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Title: Development of a measurement device and procedure for particulate matter

Ontwikkeling meetopstelling en meetprocedure voor fijnstof meting

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Summary

Wärtsilä Netherlands (WNL) counts 1500 employees in six locations spread over the Netherlands. One division of WNL is Technical Services located in Zwolle, specialized in diesel engines for inland shipping. This division is responsible for support and maintenance of Wärtsilä, Deutz, Stork, Werkspoor en Bolnes engines. There are over 19,000 engines in field and about 40 different types.

Inland shipping engines must meet certain emission standards. These standards also limit the particulate matter (PM) emissions. To make sure the standards are met, the engines are tested by SGS (Société Générale de Surveillance), a company that performs emission measurements and certification.

Before these tests are performed by SGS, Wärtsilä has no information about the level of PM emissions. Besides this, Wärtsilä wants to do research on the effects of modifications to an engine. To have an indication on the emissions, Wärtsilä would like to have a PM measurement device.

This report describes the design process and the development of a measurement device and procedure for particulate matter. It also describes the measurement procedure and validation of the device.

There are a number of measurement methods available for measuring PM emission. The methods can be split into two main categories: real-time and non real-time. Both methods use a sampling system which takes a sample of the exhaust gas en feed it to the measurement device. The real time methods are electronic devices which use light or electronic charge to detect particles in the exhaust sample. The non real-time methods involve filters or impaction plates that capture the particles when they hit the filter or collection place.

Since official measurement methods are performed using the ISO 8178 standard, this method is chosen for the test set-up. Results are expected to be comparable when using the same method. This method is a so called gravimetric method. A pre weighed filter is used to collect particles from diluted exhaust gas or exhaust gas sample which adds mass to the filter. The filter is weighted after the measurement, and therefore a non real-time measurement. Knowing the mass of the PM emission and the power output during the test the PM10 emission can be converted to g/kWh.

The measurement device dimensions are based on the exhaust gas flow of the largest and smallest engine that will be tested on emissions. From these flows a sample is taken and diluted with clean ambient air. When the diluted sample enters the filter, the temperature must be between 42 and 52 °C.

With the sample flow, temperature and an assumed gas composition the energy that the exhaust gas contains can be calculated. This energy is then used to heat up the ambient air, so with a begin temperature and an end temperature, the amount of ambient air needed to cool down a known amount of exhaust gas can be calculated. This is done in a calculation sheet, which was used for selecting the right sized components.

All components needed are listed and a measurement description and validation of the device are made.

At the moment of writing, the measurement set-up is yet to be built. This report includes a detailed description of the measurement procedure, so the measurement can be performed correctly.

The report also includes a validation method to make sure the equipment is working right.
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1. Introduction

In the fourth and last year of Automotive Engineering at the HAN University of Applied Science, students do their thesis. Finding a thesis subject is not an easy task, especially when one student studies in the Automotive Development direction and the other one Automotive Testing. The thesis subject must suit both studies.

Wärtsilä Zwolle offers students the possibility to accomplish their thesis within the company. Wärtsilä also has a suitable objective: develop a measuring device and procedure to measure particulate matter emissions.

Wärtsilä Netherlands (WNL) counts 1500 employees in six locations spread over the Netherlands. One division of WNL is Technical Services located in Zwolle. This division is responsible for support and maintenance of Wärtsilä, Deutz, Stork, Werkspoorn en Bolnes engines. There are over 19,000 engines in field and about 40 different types.

Inland shipping engines must meet certain emission standards. These standards also limit the particulate matter (PM) emissions. To make sure the standards are met, the engines are tested by SGS (Société Générale de Surveillance), a company that performs official emission measurements so Wärtsilä engines can get certification.

Before these tests are performed by SGS, Wärtsilä has no information about the level of PM emissions. Besides this, Wärtsilä wants to do research on the effects of modifications to an engine. To have an indication on the emissions, Wärtsilä would like to have a PM measurement device. The first step of designing such a device is to line up Wärtsilä’s requirements regarding the test set up. With these requirements a test set-up can be designed, which can measure PM emissions for a given range of engines.

This report describes the design process for the development of a particulate matter measurement device. In the first chapter the composition of exhaust gas is described. Chapter two covers the authorities which are involved with PM emission legislation.

In chapter three, the design requirements are listed. In the fourth chapter the design of the measurement device is explained. Chapter five and six describe the measurement method and the validation of the measurement, respectively. The conclusion of the report is found in chapter seven.
2. Emissions

In this chapter a short introduction in diesel emission is given. After this introduction the different authorities in marine legislation are mentioned. This chapter ends with an overview of different methods to measure the particle emission.

2.1. Diesel emission

The last couple of years emissions have become more and more important. Nowadays every engine that produces exhaust gases needs to meet certain emission standards. First emission rules applied to cars and trucks. When they became cleaner, the emissions for ships where limited too. Especially inland waterway vessels have to meet stricter regulations because they operate in populated areas. A typical overview of diesel exhaust gas composition can be seen in Figure 1.

![Figure 1 - exhaust gas composition of industry diesel engine (EURO 3, Truck)](image)

The harmful emissions NO\textsubscript{X}, CO and HC are all gaseous emissions and are measured differently than the solid emission PM.

Soot is produced during combustion, while volatile particles are absorbed and condensed (particulate size and composition will change) as exhaust gas cool down during the travel through the exhaust duct system and measurement system. The amount of absorbed and condensed PM strongly depends on the cooling conditions: temperature, cooling rate, residence time in the conditioning and sampling devices etc.

Ash is a result of fuel; lube oil (additives, impurities) engine wear and corrosion products.
In contrast with Figure 1, PM composition is usually summarized by:

\[ PM = Soot + SOF + IF^2 \]

SOF (soluble organic fraction) refers to organic material and IF (inorganic fraction) refers to volatile and semi-volatile compounds like sulphates and nitrates, ash and water.

**Soot**

The formation of soot in a flame is a highly complex process in which fuel molecules produce particulates very fast. As a result of different combustion strategies and fuel qualities, diesel engines are associated with higher particulate emissions compared to gas engines. In diesel engines, the stratified combustion creates regions in the combustion chamber where air/fuel ratio is lower than the local stoichiometric value (\(\lambda<1\)), which increases formation of particulates. Soot formation is related to diffusion flame process and local air/fuel ratios and temperatures which are affected by parameters like fuel quality, combustion chamber geometry and air conditions, fuel injection parameters etc. The homogenous over stoichiometric air/fuel ratio (\(\lambda>1\)) present in gas engines is associated with less formation of soot.

Soot emissions are an outcome of two competing processes of almost the same magnitudes: production and oxidation, which causes that soot emissions are strongly affected by minor changes in engine parameters.

**Soluble Organic Fraction (SOF)**

The soluble organic fraction is made up mainly from unburned hydrocarbons from lube oil and fuel. In engine tests this fraction is normally measured independently of the particulate measurements as total hydrocarbons (THC). Depending on the particulate measurement method these hydrocarbons will, to different extent, end up as the SOF fraction in particulates.

Both particulate surface growth and particulate formation will take place and are dependent on the vapour pressure of the individual hydrocarbon gaseous compounds and thus the temperature, pressure, residence time, etc (i.e. exhaust duct system and measurement method).

**Inorganic Fraction (IF)**

The inorganic fraction IF of the particulate matter is unique in that way that it is unaffected by engine technology – it is directly dependent on fuel properties. However, it is the most important part of PM from heavy fuel operated engines. IF consists of particles originating from sulphur and ash in the fuel. The most important part of IF is sulphuric acid fraction formed from fuel sulphur.

The sulphuric acid fraction is formed at combustion and in the exhaust duct and particulate measurement system by a chain of reactions:

- Oxidation of fuel sulphur to \(SO_2\)
- Partly conversion of \(SO_2\) to \(SO_3\) (~4-6%)
- Formation of sulphuric acid (\(H_2SO_4\)) from \(SO_3\) and water
- Condensation of sulphuric acid onto existing particulates (surface growth) and formation of new particulates.
2.2. Authorities

There are several authorities which are involved in the legislation for ships. Although they are situated in different parts of the world, the legislation is more or less the same, unlike the automotive industry where it is all different. To show where the different authorities are responsible for, the subjoined overview has been made. The PM emission limits from the EPA, EU, and CCNR, are shown in Graph - 1.

2.2.1. Environmental Protection Agency, EPA

(Inland waterways)

This organization protects the human health and environment in the U.S.A. EPA developed emission legislation which is called fase. The first legislation dates from 1981 with the TIER 0. Today TIER 2 is for USA flagged ships from 01-01-2007. The measurement method they are using is the direct measurement principle, see 2.3.2.3

2.2.2. European Union, EU

(Inland waterways)

The first European legislation to regulate emissions for non-road mobile equipment was introduced in 1997. The regulations where introduced in two stages: Stage I introduced in 1999 and Stage II from 2001 till 2004. Unlike the Stages I and II, the Stage III A standards also cover engines used in inland waterway vessels. Engines are divided into categories based on the displacement per cylinder and the power output. The engine categories and the standards are harmonized with the US standards for marine engines.

Inland waterway vessels are tested using the ISO 8178:2006-1.4

2.2.3. Central Commission for the Navigation of the Rhine, CCNR

(Inland waterways)

The legislation, valid for the Rhine is called CCR and set-up by the CCNR. The emission regulations are similar to those from the EU and the EPA. The CCR2 is valid up to 2012 and has the same PM limits as the EU and the EPA.

The measurement methods which are valid for the CCNR are linked to those described in the ISO8178-1:2006
2.2.4. **International Maritime Organization, IMO**

*Seagoing vessels*

The IMO developed the MARPOL 73/78. This is one of the most important international marine protocols. It is designed to minimize pollution of the seas, including dumping, oil and exhaust pollution. It gives samples for test reports, describes test cycles with weighting factors etc. It also gives formula for calculating the exhaust gas mass flow, which is needed for the determination of the PM emission.

2.2.5. **International Organization for Standardization, ISO**

ISO (International Organization for Standardization) is the world's largest developer and publisher of International Standards. ISO also describes various measurement methods to determine the particle emission.

The ISO 8178 is valid for inland waterway vessels; ISO 9096 applies to stationary sources.


Graph - 1 shows the different emission standards that apply to Wärtsilä’s D620 engine. On the vertical axis PM emission is displayed in g/kWh, and time is displayed horizontally. Before 2012 all emission standards practise a limit of 0.2 g/kWh. Large good transport (trucks) has PM emission levels that are about ten times lower compared to inland shipping. The emission levels for trucks are displayed in red.

### 2.2.6. ISO 8178

ISO 8178 is a standard which describes a particle emission measurement system. SGS, a bureau that is licensed to do official emissions tests and does the tests at Wärtsilä, is also working with a method described in the ISO8178. If Wärtsilä uses the same procedure, the results will be comparable.

Most of the authorities are referring to the ISO8178 norm. Although Wärtsilä is not authorized to do their own certification, it is easier to use a method that is advised by authorities.
2.3. Measurement methods

There are various ways to determine particle emissions. In this chapter different measurement methods are explained. The methods are divided in two types: real time and non real time. Real time measurement methods give real time results. Using non real time measurements methods the results can be determined after the test has finished. These methods are more time consuming and not applicable in transient test situations.

2.3.1. Real-time

Optical

Optical detection methods of particles are based on the blocking or scattering of a light beam by the particles. Figure 2 shows an example of an optical particle detection system. A sample is flowing through a nozzle, passing a laser beam. Particles in the sample scatter the light, which is detected by the array detector. This way size and quantity is measured.

Electrical

In Figure 3 an electrical impactor can be seen. With this method the sample gas is fed through a device where the particle is charged using a corona charger. Then the sample flows through a multiple layer impactor. Each layer consists of a collection plate and a flow control plate. The sample enters the impactor and flows through the flow control plate or nozzle. After passing the nozzle the flow is forced to flow around the collection plate, which is placed at a close distance from the nozzle. Large particles are not capable of following the flow stream lines and impact the collection plate. Smaller particles are able to follow the stream line and are collected on the next, smaller stage. On impact the particles loose their charge, which is detected by a sensitive electrometer, giving real time readout on the quantity and size of particles.
2.3.2. Non real-time

In non real-time the particulate matter is collected on a collection plate of a filter during a given period. After the test the amount of PM is determined gravimetrically or chemically.

**Impactor method**

An impactor (Figure 4) is a device containing multiple cut levels of particle size. Each level consists of a collection plate and a flow control plate. The sample enters the impactor and flows through the flow control plate or nozzle. After passing the nozzle the flow is forced to flow around the collection plate, which is placed at a close distance from the nozzle. Large particles are not capable of following the flow stream lines and impact the collection plate. Smaller particles are able to follow the stream line and are collected on the next, smaller stage.

The collection substrate (plates) can be weighed like the gravimetric method or the amount of particulate matter can be determined chemically.

**Filter method**

This method is based on the gravimetric principle. The sample gas is captured using a nozzle or a probe which is inserted in the exhaust tube. This sample is cooled down to 42 – 52 °C with dilution air (ambient air that is filtered and dried). This mix of exhaust gas and dilution air is then led through a filter, leaving all parts ≥ PM10 caught in the filter. The filter is weighed before and after the test. Knowing the amount of PM in the sample, the total of PM emission of the engine during the test can be calculated.

![Figure 4 - Impactor sampling](image-url)
Hot filter method (ISO9096)

These measurement methods use sample gas that is taken directly from the exhaust and fed through the filter. Figure 5 shows the measurement set-up according to ISO 9096, the filter is located inside the stack, in the filter holder (2). This means the filter temperatures is close to exhaust temperature (e.g. 400 - 450 °C). An advantage of this method is that the exhaust air doesn’t have to be cooled down. The disadvantage is that the filter must be resistant to high temperatures.

Measured results are expected to be lower compared to ISO 8178 due to the absence of condensates caused by the higher gas temperatures.\textsuperscript{6}

![Figure 5 - ISO 9096 filter method]

Key
1 entry nozzle
2 filter holder
3 Pitot tube
4 temperature probe
5 temperature measurement
6 static pressure measurement
7 differential pressure measurement
8 support tube (in-stack device)
9 cooling and drying system
10 suction unit and gas-metering device
11 shut-off valve
12 adjustment valve
13 pump
14 flow meter
15 dry gas volumeter
16 temperature measurement
17 barometer
3. Schedule of requirements

Due to the large range of different measurement methods there is the need to describe the requirements that Wärtsilä demands. With these requirements, the best possible measurement method can be chosen. In this chapter the schedule of requirements is listed. These are formulated in consultation with Wärtsilä Netherlands. This chapter is divided in technical requirements, functional requirements and ISO requirements. The first two sets of requirements include the demands of Wärtsilä. The measurement device needs fulfil the ISO 8178 requirements. Because of copyrights of the ISO documents, it is not possible to include these requirements in this report. The necessary requirements will be mentioned where needed.

3.1. Technical requirements

- Measurement results must be comparable to official test results. The results may be converted using formulas.
- The measured value is allowed to deviate 20% from official test results.
- The measuring equipment must be able to measure PM emissions on the inland shipping engine range Wärtsilä Zwolle offers (500 kW up to 2300 kW).
- The measuring equipment must be able to measure future standards. The equipment must be able to measure PM10 as well as PM2.5.
- The measuring equipment must meet the standards according to the measurement method.
- The equipment may be operated by hand. A automated system is not required.

3.2. Functional requirements

- The measurement equipment must be able to fit in an existing test bed.
- Filters must be easily accessible, making replacing possible.
- The measurement equipment must be installed in a way that official measuring is still possible.
- The measurement equipment must be movable to another test box.
- The measurement may not influence other measurements.
4. Design

Although the most measurement methods are not relevant, even than there are many methods left according ISO 8178. In this chapter the design choices, which are made during the development of the measurement system are clarified. It describes what systems are being used and also what components are selected. In the first paragraph both the sample system and the dilution system are explained and is shown how the choice has been made. The second paragraph gives an overview of the component selection and the relevant calculations which where needed.

4.1. Design choice

The design choices are split in two main components: the sample system and the dilution method. The design choice is the selection of the system lay-out.

4.1.1. Sample system

The sampling system of choice is the gravimetric method. This method is similar to the method that is used for official measurements, so the results are expected to be similar to the official results.

This sampling method is also prescribed by ISO8178. Figure - 6 shows the sample system as displayed in ISO8178 with pump P, two filter holders FH, flow meter FM3 and the flow controller FC3.

![Figure - 6 Sample system](image)

**Modifications**

Figure - 6 shows an example of how a sample system could look like. ISO 8178 states that the system may be altered based on good engineering practice. The system that is designed differs from Figure - 6 by the following items.

The ball valve BV and the flow controller FC3 will not be used. In stead of automated flow control, a manual operated control valve will be used. The variable sampling pump will be replaced by normal pump and a manual valve. This reduces costs, as a flow controller and
adjustable pump are not needed. Because ISO uses steady state test cycles, the need for a variable pump and flow controller is less important. For each test mode the relevant valves should only be adjusted one time. An automated system is too expensive in comparison with the simplicity of the system.

One filter holder FH will be used in stead of two. This is done since only one measurement can be done at the time. Instead of a second filter a plain tube is used to bypass the filter. When the measurement is started, the sample flow is led through the filter.

4.1.2. Dilution method

The dilution method describes the way the exhaust gas is sampled and treated before measuring the particulate emission. ISO 8178 outlines a number of dilution systems, which can all lead to the same results. By using a selection table nine different systems are validated on six different qualities. These qualities are the result of the different requirements that are set in chapter 4. A multiply factor is given to all of these qualities to make a difference between the more and less important qualities. The dilution methods are rated on their qualities by giving them a score from 1 to 4. This is done to prevent a medium score, e.g. when using numbers ranging from 1 to 5, 3 would be a medium score. When using 1 to 4, a design is either just good or just bad, making a clear difference possible. The various qualities and their multiplying factors are described below.

Estimated costs

The score is based on the number of components and the type of components. High costs result in a low score and vice versa. Two is the factor that is chosen for this demand.

Complexity

Based on the number of components and construction, a relatively complex system results in a low score and a simple construction is given a high score. An unnecessary complex system is unwanted, therefore a multiply factor of 3 is applied.

Space

Is the space that is required to house the system. The score is based on the number of parts and the estimated size of the parts. A system with much large parts gets a low score and a small compact system will be rewarded with a high score.

Maintenance

The amount of maintenance a system needs. E.g. sensitive sensors that frequently need calibration or parts that get clogged easily. The more maintenance a system needs, the lower the score.

Transportability

The transportability of a system depends on the number of parts. A system with many parts would be difficult to move around. The same applies to a system with parts that need to be installed in the exhaust permanently. Systems that are easily moved get a high score and vice versa. This feature is a less important issue and therefore the multiply factor is set to 1.

Suitability

The ease of suitability is rewarded with a high score if a system is easy applicable and a low score if the system installation requires large modifications to the set up. Since the system is going to be used on a test bed, this demand is given a factor of two.
The score is multiplied by the multiplying factor and totalled. Table 1 shows the selection table for the dilution method. The best rewarded methods are highlighted.

The nine different methods can be divided in three principles. They are different in how the methods determine how much sample gas is taken. The first two methods are based on isokinetic sampling. The pressure in the exhaust tube is equal to the pressure in the sample probe. This is measured with a pressure transducer. Because the flow is the same and the ratio between the diameter of the exhaust and the probe is known, the sample ratio can be calculated.

The following five methods calculate the amount of flow through the system by comparing data from the exhaust gas analysers.

The last two methods are similar to the first two but now the exhaust flow is calculated based on fuel consumption and CO\textsubscript{2} and O\textsubscript{2} percentage in the flue gas.

![Diagram](image1.png)

Table 1 - Selection table dilution method.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated Costs</th>
<th>Complexity</th>
<th>Space</th>
<th>Maintenance</th>
<th>Transportability</th>
<th>Suitability</th>
<th>TOTAL SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full flow dilution system with flow control and total sampling</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>Partial flow dilution system with flow control and total sampling</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>Partial flow dilution system with flow control and total sampling</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>Partial flow dilution system with flow control and total sampling</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>34</td>
</tr>
<tr>
<td>Partial flow dilution system with flow control and total sampling</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>31</td>
</tr>
</tbody>
</table>

The three methods with the highest score were discussed with our supervisors.

The selected method is “partial flow dilution system with flow control and total sampling” (see Figure 7). The main reason for this choice is that this method is also used for the official measurement by SGS, so the results are expected to be the same. The disadvantages of the 5 methods which use exhaust gas analysers are the higher costs and the extra space they needed. Exhaust gas analysers are expensive and when there are three needed, the total space they needed is large in comparison with the rest of the system.

**Partial flow dilution system with flow control and total sampling**

The system is shown in Figure 7.

Raw exhaust gas is transferred from the exhaust pipe EP to the dilution tunnel DT through the sampling probe SP and the transfer tube TT. The total flow through the tunnel is adjusted with the flow controller FC3 and the sampling pump P of the particulate sampling.

The dilution air flow is controlled by the flow controller FC2, which may use exhaust gas flow or fuel mass flow rate as command signals, for the desired exhaust split.

The sample flow into DT is the difference between the total flow and the dilution air flow. The dilution air flow rate is measured with the flow measurement device FM1 and the total flow rate with the flow measurement device of the particulate sampling system. The dilution ratio is calculated from these two flow rates.
In consultation with Wärtsilä some adjustments are made to the system. Some are added to monitor the systems performance, others are added for convenience.

The partial flow dilution system with isokinetic probe and fractional sampling method has a feature that Wärtsilä would like to have on the measuring device: isokinetic sampling. With isokinetic sampling added to the device it will be possible to measure the exhaust flow. Normally the exhaust flow for measurements like NO\textsubscript{X} is calculated from fuel consumption. Isokinetic sampling combined with the flow meters provides information about the exhaust flow. Wärtsilä would like to use the measured exhaust flow to validate their exhaust flow calculations.

The dilution system will be made as a “partial flow dilution system with flow control and total sampling” system, but the used sampling probe will be the isokinetic type.

In stead of automated flow control, a manual operated control valve will be used. This reduces costs, as a flow controller and electronic control valve are not needed.

To fulfill the ISO standards certain exhaust and dilution air temperatures have to be met. ISO also limits the pressure drop over the system. To make sure the measurement is done correct, temperature and pressure sensors will be added to the system.

The temperature and pressure of the dilution air will be measured right after the control valve CV1 and the temperature and pressure of the sample gas will be measured just before the second control valve.
4.1.3. System schematic

The dilution system and the particulate measurement system combined with the modifications of 4.1.2 results in the following system.

![Figure 8 system schematic](image)

**Figure 8 system schematic**

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPV</td>
<td>By-pass valve</td>
</tr>
<tr>
<td>CV</td>
<td>Control valve</td>
</tr>
<tr>
<td>SP</td>
<td>Sampling probe</td>
</tr>
<tr>
<td>DT</td>
<td>Dilution tunnel</td>
</tr>
<tr>
<td>DPT</td>
<td>Differential pressure transducer</td>
</tr>
<tr>
<td>EP</td>
<td>Exhaust pipe</td>
</tr>
<tr>
<td>FH</td>
<td>Filter holder</td>
</tr>
<tr>
<td>FM</td>
<td>Flow meter</td>
</tr>
<tr>
<td>P</td>
<td>Pump</td>
</tr>
<tr>
<td>P#</td>
<td>Pressure sensor</td>
</tr>
<tr>
<td>T#</td>
<td>Temperature sensor</td>
</tr>
<tr>
<td>TT</td>
<td>Transfer tube</td>
</tr>
</tbody>
</table>
4.2. Component selection

The flow through and the temperature in the filter are restrained by ISO demands. This, together with other ISO demands and data from previous measurements, means that the flow through the system can be calculated. This is needed to determine the flows through the measurement devices. Based on those flows, measurement devices with the right flow rate can be chosen.

4.2.1. Calculations

Determining the mass flow through the system:

The minimum and maximum flow rates through the system are important limits. The temperature and velocity through the filter are ISO regulated. The temperature should be maintained between 42 °C and 52 °C. The velocity through the filter is restricted between 35 cm/s and 100 cm/s. This means that the exhaust flow of a small test engine must be between these limits, but a large engine exhaust flow too. The engine range is set to be between 500 kW and 2300 kW.

To keep the filter face velocity between limits, the sample flow through the system needs to be controlled. The total sample flow depends on the amount and temperature of the sampled exhaust gas. Hotter exhaust gas will need more dilution air to be cooled down; increasing the total sample flow and less hot gas will need less dilution air. If the total dilution flow is out of limits, the exhaust sample flow needs to be adjusted. This is done using different sample probes, as smaller sample probe will sample less exhaust gas and a larger probe will sample more exhaust gas.

The probe size must be matched with the tested engine; since a large engine will produce a large amount of exhaust gas a relatively small amount of sample gas is needed. This requires a small sample probe; a small engine will produce less exhaust gas so a larger probe is needed.

With this information a calculation sheet was made. This enables the authors to vary the different variables that affect the gas flow through the system. The variables that can be altered are ambient temperature, exhaust gas temperature and flow, sample ratio and the desired diluted temperature.

Determining the sample gas flow

To determine the gas flow through the sample system, the calculations starts with the exhaust sample flow.

With the sampling factor set to 1, sampling is isokinetic meaning the sample flow relates to the exhaust flow like the section of the probe relates to the section of stack. With an exhaust mass flow of 17650 kg/h and a probe diameter of 4 mm the sample flow is:

\[ a_{\text{stack}} = \frac{\pi}{4} \cdot d^2 = \frac{\pi}{4} \cdot 0.85^2 = 0.56 m^2 \]

\[ a_{\text{probe}} = \frac{\pi}{4} \cdot d^2 = \frac{\pi}{4} \cdot 0.004^2 = 1.25 \cdot 10^{-5} m^2 \]

\[ \text{Sample ratio} = \frac{0.56}{1.25 \cdot 10^{-5}} = 45156 \]

\[ \text{Sample flow} = \frac{17650}{45156} = 0.39 kg/h \]
Calculating the dilution air flow

In order to calculate the dilution air flow we need to determine how much dilution air is needed to cool the exhaust sample to the desired temperature. Energy is stored in the hot exhaust gas (550°C) and when cooling down (47°C) this energy is released. This energy is used to heat the dilution air. To determine the energy that is released by the exhaust gas, the main components of the exhaust gas need to be calculated separately. For this basic situation the gas is assumed to consist of:

$\begin{align*}
\text{N}_2 & \sim 70\% \sim 0.26 \text{ kg/h} \\
\text{CO}_2 & \sim 14\% \sim 0.06 \text{ kg/h} \\
\text{H}_2\text{O} & \sim 7\% \sim 0.03 \text{ kg/h} \\
\text{O}_2 & \sim 5\% \sim 0.02 \text{ kg/h} \\
\text{Rest} & \sim 4\% \sim 0.02 \text{ kg/h}
\end{align*}$

Total (100%) ~ 0.39 kg/h

Using equation (1) the energy release during the cooling down can be calculated.

$$Q_{1-2} = m \cdot (c_2 \cdot T_2 - c_1 \cdot T_1) \quad (1)$$

The specific heat $c_i$ is calculated and temperature depended for each component. For $\text{N}_2$ this comes to:

$$Q_{1-2} = 0.26 \cdot (1.072 \cdot 320 - 1.04 \cdot 823)$$

$$Q_{1-2} = -133.5 \text{ kJ}$$

This calculation is also performed on the other gases, with corresponding $c$ factors for the different gases. The total amount of energy released is -208.6 kJ. Because the gas is cooled down, energy is taken from the hot exhaust gas. That is the reason for the minus sign.

The total of energy that is released, heats up the dilution air from ambient temperature (20°C) to the desired diluted gas temperature (47°C). Knowing the amount of energy, ambient and end temperature can be used to calculate the amount of dilution air that is needed.

$$Q_{1-2} = \dot{m} \cdot (c_2 \cdot T_2 - c_1 \cdot T_1) \rightarrow \dot{m} = \frac{(c_2 \cdot T_2 - c_1 \cdot T_1)}{Q_{1-2}}$$

$$\dot{m} = \frac{208.6}{(1.006 \cdot 320 - 1.005 \cdot 293)}$$

$$\dot{m} = 7.6 \frac{\text{kg}}{\text{h}}$$
The dilution ratio

The dilution ratio can be determined by dividing the diluted air flow by the sample flow:

\[
\text{Dilution ratio} = \frac{\text{diluted}}{\text{sample}}
\]

\[
\text{Dilution ratio} = \frac{7.6}{0.39}
\]

\[
\text{Dilution ratio} = 19.5
\]

Determining the heat loss over the transfer tube:

ISO regulations demands that the transfer will be insulated with a thermal conductivity ($\lambda$) of 0.05 W/m*K when it is shorter than 1 m. If the tube is longer than 1 m with a maximum of 5 m, the tube must me heated to a wall temperature of 250 °C. The exhaust tube is mounted to the ceiling and the test facility will be installed on the floor. Therefore, the transfer tube will be longer than 1 m and will be heated to the required temperature. To determine the amount of energy that is needed to warm-up the tube from 20 °C to 250°C, the amount of heat loss should be calculated.

The formula being used is:

\[
q_{1-2} = 2 \cdot \pi \cdot \lambda \cdot \Delta T \cdot \left( \frac{1}{\ln \left( \frac{d_o}{d_i} \right)} \right)
\]

(2)

$\lambda$ is the thermal conductivity expressed in W/m*K. For stainless steel the $\lambda$ is 0.51 W/m*K.

Other relevant data:

$\Delta T = 250 - 20 = 230° C$

$d_{\text{outer}} = 25.4\text{mm}$

$d_{\text{inner}} = 21.4\text{mm}$

Filling this data in Equation (2) gives:

\[
q_{1-2} = 2 \cdot \pi \cdot \lambda \cdot \Delta T \cdot \left( \frac{1}{\ln \left( \frac{d_o}{d_i} \right)} \right)
\]

\[
q_{1-2} = 2 \cdot \pi \cdot 0.51 \cdot (523 - 293) \cdot \left( \frac{1}{\ln \left( \frac{25.4}{21.4} \right)} \right)
\]

\[
q_{1-2} = 4300 \frac{W}{m}
\]
This means that a heater must add 4300 $W/m$ to keep the tube at a temperature of 250 °C. This is not in the range of possible values for heat tracing. The heat loss over the transfer tube can be significantly lower when isolating the tube. When isolating the tube with the same isolation as described in the ISO, $\lambda = 0.05 W/mK$, and a thickness of 50 mm, the heat loss will be:

$$q_{1-2} = 2 \cdot \pi \cdot \lambda \cdot \Delta T \cdot \left( \frac{1}{\ln \left( \frac{d_o}{d_i} \right)} \right)$$

$$q_{1-2} = 2 \cdot \pi \cdot 0.05 \cdot (523 - 293) \cdot \left( \frac{1}{\ln \left( \frac{75}{25} \right)} \right)$$

$$q_{1-2} = 66 W/m$$

The needed heat tracer should have a power output of at least 66 $W/m$. This is the worst scenario, because the hot exhaust gas flow will heat the tube from inside out too.

**Determinations of temperature loss in transfer tube**

To determine the temperature loss over the transfer tube when the wall temperature is heated to the recommended 250 °C is done by the following equation:

$$\frac{T_{\text{out}} - T_{\text{in}}}{T_{\text{wall}} - T_{\text{in}}} = 1 - \exp \left( - \frac{k}{\rho \cdot v \cdot c_p} \cdot \frac{4 \cdot l}{d} \right)$$  \hspace{1cm} (3)

Where $\alpha$ is determined with the equation:

$$\alpha = \frac{q}{\pi \cdot d_i \cdot (T_{\text{in}} - T_{\text{wall}})}$$  \hspace{1cm} (4)

$\alpha$ will be:

$$\alpha = \frac{66}{\pi \cdot 0.0225 \cdot (450 - 250)}$$

$$\alpha = 4.67 W/m^2 \cdot K$$

The temperature loss is calculated in excel, at different velocities. This calculation is made for a velocity of 20 $m/s$ and a length of 7 m. The other calculations are displayed in Graph 2.

Filling this data in gives:

$$\frac{T_{\text{out}} - 450}{250 - 450} = 1 - \exp \left( \frac{4.67}{1.29 \cdot 20 \cdot 1030} \cdot \frac{4 \cdot 7}{0.025} \right)$$

$$T_{\text{out}} = 414°C$$
**Conclusion**

As been seen in Graph 2, the temperature of the exhaust gas will drop to the tube diameter temperature if the velocity is $1 \text{ m/s}$. The dilution ratio depends on the temperature of the exhaust gas. So the range of ratio’s can differ strongly, depending on the velocity of the exhaust gas. The tube will be heated up to $250 \degree C$, but the hot exhaust gas will heat the tube even more. Therefore, it is possible that the temperature at the end of the transfer tube will be more than that is calculated and displayed in Graph 2.

**Validation of the filter loading**

The ISO demands a minimum and recommended filter loading according to ISO 8178. For a 70 mm filter this is 0.25 mg minimum and 1.3 mg recommended.

To determine if the exhaust/ probe ratio is in a reasonable range, the calculation of how much dust the filter will have, according to a SGS emission measurement result, is a good reference.

The calculations below are being made with results of the SGS emission measurements of the Wärtsilä Deutz Marine TBD620V8. Diesel engine (number 13207). This is an engine which is measured at standard conditions at 825 kW @ 1800 rpm.

The maximum dust, demand by CCR-2 and NRMM IIIA, is 0.2 g/kWh.
**The calculations:**

From g/kWh to g/h is:

\[
825\text{ kW} \times 0.2 \frac{\text{g}}{\text{kWh}} = 165 \frac{\text{g}}{\text{h}}
\]

The exhaust/probe ratio with diameters of 850 mm and 4 mm is:

\[
\frac{\frac{1}{4} \cdot \pi \cdot 850^3}{\frac{1}{4} \cdot \pi \cdot 4^2} = 45156
\]

The amount of dust that is going through the probe is:

\[
\frac{165 \frac{\text{g}}{\text{h}}}{45156} = 0.0036 \frac{\text{g}}{\text{h}}
\]

The amount of dust that is being sampled during the 10 minutes of sampling:

\[
\frac{0.0036 \frac{\text{g}}{\text{h}}}{6} = 0.0006 \frac{\text{g}}{10 \text{ min}}
\]

This means a filter loading of 0.6 mg. This value is twice the minimum value that ISO prescribes. However, it is still below the recommended filter loading. An option is, to increase the length of the measuring time. If the measuring time is not 10 but 20 minutes, the filter loading will be doubled too. Reaching the recommended filter loading of 1.3 mg.

**4.2.2. Choice of material**

**ISO 8178:2006-1 Paragraph 7.6.4**

All parts of the dilution system and the sampling system from the exhaust pipe up to the filter holder, which are in contact with raw and diluted exhaust gas, shall be designed to minimize deposition or alteration of the particulates. All parts shall be made of electrically conductive materials that do not react with exhaust gas components, and shall be electrically grounded to prevent electrostatic effects.

**ISO 8178:2006-1 Paragraph 17.2.1**

The dilution tunnel
- shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions
- shall be constructed of stainless steel

Because the dilution tunnel should be made of stainless steel, it is decided that the complete system will be made of stainless steel. This material will not react with exhaust gas components and it is a material that is possible to machine and weld. Connectors, filter holder etc. are all components which are also made of stainless steel.

The choice is been made between two of the most common stainless steel grades:
304 and 316. 304 is the one of the most used grades of stainless steel. This material is generally used due to its high resistance against corrosion.

316 is also a grade that is very commonly used, especially in the food industry. While our system will not be used for processing food, we have chosen for this grade. All of our connectors and valves can be made of 306 and not 304. Although 316 is difficult to weld, we have the possibility to use 316L in some cases. The `L' stands for extra low carbon grade. This means it is easier to weld but the material will be slightly weaker.

4.2.3. Pump

As seen in Figure 7 the pump must draw all the air through the system. This means the pump must be a vacuum type pump. Before a choice could be made, the pressure drop of the complete system had to be calculated. The calculation that has been made is a combination of pressure drops which were already known plus calculated pressure drops over several components.

Pressure loss calculations

The pressure loss calculation has been made according a few steps. Some data needed for the calculations is achieved from the calculation sheet; other data is looked up in books etc. The pressure loss calculations are made for the minimum and maximum speed.

Data:
Maximum speed $u$: $20 \text{ m/s}$
Minimum speed $u$: $0.7 \text{ m/s}$
Kinematic viscosity $v$: $1.5 \times 10^{-5} \text{ m}^2/\text{s}$
Density of air $\rho$: $1.29 \text{ kg/m}^3$

First the pressure loss over the transfer tube (TT) is calculated.
Data:
Maximum length $l$: $7 \text{ m}$
Inner diameter $d_i$: $0.0225 \text{ m}$
Resistance coefficient $\xi$ valve $^{10}$: $3$
Resistance coefficient $\xi$ bend $^{10}$: $1$

Step I, Calculation of Reynolds number

$$Re = \frac{\nu \cdot d_i}{v}$$

$$Re = \frac{0.7 \cdot 0.0225}{1.5 \cdot 10^{-5}}$$

$Re_{0.7} = 1050$

$Re_{20} = 30000$
Step II, Calculation of the tube roughness

Relative roughness = \( \frac{e}{d_i} \)

Relative roughness = 0.001
Relative roughness = 0.0225
Relative roughness = 0.044

Where:

\( e \) = Absolute tube roughness

Step III, Calculation of the resistance factor \( \lambda \) [-]

If \( \text{Re} > 2200 \), than \( \lambda \) can be determined from the moody diagram

If \( \text{Re} < 2200 \), than \( \lambda \) can be calculated using the next formula:

\[ \lambda = \frac{64}{\text{Re}} \]  \( \text{(6)} \)

\( \lambda = \frac{64}{1050} \)
\( \lambda_{0.7} = 0.061 \)
\( \lambda_{20} = 0.073 \)

Step IV, Calculation of the resistance coefficient of the tube

\[ \xi_{\text{tube}} = \lambda \frac{l}{d_i} \]  \( \text{(7)} \)

\( \xi_{\text{tube}, 0.7} = 0.061 \times \frac{7}{0.0225} \)
\( \xi_{\text{tube}, 0.7} = 19 \)
\( \xi_{\text{tube}, 20} = 22.7 \)

Step V, Determination and calculation of the other resistance coefficients

7 bends with a \( \xi \) of 1, so the subtotal is 7
1 valves with a \( \xi \) of 3, so the subtotal is also 3

The total of the tube plus the bends and the valves is:

\[ \xi_{\text{total}} = \xi_{\text{tube}} + \xi_{\text{bends}} + \xi_{\text{valves}} \]  \( \text{(8)} \)

\( \xi_{\text{total}, 0.7} = 19 + 7 + 3 = 29 \)
\( \xi_{\text{total}, 20} = 22.7 + 7 + 3 = 32.7 \)

Step VI, Calculation of the pressure loss

\[ \Delta p = \xi_{\text{total}} \frac{u^2}{2} \rho \]  \( \text{(9)} \)

\( \Delta p_{0.7} = 29 \times \frac{0.7^2}{2} \times 1.29 \)
\( \Delta p_{0.7} = 9.17 \text{ Pa} \)
\( \Delta p_{20} = 8437 \text{ Pa} \)
The same steps are made for all the other parts of the system. The complete pressure drop of the system, including the maximum pressure drop of 25 kPa over the filter, pressure drops over the flow meters etc is:

\[ \Delta p_{0.7} = 250.2 \text{mbar} \]
\[ \Delta p_{20} = 317 \text{mbar} \]

In Graph 3 the relation between increasing flow and pressure drop is shown.
BUSCH SECO SV 1010

After a conversation with a representative where the whole system is discussed he advised the Seco SV 1010 pump. The pump is a rotary vane type pump by Busch, type SV 1010 C. This pump is capable of pumping 10 m$^3$/h at an absolute pressure of 800 mbar. Together with this pump, also a filter and a by-pass air inlet breather is supplied. The complete datasheet of the pump is attached in Annex C.

Figure 9 - Busch Seco pump

Graph 4 – Volume flow vs. pressure
4.2.4. Flow meter

First a flow meter of Brooks was chosen. The reason for this was that Wärtsilä Zwolle already has instruments of Brooks. After some research it was clear that this flow meter has a too large pressure drop. Therefore contact is been made with a-b-t. This is a Dutch company which is specialized in flow meters of any kind. They send their representative to Wärtsilä and with him the calculated flows etc were discussed. Because of the required low pressure drop the new flow meter from SIERRA Instruments, the Smart-Trak2, was a flow meter that suits the requirements. A datasheet can be found in 0.

**SIERRA Instruments Smart-Trak2 Model 100**

ISO 8178 regulation:
- Dilution air flow ± 2 % of reading
- Diluted exhaust gas flow ± 2 % of reading

**Reasons for recommendation:**

- This flow meter has an accuracy of ± 1 %, thus will meet the ISO regulations.
- An analogue flow meter will not meet an accuracy of ± 1% of reading
- Software is included for easy use
- Signals can be read out in two ways: RS 232 and 4-20 mA
- The pressure loss over this flow meter is only 34 mbar. Other manufacturers of flow meters have pressure loses around 600 mbar
- Flow meter meets all our specifications
- Parts which are in contact with the flow are made of stainless steel. This meets the ISO regulations
4.2.5. Filter holder

The filter holder is a very important part in the test system set-up. The reason why is chosen for a filter holder from SIERRA Instruments is explained in the points below.

Figure 10 - Filter holder.

ISO 8178 regulation:
- The velocity through the filter should be between 35 cm/s and 100 cm/s.
- Particle filters shall have a minimum diameter of 47 mm. Larger diameter filters are acceptable.
- Filter holder should be made of stainless steel

Reasons for recommendation:
- The velocity through a 47 mm filter would be higher than 100 cm/s, therefore the choice is made for a 70 mm filter and holder
- The filter holder is made of stainless steel
- This filter holder can easily be mounted in-line
- This filter has a quick release system for easy filter change
- The tapered shape means a the velocity will decrease to the required ISO velocity

The development of our own filter holder might be possible, but there are a lot of details that needs attention:
- The two halves should have some sort of tapered shape
- The two separate tapered shapes have to be connected air tight
- Should have a quick release system for the filter change
- The inside of one half should have some sort of underlayment to put the filter on.
- The filter must be positioned in the centre
- The filter must be held in place when the flow is going through the filter
- Must be of stainless steel
- The ends needs connectors for in-line mounting
4.2.6. Small parts

Swagelok

Most of the connectors and tubing which we are using comes from Swagelok. The reason for Swagelok is the easy connection between connector and tube. This means no welding for most of the system. Besides this, most of the connectors should be made of stainless steel and Swagelok has almost every connector in stainless steel.

The delivery time for these parts is not as long as for the bigger components. It is therefore not necessary that these components are ordered at the same time. The complete list of all needed parts is not yet available, so the total cost are not known yet.

RS-online

Most of the electro parts will be ordered at RS-online. This will be parts like thermocouples, mounting parts and potentiometers. As with Swagelok, the ordering time will be days, instead of weeks. Therefore, there is some time to search for all the right parts.

Figure 11 – Stainless steel tubing products

Figure 12 – Fitting and thermocouple
4.2.7. Enclosure

There are no demands regarding to the enclosure of the sampling system. An industrial enclosure is chosen for aesthetic, practical and safety reasons over a self made frame. The enclosure contains the complete sampling system and most of the sensors. During testing a laptop can be installed on top of the enclosure. Because Wärtsilä has already an enclosure from Eldon, the choice to look at Eldon was easy. Before the enclosure was chosen, a 3D model is made of the complete test set-up to look if it was possible to house all parts in a relative small enclosure.

Reasons for recommendation:

This enclosure is one of the simplest enclosures Eldon offers. The enclosure in basic is just the frame, back and a door. This means the sides and internals can be configured to suit our demands.

The options we selected include a screen for a monitor, a keyboard trey, carrier bars to support the pump, and various mounting options.

When mounting all the parts in an enclosed box, the parts will be better protected against dust and will not be damaged so easily.

When mounting everything in one box, the test facility will be better movable.

The enclosure can be locked.

Figure 13 - Example enclosure
4.2.8. Heat tracing

ISO 8178 regulation:
If the tube is 1 m or less in length, it shall be insulated with material with a maximum thermal conductivity of 0.05 W/(m*K) with a radial insulation thickness corresponding to the diameter of the probe. If the tube is longer than 1 m, it shall be insulated and heated to a minimum wall temperature of 523 K (250 °C).

The situation:
The exhaust tube is mounted to the ceiling. The sample probe will take a part of this gas and via a transfer tube this gas will be let into the dilution tunnel and then to the filter. There are two options for placing the filter.
The first option is to place the filter near the exhaust tube. In Box 1, there is a step where there is place to put the complete measurement down, see figure right.
The advantage is that the transfer tube doesn’t have to be heated, just insulated.
The disadvantages are: The needed space for SGS to do their measurement would be gone, the system could only be used in Box 1 and a filter change is not very easy.
The second option is to increase the transfer tube’s length to ground floor. This way, the space at the step is remained, the filter change can be done at the floor and the complete measurement system can be build into one housing, meaning that it is movable. The disadvantage is that the tube needs heating and insulation.

Reasons for recommendation:
The intention was to develop our own heat tracing and insulation unit. After some research the conclusion was that this could be a complex system to develop, and because of the little knowledge we have on this subject we have chosen to ask a company for advice.
Kooy Isolatie has a lot of experience with heat tracing and insulation. We have contacted Leo Altena of Kooy Isolatie by telephone and explained to him our situation. We have sent him a sketch of our situation with all the relevant data and after this, they agreed on building the heat tracing for Wärtsilä.
4.2.9. Balance

Sartorius CPA2P-F

Figure 15 – Sartorius microbalance

ISO 8178 regulation:
The analytical balance used to determine the masses of all filters shall have a precision (standard deviation) of 20 µg and a resolution of 10 µg (1 digit = 10 µg).
For filters less than 70 mm in diameter, the precision and resolution shall be 2 µg and 1 µg, respectively.
To eliminate the effects of static electricity, the filters shall be neutralized prior to weighing, e.g. by a polonium neutralizer or a device of similar effect.

Reasons for recommendation:
The balance meets the ISO requirements for filters less than 70 mm in diameter, with a resolution of 1 µg and a precision of 2 µg. For weighing filters with a diameter of 70 mm and larger, a balance with lower precision and resolution would do. However, future emission regulation may require a balance with a higher resolution and precision.
This balance is specially designed for weighing filters. Many microbalances are unsuitable for this task since the dimension of the weighing pan is in the range of 20-25 mm. Balances with a high resolution and large filter pan are rare. This balance features a weighing pan 125mm in diameter, so larger filters are possible.
The balance features a metal cover, so the effects of draft and static electricity should be minimal.
4.3. 3D Design

Once all the needed components are specified, rough dimensions of every part is known. These dimensions can be used to make a 3D sketch of the measurement device. This way, the dimensions of the enclosure can be estimated and there is the possibility to give all the components a place in the enclosure. The design can be a guideline for the real building of the device later on. In this report, some impressions of the device and sample unit are shown.
Figure 18 Four different sized sample probes

Figure 19 Piping of device

Figure 20 Complete assembled sample unit
### 4.4. Overview of components and delivery time

<table>
<thead>
<tr>
<th>Description</th>
<th>Type</th>
<th>Manufacturer</th>
<th>Delivery time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Components</strong></td>
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</tr>
<tr>
<td>Pump</td>
<td>SV/SD 1010</td>
<td>Busch</td>
<td>In stock</td>
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<td>Filter holder?</td>
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<td>Sierra Instruments</td>
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<td>Whatman</td>
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<td>Kooy Isolatie</td>
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<td>Industrial Enclosure</td>
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<td>Eldon</td>
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<td>Wärtsilä</td>
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<td>Probe</td>
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<td>Wärtsilä</td>
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<td>Wärtsilä</td>
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<td>Flow meter 2</td>
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<td>* Delivery time can be 3 weeks. Extra costs*</td>
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<td>Balance</td>
<td>CPA2P-F</td>
<td>Sartorius</td>
<td>4 weeks</td>
</tr>
</tbody>
</table>
5. Measurement procedure

5.1. Instructions

Before a particulate matter measurement can be carried out, several procedures must be performed. These procedures are needed to operate the system correctly. Otherwise, the measurement could be incorrect or the parts may be damaged. The different procedures which need to be performed are described in this chapter.

**General**

Each time the equipment is being used,

Figure 21 will give a guideline of the steps that have to be performed.

![Flowchart for general use](image-url)
5.1.1. Begin state

Every time BARNIE (the measurement device) will be used, the first thing to do is check if all components are in ‘begin state’. There are some parts which are very expensive and sensitive. If BARNIE is started up wrong, parts maybe damaged.

At the exhaust pipe:

The sample probe unit should be removed out of the exhaust tube after the complete measurement is finished. Therefore, at begin state the sample probe unit should be situated on the base of the measurement platform.

At the enclosure:

Valves:

<table>
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<th>Valve</th>
<th>Open/ close</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow controller 1 (press. air)</td>
<td>Close</td>
</tr>
<tr>
<td>Pressure controller</td>
<td>Close</td>
</tr>
<tr>
<td>Flow controller 2 (upstream pump)</td>
<td>Close</td>
</tr>
<tr>
<td>Ball valve 1 (filter)</td>
<td>Close</td>
</tr>
<tr>
<td>Ball valve 2 (bypass)</td>
<td>Open</td>
</tr>
</tbody>
</table>

Table 2 initial positions valves

See Figure 22 for an overview of the different valves.

Figure 22 Overview and close-up of the valves
Check:

- If the flexible tube is mounted to the enclosure
- If the compressed air is connected to the enclosure
- If power supply is connected

Place the needed filters in a closed box in the same room as the balance at least one hour before the start of the test.
5.1.2. Leak test

The leakage test is needed to validate if the system does not draw false air into the system which can disturb the measurement results. This means that the only two places where gas or air is drawn into the system are at the sample probe and at the entrance for the dilution air.

When there is false air drawn into the system the PM results will be incorrect.

Next to this reason is calibration of the flow meters. If the system is leak tight, both flow meters should read zero.

If one or both flow meters gives another value the system is not leak tight, or the flow meters should be calibrated. If the system is checked and is 100% leak tight, both flow meters should read zero. If one or both flow meters still give another value, than both flow meters should be calibrated and reset to zero.

Leak test procedure:

This test must be performed before the engine is running. Otherwise, all the components are too hot to handle.

Do not turn the heat tracing on already. This can be done after the leak test.

At the exhaust pipe:

- Disconnect the four bolts which hold the flange and remove the complete inner work out of the exhaust pipe
- Be careful with removing, because of the bent at the end of the probe
- Put the complete assembly on the floor of the steps for easy removal and installation of the parts
- Make sure the flexible tube does not make a tight radius. There is a change the flexible tube will crack
- Don’t disconnect anything that is connected to the flange itself
- Disconnect the sample probe at the end of the tube
- Connect the end plug at the same position as that the sample probe did
- Tighten the plug making sure it is leak tight

At the measuring device:

- Close all regulating valves
- Connect all the sensors etc. to the data logger equipment
- Connect a laptop to the data logger equipment and start-up the program to monitor all the data from BARNIE
- First check all the data from the laptop
- All the temperature sensors should give a temperature which is around ambient temperature
- Pressure sensors should be around atmosphere
- Flow meters are displaying zero
- Activate the pump while all the valves are still closed
- Open the bypass, filter and pump valve. The pressure sensor upstream of the pump should give a vacuum. A vacuum of 100 mbar is enough
- If the flow meters are still displaying zero, the system is leak tight

At the start of the test, the valve upstream of the pump (flow controller 2) is closed. Therefore, if the pump is turned on there will be drawn a vacuum between the valve and the
pump. The flow meters will, if the system is leak tight, read out zero. When the two valves at
the filter (bypass and filter valve) are opened and the valve upstream of the pump is opened,
flow meter two will briefly read out another value.

When the three valves are opened, the air that is still present in the system will be drawn
trough flow meter 2 and trough the pump. For this reason flow meter 2 will show, for a brief
moment, not zero but actually a flow. After this moment the flow will decrease and eventually
should read out zero. This means that all the trapped air is out of the system.

**Finishing the test:**

- Turn off the pump
- Gently open the valve which regulates the pressurized air inlet. The
  system was drawn into a slight vacuum. By letting air in, the vacuum is
dissolved
- Close the shut-off valve upstream of the filter holder. Open the valve of the
  bypass
- Shut off the main power

**5.1.3. Flow meter check**

After the system is checked, the flow meters must be checked if they display the same.
For this check, the sample probe must be closed with an end plug. Making sure the
sample probe entrance is air tight. To check both flowmeters, a bit of dilution air must be led
trough the system. The system is leak tight, so they same amount of air that is flowing
trough flow meter one is also flowing trough flowmeter two. Thus flow meter two must
indicate the same flow as flow meter one does. If this is the case, than it is sure that the
difference between the two flowmeters can only come from the exhaust gas that is led
trough the system when it is measuring.
5.1.4. Measurement

Connect the suitable probe. See Table 3.
Connect flange unit to flange adapter at exhaust pipe. See Table 4.

Warm-up:

BARNIE and the engine shall be started and warmed-up until all temperatures and pressures have stabilized at full load and rated speed. The warm-up time will be 1 hour at 100% load. This is a value that is used for engines at Wärtsilä Zwolle.

Filter preparation:

At least one hour before the test, each filter shall be placed in the same room as the balance does. The filters shall be placed in a closed box. Before each test the used filter should be measured. If the filter is not used within 4 hours of its weighing, the filter must be weighed again.

Adjustment of the dilution ratio:

BARNIE shall be started and run on bypass. The dilution air shall be set to obtain a maximum filter face temperature of 325 K (52 °C) at each mode. The total dilution ratio shall not be less than 4.

Sampling:

According the ISO norm, sampling shall take place as late as possible within each mode. The sampling time per mode shall be at least 20 seconds, but for the required filter loading a measuring time of 10 minutes is advised.

Measurement advices:

There has been carried out research to the effects of different measurement methods etc. According a Wärtsilä PowerPoint presentation, number DBAA670037 made by Jyrki Ristimäki, there are several factors that can influence the measurement results.

The subjoined text is directly copied out of this presentation;

To obtain repeatable, reproducible and low PM results:

- 2006 version of the ISO 8178 standard should be used
- Use as high dilution ratio as possible
- Target the filter loading recommended by the standard
- Exceeding the recommendation will cause increase in result
- Filter face velocity
- Use as high filter face velocity as possible (and approved by standard)
Installation:

- Complete sample probe unit should be situated on the ground of the measurement platform.
- Choose the suitable probe according engine power output. See Table 3.
- Mount this probe and tighten it according to Table 4 - Recommended torque.
- Mount the complete sample probe unit to the exhaust flange and tighten the bolts according to Table 4.
- Be careful with inserting the probe into the exhaust, because of the bend and the thin inlet of the probe.

<table>
<thead>
<tr>
<th>Power output engine [kW]</th>
<th>Probe diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 – 950</td>
<td>25</td>
</tr>
<tr>
<td>950 – 1400</td>
<td>18</td>
</tr>
<tr>
<td>1400 – 1850</td>
<td>11</td>
</tr>
<tr>
<td>1850 – 2300</td>
<td>4</td>
</tr>
</tbody>
</table>

If power output is between to ranges, always chose smaller probe diameter

Table 3 - Matching probe diameter to power output

<table>
<thead>
<tr>
<th>Part</th>
<th>Torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample probe</td>
<td>25</td>
</tr>
<tr>
<td>4 Flange bolts</td>
<td>25</td>
</tr>
<tr>
<td>Swagelok connectors</td>
<td>See Swagelok guide</td>
</tr>
</tbody>
</table>

Table 4 - Recommended torque
Warm-up engine and BARNIE

Adjust the filter temperature and the dilution ratio

Open filter valve and close bypass valve at the same time

After 10 min. close filter valve and open bypass valve at the same time

Remove the filter from the filter holder

Place the filter in the holder

After this period, weigh the filter. Record the gross mass

Calculate the emission using the datasheet

Begin with next measurement

Figure 23 – measurement flow chart
5.1.5. **Ending procedure**

- Shut off pump
- Position valves in the correct position

<table>
<thead>
<tr>
<th>Valve</th>
<th>Open/ close</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow controller 1 (press. air)</td>
<td>Close</td>
</tr>
<tr>
<td>Pressure controller</td>
<td>Close</td>
</tr>
<tr>
<td>Flow controller 2 (upstream pump)</td>
<td>Close</td>
</tr>
<tr>
<td>Ball valve 1 (filter)</td>
<td>Close</td>
</tr>
<tr>
<td>Ball valve 2 (bypass)</td>
<td>Close</td>
</tr>
</tbody>
</table>

*Table 5 – initial valve positions*

- Disconnect all temperature and pressure sensors
- Remove the sample probe unit from exhaust tube
- Disconnect the sample probe
## 5.2. Datasheet

### Datasheet Particulate Matter

<table>
<thead>
<tr>
<th>Engine</th>
<th>Type</th>
<th>TBD620V8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>13207</td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>Testbed Box 1, Zwolle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Type</th>
<th>LFO Light Fuel Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Identification code</td>
<td>08-006506-0-RDAM(1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>Cycle</th>
<th>Date</th>
<th>Start [hh:mm]</th>
<th>End [hh:mm]</th>
<th>Measured time [min]</th>
<th>Cycle E3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>11-24-2009</td>
<td>14:09</td>
<td>14:19</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 : 100%</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2 : 75%</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3 : 50%</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4 : 25%</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5 : 10%</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engine conditions</th>
<th>Load [kW]</th>
<th>825</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of revolutions [rpm]</td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td>Dry flue gas flow [kg/h]</td>
<td>634</td>
</tr>
<tr>
<td></td>
<td>Fuel consumption [kg/h]</td>
<td>176</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ambient air</th>
<th>Atmospheric pressure [mbar]</th>
<th>1025</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature [°C]</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Relative humidity [%]</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Absolute humidity [vol%]</td>
<td>0,98</td>
</tr>
<tr>
<td></td>
<td>Absolute humidity [g/kg]</td>
<td>6,18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control data</th>
<th>Dilution air temp [°C]</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exhaust gas temp at inlet [°C]</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>Temp before filter [°C]</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Flow meter 1 Dilution air [kg/h]</td>
<td>4,8</td>
</tr>
<tr>
<td></td>
<td>Flow meter 2 Diluted air [kg/h]</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Sample flow [kg/h]</td>
<td>0,2</td>
</tr>
<tr>
<td></td>
<td>Dilution factor [ - ]</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Pressure before filter [mbar]</td>
<td>1025</td>
</tr>
<tr>
<td></td>
<td>Pressure after filter [mbar]</td>
<td>1020</td>
</tr>
</tbody>
</table>

| Dust measurement | Tare filter weight [mg] | 0,25 |
|                 | Gross filter weight [mg] | 5 |
|                 | Sample factor [ - ] | 3170 |
|                 | Dust [g/kWh] | 0,11 |

Figure 24 – calculation sheet
6. Conclusion

The subject of the thesis was to development of a device capable of measuring PM10 in marine diesel emissions.

In order to accomplish this, various measurement methods were reviewed. Of these methods, the filter method according to ISO 8178 was selected as best suited for this application. The main reasons for this choice are that all involved authorities support this method and so does SGS who performs the official measurements. By choosing a similar measurement set-up, the results are expected to be similar to those of SGS. The ISO 8178 is a gravimetrical filter method, which means that the particles are filtered from the exhaust sample. This ads mass to the filter, the difference in filter mass before and after the measurement is the mass of particles. This then can be calculated to PM emission in g/kWh.

The next step was to select the components. To do this, the gas flow through the measurement set-up was calculated. This was necessary to select the right size tubing and flow meters. The gas flow was calculated from the filter towards the sample probe, i.e. in opposite direction of the normal gas flow through the system. This calculation is based on the chemical composition and temperature of the exhaust gas. For a given sample the needed amount of dilution air can be calculated with the gas sample temperature and the desired diluted air temperature.

Knowing the gas flow, the flow meters and pump where selected. The dimensions of valves and tubing also depend on the gas flow. All components needed are listed in this report and a reason for recommendation is given in this report.

At the moment of writing, the measurement set-up is yet to be built. This report includes a detailed description of the measurement procedure, so the measurement can be performed correctly. The measurement procedure also includes a validation method to make sure the equipment is working right. Recommendations for correct installation and operation are mentioned in chapter 7.

7. Recommendations

If the complete measurement device is going to be build, there are some recommendations for building the device and for the measurement of the PM.

Before ordering the flowmeters, the position must be known. If the flowmeter is positioned vertical and not horizontal, as seen in Figure 19, this should be reported to SIERRA Instruments. The calibration at SIERRA Instruments will be performed in the same way as the flowmeter will be mounted inside the enclosure for correct measuring.

The recommended filter loading of 1,3 mg is important for an accurate weighing. If the recommended loading is not reached, the measuring time can be extended. If the filter loading is higher than the recommended filter loading, the measuring time should be shortened. The datasheet is equipped with this possibility.

It is recommended to equip the enclosure with lifting rings. It makes the device easier to move and there is the possibility of lifting the device to a higher level.
8. Bibliography

1 Dieter Rothe, Physikalische und chemische Charakterisierung der Rußpartikelemission von Nutzfahrzeugdieselmotoren und Methoden zur Emissionsminderung, Munich (2005)

2 Göran Hellén, Particulate emissions – Definitions and optimization targets, and ways to reduce them, Wärtsilä DOC-ID DAAB640398, chapter 4 (2006)

3 URL: http://www.epa.gov (date visited: November 2009)

4 URL: http://europa.eu/index_nl.htm (date visited: November 2009)

5 URL: http://www.iso.org/iso/about.htm (date visited: December 2009)


7 Ir. A.J.M. van Kimmenaede, Warmteleer voor technici (2004), 22

8 Bosch Autotechnisch zakboek, fourth print (2002), 186

9 L.C. van den Boom, Tabellen en Formules (2000), 263

10 L.C. van den Boom, Tabellen en Formules (2000), 266

11 L.C. van den Boom, Tabellen en Formules (2000), 268
Formulas:

- \[ Q_{1-2} = m \cdot (c_v \cdot T_2 - c_i \cdot T_1) \] Kimmenaede, A.J.M. van, Warmteleer voor Technici 2004, 22

- \[ q_{1-2} = 2 \cdot \pi \cdot \lambda \cdot \Delta T \cdot \left( \frac{1}{\ln \left( \frac{d_o}{d_i} \right)} \right) \] Excel datasheet of Wärtsilä Zwolle, Heat Loss, 2009

- \[ \frac{T_{\text{out}} - T_{\text{in}}}{T_{\text{wall}} - T_{\text{in}}} = 1 - \exp \left( - \frac{\alpha}{\rho \cdot v \cdot c_p} \cdot \frac{4 \cdot l}{d} \right) \] Lienhard, J IV and V, A Heat Transfer Textbook. Version 1.24. Cambridge USA: Phlogiston Press 2006, 369

- \[ \alpha = \frac{q}{\pi \cdot d_i \cdot (T_{\text{in}} - T_{\text{wall}})} \] Lienhard, J IV and V, A Heat Transfer Textbook. Version 1.24. Cambridge USA: Phlogiston Press 2006, 379

- \[ \text{Re} = \frac{v \cdot d_i}{v} \] Boom, L.C. van den, Tabellen en Formules 2000, 263

- \[ \lambda = \frac{64}{\text{Re}} \] Boom, L.C. van den, Tabellen en Formules 2000, 264

- \[ \xi_{\text{tube}} = \lambda \cdot \frac{l}{d_i} \] Boom, L.C. van den, Tabellen en Formules 2000, 264

- \[ \xi_{\text{total}} = \xi_{\text{tube}} + \xi_{\text{bends}} + \xi_{\text{valves}} \] Boom, L.C. van den, Tabellen en Formules 2000, 264

- \[ \Delta p = \xi_{\text{total}} \cdot \frac{v^2}{2} \cdot \rho \] Boom, L.C. van den, Tabellen en Formules 2000, 264
## Annex A Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$, $a_{stack}$</td>
<td>Cross sectional area, cross sectional area of exhaust tube, cross sectional area of probe</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$a_{probe}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c$, $c_p$</td>
<td>Specific heat, specific heat at constant pressure</td>
<td>$[J/kg*K]$</td>
</tr>
<tr>
<td>$d$, $d_i$, $d_o$</td>
<td>Diameter; inner diameter, outer diameter</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$l$</td>
<td>Length</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass flow rate</td>
<td>$[kg/h]$, $[l/min]$</td>
</tr>
<tr>
<td>$P$</td>
<td>Power</td>
<td>$[W]$</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
<td>$[mbar]$</td>
</tr>
<tr>
<td>$q$</td>
<td>Heat loss</td>
<td>$[W/m]$</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
<td>[-]</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>$[^\circ C]$, $[K]$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Local heat transfer coefficient</td>
<td>$[W/m^2*K]$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Resistance coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>Pressure drop</td>
<td>$[mbar]$</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference</td>
<td>$[^\circ C]$, $[K]$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Absolute tube roughness</td>
<td>[-]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Velocity</td>
<td>$[m/s]$</td>
</tr>
</tbody>
</table>

Greek symbols:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Local heat transfer coefficient</td>
<td>$[W/m^2*K]$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Resistance coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>Pressure drop</td>
<td>$[mbar]$</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference</td>
<td>$[^\circ C]$, $[K]$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Absolute tube roughness</td>
<td>[-]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Velocity</td>
<td>$[m/s]$</td>
</tr>
</tbody>
</table>
Annex B Technical drawings

The three small pipes are 1” stainless steel pipes. These pipes have been used for the rest of the design.
Annex C Busch pump datasheet

Seco
SV/SD 1010 - 1040 C

Seco SV rotary vane vacuum pumps compress totally oil-free with self-lubricating vanes made of special carbon. These vacuum generators are ideal for industrial processes in which a totally oil-free compression is required.

A compressor version of the Seco pump is also available (Type SD).

Economical and environmentally friendly
Seco vacuum pumps stand out due to their low energy consumption. They are quiet and environmentally friendly because no lubrication fluids are required for compression.

Compact design
Compact pump dimensions are guaranteed by the motor being directly flange-mounted to the pump casing.

Low in maintenance
Robust design. Lifetime lubricated bearings and the surface-cooled driving motor guarantee long service life of this pump.

Les pompes à vide à palettes Seco SV fonctionnent à l’absolument sans huile grâce à l’utilisation de palier auto-lubrifant en carbone. Elles sont spécialement conçues pour toutes les applications qui nécessitent un fonctionnement absolument sans huile. La pompe est aussi disponible en version pression (SD).

Economique et écologique
Grâce à une faible consommation d’énergie, un faible niveau sonore et un fonctionnement totalement exempt d’huile.

Compact
Grâce à un corps de pompe fixé directement sur l’arbre moteur. La nouvelle Seco SV se distingue par une ligne compacte et épurée.

Entretien facile
Grâce à une construction robuste, au graissage à vie des roulements et au moteur électrique à ventilation externe, qui garantissent une longue durée de fonctionnement de la pompe.
Trocken laufende Drehschieber-Pumpen
Dry running rotary vane pumps
Pompes sèches à palettes rotatives

Funktionssprinzip
Principle of operation
Principe de fonctionnement

Funktionssprinzip und Arbeitsweise
Ein leistungsstarker Lüfter sorgt für gute Wärmeabfuhr an Motor und Pumpenkörper.

Zubehör
- Ansaugfilter zum Vorschalten an den integrierten Feinfilter bei hohem Staubanfall.
- Schlauchmipppel für die Ansaugung und/oder den Auslass
- Rückschlagventil zum Einbau in die Saug- oder Druckleitung, um eine irrürmische Be- oder Entlüftung des Rezipienten zu verhindern
- Vakuumreglerventil zum Einstellen eines bestimmten Ansaugdruckes bei Saugbetrieb

Principle of operation
Seco vacuum pumps operate according to the proven rotary vane prin- ciple without using additional sealing fluids for lubrication. These pumps compress almost without pulsation and completely oil-free.
An efficient fan guarantees good heat removal from motor and pump.

Accessories
- Inlet filter to be coupled to the integrated fine filter in case of applications in extremely dusty environment
- Hose nipple for the inlet and/ or the outlet
- Non-return valve restricts air admittance into vacuum chamber
- Vacuum relief valve to adjust inlet pressure in vacuum applications

Principe de fonctionnement
Les pompes Seco travaillent selon le principe éprouvé des pompes rota-
tives à palettes et sans aucune lub-
rification. La compression s’effectue presque sans pulsations et 100% sans huile.
Un ventilateur efficace se charge de la dissipation de la chaleur du moteur et de la pompe.

Accessoires
- Filtre d’aspiration à monter en amont du filtre fin intégré, en cas d’absorption importante de poussières
- Raccord tuyau pour l’aspiration et/ou l’échappement
- clapet anti-retour à monter dans la conduite d’aspiration ou de refolement, pour éviter une remise de l’enceinte à la pression atmosphérique
- Soupa de réglage du vide, pour régler la pression d’aspiration
The displacement curves are valid for air at 20 °C. Tolerance: ± 10%.

Les courbes sont données pour de l'air à 20 °C. Tolerance: ± 10%.

Zubehör
Accessoires
Accessoires

Luftpfilter
Inlet filter
Filtre d’aspiration
Schlauchhülsen
Hose flanges
Raccord tuyau
Rückwärtsventil
Non-return valve
Clapet anti-retour

Vakuumregulierventil
Vacuum relief valve
Soupape de réglage du vide
(nur SV)
(only SV)
(seulement SV)

Secco 1010 C
Secco 1016 C
Secco 1025 C
Secco 1040 C

0945 501 914
0945 501 914
0945 501 916
0945 501 916
0574 000 100
0574 000 100
0574 000 101
0574 000 101
0947 531 900
0947 531 900
0947 504 331
0947 504 331
0916 530 022
0916 530 022
0916 530 022
0916 530 022

* auf Anfrage mit einem Überdruck bis zu +1 bar erhältlich
* on request, pressure up to +1 bar
* sur demande, pression de refolement jusqu’à +1 bar
Trocken laufende Drehschieber-Pumpen
Dry running rotary vane pumps
Pompes sèches à palettes rotatives

Abmessungen
Dimensions

Abmessungen Dimensions

<table>
<thead>
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<th></th>
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<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
<th>K</th>
<th>M</th>
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<td>239</td>
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<td>250</td>
<td>-</td>
<td>G 1/2</td>
</tr>
<tr>
<td>SD 1010 C</td>
<td>413</td>
<td>239</td>
<td>224</td>
<td>199</td>
<td>125</td>
<td>157</td>
<td>202</td>
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<td>303</td>
<td>75</td>
<td>250</td>
<td>461</td>
<td>G 1/2</td>
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<tr>
<td>SV 1016 C</td>
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<td>125</td>
<td>157</td>
<td>202</td>
<td>100</td>
<td>319</td>
<td>75</td>
<td>256</td>
<td>-</td>
<td>G 1/2</td>
</tr>
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<td>239</td>
<td>224</td>
<td>199</td>
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<td>157</td>
<td>202</td>
<td>100</td>
<td>319</td>
<td>75</td>
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<td>125</td>
<td>157</td>
<td>202</td>
<td>100</td>
<td>344</td>
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<td>-</td>
<td>G 3/4</td>
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<td>246</td>
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<td>383</td>
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<td>-</td>
<td>G 3/4</td>
</tr>
<tr>
<td>SD 1040 C</td>
<td>546</td>
<td>251</td>
<td>246</td>
<td>223</td>
<td>208</td>
<td>240</td>
<td>220</td>
<td>154</td>
<td>383</td>
<td>80</td>
<td>289</td>
<td>592</td>
<td>G 3/4</td>
</tr>
</tbody>
</table>

Busch – wereldwijd im Kreislauf der Industrie
Busch – all over the world in industry
Busch – au coeur de l’industrie dans le monde entier

Dr.-Ing. K. Busch GmbH
Schauinslandstraße 1 D 79689 Maulburg
Phone +49 (0)7622 681-0 Telex 49 07622 5484 www.busch.de
### Technische Daten

#### Technical data

#### Spécifications techniques

<table>
<thead>
<tr>
<th></th>
<th>Secco 1010 C</th>
<th>Secco 1016 C</th>
<th>Secco 1025 C</th>
<th>Secco 1040 C</th>
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<tr>
<td></td>
<td>SV</td>
<td>SD</td>
<td>SV</td>
<td>SD</td>
</tr>
<tr>
<td>Suction capacity</td>
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<td>16</td>
<td>25</td>
<td>40</td>
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<tr>
<td>Vacuum</td>
<td>12</td>
<td>19</td>
<td>30</td>
<td>48</td>
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<td>Debit nominal</td>
<td>150</td>
<td>-</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>Overpressure</td>
<td>-</td>
<td>+0.6</td>
<td>-</td>
<td>+0.6</td>
</tr>
<tr>
<td>Motor speed</td>
<td>0.37</td>
<td>0.35</td>
<td>0.9</td>
<td>1.1*</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>0.37</td>
<td>0.35</td>
<td>0.9</td>
<td>1.1*</td>
</tr>
<tr>
<td>Nominal motor rating</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Motor rpm</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Noise level (DIN 45635)</td>
<td>60</td>
<td>61</td>
<td>62</td>
<td>66</td>
</tr>
<tr>
<td>Power level (DIN 45635)</td>
<td>62</td>
<td>63</td>
<td>66</td>
<td>70</td>
</tr>
<tr>
<td>Weight approx.</td>
<td>21</td>
<td>25</td>
<td>31</td>
<td>38</td>
</tr>
</tbody>
</table>

* Option auf Anfrage * Option on request ** Option sur demande
Annex D  SIERRA Instruments flow meter

Next Generation
High Performance Digital Gas
Mass Flow Meters and Controllers

Features

- Measure and control gas mass flow rates up to 1000 slpm
- Ideal for OEM, Industry or Research Applications
- True linear performance provides high accuracy and great flexibility in multiple gases
- With Dial-A-Gas® Technology, you select from up to ten pre-programmed gases or substitute your own
- Unique Pilot Module (mounted or hand-held) lets you view and change critical control functions including:
  - Gas type
  - Setpoint value
  - Zero value
  - Span value
  - Engineering units
  - Output signals
  - Full scale adjust
- All control functions are also available from your PC or workstation via supplied Smart-Trak 2 software
- 316 Stainless steel construction
- Choose from multiple analog or digital signals including: RS-232, RS-485, 4-20mA, 0-5, 1-5, 0-10 VDC
- Small footprint and great flexibility facilitates replacement of older MFM or MFC
- Factory calibration done with primary standards directly traceable to NIST
- Proprietary frictionless-hopping direct-acting control valve technology
- Add Compod™ for MODBUS RTU networking capability
- Single-sided 24 VDC input power reduces installation cost and complexity

Description

Smart-Trak® 2 is the next generation of Sierra's flagship Model 100. Building upon the unprecedented performance, user-friendliness and flexibility end-users have come to expect with the original Smart-Trak, Smart Trak 2 gives users the world's most linear sensor, smoother valve performance, more robust electronics and even more control over a wide range of functions. The result is a series of mass flow meters and controllers that demonstrate premium flow instrumentation doesn't have to be difficult to use.

Smart-Trak 2 is designed so that the physics are correct. Excellent performance results from a patented, inherently linear Laminar Flow Element (LFE) design, advanced platinum sensor technology, and Sierra's proprietary frictionless-hopping control valve.

Smart-Trak 2 is available with an innovative and user-friendly Pilot Module, a front-mounted or hand-held control device that allows users to “Dial-A-Gas®”, change flow rate, modify engineering units or re-configure the instrument. With the Pilot Module, the user can set zero, span and full scale for each of 10 different gases independently to accommodate unexpected application or system design changes.

With the addition of Sierra's Compod™, Smart Trak 2 transforms into a fully network-enabled MODBUS RTU device.

Just like the award-winning original, Smart-Trak 2 delivers performance, flexibility and value.

www.sierrainstruments.com
Performance Specifications

- **Accuracy**: Standard: ± 1.0 % of full scale including linearity at operating conditions (± 2% of full scale for 100M from 20-1000 slpm)
  
- **Dial-A-Gas**: ± 1.0 % of full scale in all 10 standard gases (see chart below)
  
- **Repeatability**: ± 0.2% of full scale
  
- **Temperature Coefficient**: ± 0.020% of full scale per °F (± 0.05% of full scale per °C), or better
  
- **Pressure Coefficient**: ± 0.01% of full scale per psi (± 0.15% of full scale per bar), or better
  
- **Response Time**: 300 milliseconds time constant; 2 seconds (typical) to within ± 2% of final value (includes settling time), Faster or slower available upon request. Valve response can be tuned on site using supplied software.

Operating Specifications

- **Mass Flow Rates**: 100L Low Flow, 0-100 sccm to 0-50 slpm
  
- **100M Medium Flow**: 0-20 to 0-100 slpm (up to 400 slpm available—Consult Factory)
  
- **100H High Flow**: 0-400 to 0-1000 slpm (higher flows available—Consult Factory)
  
- **Flow ranges specified are for an equivalent flow of nitrogen at 760 mm Hg and 21°C (70°F); other ranges in other units are available (e.g., NTPM, SCFM, NAFM, LPM).**
  
- For measuring or controlling flows below 5 sccm, please consult Siena's Model 101 Micro-Trak®. For measuring or controlling flows above 1000 slpm, please consult Siena's Model 180 Max-Trak®

Gases

All clean gases including corrosives & toxics; specify when ordering

The following ten gases make up the Dial-A-Gas® feature of every Smart-Trak® instrument; up to nine alternate gases may be substituted.

<table>
<thead>
<tr>
<th>Gases</th>
<th>Max Flow Rate (slpm)</th>
<th>Max Flow Rate (scm)</th>
<th>Max Flow Rate (L/min)</th>
<th>Max Flow Rate (L/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>50</td>
<td>50</td>
<td>20</td>
<td>1800</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>72.5</td>
<td>72.5</td>
<td>24</td>
<td>1800</td>
</tr>
<tr>
<td>Carbon Dioxide (CO2)</td>
<td>30</td>
<td>30</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>50</td>
<td>50</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Methane (CH4)</td>
<td>36</td>
<td>36</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>73.7</td>
<td>73.7</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Hydrogen (H2)</td>
<td>50</td>
<td>50</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Oxygen (O2)</td>
<td>50</td>
<td>50</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Nitrogen (N2)</td>
<td>50</td>
<td>50</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Nitrous Oxide (N2O)</td>
<td>35.5</td>
<td>27</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

**Operating Specifications (cont.)**

- **Gas & Ambient Temperature**: 32 to 122°F (0 to 50°C)

- **Gas Pressure**: 500 psig (34.5 barg) maximum, burst tested to 750 psig (52 barg)

- **Leak Integrity**: 5 x 10^-9 atm cc/sec of helium or better

- **Power Requirements**: Ripple should not exceed 100 mV peak-to-peak
  
- For Mass Flow Meters: 15-24 VDC ± 10% (230 mA, regulated)
  
- For Mass Flow Controllers: 0-10 VDC ± 10% (500 mA, regulated)
  
- 4-20 mA ± 10% (1200 mA, regulated)

- **Control Range For Controllers**: 2-100% of full scale flow, automatic shut-off at 1.9%.

- **Output Signal**
  
  **Analog**
  
  - Linear 4-20 mA, 100 ohms minimum loop resistance
  
  - One of the following (user selectable):
    
    - Linear 0-5 VDC, 100 ohms minimum load resistance
    
    - Linear 0-10 VDC, 100 ohms minimum load resistance
    
    - Linear 1-5 VDC, 1000 ohms minimum load resistance

- **Digital**
  
  - RS-232 standard, RS-485 optional
  
  - Pilot Module Display optional

- **Command Signal**

  **Analog (Choice of one):**
  
  - Linear 4-20 mA, 0-5 VDC, 0-10 VDC, 1-5 VDC

- **Digital**
  
  - RS-232 standard, RS-485 optional
  
  - Pilot Module Display optional

- **Wetted Material**

  316 stainless steel or equivalent; 316 stainless steel, Viton® O-rings and valve seat standard; other elastomers are available (consult factory)

Optional Compo
d

- **RS-485 communication with MODBUS RTU protocol allows digital multi-drop networks**

- Available with optional LCD display

- Internal gas flow totalizer with adjustable pulse output

- Two digital outputs and 1 analog input can be configured by user with MODBUS or included software for a wide variety of process control tasks
### Operating Specifications

#### Pressure Drop across a Meter

Pressure must be above the values in the table below. Note that pressure increases with flow rate.

<table>
<thead>
<tr>
<th>Flow Rate (slpm)</th>
<th>Pressure Drop in PSI (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Flow (¾ inch fittings)</td>
</tr>
<tr>
<td></td>
<td>(Standard)</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>0.1</td>
<td>0.36 (24.5)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.36 (24.5)</td>
</tr>
<tr>
<td>1</td>
<td>0.37 (25.4)</td>
</tr>
<tr>
<td>10</td>
<td>0.46 (31.7)</td>
</tr>
<tr>
<td>20</td>
<td>0.66 (45.7)</td>
</tr>
<tr>
<td>30</td>
<td>N/A</td>
</tr>
<tr>
<td>40</td>
<td>N/A</td>
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<tr>
<td>50</td>
<td>N/A</td>
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<tr>
<td>100</td>
<td>N/A</td>
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<tr>
<td>150</td>
<td>N/A</td>
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<td>200</td>
<td>N/A</td>
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<tr>
<td>250</td>
<td>N/A</td>
</tr>
<tr>
<td>300</td>
<td>N/A</td>
</tr>
<tr>
<td>350</td>
<td>N/A</td>
</tr>
<tr>
<td>400</td>
<td>N/A</td>
</tr>
<tr>
<td>450</td>
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</tr>
<tr>
<td>550</td>
<td>N/A</td>
</tr>
<tr>
<td>600</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Note: Test at 2°C, with ambient pressure.

**Larger fittings recommended for these flow rates to avoid over-pressures.

#### Differential Pressure Requirement for Controllers (Lower or higher available upon request)

Minimum: See chart below. Note that required pressure increases with flow rate.

<table>
<thead>
<tr>
<th>Flow Rate (slpm)</th>
<th>Pressure Drop in PSI (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Flow (¾ inch fittings)</td>
</tr>
<tr>
<td></td>
<td>(Standard)</td>
</tr>
<tr>
<td>0.1</td>
<td>1.00 (68)</td>
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<tr>
<td>0.5</td>
<td>1.28 (87)</td>
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<tr>
<td>1</td>
<td>1.5 (102)</td>
</tr>
<tr>
<td>10</td>
<td>6.0 (408)</td>
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<td>20</td>
<td>6.6 (449)</td>
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<td>30</td>
<td>9.4 (639)</td>
</tr>
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<td>40</td>
<td>12.2 (835)</td>
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<tr>
<td>50</td>
<td>15.0 (1026)</td>
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<tr>
<td>100</td>
<td>N/A</td>
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<tr>
<td>150</td>
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<td>200</td>
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<tr>
<td>250</td>
<td>N/A</td>
</tr>
<tr>
<td>300</td>
<td>N/A</td>
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<tr>
<td>350</td>
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<tr>
<td>400</td>
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</tr>
<tr>
<td>450</td>
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</tr>
<tr>
<td>550</td>
<td>N/A</td>
</tr>
<tr>
<td>600</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Note: Test at 2°C, with ambient pressure.

**Larger fittings recommended for these flow rates to avoid over-pressures.
### Physical Dimensions

All dimensions are in inches with mm in brackets. Certified drawings are available on request.

#### M100L & C100L Front View

#### M100L & C100L Inlet View

#### M100M Front View

#### M100M Inlet View

#### M100L & C100L Bottom View

#### C100M Front View

#### C100M Inlet View

#### M100M & C100M Bottom View

---

<table>
<thead>
<tr>
<th>Fittings</th>
<th>C100/L/M100L</th>
<th>C100M</th>
<th>M100M</th>
<th>M100H</th>
<th>M100H1, H2</th>
<th>C100H</th>
<th>C100H1, H2</th>
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</thead>
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<tr>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>6.02 (154)</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>5.14 (132)</td>
<td>6.64 (170)</td>
<td>6.14 (157)</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
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<td>6.30 (162)</td>
<td>6.29 (162)</td>
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<td>NA</td>
</tr>
<tr>
<td>1/4 VCD</td>
<td>4.56 (117)</td>
<td>6.06 (155)</td>
<td>3.36 (85)</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1/2 VCD</td>
<td>5.00 (128)</td>
<td>6.50 (167)</td>
<td>6.00 (154)</td>
<td>8.56 (220)</td>
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<td>10.01 (257)</td>
<td>NA</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>8.78 (225)</td>
<td>NA</td>
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<td>1/4 VNPT</td>
<td>4.88 (125)</td>
<td>6.38 (164)</td>
<td>5.88 (151)</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1/2 VNPT</td>
<td>5.18 (133)</td>
<td>6.68 (171)</td>
<td>6.18 (158)</td>
<td>6.38 (162)</td>
<td>NA</td>
<td>10.43 (267)</td>
<td>NA</td>
</tr>
<tr>
<td>8 mm compression</td>
<td>5.94 (129)</td>
<td>6.54 (168)</td>
<td>6.04 (155)</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>10 mm compression</td>
<td>5.29 (133)</td>
<td>6.70 (172)</td>
<td>6.20 (159)</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>12 mm compression</td>
<td>5.38 (138)</td>
<td>6.88 (176)</td>
<td>6.38 (164)</td>
<td>8.90 (228)</td>
<td>NA</td>
<td>10.35 (265)</td>
<td>NA</td>
</tr>
<tr>
<td>1/4 FNPT</td>
<td>4.85 (124)</td>
<td>6.35 (163)</td>
<td>5.85 (150)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3/8 FNPT</td>
<td>NA</td>
<td>6.50 (167)</td>
<td>6.00 (154)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>1/2 FNPT</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>9.14 (234)</td>
<td>NA</td>
<td>10.59 (272)</td>
<td>NA</td>
</tr>
<tr>
<td>3/4 FNPT</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>9.24 (237)</td>
<td>8.18 (225)</td>
<td>10.69 (274)</td>
</tr>
<tr>
<td>1 inch compression</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>8.52 (219)</td>
<td>NA</td>
</tr>
</tbody>
</table>

---

Note: All mounting holes are indicated in black circles on the blueprints.
Physical Dimensions

All dimensions are in inches with mm in brackets. Certified drawings are available on request.

M100H1,H1,H2 Front View

M100H1,H1,H2 Side View

M100H1,H1,H2 Bottom View

C100H1,H2 Front View

C100H1,H2 Side View

C100H1,H2 Bottom View
### Ordering the Smart-Trak®

<table>
<thead>
<tr>
<th>PARENT NUMBER</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M  100</td>
<td>Smart-Trak Mass Flow Meter</td>
</tr>
<tr>
<td>C  100</td>
<td>Smart-Trak Mass Flow Controller</td>
</tr>
</tbody>
</table>

### FLOW RANGE
- L  Flows from 0-10 sccm to 0-50 slpm
- M  Flows from 0-20 sccm to 0-200 slpm
- H  Flows from 0-100 sccm to 0-500 slpm
- H1  Flows from 0-501 sccm to 0-800 slpm
- H2  Flows from 0-801 sccm to 0-1000 slpm

### PILOT MODULE DISPLAY/INTERFACE
- NR  No Display/Interface
- DD  Pilot Module Display/Interface
- RD  Remote Pilot Module Display/Interface

### INLET/OUTLET FITTINGS

<table>
<thead>
<tr>
<th>1</th>
<th>1/8 compression (max 5 slpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1/4 compression (10 to 10 slpm)</td>
</tr>
<tr>
<td>3</td>
<td>1/8 compression (15 to 30 slpm)</td>
</tr>
<tr>
<td>4</td>
<td>1/8 compression (50 to 150 slpm)</td>
</tr>
<tr>
<td>5</td>
<td>1/4 compression (10 slpm)</td>
</tr>
<tr>
<td>6</td>
<td>1/4 compression (50 slpm)</td>
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<tr>
<td>7</td>
<td>1/4 compression (100 slpm)</td>
</tr>
<tr>
<td>8</td>
<td>1/4 compression (500 slpm)</td>
</tr>
<tr>
<td>9</td>
<td>1/4 compression (1000 slpm)</td>
</tr>
</tbody>
</table>

### FLOW BODY ELASTOMERS
- CP1  Viton or equivalent (Standard)
- ON1  Neoprene or equivalent (Available with CP1)

### VALVE SEAT (C100 Flow Controllers Only)
- SV1  Viton or equivalent
- SN1  Neoprene or equivalent
- SK1  Kather or equivalent (100k)
- SK2  Kather or equivalent (1000k)

### INPUT POWER
- PV1/M  11-22 VDC, linear (Flow Meters Only)
- PV1/C  15-22 VDC, linear (Controllers Only)
- PV2  24 VDC, linear (Standard)

### OUTPUT SIGNAL
- V1  4-20 mA and 0-5 VDC, linear
- V2  4-20 mA and 1-5 VDC, linear
- V3  4-20 mA and 0-10 VDC, linear

### EXTERNAL SETPOINT SIGNAL (Flow Controllers Only)
- S6  Pilot Module X252 (Standard for DD, RD)
- S1  0-5 VDC, standard for NR
- S2  1-5 VDC
- S3  0-10 VDC
- S4  4-20 mA

### ELECTRICAL CONNECTION
- C0  15 pin mating connector with no cable
- C1  6 inch (15cm) cable
- C2  3 foot (1m) cable
- C10  10 foot (3m) cable
- C ( )  Custom length cable

### OPTIONS
- C1  Gas Substitution (Replace up to 9 Dial-A-Gas Cassettes)
- LF  Low Flow Calibration (required for 0-20 sccm and below)

### FOR ACCESSORIES, NORTH AMERICA
- Sierra Instruments, 1353 Eastlake Avenue, Monrovia, CA 91016
- (626) 282-8411

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