Document Front-page

01	15.07.2010	H&ETQPamine1, The Draft report of Sub Task 1	Eerik Järvinen	Sari Vilhunen	Pentti Manninen
02	20.8.2010	H&ETQPamine1, The report of Sub Task 1	Eerik Järvinen	Sari Vilhunen	Pentti Manninen
Proj. Rev.	Issued Date	Description	Made by	Chk'd by	Appr. by

Package Title:

Acceptance Code 1: *Accepted* ☐	Supplier:
Acceptance Code 2: *Accepted with comments incorporated. Revise and resubmit* ☐	Suppliers Doc No:
Acceptance Code 3: *Not accepted. Revise and resubmit* ☐	Subsuppliers Doc No:
Acceptance Code 4: *For information only* ☐	Tag No./Line No.:

Reviewer Signature:	Date:	Document Code:	Area:	System:	Responsible Unit:

Contractor: Ramboll Analytics	*Note: Where not applicable use NA* Document title: Sub-Task 1 - Design of sampling points in treated flue gas
Client: CCM Project	
Project name: CO2 Capture Mongstad Project (CCM) H&ETQPAmine1	Client Doc No:
WBS no:	PO Number: / Pages: 1 of 36

Intended for
CCM project

Document type
Report

Date
08/2010

H&ETQPAmine1

SUBTASK1
DESIGN OF SAMPLING POINTS IN TREATED FLUE GAS (MANUAL AND ONLINE SAMPLING)

SUBTASK1
DESIGN OF SAMPLING POINTS IN TREATED FLUE GAS (MANUAL AND ONLINE SAMPLING)

Revision	**2.0**
Date	**2010/08/2020**
Made by	**Eerik Järvinen, Heikki Hoffren, Sari Vilhunen**

Ref	89105265-01

CONTENTS

FIGURES

SUPPLEMENTS

1. TERMS AND DEFINITIONS

AMS, automated measuring system	Automated measuring system, permanently installed on site for the continuous monitoring of emissions
Clearance area	Area of free space at the working platform outside the waste gas duct without obstacles in which the appropriate measuring probes are moved and handled
Flue gas	flowing waste gas in the duct after the CCS-plant and demister
Hydraulic diameter d_h	Quotient of four times the area A and the perimeter P of the measurement plane: e.g. in the round ducts: diameter of the duct =d_h; in the square ducts: length of the side=d_h
LCP	Large combustion plant
Mass flow rate	Quotient of the mass m flowing through the measurement plane and the time t
Measurand	Particular quantity subject to measurement [VIM:1993, 2.6] The measurand is a quantifiable property of the waste gas under test, for example mass concentration of a measured component, temperature, velocity, mass flow, oxygen content and water vapour content
Measured component	Constituent of the waste gas for which a defined measurand is to be determined by measurement
Measurement line	Line in the sampling plane along which the sampling points are located, bounded by the inner duct wall. Measurement line is also known as sampling line.
Measurement plane (sampling plane)	Plane normal to the centerline of the duct at the sampling position
Measurement point	Position in the measurement plane at which the sample stream is extracted or the measurement data are obtained directly
Measurement port	Opening in the waste gas duct along the measurement line, through which access to the waste gas is gained
Measurement section	Region of the waste gas duct which includes the measurement plane(s) and the inlet and outlet sections
Measurement site	Place on the waste gas duct in the area of the measurement plane(s) consisting of structures and technical equipment, for example working platforms, measurement ports, energy supply
Reference quantity	Specified physical or chemical quantity which is needed for conversion of the measurand to standard conditions. Reference quantities are e.g. temperature (T_{ref} = 273,15 K), pressure (p_{ref} = 101,325 kPa), water vapour volume fraction (h_{ref} = 0 %) and oxygen volume fraction o_{ref}.
Representative measurement point	Measurement point at which the local mass flow density of the substance to be determined is equal to the mass flow density averaged over the measurement plane
RM, reference method	Measurement method taken as a reference by convention, which gives the accepted reference value of the measurand. A reference method can be a manual or an automated method. Alternative methods can be used if equivalence to the reference method has been demonstrated.
SRM, standard reference method	Reference method prescribed by European or national legislation

2. INTRODUCTION

2.1 Foreword

This technical document is focused on the basic design of flue gas sampling ports needed at the Mongstad CCS-facility and covers the basic principles of design of the measurement site. Any detailed design e.g. supporting structures, electric- or HPAC-design is not covered.

The difference between full scale, pilot scale and laboratory scale plants has been taken into account.

2.2 Scope of work

The focus of this work is on determination of how sampling points in treated flue gas process streams should be designed in order to perform representative manual and online sampling. The process stream will be saturated with water and particles might be present. Scope of work is presented in Table 1.

Table 1 Scope of work

Description	Chapter
Initial data	3
Recommended design of the sampling points (technical details etc. Both AMS and standard reference method (SRM) will be covered)	6.3, Supplements 1
The most common errors in design of sampling points (including safety, quality and practical issues)	6
Location of the sampling points (number of assembly, vertical and horizontal location)	5
Material quality in the sampling equipment , recommended sample system components and design of sampling assembly	7
Summary and recommendations	10

3. PRINCIPLES OF DESIGN

3.1 Delivered information

At the time the report was established detailed information about the CCS-plant was not available. The Common dimensions delivered by the Company are as below:

Table 2 delivered Common values for the starting point of the design

	Unit	**Large scale plant**	**Pilot plant**
Gas flow gas rate	million Sm^3/h	700 000 - 2 300 000	250-1200
Temperature	°C	25-50	25-50
Moisture		saturated probably with droplets	saturated probably with droplets
Pressure		± outside pressure	± outside pressure
Main body velocity	m/s	2-3	2-3
Gas velocity at pipe exit	m/s	About 20	2-3
Composition			
- oxygen, O_2	mol-%	15	15
- nitrogen, N_2	mol-%	81.5	81.5
- carbon dioxide CO_2	mol-%	0.5	0.5
- water, H_2O	mol-%	3	3
- amines	ppm	< 5	< 5
- ammonia, NH_3	ppm	< 50	< 50
- NO_x	ppm	n/a	n/a
- NO_2	ppm	n/a	n/a
- SO_2	ppm	n/a	n/a

The cross section of the absorber is rectangular or circular and material is either stainless steel or plastic. The duct diameter in large scale plant is estimated to be smaller than CCS-scrubber unit and the value given is 6.5 m. Combustion process before the CCS-plant is a gas turbine or two parallel ones. Significant dust emission is not estimated because of the type of fuel in use (natural gas). However, some dust may be present in the flue gas.

For the structural reasons, the measuring section of the plant was pursued as low from the ground level as possible at a waste gas duct. The final item before the duct is a demister.

3.2 Estimated values

Taking account the delivered information above the study was divided in three different cases. The composition of the flue gas is shown in the Table 2. Other estimated design values are presented in the Table 3.

Table 3 Estimated case studies

	Laboratory scale	**Pilot scale**	**Full scale**
Description	"Laboratory bench scale size" process for the development purposes. Installed inside the laboratory building.	"From shipping container size to small plant size". About 1:10 capacity of the full scale. Pilot plant is connected to the minor flow of the existing full scale LCP-process	"Full scale size" As planned to be build at Mongstad
Flue gas velocity in the duct	2-20 m/s	2-20 m/s	7-20 m/s
Duct diameter	0.2 - 1 m	1-3	3 – 10 m
Measuring section from the ground level	< 3 m	2-20 m	> 20 m

On the laboratory scale the cross-sectional area must be sufficiently large to avoid increasing the duct gas stream velocity by more than 3 % due the blocking caused by the Pitot tube and any thermocouples attached to it[1]. In practice this reduces the smallest accepted diameter of the duct to about 0.2 m, if accurate velocity measurements are needed. In practice other probes will also be installed for the sampling purposes. Common heated in-stack probe diameter is about 50 mm, so, if the isokinetic samples will be taken the practical minimum diameter of the duct is 0.6 m. However, the dimensions of the Pitot tube and the sampling equipment could be reduced, if only small diameter duct is available, yet it is not recommended.

For the isokinetic sampling the flue gas velocity should exceed 2 m/s. Recommended design velocities are between 10 to 20 m/s. Velocities over 40 m/s should be avoided and the upper flow velocity limit should be reduced to 45 m/s in the sampling section.

4. STANDARDS

In selection of standards for the design of sampling site/ports national legislation should be taken into account. Norway is one of the CEN-countries. All EN standards are bound to implement at CEN –countries, thus the normative standards of design of sampling points are EN-standards. If suitable EN standard is not available, ISO standard is used instead in this work.

Basically there are only small differences between standards related to sampling site and measurements of dust and flow. Some relevant standards used in this work are presented below.

Table 4 Overview and ranking of relevant standards for the design of the sampling ports and site (*=informal; **=important or advisable ; *=normative)**

Ref./std. number	Name	Description and notes	Ranking
EN 15259:2007	Air quality. Measurement of stationary source emissions. Requirements for measurement sections and sites and for the measurement objective, plan and report	Includes design of measuring sites and ports.	***
ISO 10780:1994	Stationary source emissions -- Measurement of velocity and volume flowrate of gas streams in ducts	Standard specifies manual methods for determining the velocity and volume flowrate of gas streams in ducts, stacks and chimneys vented to the atmosphere. Includes the choice of sampling location and principle of flow straightening device.	***
ISO 14164:1999	Stationary source emissions — Determination of the volume flowrate of gas streams in ducts — Automated method	Standard covers the operating principles and the most important performance characteristics and installation principles of automated flow-measuring systems for determining the volume flow rate in the ducts of stationary sources.	***
EN 13284-1	Stationary source emissions. Determination of low range mass concentration of dust. Part 1: Manual gravimetric method	Standard specifies a reference method for the measurement of low dust concentration in ducted gaseous streams in the concentrations below 50 mg/m³ standard conditions by isokinetic sampling. Measuring locations, points and principles could be applied to other isokinetic sampling too e.g. droplets. Standard is primarily developed and validated for gaseous streams emitted by waste incinerators. More generally, it may be applied to gases emitted from stationary sources, and to higher concentrations.	***
EN 13284-2	Stationary source emissions. Determination of low range mass concentration of dust. Part 2: Automated measuring systems	Standard specifies specific requirements on automated measuring systems (AMS) for dust monitoring. It is derived from EN 14181 which is the general document on the quality assurance of AMS. It is applicable only in conjunction with EN 14181. Standard is primarily developed for emissions from waste incinerators. From a technical point of view, it may be applied to other processes, for which measurement at an emission limit is required with defined uncertainty. Includes recommendation for the AMS location.	***

U.K. TGN M1, Version 6, January 2010, Environment Agency, UK	Sampling requirements for stack emission monitoring	Technical Guidance Note provides guidance on European standard BS EN 15259:2007 Requirements for measurement sections and sites and for the measurement objective, plan and report. It focuses on the parts of the standard that deal with measurement sections and sites. An exploratory survey of the proposed sample plane should be undertaken. This should include a stack gas velocity survey. Covers the standard EN 15259	**
U.K. TGN M22, Version 1.1, August 2010, Environment Agency, UK	Measuring stack gas emissions using FTIR instruments	Technical Guidance Note specifies the requirements for the use of manual extractive Fourier Transform Infrared (FTIR) spectroscopy for the speciation and quantification of gases monitored within stacks.	*
U.S. Environmental protection agency (EPA) Emission measurement center methods	METHOD 1 - Sample and velocity traverses for stationary sources	Guidance for the selection of sampling ports and traverse points at which sampling for air pollutants will be performed pursuant to regulations set forth in this part. Duct diameter should exceed 0.3 m.	**
U.S. EPA	METHOD 1A – Sample and velocity traverses for stationary sources with small stacks and ducts	As method 1 but duct diameter is limited to 0.1-0.3 m. This may be applied to the laboratory scale design of CCM-plants	**
U.S. EPA	Method 2 A-H	Information about the flue gas velocity, traverse and turbulence measurements (including wall effect measurements)	*
ASTM	D3154-00(2006) Standard Test Method for Average Velocity in a Duct (Pitot Tube Method)	Test method describes measurement of the average velocity of a gas stream for the purpose of determining gas flow in a stack, duct or flue. Although technically complex, it is generally considered the most accurate and often the only practical test method for performing velocity measurements.	*
ASTM	ASTM D3685 / D3685M - 98(2005)	Standard Test Methods for Sampling and Determination of Particulate Matter in Stack Gases	*

5. MEASUREMENT SECTION

5.1 General

Suitable measurement sections and sites are necessary to obtain reliable and comparable results. [2][3, 4].
Basically general requirements are:

- flue gas on the sampling location should be stable and ordered
- appropriate sampling ports and working platforms are available for both AMS and SRM measurements including safety, reasonable access and practical point of view

At least for full scale plant it is recommended to make two or more measuring sections at the different heights of the stack. The demands for the main measurement section are described below. Subsidiary measuring sections could consist of at least two measuring ports at right angle to each other. Measurements by the means of studying the concentrations and flow profile could be arranged by the subsidiary measurement ports by reference methods.

5.2 Position

The measuring section and access ports should be located on such a place where the flue gas is homogeneous on the whole measurement plane without vortex or backflow.

The sampling location is recommended to be located at the section where the duct is preferably vertical to avoid possible deposition on the bottom of the duct (e.g. dust, water). Vertical duct is also easier to access from different directions. In addition, installation of the measuring section at the part of the duct where overall flue gas flow is going upwards is recommended to avoid the possible deposition of heavier particles etc. (for example salt lumps) in the case of shutdown causing the risk of damaging the AMS.

5.2.1 Representativeness of concentration

Measurement section should allow that representative samples of the emission can be taken in the measurement plane for the determination of volumetric flow and mass concentration of pollutants. The measured component can still change due to secondary reactions (degradation or synthesis) between the measurement plane and the point of escape to the open atmosphere. [2]. When considering the sampling of the flue gas after the demister there are some factor related to humid and mild temperature of flue gas that should be taken account.

In the northern circumstances, especially during the winter time, condensation of the humid gas by the un-insulated stack walls might be remarkable. This leads to liquid backflow of water and water dissolved pollutants by the stack wall. If the stack is long and the measurement ports are assembled in the lower section of the duct the backflow may affect to the concentration between the measurement sections and the stack exit. Also the concentration of the pollutants between the gas phase and droplets may be different between the sections of the stack because of washing effect of the humid flue gas. For this reason it is recommended to choose the measurement section as high as possible and take into account the exit of the stack as described below. In some of the cases the measurement ports or the AMS-systems, such as O_2-measurement, could be assembled to almost any place where the flue gas is fully mixed.

After the multi-bed wet scrubber and the demister flue gas is expected to be fully mixed and homogeneous even if there are multiple combustion units connected to the wet scrubber. However, if very large inside diameters of the scrubber and multiple combustion units are connected with flue gas fans before the scrubber, stratification may occur and gas flow will not be fully mixed at the measuring plane. Also, if the catalytic converters are in use after the demister, significant stratification may occur especially in case of the defective catalytic unit.

5.2.2 Homogeneous flow

According to EN 15259:2007 measurements at all the sampling points shall prove that the gas stream at the measurement plane meets the following requirements:

1. angle of gas flow less than 15° with regard to duct axis;
2. no local negative flow;
3. minimum velocity depending on the flow rate measuring method used (for Pitot tubes a differential pressure larger than 5 Pa);
4. ratio of the highest to lowest local gas velocities less than 3:1;

The requirement for homogeneous flow conditions is generally fulfilled if the measurement plane is:
– as far downstream and upstream from any disturbance, which could produce a change in direction of flow (e.g. disturbances can be caused by bends, fans or partially closed dampers),
– in a section of a duct with at least five hydraulic diameters of straight duct upstream of the sampling plane and two hydraulic diameters downstream1[1] *(five hydraulic diameters from the top of a stack) and*
– in a section of a duct with constant shape and cross-sectional area

According to initial data the last item to make disturbance to the gas flow is the interface of the main body and the stack (Figure 1).

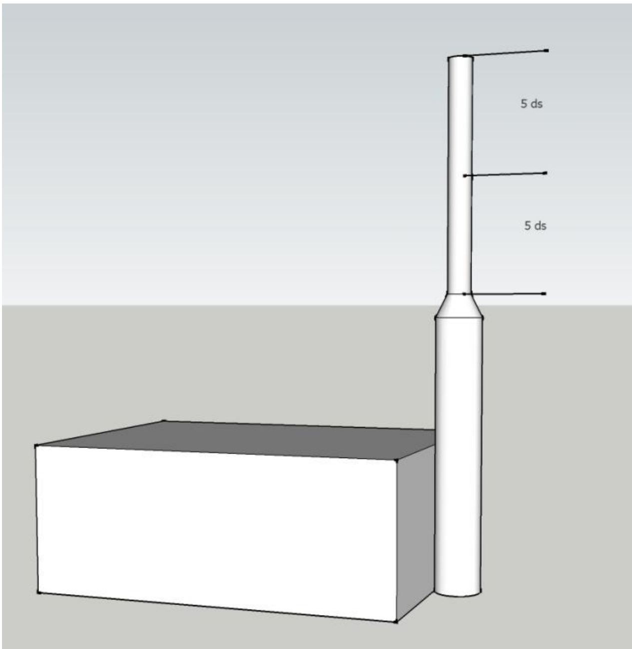


Figure 1, Illustration of the recommended measuring section according to EN 15259:2007

According to EN 15259 to obtain recommended flow-profile straight and undisturbed stack length should be at least 10 times of diameter of the stack. For example, if the diameter of the stack is 2.5 m the stack height should be 25 m from last disturbance to the exit.

The dimensions presented above are strongly recommended. However, depending on the plant structure the straight and undisturbed length are not always possible to be executed. In that case it is possible to use a flow straightening device (FSD) as presented in ISO 10780:1994[1]

The flow-straightening device is installed inside of the stack. Device structure is based on plate lattice as illustrated in Figure 3. This device should be installed in the stack at a point no closer than one stack diameter upstream of the sampling point. The length of the device L should equal or exceed the width b of the cell. The optimum performance (effective flow straightening with

[1] NOTE: Length before stack exit is extended from 2 x hd to 5 x hd because of possible of disturbances of the stack exit e.g. by ejector effect or turbulence caused by wind. It may be possible to improve flow profile in short stacks by installing FSD after the measuring location before stack exit. However, it should be studied case specific.

minimum head loss) is obtained when b equals one fourth of the stack diameter D (dimensions presented on U.S. EPA 5D are b=0,2 x D and the length of the straightener is 0,45 D). The device should work in either rectangular or circular stacks.

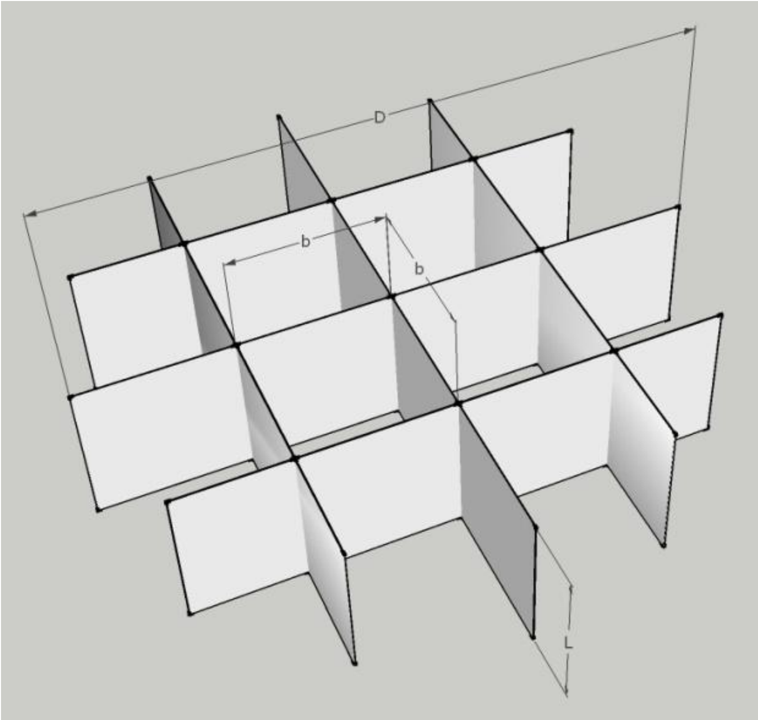


Figure 2, Illustration of the flow-straightening device according to ISO 10780:1994

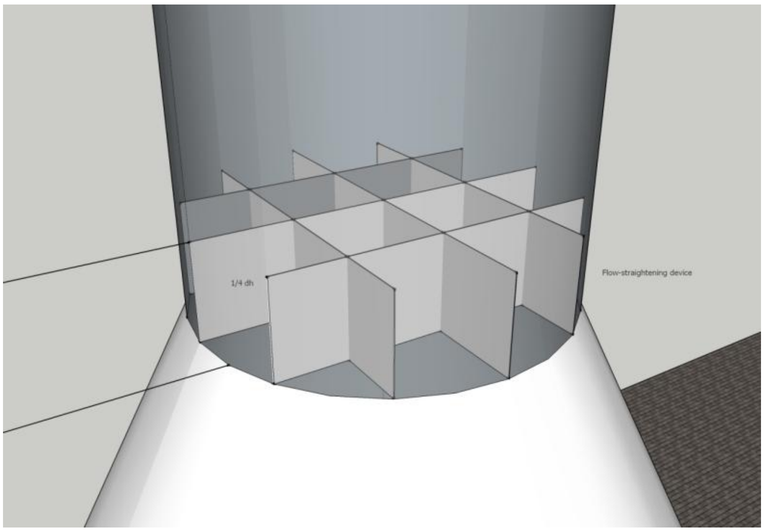


Figure 3, Illustration of the flow-straightening device installation; dimensions at optimum performance (head loss vs. straightening effect) according to ISO 10780:1994

If the flow straightening device will be installed it is important to study possible salting or clogging properties of the flue gas to avoid increasing of the head loss. If the head loss of the flow straightening device is not remarkable, the length of the L is recommended to be increased. The head loss should be taken into account in the overall plant design. Good results to enhance the flow profile could also be obtained if the flow profile will be taken into account while designing demister. At some cases it is possible to combine demister and flow-straightening device.

Using the flow straightening device it is possible to decrease stack height from 10 x diameter down to 6.25 x diameter (Figure 4).

Recommended evaluation of the minimum stack height should also be based on emissions released to environment and modelling of ground level concentrations. Also the stack and tall buildings nearby should be modelled because of the downwash effect. Oxygen concentration of the exhaust gas may be very low and should be taken into account while designing ventilation for the measurement site building to diminish suffocation risk of the service persons and RM measurement group. Thus, the length from the measurement site to the top of stack is not only regulated by the flow profile inside the duct, but also the health and safety reasons.

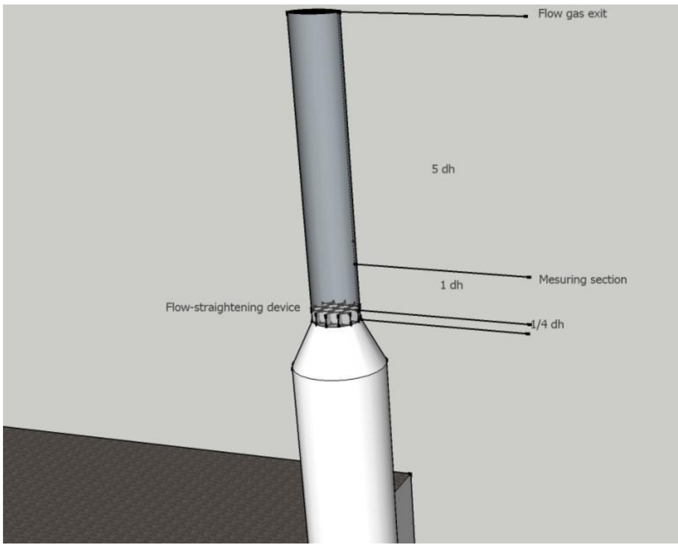


Figure 4, Illustration of the flow-straightening device installation; dimensions of the stack, according to ISO 10780:1994

If the most accurate flow measurement would not be essential or the quantification could be possible by another manner and the isokinetic sampling would not be needed, the stack height would be limited only by the HSE-reasons.

At the laboratory scale (duct diameter 0,1-0,3 m) undisturbed distances are recommended 8 x D_h before isokinetic sampling point after that 8 x D_h to the flow measurement point and after that 2 x D_h from first disturbance on downstream[5], see figure 5. Pilot scale should be evaluated depending of the plant size.

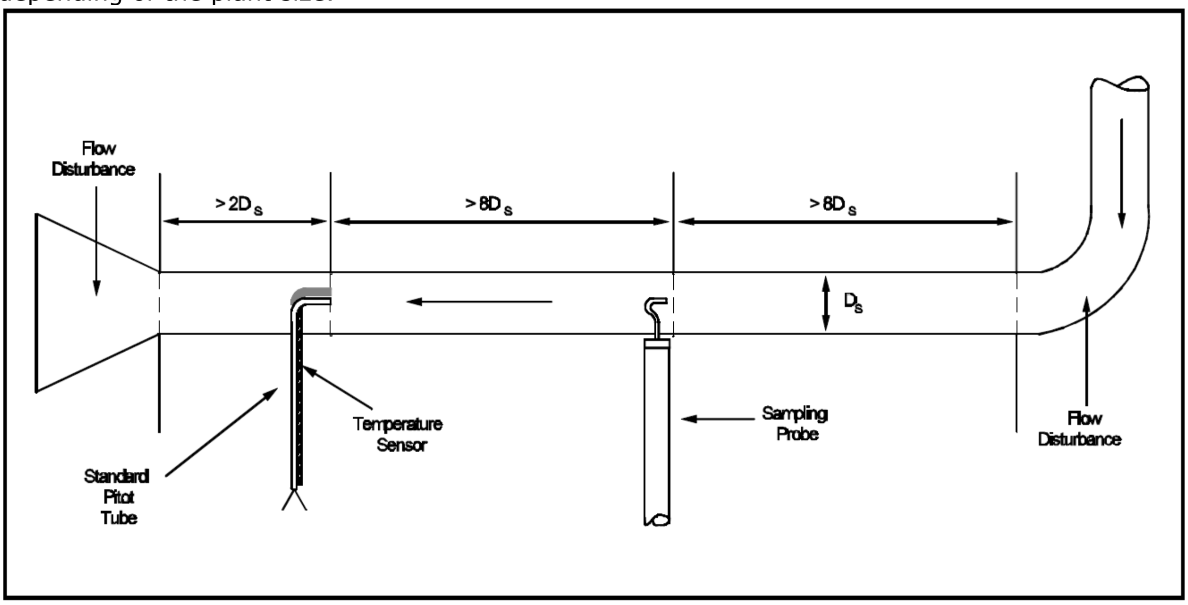


Figure 5, Illustration of recommended sampling arrangement for small ducts, U.S. EPA 1A

If undisturbed distanced cannot be obtained at existing plants, at some cases emission measurement persons use a rough rule of thumb "three before, one after". If it is not possible, undisturbed part of the duct is divided in relation 3:1 to obtain best estimation of flow conditions. This rule is not recommended for the demanding measurements.

5.2.3 Flow measurements and isokinetic sampling

The major reasons for the dimensions presented are related to measurement of flow rate, dust and droplets. In the case of amine based CCS-process most of the chemicals are water soluble and the droplets might be a significant carrier of the chemicals discharged into environment. Thus, if bigger drops are present, samples should be taken according to EN 13284-1 as isokinetic sampling. In general, sampling of droplets is related to sampling of particles and dust.

Chao Zhu states[6], that in practice, the isokinetic sampling is easily approached but almost impossible to be rigorously realized. The anisokinetic sampling refers to the mismatch of velocity, misalignment of the sampling orientation, or both. Many factors contribute to this "anisokinetic" sampling. For example, in the aerosol sampling in stack or in an essentially still air, it is extremely difficult to achieve a precise velocity match. For some confined three-dimensional flows, the matching of the sampling orientation is impossible due to the length restriction of the sampling probe. For the flows with rapid or erratical change in velocity, instantaneous matching of sampling velocity is also nearly impossible. In addition, the insertion of sampling probe inevitably disturbs the original flow field. For the sampling of large or heavy particles or sampling in dense suspensions, the isokinetic condition constantly fails to provide sufficient aerodynamic lift to take the particles through the sampling system. Thus, an anisokinetic sampling (over-sucking) may be operated to keep tracking the particle mass flux in a dense suspension or dilute suspension with large particles. Hence, an investigation of anisokinetic sampling is essential to estimate the departure from the ideal isokinetic sampling.

Anisokinetic sampling can be roughly divided into three different categories, namely, over-sucking (sampling velocity > stream velocity), undersucking (sampling velocity < stream velocity), and misalignment (probe not aligned with flow).
It is necessary to examine the limiting cases when sampling of very small or very large particles. Fine particles always follow closely the motion of a gas stream. Therefore, assuming that the sampling velocity or flow rate can be determined, the concentration measurement of very small particles during an anisokinetic sampling is the same as that in the mainstream, unaffected by the change of sampling velocity. For very large particles, the great inertia of particles keeps the particle motions unaffected by the sudden change of gas stream near the entry of sampling probe.
In other words, the amount of particles entering the probe is nearly the same regardless of the sampling velocity, which means that the mass flux measurement of very large particles is independent of the departure in sampling velocity from the isokinetic condition. Therefore, it does not matter whether the sampling is over-sucking or under sucking, the error from an anisokinetic sampling is resulted mainly due to the particle inertia. The effect of particle inertia is typically characterized by the Stokes number. Stokes number may be interpreted as the ratio of the particle stop distance to the characteristic dimension of the flow system. For small particles (e.g., most aerosols) whose Reynolds numbers based on their terminal velocities are within the Stokes regime (say, Re, < l).
It should be noted that, due to the different inertia of different sized particles, an anisokinetic sampling of polydispersed particle suspension affects not only the mass of particles in the sample but also the particle size distribution. Sub-sucking sampling results in a skewed size distribution with excess of large particles whereas over-sucking sampling leads to a biased size distribution with excess fine particles. For aerosol suspensions, the velocity slip between particles and the carrying gas is usually negligibly small compared to the sampling velocity due to the tiny size of aerosols. Measurements from a sampling probe can hence be directly linked to the aerosol concentration.

Particle size (more precisely, particles inertia) plays an important role in an anisokinetic sampling. The concentration of extremely small particles and mass flux of very large particles can be correctly sampled regardless of the sampling velocity. Figure 6 shows that an isokinetic sampling always yields the correct sampling of particle mass flux.

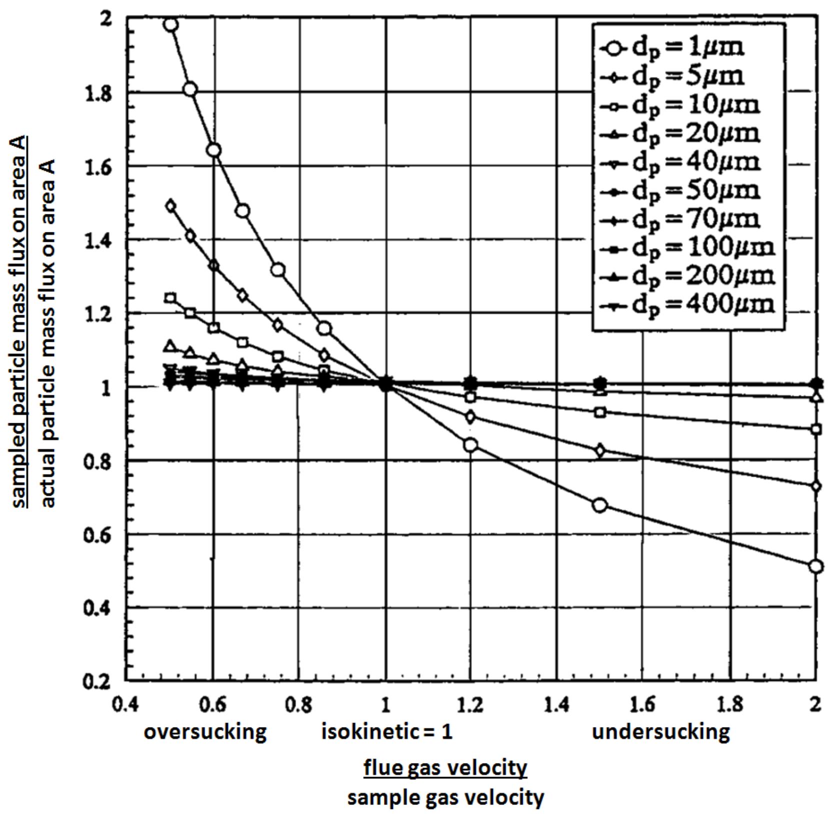


Figure 6, Particle mass flux in anisokinetic sampling (d_p = particle diameter), Zhu 1999

Figure 6 illustrates that oversucking of 1 μm particles twice as fast as needed for the isokinetic sampling (isokinetic factor 0.5 on x-axis) will lead the volume of sample gas to be 2 times more than needed for the isokinetic sampling. This yields the sampled particle mass of two times more than actual flux on sampling area (particle mass/actual mass on area sampled is 2 on y-axis). This leads to situation where actually sampled particle mass/area is twice as much as actual mass flow at the same area. However, the sampled volume is also twice as much as actual mass flow at the same area. So calculated concentration c=m/V is c=2/2=1, which is actual mass concentration in the duct. The result is valid regardless of the sampling velocity of < 1 μm particles.

Respectively if particle size is 20 μm, the oversucking of isokinetic factor 0.5 during sampling leads to sampled particle mass flux of 1.1 and calculated mass concentration of particles is 1.1/2=0.55, about half of the real mass flux.

In order to yield the concentration of not very fine particles from an isokinetic sampling, the particle velocity should be determined independently.

In practice, there can be a significant difference in velocity between the gas and particles, especially for large particles. For instance, for the pneumatic conveyance of glass beads sizing from 100 to 400 μm with carrying air velocity between 8 to 15 m/s, the local particle velocity is about 40 - 60% of the local gas velocity[6]. Therefore, for medium sized particles (5 - 100 μm), anisokinetic sampling in principle provides neither the correct measurements of concentration of particles nor the correct measurements of particle mass flux. This problem is complicated by the coupling of the slip nature (particle inertia) of particles in a carrying flow and the mismatch between the sampling velocity and stream velocity (flowrate and/or orientation).

In a particle sampling process, numerous other mechanisms contribute to the error in the particle mass flux measurements. These mechanisms include gravitational sedimentation, impaction on the wall or at the tube bends, wall deposition due to the diffusion of small particles, flow turbulence, surface drag, agglomeration of fine particles, electrostatic charge, adsorption of particles to the wall, and flow disturbance by the insertion of the probe, in addition to anisokinetic sampling discussed above.

In CCM-project isokinetic sampling of flue gas is strongly recommended for the water soluble compounds and particles. This applies even though the droplets would not be present in normal conditions of flue gas. Possible malfunction of process (especially in demister) may lead to escape of droplets and significant increase of emission levels.

However, flue gas velocity measurement is an important factor while specifying total emission of the plant. Reliable flue gas flow measurement is practically possible only if the gas flow is relatively homogeneous. Without more detailed flue gas modelling or measurements, it is difficult to assure high-level flow rate measuring conditions, if dimensions presented above are shorter.

6. MEASUREMENT PORTS

6.1 General

Measurement ports shall be provided to allow sampling at specified measurement points. Also additional measurement ports shall be provided in the same measurement plane or section to allow calibration of the AMS-systems including sampling train (e.g. flue gas velocity, water content, and other impurities).

6.2 Number of ports

At the upcoming Mongstad CCS-plant emission measurements are estimated to have much higher quantity compared to ordinary gas turbine. At this point all analysing methods needed are not available and accurate quantity of the measurement ports needed should be estimated, see Table 5.

Table 5 Estimation of the AMS emission measurement ports on the stack

Type	Ports needed	Notice
AMS, SO_2, NO_x, O_2, CO_2, CO etc.	1	
AMS, dust*	3	optical head + reflector; extractive
AMS, wet gas measurement (water vapour, TOC, multicomponent analyser)	1-3	
AMS, volume flow	4	transmitter + receiver, orthogonal transmitter + receiver, 45-60°
AMS, temperature	1	
AMS, pressure	1	
Reference method	4-6	

** not needed on ordinary gas turbine, however may be required for test purposes. Scattering based method may not be suitable for the flue gas conditions after the wet scrubber*

If the distance between the measurement port and opposite wall is long (more than 2 meter) two opposing measurement ports should be provided to each measurement line. It can be necessary to install additional measurement ports for the operational measurements or for the AMS-instruments at the region of the measurement plane.

Some common design errors are:

- number of ports will cover only requirements of the present AMS-system. Future requirements and reference measurement ports are not available
- at large ducts only one measurement port/line is available

6.3 Structure of the measuring ports

Recommended structures of the measurement ports are presented in the supplements 1.
It is recommended to use a flange-type measurement ports to prevent stucking and allow easy mounting of sample probes. Recommended internal diameter of flange type measurement port is 125 mm at the full scale plant. However, on small ducts (diameter < 0.7 m) internal dimension of the measurement port should be reduced to 75 mm. Diameter of 70 mm is an absolute minimum for the SRM measurement ports while the probe diameter is commonly 62 mm.

Some of the measurement instrument vendors offer the purpose-built measurement ports for the instruments. Usually those are smaller than described in the standards.

Thread type ports are also accepted and standard dimensioning is preferred. Smaller ports could be installed for the AMS pressure and temperature measurements.

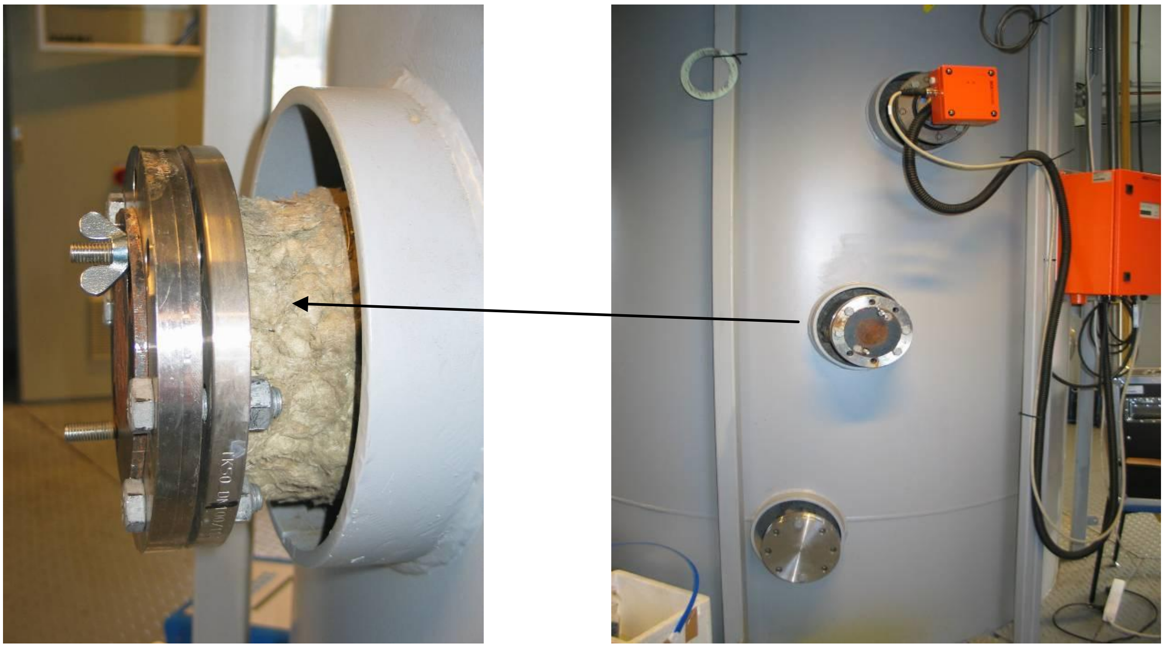


Figure 7, Measurement ports, flange type VTT 2008

The frame and sealant material should be proven to be resistant for the long time chemical expose of the flue gas and its pollutants. Recommended material of the measurement port body is stainless steel (304 SS, 304L SS, 316 SS and 316l SS are recommended for general use) [7] or acid-proof steel, if SS is discovered to have corrosive properties during plant design. Any copper bearing metals cannot be used[7]. Also the same material as on inner duct is allowed. In the Figure 7 the seal and the closing cover is assembled between the flanges and the body from the duct wall to the measurement port is made of fibreglass (internal duct inside the metal stack is also made of fibreglass).

The installation of SRM probes may be unsupportive if other than standard measuring ports are used, especially in large ducts. In that case it is recommended to install supporting frame beneath the SRM measurement ports to enable solid installation (Figure 8).

Figure 8, Self-made measuring port with U-type of supporting frame, VTT 2008.

Some common errors of measurement port design are listed below:

- internal diameter is too small; 75, 100 and 125 mm is recommended
- internal diameter of the measurement body is sufficient but the cutting on the duct wall is too small. This is a common error on retrofitted measurement port.
- diameter of the measuring port is too large in a small duct. Ducts of hydraulic diameter below 0.7 m recommended measuring port diameter is 75 mm.
- unsuitable material leads to stucking of the thread type of measurement port (Figure 9) or the rupture of the measurement body from the duct
- body of the measurement port is too long; recommended length is 100 mm from the duct wall to the flange on a 125 mm flange type measurement port.
- the body on flange type measurement port is too short; the flange bolts are difficult to be installed from backside of the flange
- leaking, no seal; this is significant in the stacks with overpressure or flow gases with condensing moisture which may leak condensing water inside the working/instrument area
- body of the measurement port is pierced too deep into the duct so that the nearest measurement points from the duct wall will not be in order for e.g. on grid measurements

Figure 9, Internal-thread type of measurement port which is strongly stucked

6.4 Mounting locations of measuring ports

Measuring ports should be located taking easy installation of the AMS-probes and working of reference measurement groups into account. It is crucial that the flue gas flow within the measuring section will not be disturbed. This is important especially if flow rate measurement, dust concentration or other isokinetic sampling methods are in use in the same section.

It is recommended to set fixed markings to the each measuring port to confirm overall traceability.

If the flow or dust measurement is compelled to be installed near to bend, it should be positioned as in Figure 10. The dust measurement probe is recommended to be installed in the position where the dust concentration is expected to be the highest, which normally is the outer edge after the bend.

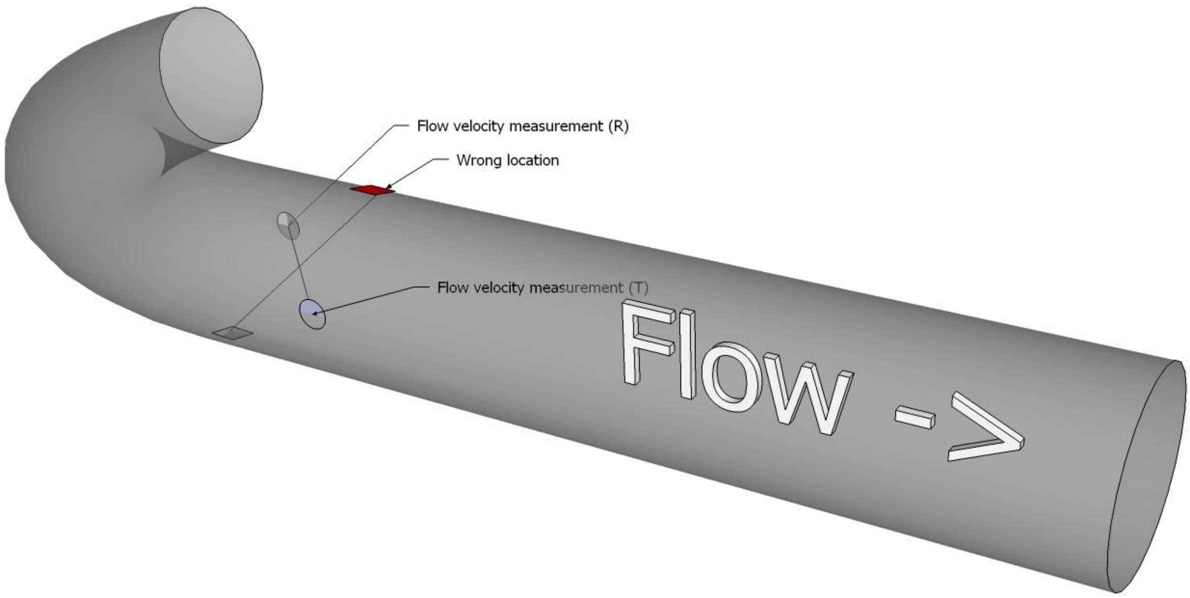


Figure 10, recommended location of the velocity measurement after the bend, SICK Maihkak Ltd.

6.4.1 Vertical locations

Measurement ports within measurement section are divided into the vertical sampling planes. Basic rule is to situate flow sensitive measurements upstream before the disturbances caused by the other sampling probes appear. Installation of two transmittance based measuring instrument next to each other should be evaluated by taking the cross sensitivity into account. The sufficient distance between the planes 1 and 2 is 0.5 m if the laser diffraction based dust analyser is in use.

Recommended order of the measurement planes are, (see also supplement 2):

Table 6 Recommended minimum arrangements of the measuring ports, basic arrangement

	Measuring plane	Type	Description	Quantity
downstream				
gas flow -->	1	SRM	measurement ports	2
	2	AMS	dust concentration, extractive 30° angle[1]	1
	2	AMS	cross stack (dust concentration[2], multicomponent analyser)	2
	3[3]	AMS	Gas analysers e.g. SO_2, NO_x, O_2, CO_2, CO	1
	3[3]	SRM	Gas analysers e.g. SO_2, NO_x, O_2, CO_2, CO	1
	4	AMS	Moisture, TOC, multicomponent analysers	1-3
	4	SRM	Moisture, TOC, multicomponent analysers, manual sampling	1
	5	AMS	cross stack (flue gas flow, one measurement port installation angle 45…60°)[4]	1
	5	AMS	cross stack flue gas measurement, orthogonal to the flue gas flow	2
	6	AMS	temperature, pressure	2
upstream				

1) *branch should be located pointing upwards to enable condensing water to flow out of the probe*
2) *cross stack or laser diffraction based methods are not necessary suitable for the flue gas conditions after the wet scrubber*
3) *AMS and SRM measurement ports could be installed in the same plane if vertical space (usually room height) is limited, multiple measuring planes are needed and the tip of the AMS probe is installed in the first quarter of the stack diameter and position is fixed. In that case SRM measurements could be performed properly without collision. However, the vertical position between AMS and SRM is recommended to be increased to 0.2 m, if vertical space is not limited or if long AMS probe is in use.*
4) *maximum diameter of the duct is often limited to about 10 meters*

On some methods the cross-stack analyser transmitter and emitter (e.g. flue gas) need to be installed in 45…60° angle to the duct. The measuring principle possibly allows the measurement through the all measuring planes presented above. This is possible, if the measuring principle has no cross sensitivity to the other instruments. However, installation through the vertical measuring planes is not recommended because of possible interference with the SRM probes or the AMS installations in the future.

The recommended location of the flow velocity measurement is 3 x d_h upstream from the main measurement section or 5 x d_h downstream from the measurement section. Distances to the nearest disturbance or stack exit should be taken into consideration as described in 5.2.2.

Before deciding on which AMS flow measuring device to buy, a thorough characterization of the flow profiles in the duct at the candidate locations should be conducted. All continuous flow measuring systems measure the velocity in a small segment of the duct and use this value and the dimensions of the duct to obtain an estimate of the total volume flow in the duct. Thus, it is important to select an AMS which will be accurate under the flow conditions in the duct and to locate the sensor(s) of the AMS at a point(s) which will provide velocity measurements representative of the duct's total volume flow. [8]

6.4.2 Horizontal locations, round duct

On the horizontal plane the sampling areas on the duct are divided in two areas as illustrated in Figure 11:

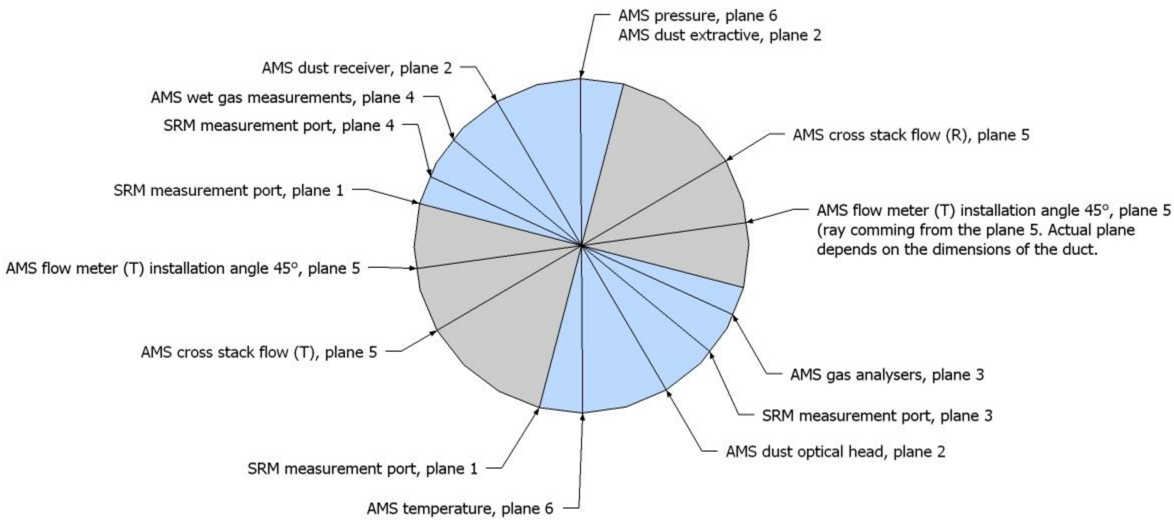


Figure 11, top view of proposed mounting locations, modified from EN 15259:2007

The light blue sectors are reserved for the receiver and transmitter of the flow measuring instrument and grey sectors for the other instruments and SRM measurement ports.

Optional SRM ports are recommended especially for large ducts (d_h > 2.5 m)

The basic arrangement for the pilot and full scale plant presented below should be re-evaluated (e.g. dimensions, measurands etc.) when the accurate plant and stack design are known.

6.4.3 Horizontal locations in rectangular and square ducts

In rectangular ducts the SRM measurement ports should be assembled to the longer side of the duct. At large ducts measurement ports may be needed for the both long sides to avoid too long measuring probes.

Minimum quantity of the measurement lines are:

Table 7 Minimum number of sampling points for rectangular ducts

Sampling plane area m²	Minimum number of measurement lines	Minimum number of SRM sampling points
< 0,07	-	1[a]
0,07…0,38	2	4
0,38…1,5	3	9
> 1,5	≥ 4	16 (at least 4/m²)[b]

a) one point measurement may suffer unexpected errors

b) in large ducts 20 points is usually sufficient

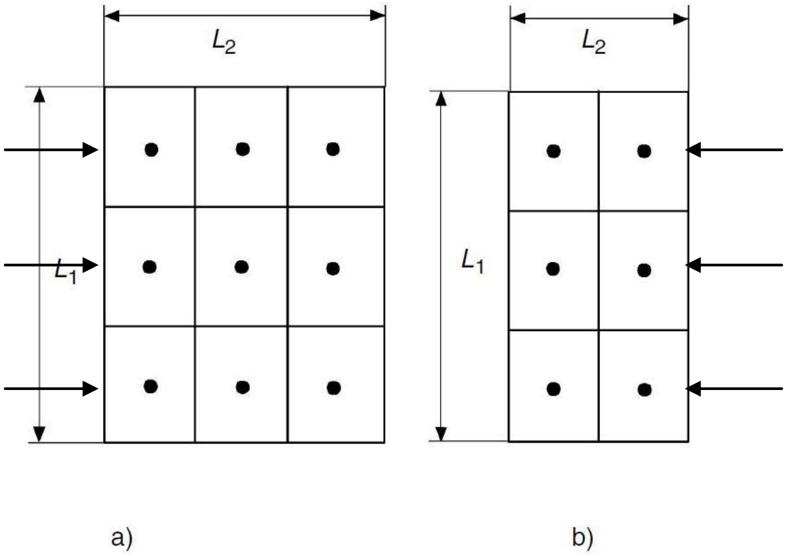


Figure 12, Sampling point positions in rectangular and square ducts according to EN 15259:2007

Division presented in the Figure 12 a) is used when — and b) when — .

In Figure 12, the SRM sampling points should be located on side L1. Recommended locations of the measurement ports are pointed by arrows.

AMS ports should be located upstream and centre between the SRM measurement lines. It is recommended to install reservations (if possible) to the AMS flow measurement device also on the shorter side of the rectangle.

Some common errors on mounting are:

- measurement ports are too close to each other
- AMS and SRM measurement ports are in a same vertical plane which leads to SRM probe collision while taking samples for the grid measurement
- wrong overall alignment, grid measurement is not representative (e.g. normal between two SRM measurement ports is not available)
- measuring ports has no fixed identifier

7. SAMPLING SYSTEM

7.1 Sampling system components

Components for the treated flue gas sampling systems are dependent of the AMS instruments chosen. A normal extractive sampling and analysing is needed for the water soluble compounds, if significant amount of droplets are present as expected.

Because some of the compounds are thermally labile the heated sample lines and filters may not be sufficient for the purpose. However, most of the FTIR analysers operate only in elevated temperatures. Also sample preparation is done on elevated temperature (usually > 100 °C).

AMS-systems for the water soluble compounds are developed for example to measure SO_4 concentration from very humid flue gas. Sampling systems are not heated (excluding deicer of the sample lines) because of strong salt formation. The basic idea is to have isokinetic sample and lead it through the sampling systems to the condenser. Later on the condenser gas will go through different absorption towers. Combined sample will be analysed by automatic online system or in laboratory.

Estimation of suitable analysing and sampling system (manual and online) is ongoing while preparation of the current report. Strong relation between sampling and analysing of treated flue gas recommendations for the analysing and sampling system is given at CCM project reports of H&ETQPAmine1 Subtasks 2 and 3.

7.2 Materials of sampling system

The corrosion in amine plants or instruments installed is not caused by the amine itself, but is caused by the CO_2 or H_2S (estimated to be not significant in CCS-processes) and by amine degradation products. Problems with amine units can be corrosion or by cracking (sulphide stress cracking, hydrogen induced cracking associated with hydrogen blistering, stress-orientated hydrogen induced cracking, and alkaline stress corrosion cracking).
Areas to have a close look at is where impingement erosion could occur, where there is elevated temperatures, where flashing off of CO_2 could occur, and where heat stable salts could cause scaling[9].

Recommended material for the body and the sample lines of the AMS probes is stainless steel. According to feasibility studies conducted by MIDAC, PTFE could be useable at elevated temperatures around 120 °C[10]. At lover temperatures PTFE as other plastics might have significant adsorption against organic compounds which may have negative impact for the response time.

Empirical experience has shown glass tubing to be unsuitable on AMS systems because of mechanical reasons. However, it could be used in SRM sampling systems.

Use of titanium alloys in sampling system is unclear. They are resistant against most of the compounds included in flue gas. Report of galvanically induced hydrogen embirttlement corrosion with rich MEA based processes at elevated temperatures (120 °C) have been presented[11].

Suitable materials for the sampling system and possible degradation conditions are discussed at more detailed in the CCM project, H&ETQPAmine1 Subtasks 2 and 3.

8. MEASUREMENT SITE

8.1 Requirements

Early stage CCS-plants are commonly under interest and different kind of flow gas measurements are performed in a wide scale. For that reason the minimum recommendations for the measurement site required for e.g. conventional fuel LCP-plants are not sufficient meaning that the working area should be covered from weather changes. There should be at least a weather guard with temperature control for the AMS- and SRM analysers near the working area to avoid long sampling lines.

Figure 13, Covered measuring section after the wet-scrubber, VTT 2008

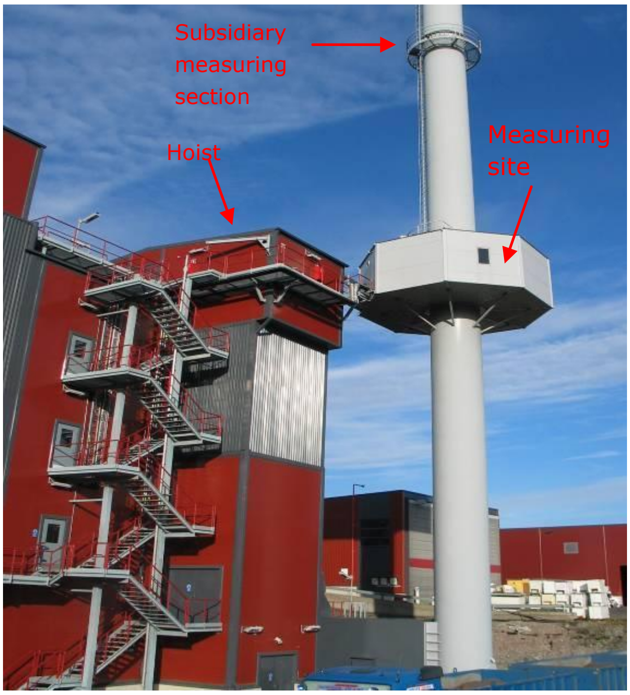


Figure 14, An example of a good measuring site. Note the subsidiary measuring section above the primary measurement "nut", VTT 2008

8.1.1 Access to working area

In all cases easy access to the working are is needed. Access should also be suitable for the heavy and/or long objects.

On laboratory scale it is estimated that device and measuring ports will be near the ground level and access could be arranged by stairs or using temporary installed scaffolding. A ladder is not allowed on measurements for safety reasons.

Access to the measuring section of the pilot plant should be by stairs. However, lift for the measuring equipment is recommended.

Recommended access to the measuring section of the full scale plant is by lift. Depending on the plant design stairs could adequate if hoist is available (Figure 14) for the SRM-equipments. Important design principle is to allow fast transport of a person in the case of injury (e.g. unconscious person).

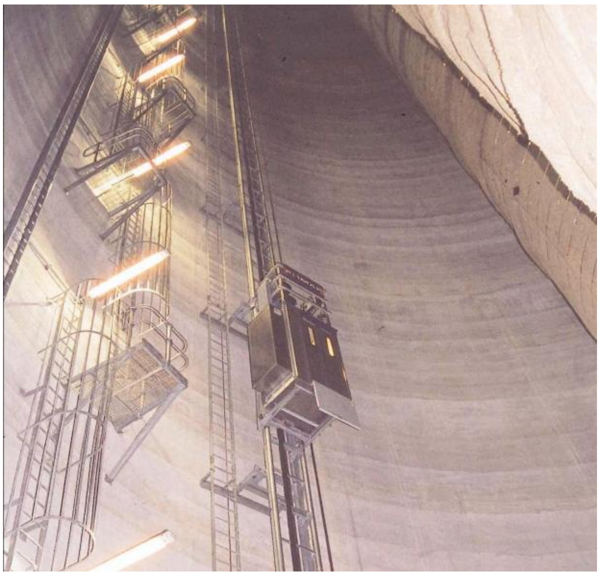


Figure 15, At large plants lift to the working platform could be installed on the internal wall of the stack core, Talhu Oy

8.1.2 Load bearing capacity

If AMS instruments are installed at the working platform a load bearing capacity should exceed 1000 kg (6 persons + SRM + AMS equipments). Snow, wind and other weather related matter should be taken into account. Load bearing capacity does not include mass of the platform constructions such as walls, roof and frame structure.

At subsidiary measuring sections the load bearing capacity should be at least 500 kg.

8.1.3 Position and working space

Working platforms should provide sufficient working area and height (working space) for the task, i.e. to manipulate the probes and operate the measuring instruments. Clearance area at the working platform should be dimensioned appropriately and the probes should not be obstructed for example by the guard fences and other built-in elements.

Figure 16, a service hatch of the flight alert light is used to enhance free clearance area; measurements from internal duct inside the concrete stack, VTT 2008

Grid measurements require a sufficiently large working area outside the waste gas duct along the measurement lines so that the sampling can be performed with the appropriate probes in the measurement plane. The minimum probe length depends on the internal diameter or depth of the waste gas duct and the wall thickness.

A sufficient depth of the working area is given by the sum of the internal diameter or depth of the waste gas duct and the wall thickness plus 1.5 m for flanged-on instruments. If two opposite measurement ports are installed for one measurement line, a correspondingly smaller operating area depth is sufficient.

It is recommended that if a round duct diameter is larger than 2 meters the working platform should be extended around the duct at the width of the 50 % diameter of the duct. Clearance areas in the front of the ports are as above.

Recommended working areas are as below. Area of the AMS-instruments is excluded:

Table 8 Recommended working area for the SRM-group

Laboratory scale	Pilot scale	full scale
18 m²	18 m²	20 m²

Areas are estimated according to EN15259:2007 at chapter 6.2.3.2. Recommended workspace for the SRM measuring group in waste incineration plant is about 18 m² *(open width of the vertical waste gas duct: 2 m width (measurement ports) and 1.5 m depth, wall thickness: 0.3 m, measurement: total dust, total carbon, hydrogen chloride, hydrogen fluoride, sulphur dioxide, nitrogen oxides, carbon monoxide, PCDD/PCDF, heavy metals, oxygen, waste gas volumetric flow rate, waste gas pressure, waste gas temperature, carbon dioxide, water vapour).* Number and structure of the emission measurement analysers and other equipment in waste incineration plant and CCS-facility are estimated to be at the same scale. Recommended area includes the possibility to have two independent measuring groups working simultaneously. Recommendation at laboratory scale is based on assumption of area needed for the analysers (incl. at least basic flue gas-, VOC-, FTIR- and dust analysers), filter housings, probes, other sampling systems (e.g. two or more separate wet sampling systems) and moving area. Area needed for the one group is about 9 m² and 18 m² for two groups and it is same in both laboratory and pilot scale.

8.1.4 Heat and ventilation

Measurement site should be covered and heat regulated. Air-conditioning is recommended especially if AMS-instruments will be installed on the measurement site. Ventilation should be arranged taking possible down wash effect from the stack exit into consideration. This is important especially if the stack exit is diminished from 5 d presented in chapter 5.2.2. Intake air should be filtered. Pressure in the measuring building should exceed the pressure inside the duct. Forced ventilation is recommended e.g. in the case of sudden emission from the duct. A proper vent or outlet for the exhaust gas of the SRM- and AMS-instruments should be available.

Figure 17, an air-conditioning unit on the roof of a measuring site, VTT 2008

8.1.5 Accessory hardware

Appropriately sized and safeguarded power connections in accordance with national requirement shall be installed at the measurement site. Compressed air (oil and water free), water connections and wastewater disposal are recommended. A supply of cold water is strongly recommended for the cooling purpose of SRM systems.

Figure 18, Overview of a measuring site; 1 fire alarm button, 2 power connections, 3 water supply, 4 compressed air supply, VTT 2008

9. HEALTH AND SAFETY

The measurement sites shall be installed in a way to comply with national safety at work requirements. Some items for the consideration are presented below.

Access to the measurement site has to be easy and safe. In the case of measurement sites which are not at ground level hoists, lifts and stairs to transport measuring instruments should be safe and easy to use. The ground level areas should be isolated or kept out of common passage to avoid injuries of falling objects. Falling ice should also be taken into account.

Measurement site with access should be planned in order to avoid unexpected risks such as rupture disks, overpressure valves or steam discharges.

Measurement site should be covered by the fire alarm sensors and the warning system of the plant. Fire extinguisher, smothering blanket and heat resistant cloves should be available. Telephone line (wired) from the measurements site to the control room is recommended.

Figure 19, Warning signal in a measuring site assured by the loudspeaker[12]

Risks by engineering (e.g. unpractical design principles, wrong materials or dimensions of measuring site, ports etc.), procedural measures (e.g. inexperienced measuring group) or areas of significant positive pressure (e.g. working area near pressure relief valve) should be avoided.

If release of toxic gas or oxygen deficit is possible in the plant area, compressed air breathing apparatus or suitable breathing mask should be available. Sensors for the dangerous gas (e.g. carbon monoxide, oxygen) and warning system related are recommended on the working area.

Need of the secondary emergency exit from the measurement site should be evaluated.

Some common design errors:

- the upper handrail on the spiral stairs to the measurement site is too low. Possible risk of dropping over the handrail if person falls
- kick-plate on the edge of the working platform is missing
- floor on the measurement site is not closed so objects may drop onto ground level
- low air pressure on the measurement site compared to pressure in the duct
- first-aid extinguishing is not available
- lift or hoist is not available
- alarm system will not cover the measurement site

10. SUMMARY

The design of the flue gas sampling site and sampling ports plays important role in obtaining reliable emission measurement results. First CCS-plants are under great interest and many different measurements are expected to be performed raising the demands for the sampling site.

Recommended flue gas sampling site is easy and safe to access and work. It will also offer full cover from the weather. Supplementary services like electricity, tap water and compressed air are easily available. Also adequate amount of sampling ports are needed. At the full scale CCS-plant the amount of sampling points depend on instrumentation but at least 9 ports divided to 6 levels are expected including AMS and SRM ports.

Additional ports are strongly recommended for both AMS and SRM purposes. This is important to be kept in mind if stack will be insulated or coated inside. Recommended sample ports are 125 mm and flange type. Diameter of the duct may limit the number and size of the ports at pilot and laboratory scale plant. In practice, minimum amount of ports is AMS ports + 2 for the SRM group in the laboratory and pilot scale. Recommended principles for the measurement section and port design are presented in standard EN 15259:2007.

Recommended material for the sampling ports is stainless steel (SS quality should have been proven against the flue gas components during CCS-plant design). Material used in the duct is usually suitable for the sampling ports. Case-specific evaluation should perform if PTFE and titan based materials are used in sampling system.

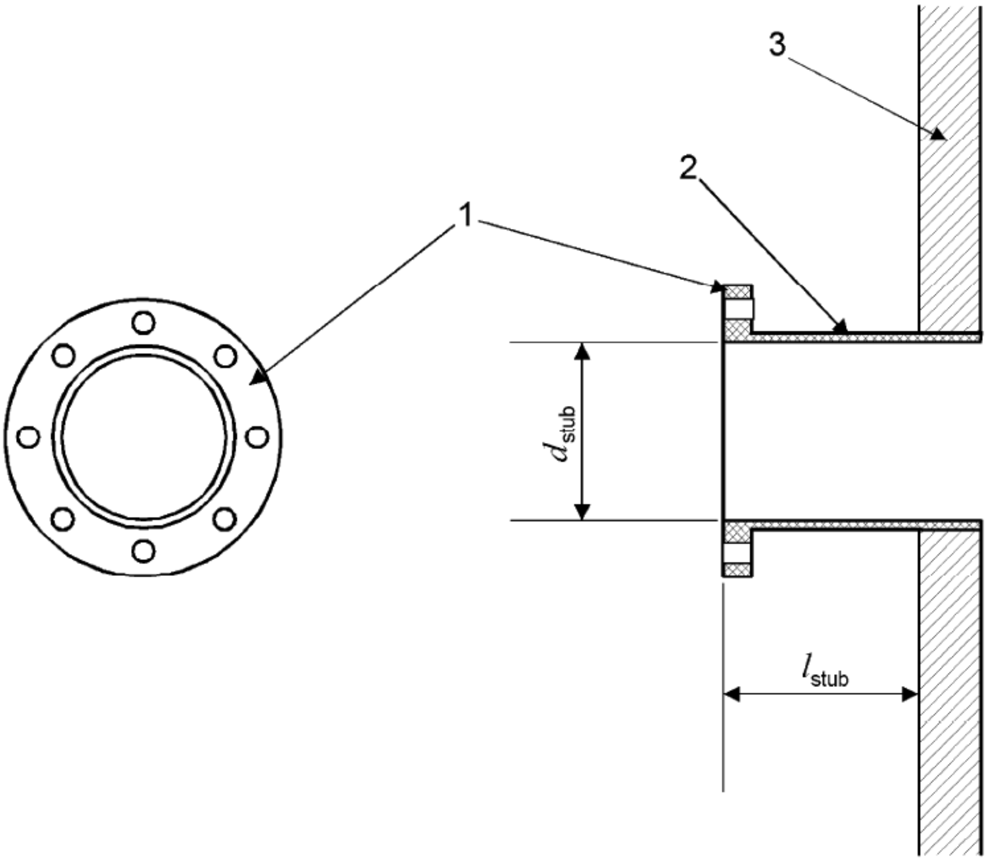
After the demister, flue gas is expected to be humid and droplets may be present. Isokinetic sampling is recommended for the water soluble compounds. It should be kept in mind that gases which are normally practically insoluble into water (e.g. CO_2, NO_x) at normal LCP emission measurements may be bounded in droplets at CCS plant flue gas. Isokinetic sampling may be difficult to perform at laboratory and pilot scale plants where the gas flow is slow. In some of the cases a duct diameter has temporary been decreased to 10-15 m/s to obtain proper flow conditions for the sampling and flow measurement.

Flow at the measurement location should be homogeneous. The requirement of homogeneous flow conditions is generally fulfilled if the measurement location is in a section of a duct with at least five hydraulic diameters of straight duct upstream of sampling plane and five hydraulic diameters from the top of the stack. Using flow straightening device or advanced design of demister the upstream distance could be reduced to one hydraulic diameter. It may be possible to obtain homogeneous flow in a shorter distances but any general rule is not available. At the laboratory scale (duct diameter 0.1-0.3 m) undisturbed distances are recommended 8 x D_h before isokinetic sampling point after that 8 x D_h to the flow measurement point and after that 2 x D_h from first disturbance on downstream. Pilot scale should be evaluated depending of the plant size.

Recommended evaluation of the minimum stack height should also be based on emissions released to environment and modelling of ground level concentrations. Also the stack and tall buildings nearby should be modelled because of the downwash effect. Oxygen concentration of the exhaust gas may be very low and should be taken into account while designing ventilation for the measurement site building to diminish suffocation risk of the service persons and RM measurement group. Thus, the length from the measurement site to the top of stack is not only regulated by the flow profile inside the duct, but also the health and safety reasons. In the case of full scale plant, if the undisturbed diameters cannot be obtained, best sampling location may be estimated by modelling after the more detailed plant design.

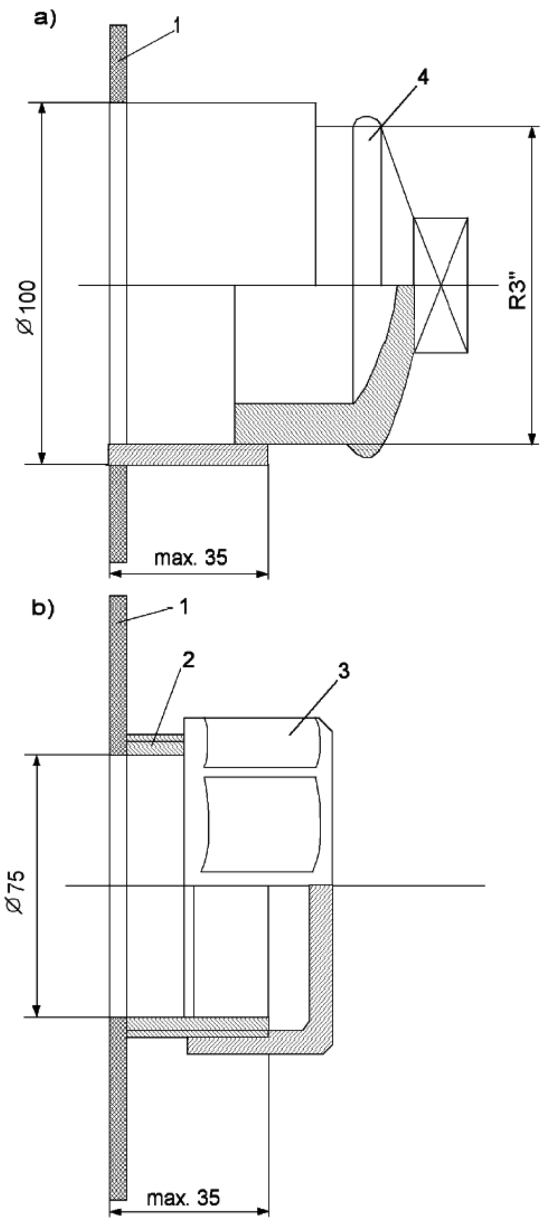
SUPPLEMENTS 1
RECOMMENDED MEASUREMENT PORT DESIGN

Example of a round measurement port (i.d. = 125 mm) according to EN 15259:2007



(1) Flange with internal diameter d_{sub} 125 mm
(2) pipe stub with internal diameter d_{sub} 125 mm and minimum length l_{stub} = 75 mm from duct wall (recommended 100 mm)
(3) duct wall

Example of a round measurement port with internal diameter and internal thread (a) and external thread (b) according to EN 15259:2007



(1) duct wall
(2) 75 mm pipe nipple
(3) closure cap
(4) closure stopper

Dimensions in millimetres

SUPPLEMENTS 2
SAMPLING PLANES, CIRCULAR DUCT

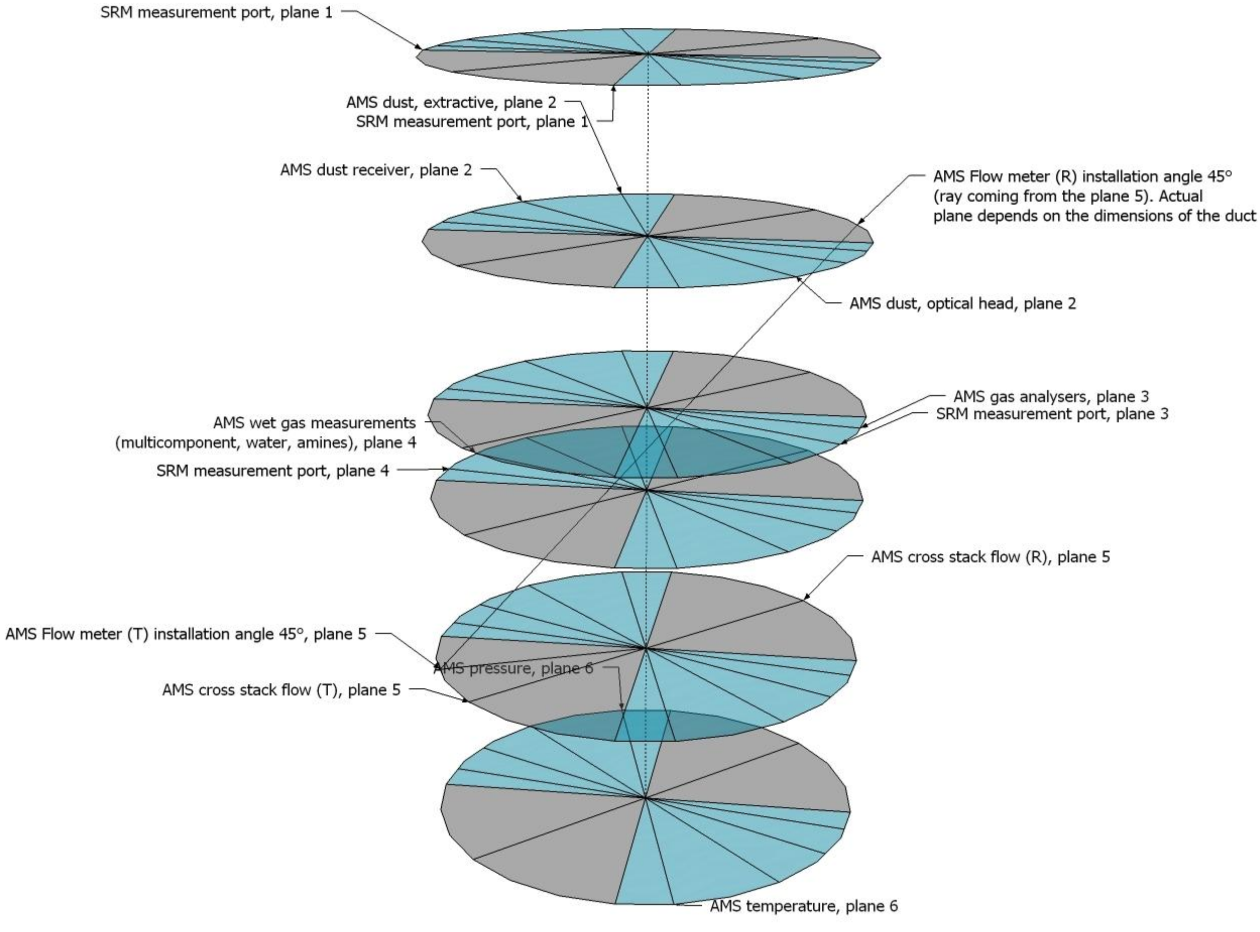


Figure above, cake view of the measurement planes (gas flow upwards) modified from EN 15259:2007

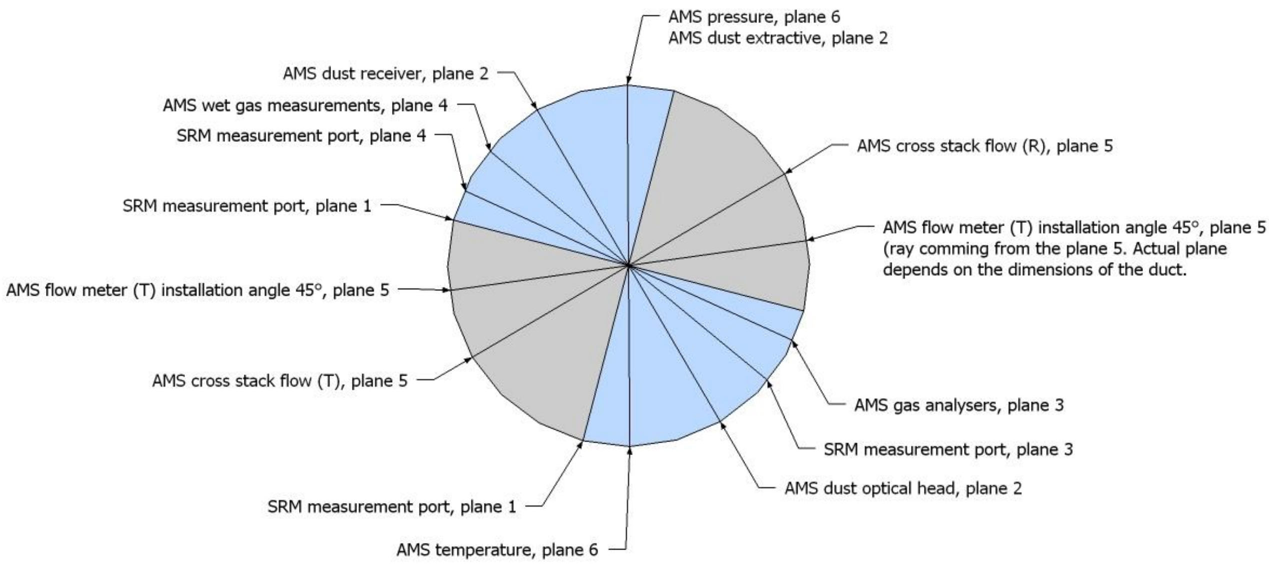


Figure above, top view of the basic principle of the measurement locations modified from EN 15259:2007

BIBLIOGRAPHY

(1) THE INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 1994. ISO 10780, Stationary source emissions - Measure of velocity and volume flowrate of gas streams in ducts. .
(2) EUROPEAN COMMITTEE FOR STANDARDIZATION, 2008. EN-15259:2007, Air quality. Measurement of stationary source emissions. Requirements for measurement sections and sites and for the measurement objective, plan and report. .
(3) EUROPEAN COMMITTEE FOR STANDARDIZATION, EN 13284-1:2001, Stationary source emissions – Determination of low range mass
concentration of dust – Part 1: Manual gravimetric method.
(4) EUROPEAN COMMITTEE FOR STANDARDIZATION,
EN 13284-2, Stationary source emissions. Determination of low range mass
concentration of dust. Part 2: Automated measuring systems.
(5) U.S. EPA, 2000.
METHOD 1A - SAMPLE AND VELOCITY TRAVERSES FOR STATIONARY
SOURCES WITH SMALL STACKS OR DUCTS.
(6) ZHU, C., 1999. Isokinetic Sampling and Cascade Samplers. In: SHAO LEE SOO, ed, *Instrumentation for Fluid Particle Flow.* Park Ridge, NJ: William Andrew Publishing, pp. 9-46.
(7) M.S. DUPART, T.R. BACON AND D.J. EDWARDS, 1993. Understanding corrosion in alkanoamine gas treatment plants, Part 1&2.
(8) INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ISO 14164, Stationary source emissions — Determination of the volume flowrate of gas streams in ducts — Automated method.
(9) RENNIE, S., 2006.
Corrosion and material selection for amine service.
(10) RINTEKNO AB, 2010. Gassnova, Amine emissions and monitoring WTO nr 24 _Open version Nr. RF0041U-100A-001.
(11) MCMASTER, J.B.P.N. and ROWAN, D., 2000. Titanium - Proven Performance in Hydrocarbon Processing.
(12) VTT, 2008. *Ohjeistus päästömittauspaikalle ja mittausyhteille asetettavista vaatimuksista.* VTT-R-11101-08.