.3	9.323
Water#5	16:35	16:37	514	516	6.35	9.129
Water#6	16:40	16:42	519	521	6.4	9.112
Background			6.76	6.8		
Control			510	507		
Dilution factor = 61.3						
Flow rate = 9.20 am ³ /d ± 0.9 % (variance)						

Based on the Δp_1 and Δp_2 as retrieved from the PI-server, the $Q_g = 14590 \text{ Am}^3/\text{d}$.

APPENDIX 9 STANDARD PROCEDURES

Before actual tracer test:

- Check condition of equipment: pumps, hoses, fittings, generator, fuel for truck and generator, drinking water, journey management, sample bottles, etc.
- Visit to control room:
 - o agree test schedule
 - o check stability of the selected well
 - o if the selected well is not sufficiently stable, select another one and make sure that it will not be changed during the tracer test (manual, fixed choke)
 - o obtain permit to work
 - o get the key to the gate of the wells
 - o submit journey plan

At the well site:

- HSE-Gas check done by operators (on PTW)
 - o visual / audio check on arrival (leaks, damages)
 - o wind direction
 - o spotting vehicle and equipment
- Check the sample point to see if it flows (operations should check flush and clean when necessary 24 hours in advance)
- Take background sample
- Prepare injection skid:
 - o fill reservoir(s)
 - o hook up to line
 - o pressure test (10 to 11 MPa) before injection starts
 - o begin injection
 - o check injection flow rate
 - o 10 minutes flush with stable injection rate before sampling starts.
 - o sample point connection
- Actual sampling
 - o use a jerrycan (or another waste container) to collect waste
 - o label all sample bottles in advance
 - o 5 to 10 samples (water, if possible also for condensate)
 - o if not sufficiently clean, rinse the sample bottles with the correct fluid (background with background, tracer with tracer)
 - o collect samples in 250 - 500 ml bottles (make sure that enough of the desired phase is collected)
 - o measure temperature of sample
 - o cap the samples after finishing collection and store samples in the car or a box to avoid solar irradiation and preferably on ice.

- o continue to check injection rate
 - o take control samples of the injection solutions
- Leaving site:
 - o shut down pump, depressurize pump, drain the system
 - o prepare tracer for the next well
 - o restore injection and sample points
 - o store sample bottles safely
 - o close the gate and lock
 - o (check next well site)
 - o go back to the control room
- Control room:
 - o journey management
 - o DCS data to check well behaviour over the test period, record the essential data
 - o PTW close out
 - o may collect new condensate
 - o drive back to the laboratory

APPENDIX 10 METHOD UNCERTAINTY

The tracer dilution technique is relatively simple: a solution of a fluorescent tracer is injected into a flow line, where it mixes with the target liquid, either water or hydrocarbon condensate. Two tracers are used: a hydrophobic and a hydrophilic. It has been shown that the concentrations of tracers in the "opposite" phase are negligible (nothing can be found) and because the tracer molecules are large, they do not evaporate either. They do not degrade at temperatures below 150 °C (higher has not been tested), so these aspects can be ignored when discussing the accuracy of the technique.

The basic equation for the tracer dilution technique is:

$$Q_p = \frac{c_i}{c_p} Q_i - Q_i$$

in which:

Q_p	=	Volumetric flow rate of target phase in the flow line, m ³ /s
Q_i	=	Volumetric flow rate of tracer solution into the flow line, m ³ /s
c_p	=	Concentration of fluorescent tracer in the flow line, mol/m ³
c_i	=	Concentration of fluorescent tracer in the injected solution, mol/m ³

As $Q_i \ll Q_p$ in most cases, this can be approximated by:

$$Q_p \approx \frac{c_i}{c_p} Q_i$$

The error in Q_p is now easy to see as this is the summed relative errors of c_i , c_p and Q_i .

Depending on the conditions, the relative errors can be added directly or the square root taken of the summed squares.

In order to estimate the error of the three contributors, each shall be looked at in isolation.

The injection flow rate can be measured with a Coriolis meter. The uncertainty of the readings of such meters is usually < 0.5 %, but usually, the pump is not completely stable. The reading from the Coriolis meter can be used to control the pump, but its variations will introduce a slight additional uncertainty. The total injection flow rate error is therefore estimated to be < 1 %.

The concentrations of fluorescent tracer are measured using a fluorometer. Such a meter has only a limited range and therefore, the concentration of the injected solution is determined by dilution to bring it to a similar concentration as the tracer in the flow line. The dilution involves the determination of volumes using measuring flasks and pipettes. It is usually done in a two-way step so two measurement flasks and two pipettes are involved. As the relative error in the pipettes is far larger than the error in the measurement flasks (≈ 1 % and ≈ 0.1 %), the total error introduced by this step is ≈ 1.5 %.

The samples from the flow line have to be brought to ambient conditions. This will cause a change in the properties and thus of the concentration of the tracers. The changes are more severe for condensate (oil) than for water.

- The water sample will change its density due to changes in pressure and temperature and it will lose some water due to evaporation. The changes due to P&T can be calculated with a PVT simulator like STFlash, so it can be corrected; the maximum error for the volume flow rate when P&T do not exceed 100 °C and 100 bar is 4.4 % without correction. If we assume that all the heat in the water sample is used for evaporation, the sample loses 0.2 % / K. With a maximum of 80 K difference, this would amount to 16 %. In practice, it is far lower but it can be dependent on the (ambient) conditions. It can, however, easily be avoided by transferring the sample to a closed sample container and letting it cool down to ambient temperature before transferring it to a sample bottle.

Therefore, the error of the tracer concentration is basically limited to the error in the PVT simulation, which can be estimated to be < 1 %.

- The condensate sample will lose its lighter components because of the reduction in pressure from the flow line to ambient. This is, even under well-defined conditions, hard to predict with a high accuracy. Therefore, the mini-separator should be used as described in this DEP. The volume of the sampling vessel in the mini-separator should also be calibrated with the aid of the same flask as in which the samples will be collected, as this will eliminate any systematic errors in the sampling flask. What remains is the expansion of the sampling vessel due to the higher temperature (usually) in the mini-separator, which is small (with 80 K temperature increase it is roughly 0.3 %) but can be corrected for, and the reading error of the sampling flask, which is around 0.5 %. Together, the error in the shrinkage of the condensate sample can be estimated to be < 1%.

The fluorescence is measured by means of a fluorometer. Its readings are used in a relative way, the absolute values are not important, so only the error in the reading itself and the error due to non-linearity of the fluorometer are of importance. The error in the reading is ± 1 digit and usually the reading is > 200, so this error is around 0.5 %. As the readings of the sample from the flow line and the sample from the injected tracer solution should be almost equal, non-linearity can be ignored. As, however, two readings are required, both with an error of 0.5 %, the total error is 0.7 % (independent errors) or 1 % (adding both errors).

A more complex situation unfolds when the condensate has a background fluorescence, which is a significant fraction of the total (background + tracer) fluorescence. In that case, the errors in the shrinkage and the fluorescence have to be multiplied by the factor:

$$Factor = \frac{Total\ fluorescence}{Total\ fluorescence - Background\ fluorescence}$$

This explains why the recommendation is made that the induced (tracer) fluorescence should be at least equal to the background fluorescence.

In summary:

Error source	Water Root Sum Squares / Sum	Condensate Root Sum Squares / Sum
Injection flow rate + pump instabilities	1 %	1 %
Dilution ratio	1.5 % / 2 %	1.5 % / 2 %
Shrinkage of sample	1 %	1 %
Fluorometer readings	0.7 % / 1 %	0.7 % / 1 %
Total error	2.2 % / 5 %	2.2 % / 5 %

NOTE: When two numbers are specified, the one on the left hand side of the slash is the result, assuming the error sources are independent (square root of errors squared, which is an expression of the most likely error), on the right hand side when the errors are added directly (maximum error approach).

As long as the background fluorescence is relatively small, the error in the tracer results can be estimated to be below 5 %, provided the best practices for the technique are applied. This is in agreement with the latest results.

The above assumes that the liquid flow rates are "steady", which means that the fluctuations (with time scales > axial dispersion between the injection and sampling points) are "small". Such fluctuations will induce systematic errors as explained in Appendix 5 and will add to the errors as specified above.

NOTE: Assume an uncertainty of 3 % in accordance with Appendix 10. Furthermore, the flow fluctuation is assumed to have an amplitude of 0.3, which results in an error of the concentration of 4 % relative; refer to Appendix 5. Hence, the error covering this effect will be ($\pm 3\% - 4\%$), i.e. an error of between -1% and -7% .