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SINTEF REPORT

TITLE

H&E TQP ID1: Establish sampling and analytical procedures for potentially harmful components post combustion amine based CO_2 capture.

Subtask 1: Design of sampling points in treated flue gas

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ABSTRACT

The major objectives of the project are described in the Tender Invitation of H&ETQPAmine1: “Establishing sampling and analytical procedures for potentially harmful components for post combustion amine based CO_2 capture”.

The present report covers Subtask 1: *Design of sampling points in treated flue gas.*

The report presents design guidelines for measurement sites on pilot and full scale CO_2-absorption plants. The recommended design is based on international standards and guidelines. The presented compilation of guidelines suggests placement and conditions for an appropriate measurement section and neccessary types of measurement ports for manual sampling, high volume sampling and the extension to online monitoring systems. Procedures for verification of the measurement site and chosen measurement plane are presented. Material selection for components of the measurement ports and sample equipment are given. For the structural design we give recommandations for workplace design. The most common errors are looked at to emphasize importance of a proper design. A recommandation of the necessary equipment for sampling is given and a commercial system for manual sampling and high volume sampling is presented.

The report is limited to give guidelines which needs refinement when a more mature design of the plants is available (especially dimensions). The guidelines will enable Company to incorporate an appropriate design easily.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Process technology	Prosessteknikk
GROUP 2	Measurement	Måling
SELECTED BY AUTHOR	Flue gas	Røykgass / forbrenningsgass
	CO_2 Capture	CO_2 innfanging
	Sampling	Prøvetaking

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1 INTRODUCTION

1.1 Background

The fundamental objective of the planned CO_2 capture plants is to minimize the emission of CO_2 and contaminants in the treated flue gas released to the atmosphere. For the qualitative and quantitative measurements of the emissions it is crucial to establish appropriate measurement sites, sampling procedures, analytical procedures and subsequently evaluate automized analysers and if possible online-monitoring system. The aim of the present subproject (H&E TQP Amine 1.1) is to develop a generic design of a measurement section which is applicable for both pilot plant test and need minimum modification to transfer to full scale.

Further details about the background of the project are given in the tender document H&ETQPAmine1: Attachment A1: *"Scope of Service: Establish sampling and analytical procedures for potential harmful components post combustion amine based CO2 capture"*.

1.2 Scope of work

In order to support the Company in the design of measurement sites (measurement ports and points) in treated flue gas relevant literature (international standards and guidelines) is reviewed and contact established with potential equipment suppliers. The provided information will be reviewed and a design proposed.

Parts of the present work is retrieved from SINTEF Report F6335: CO2-Kårstø – Concept study no. 9, selection of gas analyser and monitoring system, March 2008.

The objective at hand requires considerable attention to take care of a series of subsequent considerations which arise through the follow-up project within the TQP-Amine project:

- Design of a complete measurement site itself; guidelines shall be applicable for manual and high volume (manual and/or semi-automized) sampling
- Measurement section placement and preferably design of measurement ports shall be generic to accommodate online monitoring equipment later
- The sampling system and procedures shall not generate alternations (degradation) of the samples taken and allow for efficient sample handling considering valid EHS-requirements
- High volume sampling for toxicology tests will require systems which are not dependent on adsorbents or absorbents which in itself will have adverse effects

The sampling problem at hand requires that samples are taken at ambient temperature to collect appropriate samples of both gas and liquid phase. Depending on the purpose of the sampling several alternatives need to be considered:

- Manual sampling for analysis of gaseous and condensed components: The collection of samples, need to be designed such that components are collected by appropriate absorbents or adsorbents for further processing. Collection can be performed in a series of generally cooled impingers where characteristics of the absorbents or adsorbents are tailored for given components.
- High volume sampling for toxicology tests: this task requires a slightly different procedure since the components from the flue gas shall neither be diluted nor mixed with other components which might have influence on the toxicology of the resulting mixture. Further, the samples need to be protected from other effects like UV or oxygen to avoid photocatalytic or oxidizing reactions.

- Online sampling for emission monitoring

The present study shall cover design of the measurement site for both pilot and full scale design of a CO_2-capture plant. Though information on these two systems is still limited, we assume that operation conditions are similar; the principal difference will be the emission cross section. For the full scale plant the dimensions are not given yet, for a proposed pilot plant a circular cross section is assumed.

1.3 Report outline

Chapter 2 gives the basis for this study, which is mainly a summary of the information given by the Company. Chapter 3 deals with basics necessary for the design of sampling points for emissions in water saturated and dusty flue gases. An appropriate design is strongly dependent on flue gas conditions and operational conditions to find the correct measurement plane. In chapter 4 relevant information from several international standards are presented to give comprehensive guidelines for location of the measurement section and design of measurement ports. Guidelines for defining appropriate sample points are given. In chapter 5 generic design suggestions for a full scale plant and a measurement section for pilot plant experiments are presented. Chapter 6 presents some common errors and pitfalls in the design of measurement section and placement of representative sampling point(s) in the emission cross section. Finally, chapter 7 sums up the given recommendations.

2 BASIS FOR THE STUDY

The present objective requires considerable attention to take care of the series of subsequent projects since the design shall be generic, thus application to both pilot and full scale plant needs to be considered. Design of the measurement site shall also be flexible enough to accommodate manual sampling, high volume sampling and later on serve for installation of online monitoring equipment.

Uncertainties arise partly because of the immaturity (layout/design: dimension and shape of the stacks) of the project and partly because of the components to be measured, gas conditions and analysis. It is expected that water droplets are carried out with the sweet gas from the water wash section at the absorber top. The sweet gas temperature is expected to be 25 - 50° C and components as degradation products, absorbents (e.g.: amines), organic acids, ammonia and traces of sulphur dioxide will be absorbed in these water droplets.

The design of the measurement site is strongly dependent on the state of the gas to be analysed and the sampling purpose like: manual sampling, high volume sampling for toxicology test and online analysis systems. Online monitoring systems can be based either on in-situ (measurement inside the gas stack) or extractive systems were a partial gas stream is withdrawn from the gas stack, this will be considered in a subsequent study. Online analysers operate in general with either dried gases or heated sample lines. For dried gases, we will lose some water soluble components with the liquid from a knock-out condenser. For analysers which operate with heated sample lines, it is not yet well understood how components might change (decomposition and catalytic effects with materials of measurement equipment or salts) when they are heated to normal operation temperature of ~180°C.

2.1 Process design

The basic flowsheet of a CO_2-capture plant together with mark-up of a specific location of a measurement site is given in Figure 2-1; operational parameters for treated flue gas (sweet gas) are given in Table 2-1. Note, some of the parameters are estimated.

For simplicity, the description of the operation mode of a CO2-capture plant is omitted and we limit attention to the absorber system itself. Flue gas entering from the up-stream process will be cooled and enters the absorber from the bottom; flue gas will be distributed over the absorber packing material (potentially in several parallel sections) and get in contact with the absorbent (water-amine mixture). A main body velocity (superficial) in the absorber of 2 – 3 m/s is suggested.

On top of the absorber section a water wash section will be installed to minimize emissions of amine and other possible hazardous components. Treated flue gas exiting from the wash section will be transferred into an exit pipe placed on top of the absorber and wash section structure. The mechanical design of the stack (exit point) is not yet given we therefore assume a circular cross section with a smooth transition from water wash section into the exit stack.

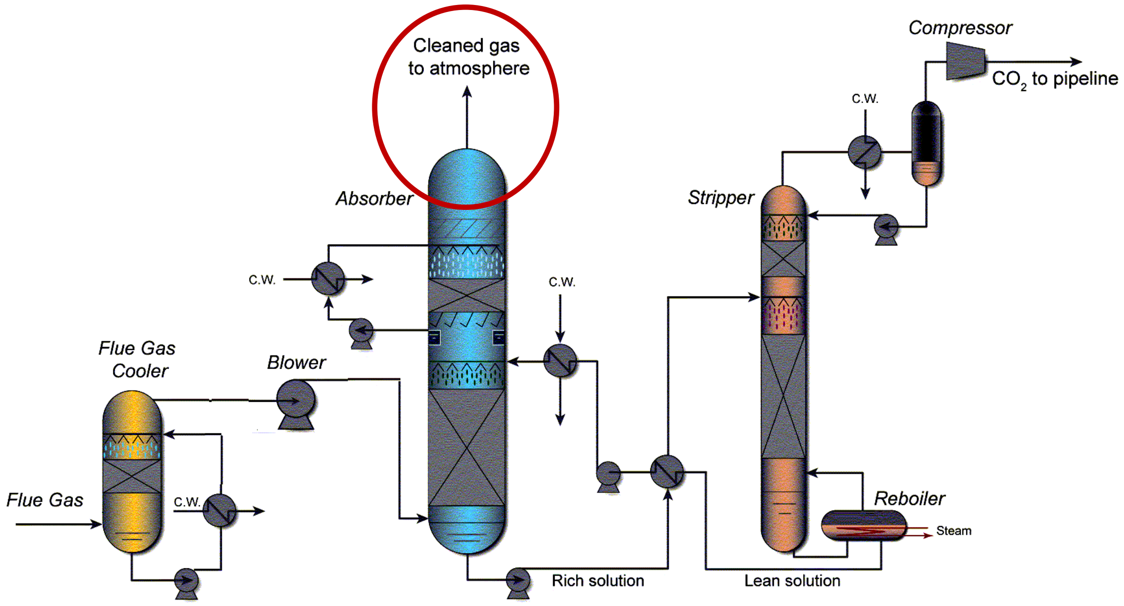

Figure 2-1: Simplified process diagram, circled part is focus of the study (SINTEF)

2.2 Operational conditions

We assume that operational conditions (both with respect to flue gas components as well as flow conditions) in full scale and pilot will be kept as similar as possible. The flue gas conditions and composition, sweet gas (absorber outlet stream) conditions and composition, given here are based on information extracted from the document H&ETQPAmine1: Attachment A1 and given directly from Company. The treated flue gas from the stack will be saturated with water and the conditions and compositions are given in Table 2-1.

The velocity in the exit pipe is estimated to 20 m/s (information from Company), with the data given by company this corresponds to a diameter of 6.6 m and an area of app. 35 m^2 @ 2.3M Nm3/h and 25°C.

Table 2-1: Nominal conditions and composition of treated flue gas (sweet gas)

Conditions	**Units**	**Nominal values Pilot scale**	**Nominal values Full scale**
Flow (Normal)	kg/s		400
	Sm^3/h	250 - 1200	$0.72 – 2.3 *10^6$
	kg/s @ 1.2 kg/Nm^3	0.08 – 0.4	200 – 640
Temperature (Normal)	°C	25 - 50	
Pressure (a)	bar	1.01325	
Main body velocity	m/s	2.0 – 3.0	
Exit velocity after water wash	m/s	20	20
Composition			
Oxygen (O_2)	wt-%	15	
	Mol-%	13.8	
Nitrogen (N_2)	wt-%	80.7	
	Mol-%	81.5	
Carbon Dioxide (CO_2)	wt-%	0.6	
	Mol-%	0.5	
Water (H_2O)	wt-%	3.9	
	Mol-%	3	
NOx	ppm	?	$2 – 20^+$
NH_3	ppm	?	< 50
SO_2	ppm	?	0.10^+
Amines	ppmv	?	< 5
Properties (air)			
Kinematic viscosity[1] ν	m^2/s	$153.2 * 10^{-7}$	
Derived data	Re = $(u*D_h)/\nu$	$8.6 * 10^6$	

$^+$estimated, verification needed

2.3 Definitions

The definitions of technical terms[2] regarding design of an appropriate measurement section is given in Table 2-2 and presented in Figure 2-2.

Table 2-2: Definition of terms for measurement sections

Stack, duct	Structure through which gases pass. Stacks are intended to be of sufficient height to disperse emissions to atmosphere. Ducts are horizontal pipes.
Measurement section	Region of the stack or duct that includes the sampling plane including inlet and outlet section
Measurement plane	The plane normal to the centreline of the stack or duct at sampling location
Measurement location or site	The working area around the sampling plane on a stack or duct
Sampling lines	Imaginary lines in the sampling plane along which sampling points are located; bounded by inner wall of stack/stack. Piping which connects measurement point

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[1] VDI Wärmeatlas, 10. bearbeitete und erweiterte Auflage, 2006

[2] EN 15259:2008 Air quality. Measurement of stationary source emissions – Requirements for measurement sections and sites and for the measurement objective plan and report

	with a sampling system or analyser
Measurement ports or access points	Points in the wall of the stack through which access to the flue gas is enabled
Measurement point	The specific position in the measurement plane or on the sample line from which the sample is extracted.
Mass concentration	Concentration of the measured component averaged over the cross section of the stack and averaged over a defined time period

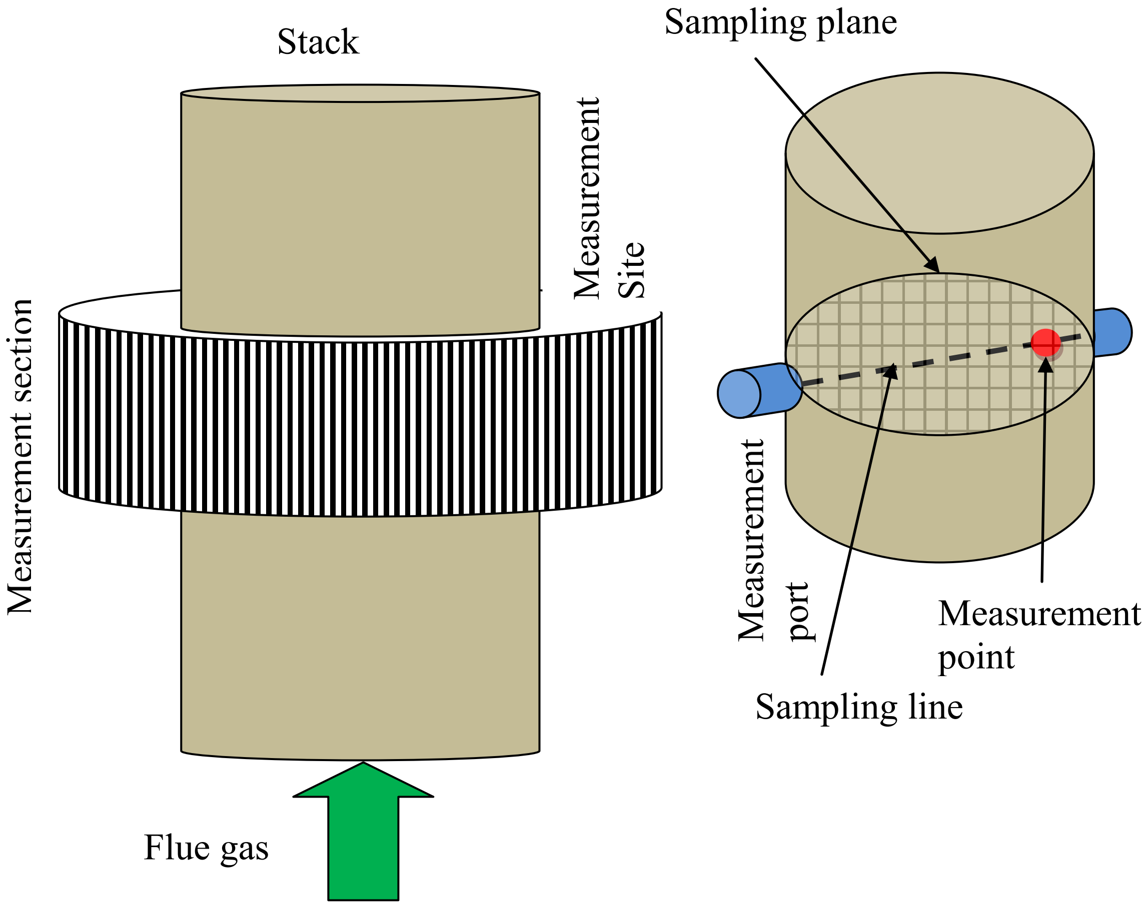

Figure 2-2: Schematic drawing of a measurement section (SINTEF)

3 BACKGROUND SAMPLING FROM STATIONARY SOURCES

3.1 Relevant guidelines and standards

An overview of relevant guidelines and standards which have been used for this work are given in Table 3-1

Table 3-1: Overview Guideline and Standards relevant for measurement section design for Emission Monitoring

Identifier	**Title**
DIN EN 1948-1; 2004	Emissions from stationary sources – Determination of the mass concentrations of PCDD/PCDF and dioxine like PCBs – Part 1: Sampling
EN 13649; 2002	Stationary source emissions – Determination of the mass concentration of individual gaseous organic compounds – Activated carbon and solvent desorption method
EN 13284	Stationary source emissions. Determination of low range mass concentration of dust. Automated measuring systems
EN 13284-1; 2002	Stationary source emissions – Determination of low range mass concentration of dust – Part 1: Manual gravimetric method
EN 14385; 2005	Emissions from stationary sources – Determination of the total emissions of As, Cd, Cr, Co, Cu, Mn, Ni, Pb, Sb; Tl and V
DIN EN 15259; 2008-1	Air quality. Measurement of stationary source emissions. Requirements for measurement sections and sites and for the measurement objective, plan and report
VDI 2066 Part 1; 2006	Particulate matter measurement. Dust measurements in flowing gases. Gravimetric determination of dust load
VDI 3868-1; 1994	Measurement of the total emissions of metals, semi-metals and their components - Manual measurement in flowing and emitted gases – Sampling system for particulate and filterable substances
VDI 3862-2; 2000	Determination of gaseous emissions – Measurement of aliphatic and aromatic aldehydes and ketones using the DNPH-procedure – Gas wash-bottle method
VDI 4200; 2000	Realization of stationary source emission measurements
ISO 11338-1; 2003	Stationary source emissions – Determination of gas and particle-phase polycyclic aromatic hydrocarbons – Part 1: Sampling
ISO 11338-2; 2003	Stationary source emissions – Determination of gas and particle-phase polycyclic aromatic hydrocarbons – Part 2: Sample preparation, clean-up and determination
ASTM D3685 / D3685M-98	Standard Test Methods for Sampling and Determination of Particulate Matter in Stack Gases
ASTM 6331-98	Standard Test Method for Determination of Mass Concentration of Particulate Matter from Stationary Sources at Low Concentrations (Manual Gravimetric Method)
ASTM 3154-00	Standard Test Method for Average Velocity in a Stack (Pitot Tube Method)

* Standards and guidelines marked in **bold** are most relevant

** Note, there is no principal difference between EN 15259 and the national versions NS-EN15259 or DIN-EN15259

Based on the standards given in Table 3-1 the measurement section is designed; because of the more general character of DIN EN 15259 (2008) and VDI 2066, these were chosen as basis for the following design recommendations[3]. Further, VDI 4200 has implications on the design of the measurement port itself to ensure that instrumentation can be inserted into the stack. The two American standards ASTM D3685 and ASTM 3154 cover similar issues but are less generic than the primary applied documents.

3.2 Measurement in gas flows in stationary sources

Flue gases may be in-homogeneous because of differences in chemical composition, temperature and velocity profile caused by stratification or swirl caused by changes in stack design and geometry. **Concentration distribution[4] and velocity profiles** may differ across the stack cross section (space) and over time, therfore they need to be determined as integral over time and space over the stack area. Thus, average concentration and velocity at several evenly spaced measurement points across a measurement plane need to be determined. These integral measurements are performed as grid measurements over the measurement plane.

For gases carrying **particulates or droplets**[5] effects introduced by inertia (a measure of an objects resistance to changing its motion and characterized by its mass and the stack geometry lead to unevenly distribution over the measurement plane. Similar considerations are needed if the flue gases are not **well mixed.** Furthermore for systems including particulates or droplets it is paramount to avoid artefacts introduced by the sampling equipment itself, which could lead to selective sampling/under sampling of a given phase. Samples by means of extractive methods must therefore be obtained iso-kinetically from multiple sample points

For further clarification of proper measurements, dust and volume flow is treated in more detail as introductory examples. The reason is that the aerodynamic conditions are similar for dust particles and liquid droplets and explanation is more intuitive for dust particles than for fluid gas and liquids. For volume flow a mal-distribution over the cross section will give highly erroneous measurements.

3.2.1 Volume measurement

The pipe flow profiles in actual installations is rarely ideal, in many installations the flow is not well developed, practically any changes to the piping, such as elbows and reductions or expansions can disturb well-developed flow patterns. A fully developed velocity profile is established in general after $10*d_h$[6]. Trying to measure disturbed flow can create substantial errors.

When measuring the velocity of an air stream (see Figure 3-1 and Figure 3-2), a sensor is placed into the air stream so that the sensing tip points directly into the moving air stream (e.g.: Pitot tube, annubar). To obtain the most accurate readings, the sensing tip of the instrument must be parallel to the direction of flow of the moving air stream.

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[3] Please note the VDI 2066 is a guideline and not a standard.

[4] VDI 4200, Realization of stationary source emission measurements, 2000

[5] VDI 2066 – Part 1 Particulate matter measurement. Dust measurement in flowing gases, Gravimetric determination of dust load, 2006

[6] Definition hydraulic diameter: $d_h = 4*\text{Sample area/perimeter}$, ciruclar: $d_h = 4*(\Pi/4* d^2)/(\Pi* d)$; rectangular: $d_h=4*a* b / (2(a+b))$

When a Pitot tube is used, the radial placement of the Pitot tube influences the accuracy of the flow calculations. As the air mass flows through a closed pipe, friction is generated where the air mass contacts the pipe wall; the frictional drag reduces the velocity of the air stream near the pipe wall. Since the volumetric flow calculations are based on the average airflow velocities, the ideal radial placement of the measurement sensor needs to be determined in the velocity profile for a representative operation point[7].

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[7] Olsen, Odd A., Instrumenteringsteknikk, Tapir, 1989

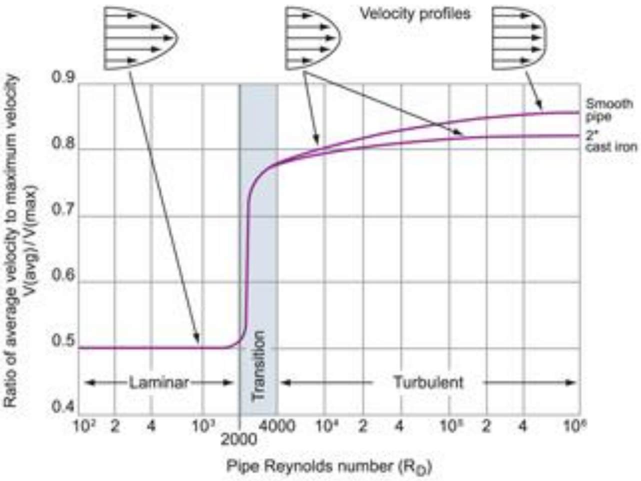

Figure 2. *Ratio of average to maximum (centerline) velocity for smooth and rough pipe.*

Source: *Richard Miller, Flow Measurement Engineering Handbook.*

Figure 3-1: Ratio of average and maximum velocity for stratified flow in pipes

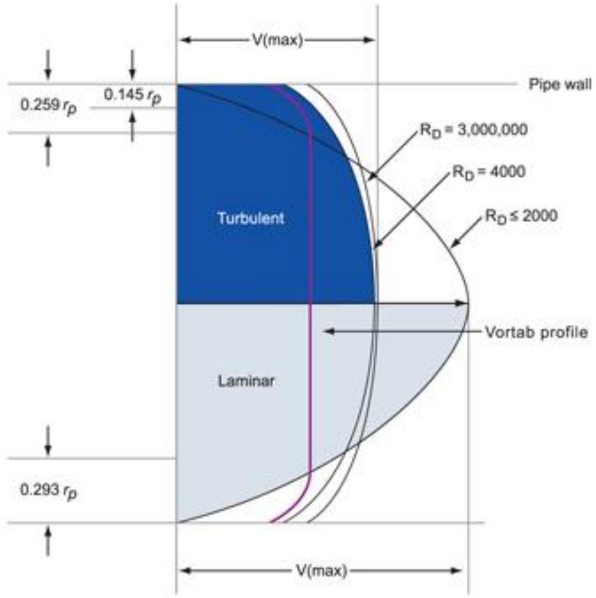

Figure 1. *The laminar profile takes on a parabolic shape where the relationship between the average velocity and centerline velocity is quite dramatic when compared to the turbulent flow profile.*

Source: *Richard Miller, Flow Measurement Engineering Handbook. Vortab profile added by FCI.*

Figure 3-2: Flow Profile as function of Reynolds number for stratified flow

Table 3-2: Straight run requirements for flow sensors

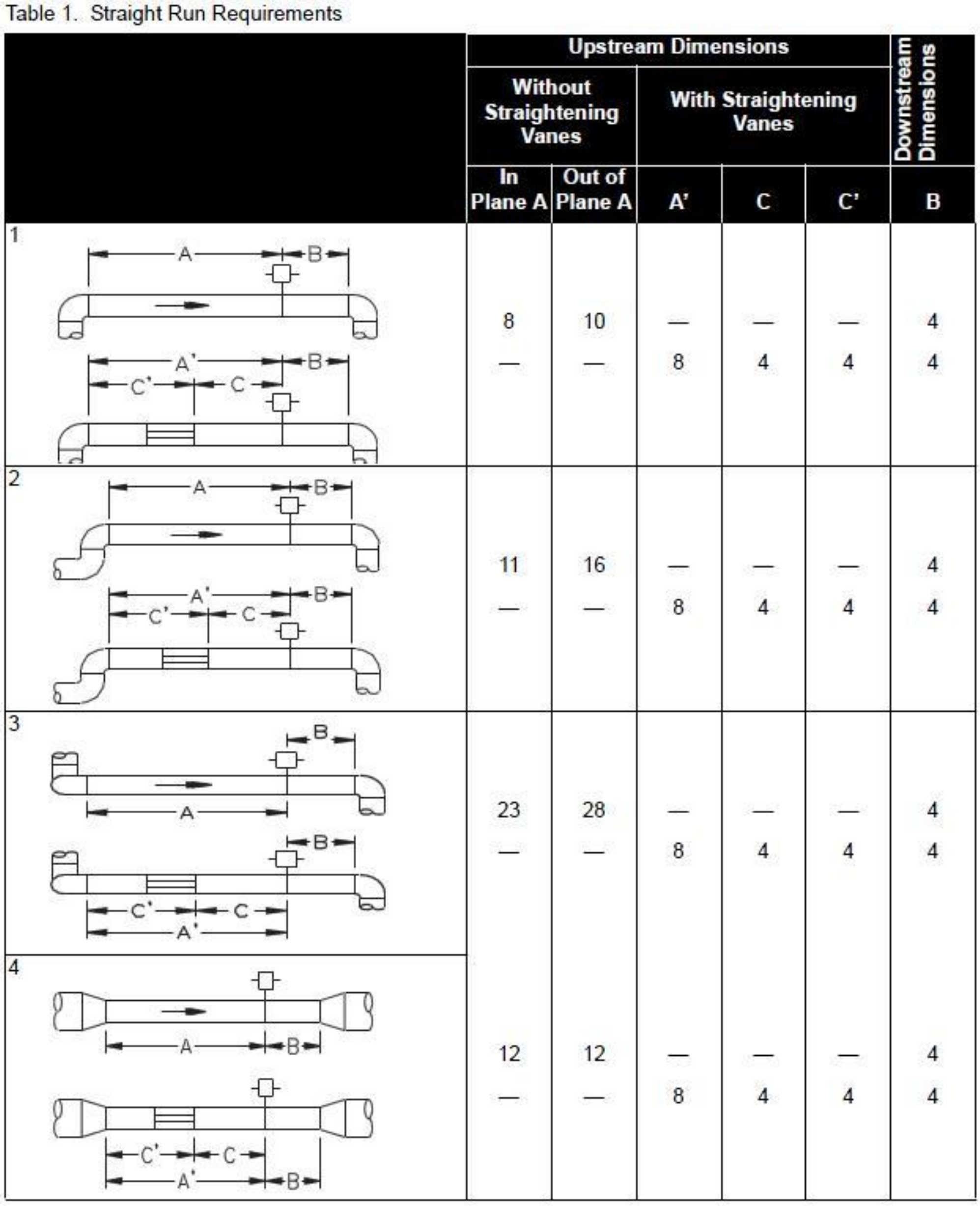

Table 1. Straight Run Requirements

	Upstream Dimensions					Downstream Dimensions
	Without Straightening Vanes		With Straightening Vanes			
	In Plane A	Out of Plane A	A'	C	C'	B
1	8	10	—	—	—	4
	—	—	8	4	4	4
2	11	16	—	—	—	4
	—	—	8	4	4	4
3	23	28	—	—	—	4
	—	—	8	4	4	4
4	12	12	—	—	—	4
	—	—	8	4	4	4

Contrary to information from Miller and Rosemount it is found in another publication[8] that flow straightening vanes are not able to remove distortions induced from reductions, while vanes reduce swirl. In **Table 3-3** their recommended distances upstream of the measurement plane are summarized.

Even though swirl can efficiently removed by flow straightening vanes, a non-uniform velocity distribution over the cross section will not be transferred into a uniform flow profile, a point that must be taken into consideration. Further, especially asymmetrical restrictions will generate non-uniform flow profiles which require longer straight inlet sections, recommendations for the length of inlet sections as indicated in Table 3-2. A uniform flow profile can be generated in a certain degree by static mixers, alternatively installation of an orifice plate. A properly designed orifice plate will flatten the velocity profile, but generate a

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[8] Perry, Chemical Engineers Handbook, 8th edition, McGrawHill, 2007; based on *Trans. Am. Soc. Mech. Eng.,* Vol. 67, pp 345-360, 1645

considerable pressure drop at the stack inlet[9]. The given recommendations should be verified by means of CFD-simulations.

Table 3-3: Location of measurement point relative to pipe fittings

Contraction D_2^*/D_1	0.2	0.4	0.6	0.8
Distance upstream measurement plane (A)	8 * D_2	9* D_2	10* D_2	15* D_2
Distance downstream measurement plane (B)	2* D_2	2* D_2	2* D_2	4* D_2

* D_2 is the diameter in the measurement plane

The **minimum** straight inlet section recommended in DIN 15259 is 5*d_h, however the standard requires a confirmation of the velocity profile over the measurement plane to confirm that a uniform profile is established; this is (DIN 15259):

- Angle of gas flow less than 15^0 with regard to stack axis
- No negative local flow
- Ration of highest to lowest local gas velocity less than 3:1

The recommendations given in DIN 15259 and installation guidelines like Rosemount are not contradictory but the installation requirement for a flow sensor are slightly stricter than for an emission monitoring side. Putting this into context, sampling equipment placed in an area where a higher than average velocity is present will result in an erroneous increase in emissions (and vice versa). Therefore a trade-off is necessary between length of inlet (this is costs of design) and expected accuracy of the performed measurements.

The minimum straight length for outlet section below the stack exit is recommended in DIN 15259 to be 5*d_h from the top of a stack. Provided the velocity in the stack is considerably higher than the average velocity of air streams in the surrounding of the exit cross section, the recommendation of DIN 15259 are sufficient.

Application of multiple annubars or ultrasonic sensor Figure 3-3 will reduce uncertainty regarding the volume measurement since these sensors span over the cross section/sampling lines. These sensors allow for an integration of the measurement signal over the cross section, thus reducing the error in the measured superficial velocity in a cross section. However, calculation of mass emission over time is still dependent on properly placed sampling point (or several sampling points over a cross section) for concentration measurements, especially for flue gas flows with particles or droplets (see chapter 3.3).

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[9] Note, the design of the absorber and /or inlet to the stack with internals to provide a proper velocity and concentration profile is outside the scope of the current document.

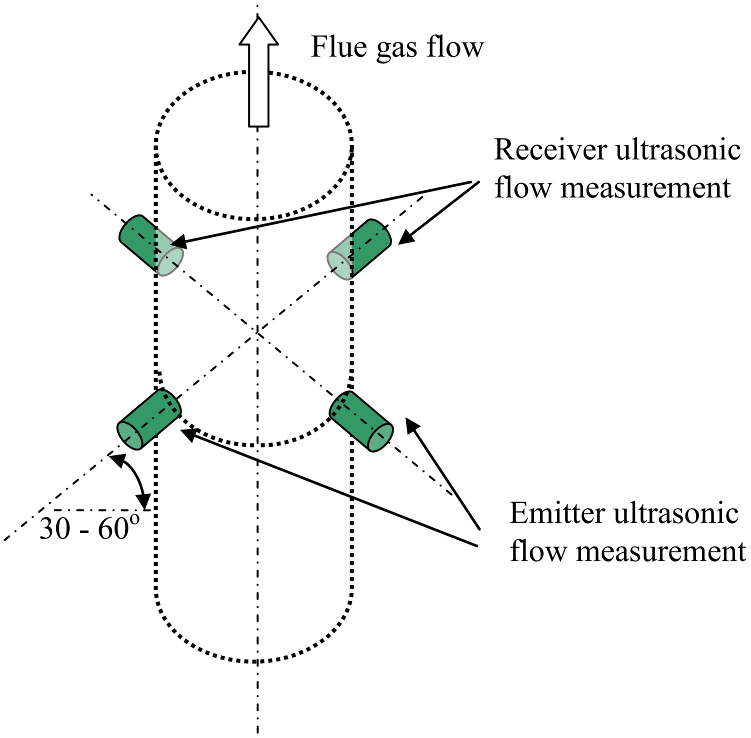

Figure 3-3: Principal arrangement of ultrasonic flow measurement

3.2.2 Isokinetic sampling of inhomogeneous particle loaded gas flows

The gas flow to be sampled will consist of a mixture of gaseous components, aerosols and droplets at varying sizes. An extractive method implies here that a representative sample of a fraction of the sweet gas flow is withdrawn through a sample system and made available for analysis, irrespectively of the size or density of possible non-gaseous compounds. In order to obtain a representative sample from an inhomogeneous gas stream independent of particle size (or droplets size), it is necessary to remove the sample stream iso-kinetically, i.e. with the same velocity as the main stream; any other means of extraction will result in erroneous measurements. Figure 3-4 shows the pattern of the time averaged flow lines in the vicinity of a thin-walled sampling probe.

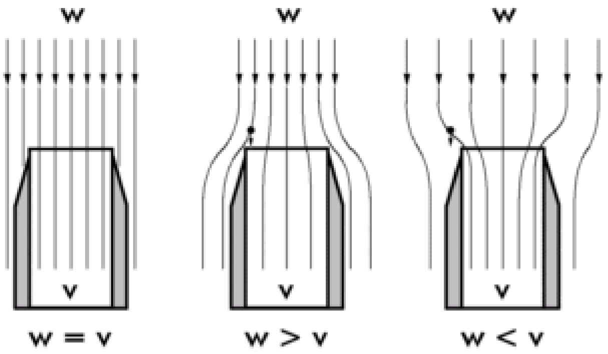

Figure 3-4: Iso-kinetically sampling of gas with droplets / particles (drawing from http://www.photometer.com/en/abc/abc_052.htm)

In the iso-kinetic case (w=v), all particles flowing towards the intake opening are equally collected. If the sample taking velocity is too low (w>v), heavy particles can enter the probe even if the flow line on which they were located passes by the probe. Thus too many large particles are collected. If the sample taking velocity is too high (w<v), heavy particles fail to

adhere to the flow lines and end up bypassing the probe. Thus too few large particles are collected. The error occurring in the case of *under*-iso-kinetic sampling (w>v) is many times larger than in the reverse case. This can be explained using again the dust analogy**.** Figure 3-5 shows the relative dust content ε as a function of the velocity ratio of sample stream/main stream (v/w) and the factor B, which includes the particles' rate of fall and the probe diameter, B is installation specific and determined on-site during a gravimetric calibration. The curves are valid for a defined particle size, gas velocity and probe (nozzle) diameter. The possible error is reduced with smaller particle size, smaller gas velocity and larger probe diameter. Available standards normally specify a minimum diameter of the probe in the range 4 - 8 mm for iso-kinetically sampling. The minimum diameter, depend on particle/droplet size, gas velocity and the intended sampling volume to be extracted.

Obviously the **error** at equal velocities is zero, and it rises sharply for lower sampling velocities. In the range of higher sample stream velocities, however, the error is lower and, even more important, is virtually constant from v/w = 1.5 and upwards. Similar reasoning is applicable for the sweet gas containing tiny water droplets. The velocity of the sample gases has to be high enough to ensure proper sampling. The error introduced due to choosing a too high sampling velocity is easily accounted for in a calibration of the system.

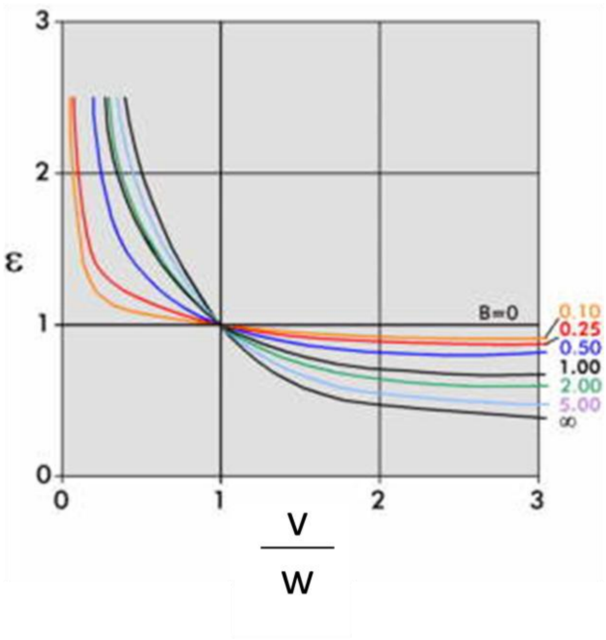

Figure 3-5: Relative dust content vs. velocity ratio of sample stream/main stream (plot adapted from http://www.photometer.com/en/abc/abc_052.htm)

The **size of droplets** emitted from an absorber is dependent on numerous effects; such as: type and number of demisters, velocity of the flue gas main body, physical (density, viscosity, surface tension, temperature) and chemical (composition, pH) properties of the wash water and design of the emission cross section. The range of aerosol concentration[10] for stack effluent can be in the order of 0.01 to 100 mg/m^3; droplet types emitted from an absorber will be: Fog, Mist: 0.1 – 200 μm; Spray: 3 – 1000 μm, Cloud droplets 2 – 90 μm

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[10] William C. Hinds; Aerosol Technology Properties, Behavior and Measurement of Airborne Particles, Wiley, 1999

and probably droplets of unknown size because of aerosol agglomeration. Information from vendors regarding the droplet size and number is limited and case specific thus for the current case not available. The lack of information allows not for estimation of a minimum aerosol dimension which might relax the requirement for isokinetical sampling. The rule of thumb is that for aerosols of more than 10 µm is mandatory, however, literature[10] states irrespective of aerosol dimension: *"If sampling is not done isokinetical, there is no way to determine the true concentration unless the original particle size distribution is known or can be estimated"*. If sampling is isokinetic, there is no particle loss at the inlet, regardless of particle size or inertia.

Systems for isokinetical extraction from a flue gas stack are available from different vendors, these can either operate manually or automized 24/7 for long term (quasi) online sampling. However, these systems are designed for sampling in one location, modifications in cooperation with supplier are possible to adapt the equipment to allow besides normal operation sampling, high volume sampling and simultaneous multi-point sampling if necessary. The sampling unit itself needs to facilitate accumulation of gaseous compounds, particular matter, liquids and aerosols in one single unit; therefore a modification of these standard systems is expected.

4 DESIGN OF A REPRESENTATIVE MEASUREMENT LOCATION

Suitable measurement sections (actual measurement plane, inlet and outlet sections) and measurement sites are necessary to obtain reliable and comparable emission measurements; the design of the measurement section needs to consider the design of the stack, varying operational conditions and load of the plant. Emission measurements require appropriate measurement ports (number and types) and working platforms. A design procedure to determine an appropriate measurement location which that will be applicable for both pilot plants and full scale plants, will be presented. Further, a simple verification procedure for establishing appropriate sampling points will be given.

4.1 Measurement Section and measurement site

A generic illustration of a measurement section and site is given in Figure 4-1. The sample plane location shall be as far as possible downstream from any disturbance which could introduce a change in direction of flow, see chapter 3 for more information. The measurement plane shall be in a stack section with constant shape and cross sectional area; further vertical sections are advised for flue gases with particles or droplets to avoid sedimentation. **Minimum** requirement (EN 15259) for straight inlet section is 5* d_h [11] and outlet is 5*d_h from top of stack.

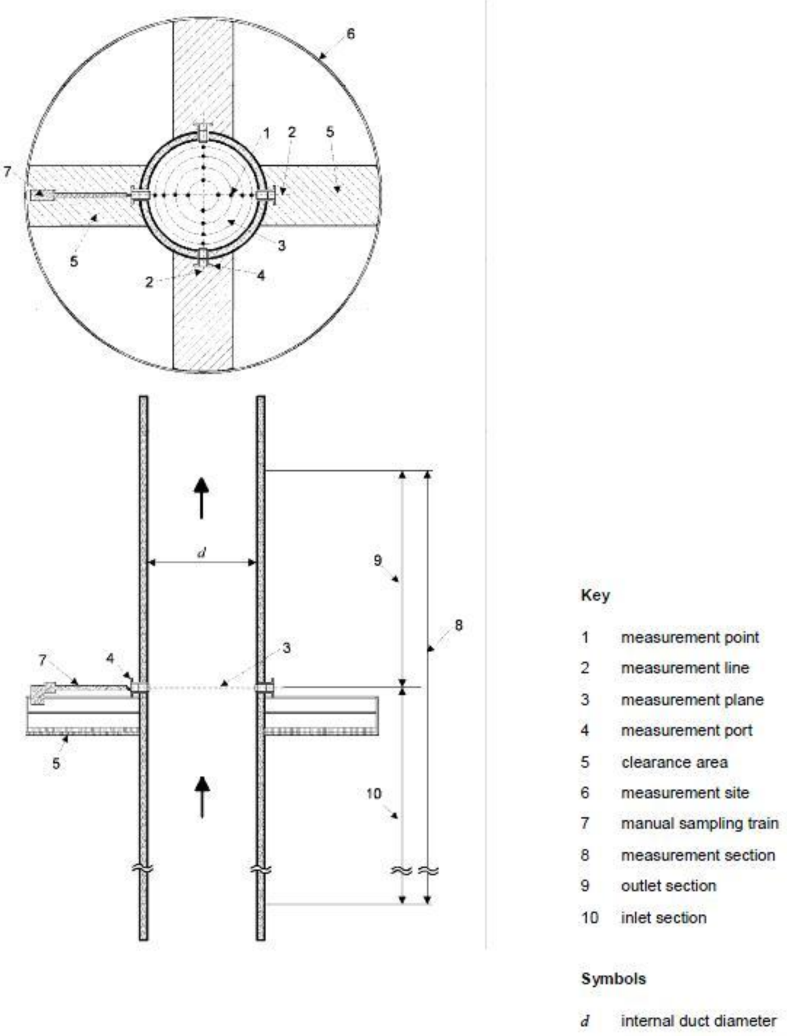

Figure 4-1: Illustration of measurement site and measurement section for full scale plant (DIN EN 15259)

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[11] The hydraulic diameter is defined as; (4* area of sample plane) / length of sample plane perimeter

4.2 Mounting location of measurement planes

A comprehensive example of a generic mounting location for an emission measurement system including manual sampling is presented in Figure 4-2. The position of the sampling ports is chosen such that there is no interference between the individual measurement lines. The ports in planes A6 to A9 are designed for manual sampling, A5 for temperature and pressure respectively. The remaining ports[12] in planes A1 to A4 are prepared for online sampling (not part of the present study since types of instruments not determined yet, in Figure 4-2 an optical dust sensor is depicted). The number of ports for manual sampling lines should be at least four to allow for simultaneous sampling of different parameters.

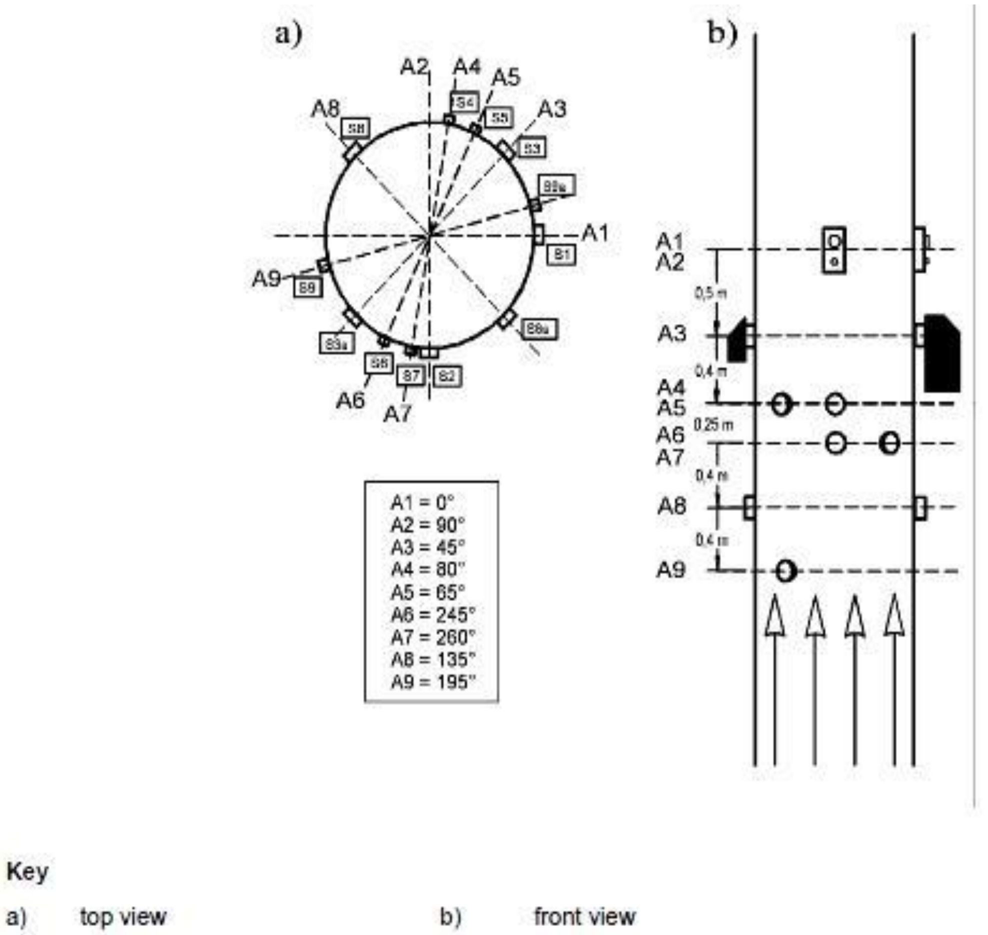

Figure 4-2: Mounting location of sample ports (adopted from DIN EN 15259)

Distance between sample planes should be sufficient to avoid interference between individual instruments; between planes A5 to A9 a distance of 400mm is suggested for a full scale plant (stack diameter ≥4000mm); for a pilot plant (stack diameter ≤ 500mm) a minimum distance of 200mm is advised.

4.3 Measurement ports

If measurement ports are installed according to Figure 4-2 in the stack; ports need to be equipped with tight sealing covers (cap or blind flanges). Replacement caps or blind flanges can be readily adapted to a given measurement objective. It is recommended that access ports

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[12] Note, the dimensions and type of fittings and ports need to be verified when online sampling instrumentation is specified.

have a minimum diameter of 100 mm and that they do not protrude into the gas stream (level with inner stack wall). The minimum number of access ports is given in Table 4-1. For velocity and composition measurements access port a standard DN125 (e.g.: DIN 2530, DIN 2573 or DIN 2630; ASME/ANSI B16.5) flanges with blind flange is recommended, the pipe stub should be 100 mm from insulation of the stack (see Figure 4-3). Manual temperature and pressure measurement sensors can be accommodated in DN50 (e.g. DIN 2986, DIN 2991 or BS21) flanges with pipe stub, alternatively nipple and cap (see Figure 4-4 pipe stub with thread and threaded cap). Because of corrosion of the threads; the design with flanges is preferred.

Various specification of flanges are possible, the chosen DIN standards are merely for example purpose. Alternative standards for sample ports are ASA/ANSI/ASME (American), PN/DIN (European) and BS 10 (British). The selection of appropriate flanges/fittings should for simplicity reasons depend on the system chosen for the remaining plant (type of flange, pressure class and material); important is the free cross sectional area within a fitting, not the type/standard of the fitting.

Table 4-1: Number and type of sample ports for manual sampling

Area of measurement plane [m^2]	Stack diameter	Minimum number of sample lines	Measurement/sample ports			
			Velocity	Temperature	Pressure	Composition
			DN100 or DN125	DN50 or Ø75 Nipple	DN50 or Ø75 Nipple	DN100 or DN125
< 0.1	<0.35	1	1	1	1	2
0.1 to 2.0	0.35 to 1.6	2	2	2	2	2 (+2)
>2	>1.6	2	4	4	4	6

For installation of the individual measurements the blind flange or cap are replaced by fittings which allow a gas tight and solid installation of the instrument in the measurement port.

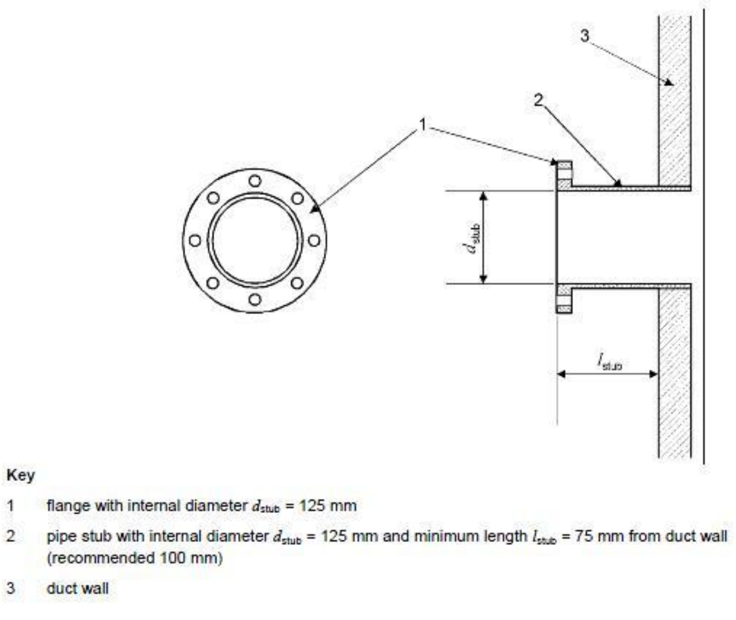

Figure 4-3: Measurement port DN125 (DIN EN 15259)

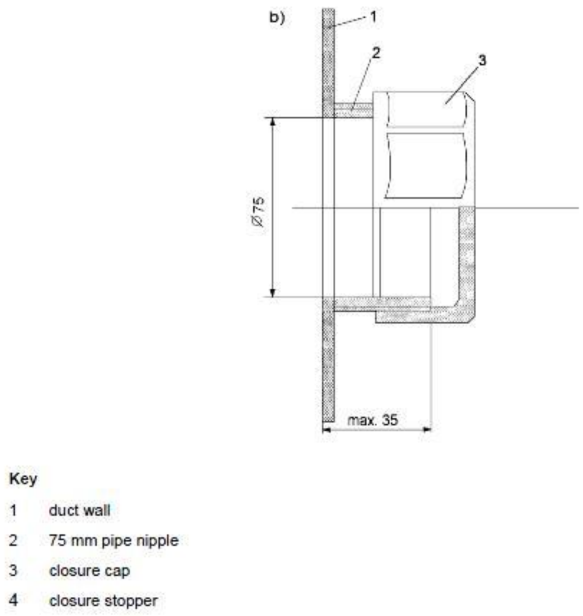

Figure 4-4: Measurement port Nipple Ø75mm (DIN EN 15259)

For stacks with diameter up to 1.6 m two pairs of ports at 90° are minimum (for each measurement; see Table 4-1), two additional ports should be installed if simultaneous measurements shall be performed to reduce time for a measurement campaign. For larger stacks (>1.6 m), pairs of measurement ports shall be placed on opposing sides of the stack along the measurement lines. For rectangular stacks, similar consideration apply, however, here the ports shall be installed on the longest side.

4.4 Position of sample points along sample lines: grid measurement

Depending of the sample line length or alternatively measurement plane dimension (shape and cross section), a grid approach will be necessary. The minimum number of measurement points in a sample plane for circular and rectangular stacks is presented in Table 4-2 and Table 4-3, respectively.

The design of a measurement location with a sample plane for grid measurement is as follows[13]:

- Define a suitable sampling location during design phase of the plant, avoid constrictions, bends and other intrusion upstream the measurement plane to minimize undesired variations. Definition of the location is based on flow pattern within the stack and an evaluation regarding the homogeneity of the gas body
- Decide number and position of sampling points, design sampling ports and access to the sampling location
- Definition of sampling point position:
  - Carry out preliminary velocity and composition measurement through traversing (see Table 4-2) at different loads along two perpendicular sampling lines to **determine velocity and concentration profiles**. For placement of the measurement point(s) we refer to Figure 4-5 and Figure 4-6 the cross section of the stack is divided in suitable "rings" plus one centre circle of equal surface[14,15]. Sampling points are placed in the centre of each surface. For

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[13] Environment Agency, Technical guidance Note (Monitoring) M1: Sampling requirements for stack emission monitoring, www.mcerts.net, Ver. 6, 2010

[14] VDI2066-1; Particulate matter measurement Dust measurement in flowing gases Gravimetric determination of dust load

homogeneous gas concentrations, the sample point(s) shall be placed at the average velocity.

Provided the preliminary measurements show a uniform velocity and concentration profile; the position of the measurement point can easily be defined. For stacks diameters up to 1 m, one sample point at average velocity is sufficient. For non-uniform profiles multiple measurement points are required.

- For stacks with large diameters the procedure is similar. Carry out preliminary velocity and composition measurement traverses at different loads along a grid of perpendicular sampling lines to determine velocity and concentration profiles; which in turn defines the measurement point for manual and/or online sampling.
- For circular and rectangular stacks the procedure is analogue, the measurement plane is divided in a suitable number of surfaces and a measurement point is placed in the centre of each surface.
- The above procedure assume close to uniform flow and concentration profiles. If this is not the case care must be taken and CFD-simulation (Computational Fluid Dynamics) should be used to investigate the flow and mass distribution in the stack. Thus, an alternative procedure is an a priori CFD-simulation of the absorber head space and stack at different loads to determine the most suitable position of the measurement section. However, the experimental verification shall not be omitted.

Table 4-2: Verification measurements: minimum number of measurement points for round stack (based on EN15259, iso-kinetically dust measurement) see Figure 4-5 for visualization

Area of measurement plane [m^2]	Stack diameter	Minimum number of sample lines /ports	Minimum number of Sample points in each measurement plane
< 0.1	<0.35	1	1
0.1 to 1.0	0.35 to 1.1	2	4 + center
1.1 to 2.0	1.1 to 1.6	2	8 + center
>2	>1.6	2	Minimum 12 max. 20 or minimum 4/m^2

Table 4-3: Verification measurements: minimum number of measurement points for rectangular stack (EN15259) see Figure 4-6

Area of measurement plane [m^2]	Minimum number of sections per side	Minimum number of sample points in each measurement plane
< 0.1	-	1
0.1 to 1.0	2	4
1.1 to 2.0	3	9
>2	> 3	Minimum 12 max. 20 or minimum 4/m^2

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[15] DIN EN 15259 Air quality – Measurement of stationary source emissions – Requirements for measurement sections and sites and for the measurement objective, plan and report; German version EN 15259:2007

For determination of the position of sample points two slightly different methods are in use. In Figure 4-5 the general method is presented where the minimum number of sampling points (red) for a stack diameter of Ø<2m is presented together with additional measurement points for verification measurements (green). The second method (tangential method) does not employ the centre measurement point, instead one of the additional points in the sections close to the centre (yellow is used) is employed. The authors didn't find any conclusion in DIN EN 15259 which of the two methods should be preferred, the number of sample points for actual measurements is identical, thus there are no cost implications for installation or operation.

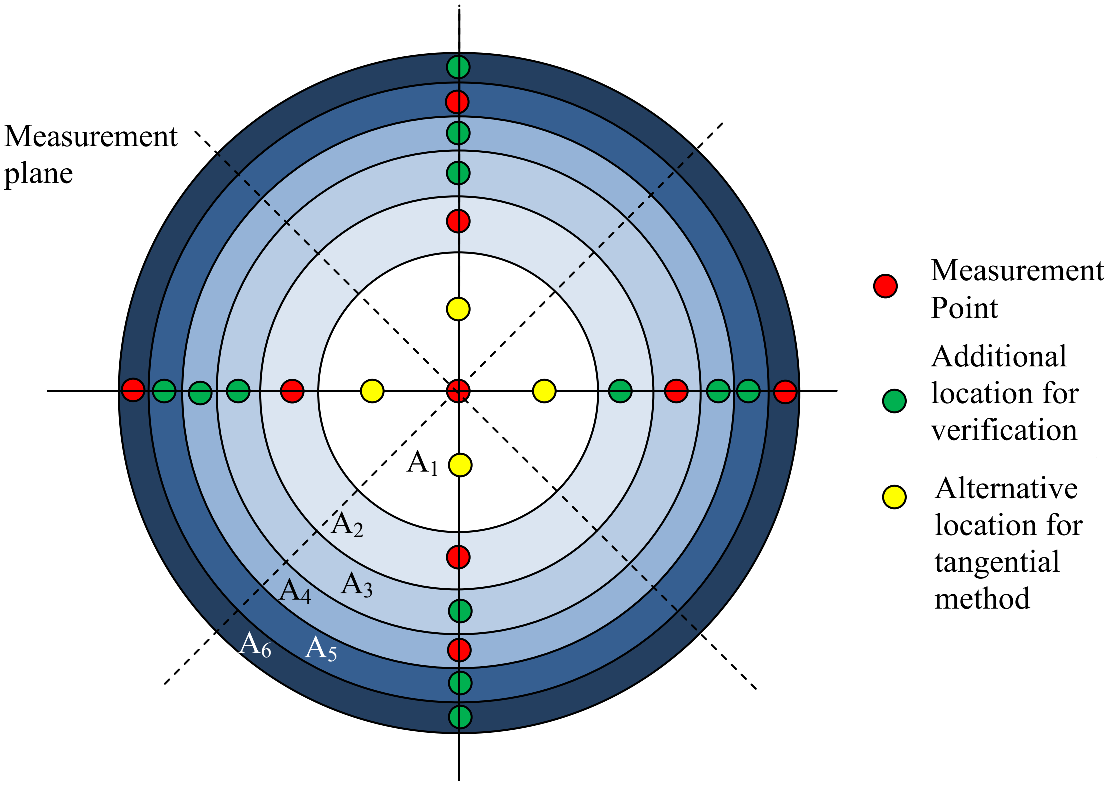

Figure 4-5: Placement of measurement points in a measurement plane for velocity and concentration profile (General method adapted from DIN EN 15 259 and VDI 4200)

The data given in Table 4-2 and Table 4-3 represent a minimum of sample points per measurement plane. A substantially increased number of measurements/sample points per sample line are necessary to perform the flow profile and composition verification measurements which determine the final position of a single or several measurement points. For larger stack areas a comprehensive evaluation should be performed to minimize the number of measurement points.

The measurement plane is positioned correctly if:

- No negative/reticulating flows are registered for expected loads of the plant
- The minimum velocity of the gas body is >3 m/s
- The ratio of highest to lowest gas velocity is less than 3:1

For visualization of homogeneous and inhomogeneous profiles of velocity, species mass concentration and species mass flow density it is referred to Figure 4-7. It is obvious that placement of a representative sampling point for the profiles to the right is challenging.

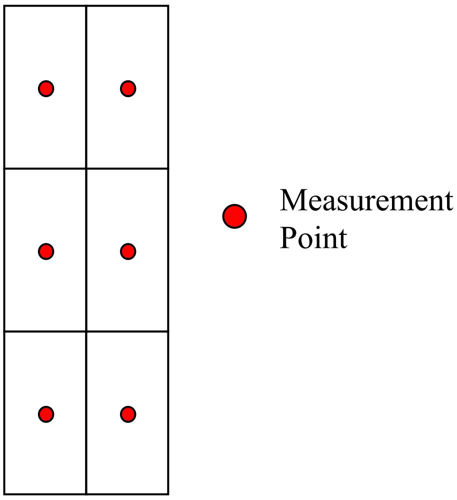

Figure 4-6: Illustration of sampling points in a rectangular stack (DIN EN 15259 and VDI 4200)

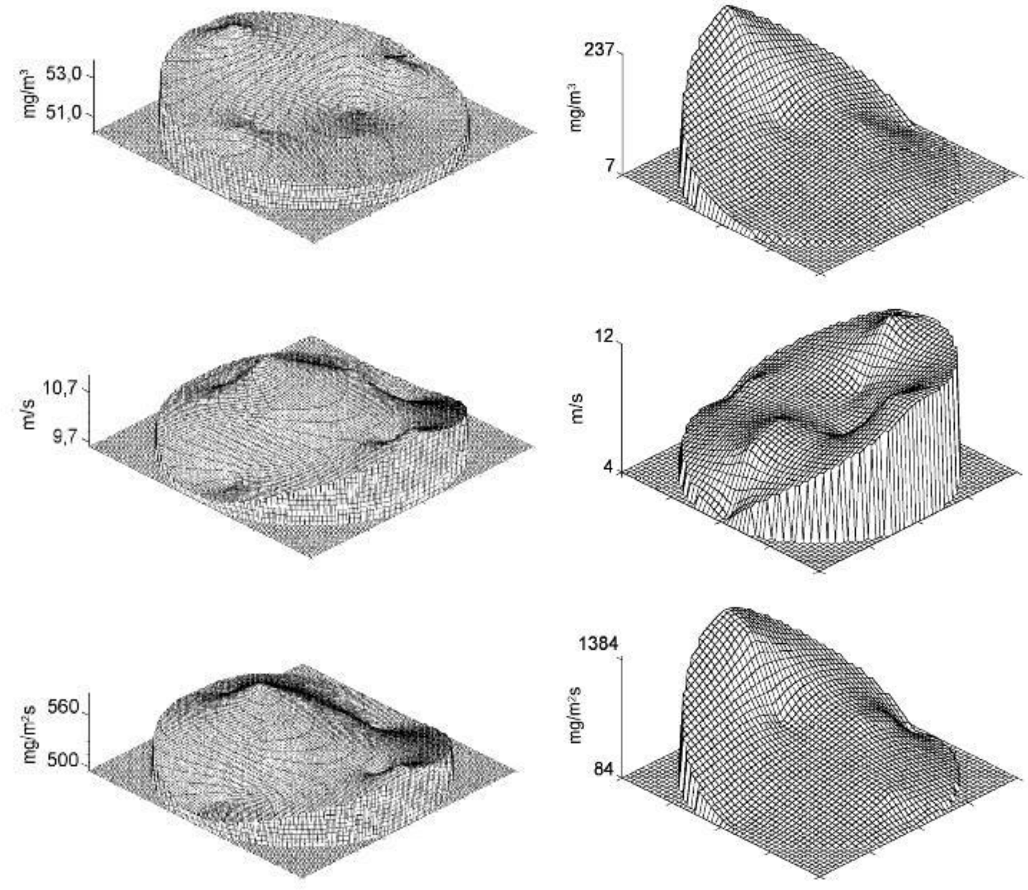

Figure 4-7: Example of homogeneous (left) and inhomogeneous (right) profiles of mass concentration, velocity and mass flow density, please note axis scaling (from DIN EN 15259)

4.5 Working platform and infrastructure

Permanent platforms (see Figure 4-8 and Figure 4-9) must be provided to allow access to measurements ports, platforms need to be equipped with handrails (h = 950 mm minimum height) and kick-boards that meet the EHS-requirements of the workplace (EN 14122 parts 1 to 4), for permanent platforms as well as temporary platforms. Safe access to the platforms for personnel and equipment needs to be ensured.

The size of the platform shall be chosen such that 4 people with up to 300 kg of equipment are supported simultaneously. The working area needs to be sufficient to manipulate probes and operate measuring instruments without equipment overhanging guardrails, sufficient depth of the working area is e = 1.5 m (distance outer perimeter of stack wall/insulation to kick-board)[16]. The depth of the platform can be reduced to 1 m if opposing ports are installed. For comprehensive measurements[17], the minimum area for a platform is estimated to 18 m^2. A weather protection for use of electric equipment is strongly recommended, temperature at measurement site should be within +5 to + 40°C.

The ports shall be installed at least 1 m from the platform base, but not lower than height of guardrail, height of measurement ports is 1.4 m for ports where heavier equipment need to be handled; 1.6 m for ports accommodation pressure or temperature sensors. Probe introduction shall not be impeded by protecting mesh and other equipment.

Access to power supply (at least 3 x 16A, 230V), pressurized air (instrument quality, no oil) and cooling water is necessary for sampling probes and instrumentation.

Protection from adverse weather may be desirable for exposed sampling positions, if no cladding is possible, measurement campaigns need to be performed in favourable weather conditions. Please note, we do not elaborate effect from cladding on wind loads of the stack.

Exposure to possible hazardous off-gases passing through the manual sampling system has to be considered; safe ventilation from the working area is necessary.

Parts of the Mongstad site are defined as EX1-Zone, Company needs to take a future area classification into consideration for application of sampling equipment.

Further, the present paper does not consider structural design of working platforms (design, construction and dimension) or access thereof; we refer to NS-EN 14122 part 1 to part 4 for necessary information. However, the following issues need consideration:

- For horizontal stacks, multilevel platform will be necessary; here careful design is necessary to allow handling of sampling probes without interference with the structure.
- Access to platform shall be easy and safe, vertical ladders shall have either restraint system (back bow) or personal protection systems (antifalling device).
- Installation of lifting systems for lifting and lowering of equipment where access is by vertical ladders or stairs is necessary. Alternative installation of support structure for securing portable lifting systems.
- For large stacks which require long sampling devices, a traverse carriage should be considered to enable insertion of the sampling device into the stack.

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[16] Note, for a stack of Ø=6.6m, sampling probes of at least 3.5 m need to be handled; a clearance between stack out wall and adjacent process equipment need to be ensured.

[17] VDI 4200 Realization of stationary source emission measurements, 2000

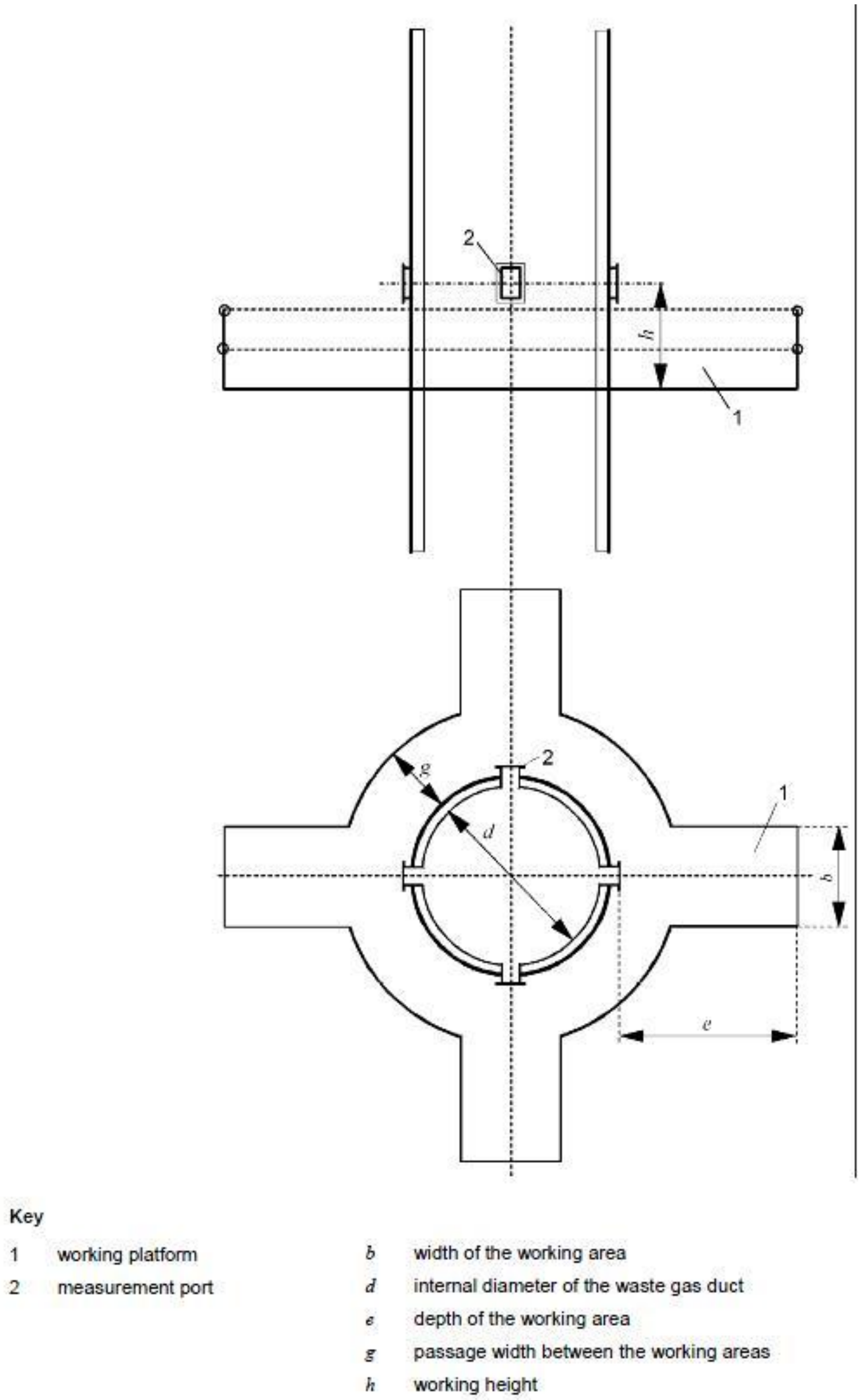

Figure 4-8: Working platform and position of main measurement ports on a vertical round stack (DIN EN 15259)

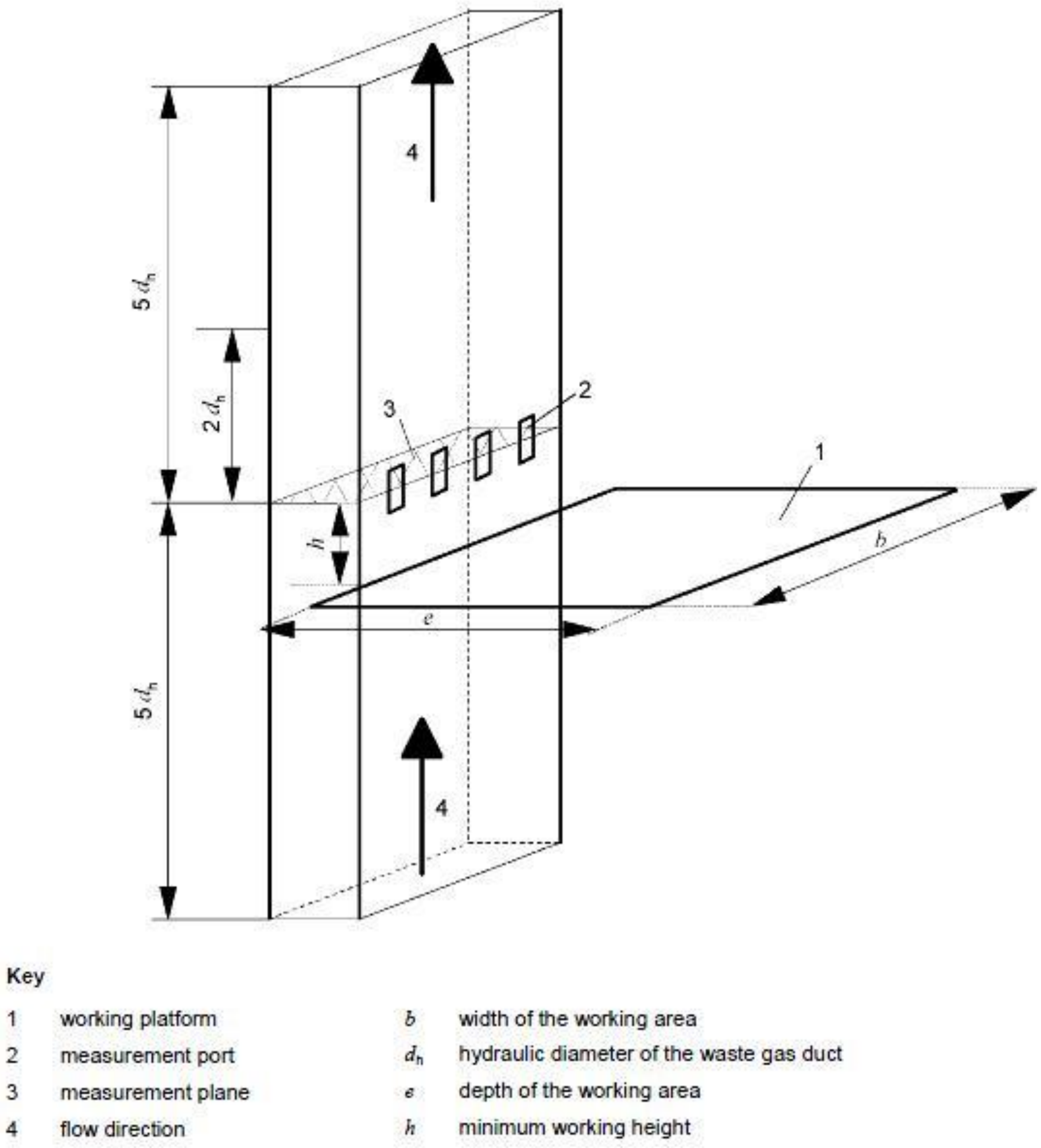

Figure 4-9: Working platform and position of main measurement ports on a vertical rectangular stack (DIN EN 15259)

4.6 Material for measurement sites and measurement ports

The low sweet gas temperatures of the system require that the entire gas sampling system is designed in corrosion resistant material and is properly insulated. Possible corrosion of the system will be caused by amines, organic acids from amine degradation, further SO_2, CO_2 and NH_3 since the sample temperature drops below the respective dew-points and components are dissolved in water. Materials of choice for the stack system will be either stainless steel, PTFE or rubber coated steel. Please note, for internally coated stacks require considerable attention if alterations are necessary.

4.6.1 Material for online sampling systems

For an extractive based online emission monitoring systems, the sample tubes must be heated to a temperature above the acid dew point of the gas. In absence of sulphuric acid, this dew point will be close to the water vapour dew point. However, even a very small concentration of 1 ppm H_2SO_4 will increase the dew point to 115°C and thus many extractive systems have a sample line temperature of 160 to 180°C. Based on the fact that the sulphur content is claimed to be zero by the Company, the content of amine will be more decisive for the required temperature. As seen from Figure 4-10, in which some vapour-liquid equilibrium curves for aqueous MEA solutions are given, the dew-point for a solvent containing 30 % per weight of MEA at atmospheric conditions is approximately 105°C. Even though the equilibrium concentration after the washing section will be much lower than indicated, there will be some uncertain effects of other components and it is recommended to heat the sample gas to a minimum of 140°C in order secure evaporation of the water droplets and to avoid condensation on any optical surface or in colder zones of the sample lines. Condensation on optical surfaces will, dependent on the analyser design, give irreversible damage, and thus it is vital to keep all surfaces dry. As sample line material it is recommended to use smooth stainless steel (SS 316) or steel tubes with internal Teflon tubing. It is important that the inner surface of the tubes do not adsorb any of the gas components to be analysed.

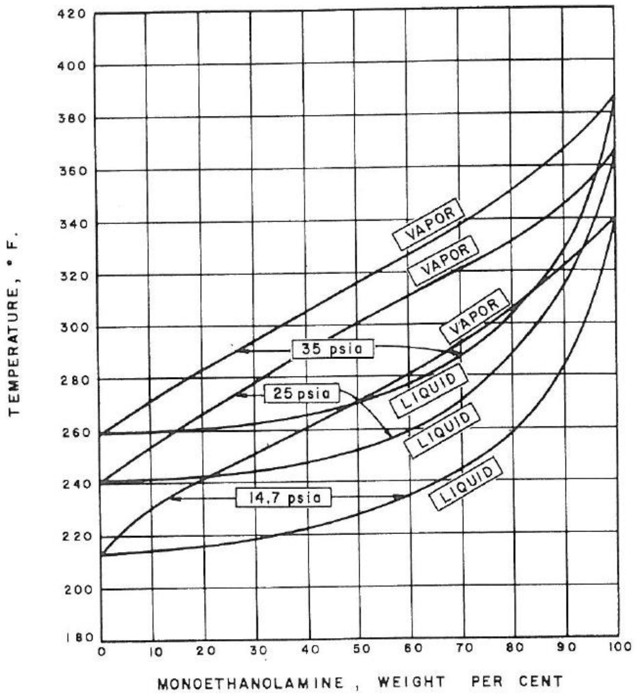

Figure 4-10: Vapour-Liquid equilibrium data for aqueous monoethanolamine solution at various pressures (Source: Gas Purification by Kohl and Nielsen)

Small amounts of particles cannot be avoided when acid and alkali components are present. Reactions between amines and SO_2 and NH_3 have to be considered as those reactions might lead to salts which will precipitate from droplets on surfaces. Especially, the scrubbing water will contain salts and some of these compounds will be transferred to the gas phase as small liquid- or solid particles. For systems operated at ambient temperature, particles will be collected in the liquid phase. However, dust or salts formed inside the absorber are assumed to be low, salts might precipitate in sample lines (especially if heated) clogging them over time. Utilization of sample lines with increased diameter is therefore recommended and some control of dust formation in the sample lines has to be performed as part of the maintenance of a sampling system.

Further, there is limited knowledge on possible catalytic effects of salt deposits or corrosion products on components in the flue gas; therefore prior to installation, materials should be tested with respect to reactions with gas components.

4.6.2 Material quality in the sampling ports

Material quality for the sampling equipment should be stainless steel (SS316; DIN 1.4401; X5CrNiMo17-12-2) because the necessary corrosion resistance; further, the material shall not absorb flue gas components during operation. The application of alternative stainless steel types (SS 304L; 1.4307 X2CrNi18-9 and/or SS316V; 1.4406 X2CrNiMoN17-12-2) need to be considered to avoid corrosion because of welding of flanges to the structure. Further, dependent on the material of the absorber and emission reduction unit, proper precautions for avoiding electro-chemical effects (acids and two different metals form an electrochemical cell) are necessary.

Introductory experiments performed at SINTEF show that the individual amines have considerable different corrosive capability, limited knowledge is available on combinatory effects of e.g. different amines together with acidic components like SO_2 and CO_2. It is therefore necessary to consider corrosion testing of materials or their combination with a given absorbent mixture to determine compatibility.

5 Generic design for measurement site

5.1 Generic design for stack (full scale)

A possible design for the transition from a single water wash section to the exit stack is given in Figure 5-1, for details of the sample port location we refer to Figure 4-1 and Figure 4-2.

Provided a symmetrical flow pattern upstream the constriction without eddies or backflow, the estimated Reynolds number indicate a strong turbulent flow, thus a plug flow profile over the measurement plane is expected. Assuming a smooth transition (cone not constriction as presented in Figure 5-1) and symmetrical operated absorber sections an inlet section with a length corresponding to $5*d_h$ and outlet section of $5*d_h$ from top of stack seems appropriate. For all other designs (and especially the design presented in Figure 5-1) or operation modes a considerable longer inlet section is necessary.

In case that the final design of the plant incorporates a considerable change in dimension or several independently operated parallel absorber trains installed in one single casing, the flow pattern will be difficult to determine a priori without further investigation. In Figure 5-1 we try to visualize the expected flow patterns close to the connection absorber - stack, dependent on which absorber train is active, we strongly recommend finding an appropriate design[18]. There is limited experience how long such a mal-distribution over the cross section propagates into the stack (see Table 3-2), further back-flow on opposite side of the entrance might be possible. Provided there is no back flow for flow measurements this can be partly resolved by sensors integrating over the cross section (ultrasonic and annubar)[19], for monitoring mass emissions such a profile will generate highly erroneous results.

Special consideration is necessary regarding flow path design from head of the water wash section (packing material) via absorber roof design and transition into the stack and measurement section. Installation of distributor plates or static mixing elements in the transition water wash – stack, these might level out the velocity profile. However, installation of these devices will increase pressure drop in the outlet section. It is advised to perform CFD computations when design of the plant is more mature to identify correct design of the absorber roof, stack inlet section and placement of the measurement section.

5.2 Measurement section for pilot plants

The design of the various pilot plants is unknown for the authors, and will differ from case to case; we therefore assume that a generic sampling unit is produced which can be installed on top of a pilot plant. A generic design of a measurement section for pilot plants is presented in Figure 5-2. The presented section is adapted to an exit cross section from a pilot plant of Ø100mm and consists of an expander cone and a cylindrical section of Ø200mm. The measurement section combined with the sampling system (specific nozzle and vacuum pump) is optimized for a flue gas velocity between 5 and 10 m/s in the cylindrical measurement section. For higher gas velocities only adjustment of nozzle and vacuum system are required.

Necessary changes to adapt this unit to other geometries of pilot plants are limited to change the (here conical) transition between flange at pilot plant and measurement section to a different design, e.g.: transition from rectangular (100x100mm) to circular (Ø200mm) which

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[18] The design of the transition absorber and /or inlet to the stack with internals to provide a proper velocity and concentration profile is outside the scope of the current sub-project.

[19] Trenkler, H.-R., E. Obermeier, Sensortechnik, Handbuch für Praxis und Wissenschaft, Springer Verlag, 1998

is easily facilitated. Comparable results from pilot runs will be achieved if the flue gas velocity within the measurement section is similar to the full scale system.

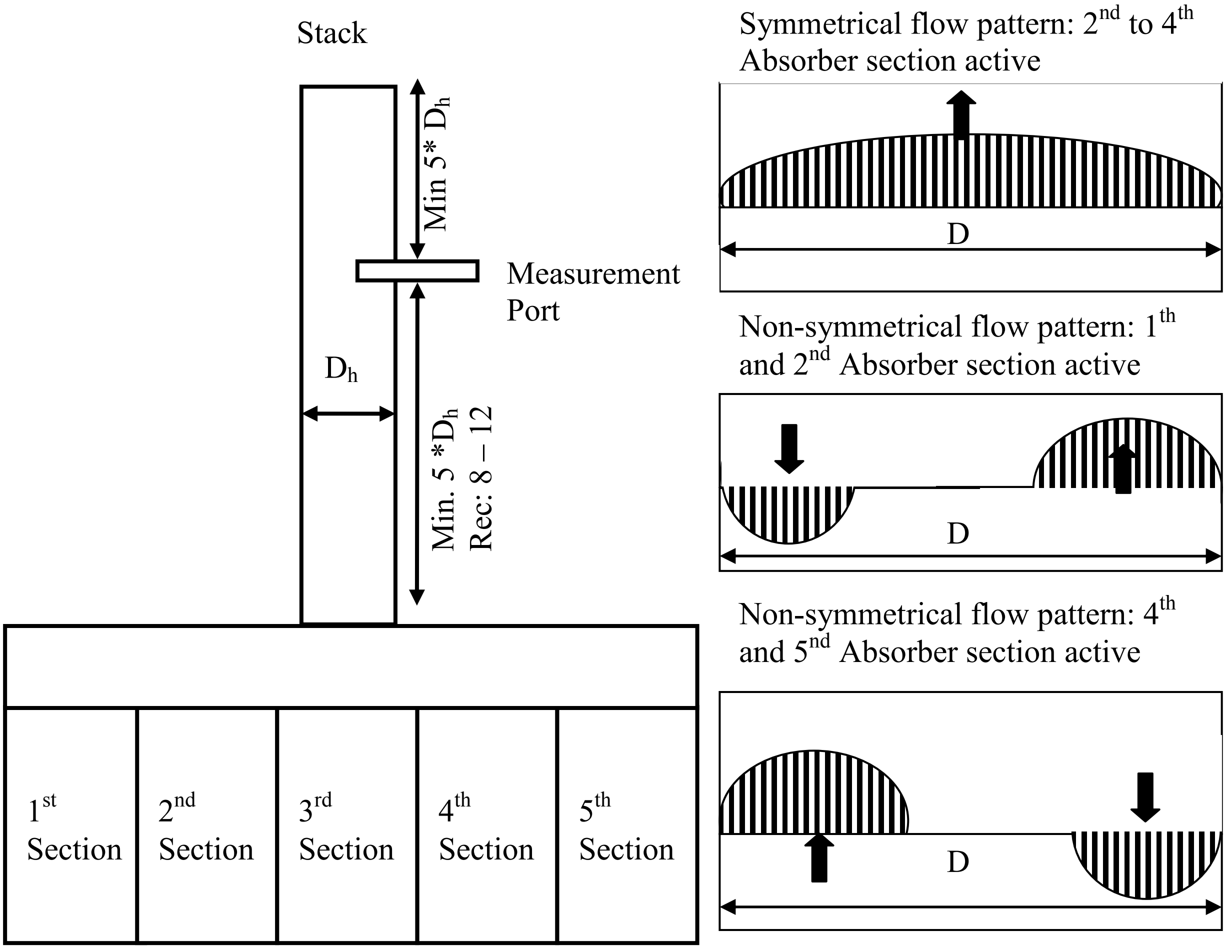


Figure 5-1: Assumed design for full scale CO2-capture plant and possible velocity profile near the entrance to the stack (SINTEF)

5.3 Recommended sample system components

A multipurpose sampling system for the given application will consist of:

- sample probe (most probably several in parallel to cover the measurement plane / cross section) with integrated velocity, pressure and temperature measurement for adequate control of iso-kinetical sampling
- sample train for absorption of gaseous and liquid flue gas components; further aerosols and particular matter need to be collected
- gas dryer and gas flow meter to determine the dry flue gas flow at normalized conditions
- gas pump with control unit to enable and maintain iso-kinetically sampling.

From experience we suggest to use standardized systems which are commercially available. One particular system is presented because of it versatility and flexibility for adaption to different measurement objectives, supplier is Environment S.A., Eschborn, Germany; see Appendix A.

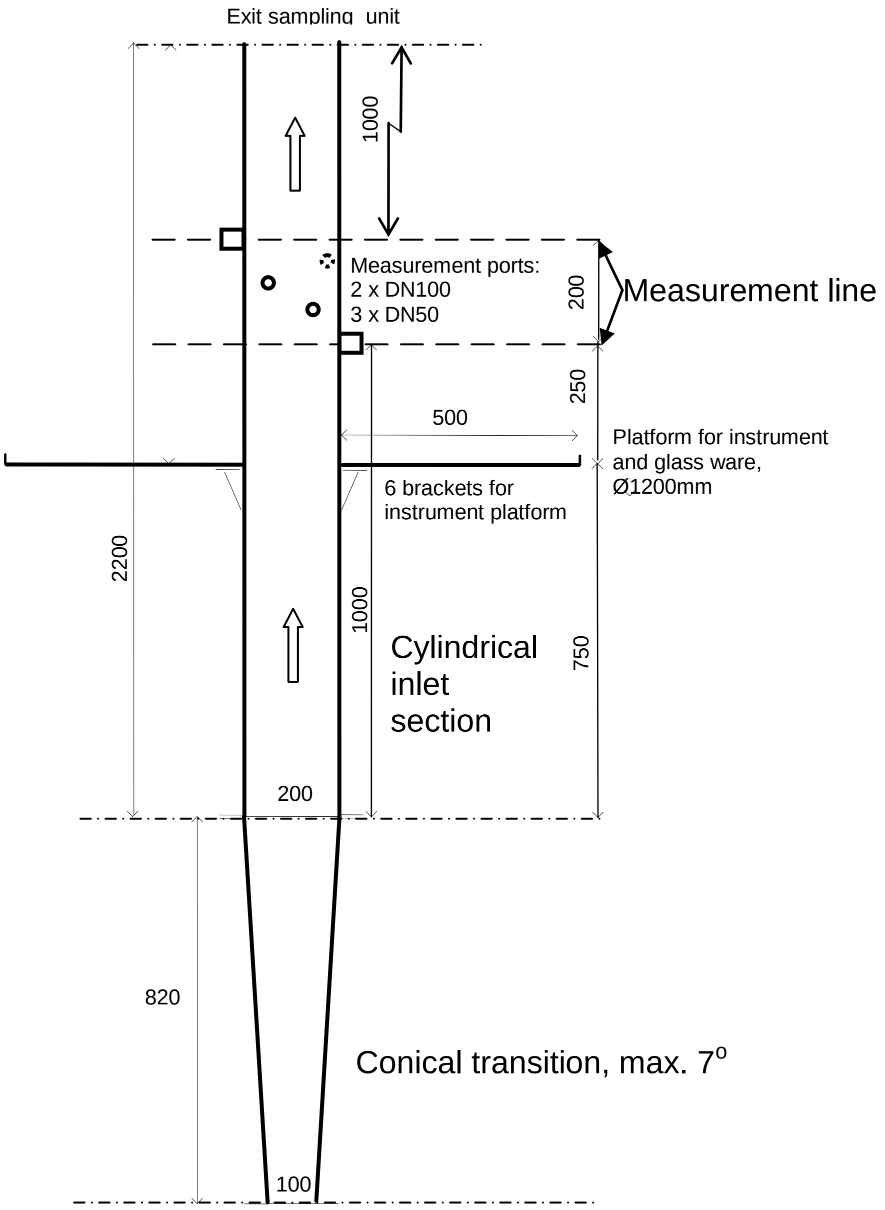


Figure 5-2: Sampling unit adopted for transition from Ø100mm to Ø200mm at measurement plane (SINTEF)

6 Most common errors in design of sampling points

The design of an appropriate measurement section is straight forward if the measurement section is an integral part of the plant design. Most design considerations can be resolved at an early stage, implementing a proper design of a measurement section at a late stage or after installation of a plant is often sub-optimal and is performed at increased costs.

Provided the measurement section is sufficiently downstream from disruption of the flow, such that a proper velocity profile is established and the flue gas has a homogeneous composition, the following issues need consideration:

- The accuracy of mass emission calculation is strongly influenced by
    - Non-uniform flow and concentration profile
    - Non-iso-kinetically sampling
    - Alignment of the sampling device relative to the predominant gas flow (direction)
- Condensation and precipitation of flue gas components within and outside the sampling port or device leads to clogging and change in local flow pattern respectively. Liquid accumulation in sample port needs to be considered, sample port itself shall have inclination of 5^{o} inwards to ensure drainage, since gas is far below dew point.
- For manual sampling of gas streams with droplets / saturation / condensing gases the sample train shall have an inclination of app. 4^{o} to ensure that liquid is drained from sample point into collection system. Please note, these are not contradictory statements, angling of sample port and instrument/sample train in different direction can easily facilitated by the chosen design (pipe stub and flanges) were the fitting for the instrument itself is installed on a flange.
- Absorption effects of flue gas components on the sampling equipment.
- Insufficient information on the velocity distribution will result in improper placement of the sample point or most probably multiple sampling points.
- The design of the measurement site is strongly dependent on the state of the gas to be analysed and the sampling purpose like: manual sampling, high volume sampling for toxicology test and online analysis systems. For online monitoring systems can be based either on in-situ (measurement inside the gas stack) or extractive systems were a partial gas stream is withdrawn from the gas stack, this will be considered in a subsequent study. Online analysers operate in general with either dried gases or heated sample lines. For dried gases, we will lose some water soluble components with the liquid from a knock-out condenser. For analysers which operate with heated sample lines, it is not yet well understood how components might change when they are heated to normal operation temperature of ~180^{o}C.
- Inappropriate choice of materials or combination thereof in relation to the flue gas type, temperature and components.

In case of a multi-train absorber an estimate of the velocity profile for asymmetric operation (see Figure 5-1) of the parallel absorber trains is possible based on the currently available design information. The design presented in Figure 5-1 is actually a design which is not recommended because eddies, back flow and non-developed velocity profile is expected, thus a very long inlet section will be necessary. It is strongly advisable to perform CFD-modelling of the velocity and concentration profile when more reliable data are available. The costs for such simulations will be considerable lower than a possible re-vamp of the measurement section if it is placed incorrectly in the design.

7 Discussion and recommendations

The **design of the CO_2-capture plant** has not come so far that reliable design drawings are available, simultaneously the time scale of the project is important and information needs to be made available such that it can be incorporated into design considerations. Further, there is at present no comprehensive experience available on the design of an appropriate (online) analysis system for the components expected in the flue gas. The present report covers the generic design of measurement sections for emission monitoring. The measurement sections are designed such that manual sampling, high volume sampling and online monitoring can be performed with one design.

Uncertainty arises because of the immaturity of the design of pilot and full scale plants. However, the compilation of the most relevant standards and guidelines should be sufficient to enable the design of appropriate measurement sections.

The design of the stack itself will primarily depend on the combination of the absorber design (e.g.: parallel trains), dimensions thereof and material. The relevant standards for the design of a measurement section recommend minimum $5*d_h$ up- and downstream the sampling plane. However, a careful examination of a proposed design through computational fluid dynamics might open up for shorter sections. Evaluation of design alternatives for the absorber / stack unit is recommended. A proper review will avoid from a structural design point of view inappropriate designs which might be optimal for emission monitoring and vice versa.

The design suggestions given in chapters 4 and 5; if implemented, will allow for manual sampling, high volume sampling and online sampling. Even though we present a versatile (commercial) system for manual and semi-automatic sampling, a more comprehensive treatment of sampling procedures and sampling systems will be given in TQP ID 1 Subtask 2 and 3.

The adaption of the measurement ports will be necessary at a later stage to interface online analysis equipment when available; therefore a sufficient number of “spare ports” need to be installed. It is advised that the number of ports for manual sampling as presented in Table 4-2 and Table 4-3 and the number of ports for online sampling should at least be equal. The given number of ports allow for comprehensive manual sampling as well sufficient capacity to interface analysis instruments.

The flue gas conditions with low temperature and expected high water load (saturation and droplets) will be a challenge for analysis and sampling; **iso-kinetically sampling** is not an option, but mandatory. From a regulatory point of view, isokinetical sampling is the only appropriate method if any uncertainty on the flue gas matrix or condition exists. In the present case there is not sufficient information available to estimate the **size of droplets** emitted and their influence on component emitted. Because of the lack of information, isokinetical sampling is strongly advised until sufficient information is available to relax this requirement.

In manual sampling with absorbents or adsorbents, the high water load will either dilute the absorbent or flood adsorbents. Considerable care needs to be taken to protect the sampling unit from excess water, simultaneously; most of the components which shall be analysed are soluble in water. The design of the sample ports is independent of these issues, but need to be considered later.

High volume sampling can easily be accomplished by the proposed measurement section design, however sampling for toxicity tests require that the sample taken is neither diluted nor mixed with any other component. Further, the high concentration of NH_3 in the flue gas needs consideration especially for toxicity tests.

Commercial analysers for online monitoring of MEA (or other amines) and degradation products are not available “from the shelf”. However, producers of emission monitoring systems seem to be aware of a “new market” and slowly look into this opportunity. However, discussions with suppliers so far do not give any conclusive indication on how analysers will be interfaced to the process.

The present report is the first of three reports covering sample point, sampling procedures and online analysis; it is recommended that this report is revisited after finalizing Subtask 2 and 3 to incorporate conclusions and update the current work.

APPENDIX A

The **T**ransportable **P**article **S**ampling system described in this Appendix is designed for dust-containing flue gases, but has in addition the ability to sample gaseous compounds in adsorption solutions, filters and solid adsorbents. A stationary version of the system is also available from the supplier. The TPS-system has been used in experimental studies in-house at SINTEF, and in on-site samplings. The individual units of the system are depicted below.

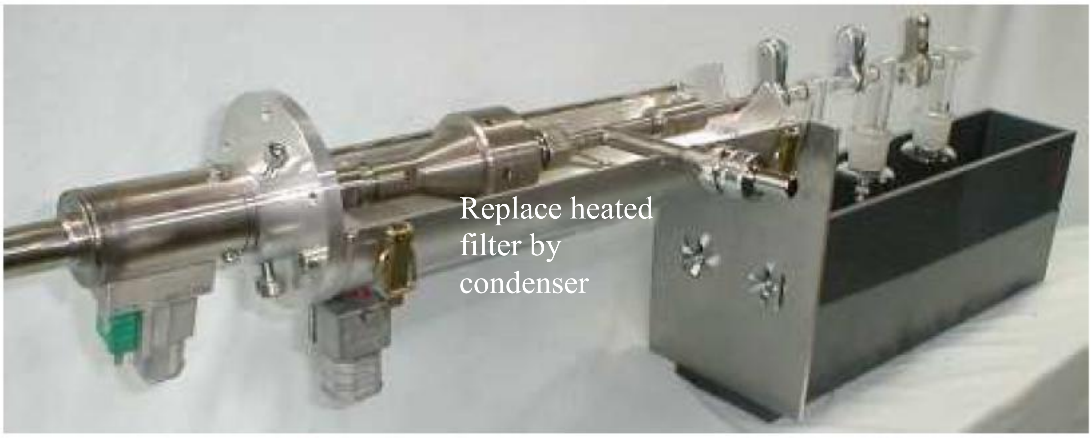
Probes / Suction Tube for Isokinetic Sampling (Courtesy: Environnement GmbH, Germany)

Nozzles according to EN 13284-1,
ISO 9096 and VDI 2066.

Variation with exchangeable S-Pitot Tube (ferrules connections) here short variation, long S-Pitot necessary, if filter device behind gooseneck nozzle, thermocouple and small Pitot Tube for static pressure (here probe with gooseneck nozzle).

Variation with short exchangeable Prandtl - Pitot Tube (Filter Out-Stack), exchangeable Thermocouple, (here with nozzle and bent acc. to EN 13284).

Exit Combination probe with Pitot pressure tube and plug from the thermocouple NiCr-Ni. Electrical heated or water cooled from the front of the suction tube up to the arrow.



Heated suction tube with heater for the filter device, mounted at the probe. The heater for the filter is a swing open system, that the filter can take out easy.
Equipment shown with heated suction tube, filter device and gas distributor in a heater, to the right a box to accommodate for one, two or three bubbler-streets. The heater is fixed with the suction tube and also the carrying-system for the bubblers, changing of the sampling position is easy because the entire unit can be repositioned without dismantling.

The parts depicted above present a number of different sampling options. For the problem at hand a cooled probe with a knock-out condenser will be used. The knock-out condenser will replace the heated filter unit presented above. Objective of the knock out condenser is to remove excess water from the remaining sampling train to avoid dilutions of absorbents. It is mandatory, that the liquid phase from the condenser is collected and analysed. The wash flasks are placed in a temperature controlled bath.

TPS Automatic Isokinetic Control Unit

The Isokinetic Control Unit for existing manual emission monitoring equipment is an intelligent control unit, is developed to fulfil all requests of the European Guideline for Isokinetic Emission-Measurement. This new, simple and easy handling control unit has been realized to work in industrial environments; the case, made of stainless steel, offers a high protection also to light rainy weathers. The plugs panel is located inside the case. All parameters can be accessed from the main panel allowing the complete control of the operations. 1000 single data during the measurement are stored automatically and can be transferred with a software to an Excel file. For example: Measuring time 30 minutes and 10 measuring points, means every 2 seconds is stored the actual measuring point, damping factor, sampling flow, difference pressure of the pitot tube, temperature and static pressure of the stack and the impulse from the gas meter.

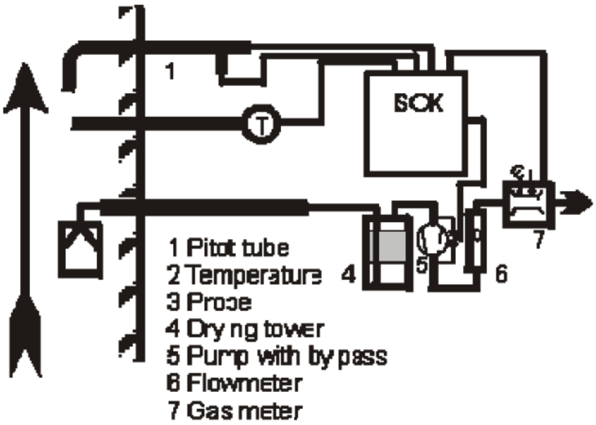


Figure 1: Example of a sampling line with TPS-Control unit.

Figure 1 shows an example of sampling line with automatic isokinetic setup. The TPS includes the TPS-Control Unit (temperature, static and difference pressure sensor, gas orifice meter, cable for control valve), one control valve for the bypass at the vacuum pump and software. This control unit can also use for the isokinetic regulation with zero pressure nozzles.

Drying tower, flowmeter and gas meter
Separator in carrying rack.

Gas tight pump can set in front of the gasmeter.

Gas Cooler with Water